Santé, environnement, risque et incertitude : analyse des comportements individuels et des investissements des entreprises

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Santé, environnement, risque et incertitude : analyse des comportements individuels et des investissements des entreprises

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Table des matières

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Santé, environnement, risque et incertitude : analyse des comportements individuels et des investissements des entreprises

Résumé

Ce mémoire d'Habilitation à Diriger des Recherches présente mes travaux de 2011 à 2018 qui ont porté sur les comportements des individus face à un risque et sur les choix d'investissement des entreprises innovantes. Tout d'abord, le comportement individuel est estimé à partir des méthodes de préférences déclarées. L'impact de l'information et de plusieurs dispositifs fiscaux et réglementaires (taxe, subvention et norme) est alors examiné afin de déterminer les politiques publiques de santé et/ou environnementales efficaces pour inciter les individus à adopter un comportement réduisant le risque étudié. Trois comportements affectant l'exposition au risque sont analysés : la mise en place du confinement à domicile afin de lutter contre une épidémie de grippe ; l'utilisation de bouteilles d'eau en plastique générant de la pollution et des déchets ; et l'usage de véhicules à fortes émissions de gaz à effet de serre accroissant la pollution de l'air. Ensuite, le comportement des entreprises innovantes dans leurs choix d'investissement (réversible ou irréversible), d'acquisition d'information et de communication (lobbying) est étudié en utilisant la théorie des options réelles et les méthodes bayésiennes. L'importance des préférences des dirigeants de ces entreprises, l'effet du principe de précaution et des règles de responsabilité sur ces choix, ainsi que celui de l'incertitude sur la demande et de l'ambiguïté sur le niveau de concurrence du marché, sont alors approfondis.

Mots clés : comportement, environnement, incertitude, information, investissement, lobby, politiques publiques, risque, santé.

Health, environment, risk and uncertainty :
analysis of individuals' behaviours and firms' investments

Abstract

This thesis for the accreditation to supervise research presents my work from 2011 to 2018, which focused on the individuals' behaviours faced with a risk and the innovative firms' investments. First, the individual's behaviour is estimated from the stated preference methods. The impact of information and several tax and regulatory devices (tax, subsidy and standard) is then examined in order to determine public health and/or environmental policies that are effective in encouraging individuals to adopt behaviour that reduces the risk studied. Three risks are analyzed : setting up home confinement to fight against an influenza epidemic ; the use of plastic water bottles generating pollution and waste ; and the use of vehicles with high greenhouse gas emissions increasing air pollution. Then, using the theory of real options and Bayesian methods, the behaviour of innovative firms in their investment choices (reversible or irreversible), acquisition of information and communication (lobbying) is studied. The importance of the firm's leadership preferences, the effect of the precautionary principle and the liability rules on these choices, as well as the demand uncertainty and ambiguity on the level of market competition, are then deepened.

Keywords : behaviour, environment, health, information, investment, lobby, public policies, risk, uncertainty.

Introduction

Les risques sanitaires et environnementaux occupent une place importante dans le débat public en France. Les vives polémiques suscitées par l'extension à onze vaccins obligatoires pour la petite enfance mise en place en janvier 2018, ou les confrontations liées à la création d'une zone piétonnière dans Paris pour limiter la pollution de l'air, montrent l'intérêt public porté sur les risques. Le risque est défini par l'ensemble des événements possibles qui peuvent en résulter, ainsi que par la probabilité connue associée à chacun de ces événements. Cependant, nos connaissances peuvent être insuffisantes pour déterminer ces probabilités. Il est actuellement difficile de déterminer les probabilités d'occurrences des conséquences de l'utilisation des organismes génétiquement modifiés (OGM) ou de l'implantation d'antennes-relais de téléphone mobile (ondes électromagnétiques) sur la santé et sur l'environnement. C'est en ce point que réside la différence entre risque et incertitude (Frank Knight, 1921).

Définir les politiques de santé et environnementales qui permettent de réduire le risque et l'incertitude est à l'origine de mes questionnements. Traiter économiquement ce problème permet de fournir des arguments afin d'aider les décideurs publics à inciter les agents économiques à gérer, de façon socialement souhaitable, le risque ou l'incertitude auxquels ils sont confrontés. Cependant, avant toutes recommandations, la question de savoir comment les différents acteurs économiques (individus, entreprises et institutions publiques) décident de leurs actions quand ils sont en présence de risque et d'incertitude est crucial. Notamment, étudier leur prise de conscience de ces risques, leur appréhension et leur stratégie, est devenue un objectif central dans mes réflexions de recherche. Le choix d'application aux domaines de la santé et de l'environnement est motivé par les nombreuses crises sanitaires et les modifications que notre écosystème subit suite à l'activité humaine auxquelles nous avons dû faire face ces dernières années.

Les travaux présentés dans cette synthèse utilisent deux approches : théorique et empirique. La théorie concernant l'offre est très riche en économie. Ce développement théorique permet de modéliser les préférences des dirigeants de firmes, et d'introduire des notions telles que l'aversion à l'ambiguïté qu'il est difficile d'analyser empiriquement. Les données portant sur les comportements des firmes étant très compliquées à obtenir. Je me suis focalisée sur les choix des entreprises innovantes, c'est à dire des entreprises dont la production pouvait générer de l'incertitude sur les futurs profits et sur les coûts de potentiels dommages sur la santé et l'environnement. A l'aide de la théorie des options réelles et des méthodes bayésiennes, j'ai abordé dans mes travaux la question de l'interaction entre les choix d'une entreprise innovante et des politiques publiques de santé et environnementales.

Du côté de la demande, l'obtention de données est plus aisée. J'ai utilisé une approche empirique, une enquête, afin d'extraire et d'expliquer les préférences déclarées des individus. L'individu est placé dans un contexte de risque et interrogé sur ses choix entre différents biens ou actions pouvant réduire ou au contraire amplifier l'occurrence des situations les plus défa-

vorables. Des politiques publiques sont alors testées afin d'analyser les modifications des choix des individus et les impacts économiques que celles-ci engendrent. L'étude du comportement de l'individu face au risque permet ainsi d'aider les décideurs publics dans leurs choix de politiques de santé et environnementales.

En définitive, dans mes travaux, les approches théorique et empirique ont la même finalité. Elles me permettent d'expliquer et de prédire le comportement des agents économiques (individus, firmes et institutions). Elles m'autorisent également à étudier l'effet des politiques publiques sur la modification des choix des individus et des firmes innovantes, et à fournir des recommandations.

Ce document présente tout d'abord la synthèse de mes travaux de recherche depuis ma thèse. Cette synthèse repose sur la présentation de sept articles publiés dans des revues internationales à comité de lecture. Elle se décline en deux parties ayant comme fil conducteur l'interaction entre les décisions des agents économiques en présence de risque et d'incertitude, et les politiques publiques mises en place. La première partie s'intéresse à la demande, plus précisément aux choix des personnes (individus ou consommateurs) et la seconde à l'offre, en particulier aux décisions d'investissement des entreprises innovantes.

La première partie s'appuie sur trois travaux empiriques publiés. Tout d'abord, je me suis intéressée aux mesures de prévention pour lutter contre les épidémies de grippe. Plus spécifiquement, je me suis concentrée sur le confinement à domicile, une mesure efficace pour réduire le nombre de malades mais qui est peu utilisée en France contrairement aux autres pays. J'ai ainsi réalisé une enquête auprès de français pour analyser leur comportement face à la mise en oeuvre de cette politique. Puis, j'ai étudié l'efficacité économique de cette mesure. Je me suis ensuite interrogée sur le comportement des consommateurs de bouteilles d'eau en plastique en France et sur leur prise de conscience de l'impact sur l'environnement que la pollution par le plastique peut engendrer. A l'aide d'une enquête, j'ai pu déterminé les politiques économiquement efficaces à mettre en place pour réduire le risque environnemental. Puis, j'ai tenté d'expliquer l'échec des campagnes d'information incitant l'utilisation des véhicules à faibles émissions de gaz à effet de serres. A travers une enquête, j'ai pu comprendre les déterminants des choix des utilisateurs de véhicules à fortes émissions. J'ai par la suite recommandé des mesures et des instruments de régulation aux décideurs publics afin de réduire le risque de pollution de l'air.

La deuxième partie se fonde sur quatre travaux théoriques publiés qui s'intéressent aux décisions d'acquisition d'information (recherche), d'investissement (irréversible ou réversible) et de communication (stratégie de lobbying) d'une firme innovante. L'importance des préférences du dirigeant de cette firme, l'effet du principe de précaution et des règles de responsabilité sur ces décisions, ainsi que celui de l'incertitude sur la demande et de l'ambiguïté sur le niveau de concurrence du marché, sont étudiés.

Pour chacun des travaux, les apports à la littérature existante, les modèles ou méthodes utilisés et les principaux résultats sont abordés. Tous les articles mentionnés dans cette synthèse

sont regroupés dans le volume reprenant les publications joint à ce document.

Étant enseignant-chercheur, une grande partie de mon travail est consacré à l'enseignement. Je forme des étudiants ingénieurs et de l'université à partir du niveau Master. Le choix de mes enseignements est très connecté avec mes intérêts de recherche. Je présente dans une seconde partie le lien entre mon activité d'enseignement et de recherche, ainsi que les encadrements qui en découlent.

Dans une troisième partie, j'aborde mes perspectives de recherches à travers deux projets en cours. Je développe également mes motivations pour le passage de l'Habilitation à Diriger des Recherches à savoir : le montage de projets de recherche, l'encadrement de doctorants et post-doctorants, la direction de Master ou Mastère spécialisé, et la possibilité de passer le concours pour le grade de Professeur.

Finalement, dans les quatrième et cinquième parties, la liste des travaux et références bibliographiques, ainsi que le Curriculum Vitae détaillant les responsabilités et communications, sont respectivement fournis.

1 Synthèse des travaux de recherche

Dans cette synthèse, je présente tout d'abord des travaux analysant les comportements individuels face au risque. Le premier travail s'intéresse à un risque sanitaire, la mise en place du confinement à domicile afin de lutter contre une épidémie de grippe. Le deuxième travail concerne un risque environnemental, l'utilisation de bouteilles d'eau en plastique générant de la pollution et des déchets. Finalement, le troisième travail traite d'un risque qui peut être à la fois sanitaire et à la fois environnemental, l'usage de véhicules à fortes émissions de gaz à effet de serre accroissant la pollution de l'air.

Dans la seconde partie, j'expose des travaux étudiant les comportements des entreprises innovantes dans leurs choix d'investissement, d'acquisition d'information et de communication. Le premier travail aborde la question de l'acquisition d'information (à travers de la recherche) de firmes, ayant différents types de préférences, pour réduire l'incertitude sur les conséquences sur la santé et l'environnement de la fabrication d'un produit innovant. Le deuxième travail étudie l'effet du principe de précaution sur le niveau d'investissement irréversible et l'acquisition d'information d'une firme innovante. Le troisième travail examine les niveaux d'investissement irréversible et de production d'une firme dans un contexte d'incertitude sur la demande et sur le niveau de concurrence du marché et introduit la notion d'ambiguïté. Finalement, le dernier travail observe l'interaction entre l'incertitude scientifique, l'effort de communication (pouvant être falsifiée) des firmes et les politiques publiques.

1.1 Comportements des individus face au risque

Les travaux présentés dans cette partie analysent les comportements des individus face à des risques sanitaires et/ou environnementaux. Ils s'intéressent plus précisément à la valeur que les individus attribuent à différents dispositifs de réduction des risques. La méthode des préférences révélées n'étant pas utilisable dans notre cadre à cause du manque de données sur les choix réels, nous avons choisi d'utiliser des méthodes de préférences déclarées, notamment le consentement à payer et le consentement à accepter. L'utilisation des méthodes de préférences déclarées est présentée et développée par Kroes et Sheldon (1988) et Louviere et al (2000) dans divers domaines. Le consentement à payer permet de révéler la valeur attribuée par les individus pour un bien à travers le prix maximal qu'ils consentent à payer pour ce bien. Cette méthode repose sur les modèles de la théorie du consommateur. Le consentement à accepter permet de définir la participation ou la non-participation des individus pour faire une action.

Nous avons mis en oeuvre les enquêtes d'évaluation des préférences des individus à l'aide de questionnaires en ligne [1]. Cobanoglu et al (2001), Couper (2000), et McDonald et Adam (2003) soulignent que les études en ligne permettent de gagner du temps et de l'énergie dans la collecte de données. De plus, Fricker et al (2005), Heerwegh et Loosveld (2008), et Kreuter

1. La mise en ligne du questionnaire et la collecte des données ont été effectués par la société Createst, un cabinet d'études marketing français.

et al (2008) montrent qu'elles permettent d'obtenir des réponses de qualité avec moins de « je ne sais pas » et moins de non réponses que les sondages par téléphone ou face à face. Par conséquent, la collecte en ligne ne présente pas moins de désavantages que d'autres types de méthodes de collecte.

Pour étudier les choix individuels, en guise d'introduction au questionnaire, une présentation des auteurs de l'analyse, le détail des objets d'étude traités, et l'objectif du questionnaire sont fournis aux participants. Comme Lusk (2003) le suggère, cela permet de réduire le biais hypothétique des études. Nous complétons le questionnaire par des questions de contrôle sur le genre, l'âge, le revenu, la composition du ménage, la catégorie socio-professionnelle et d'autres questions spécifiques liées à la sensibilité de l'individu pour l'objet d'étude traité. Les participants sont sélectionnés en utilisant la méthode des quotas, c'est-à-dire les mêmes proportions de genre, d'âge, du revenu, de la composition du ménage et de la catégorie socio-professionnelle que celles du recensement de la population française par l'Institut national de la statistique et des études économiques (INSEE) en 2013.

Commençons tout d'abord par un risque sanitaire, avec l'étude de la mise en place d'une mesure de prévention, le confinement à domicile, pour lutter contre une épidémie de grippe. En France, la grippe affecte entre un et quatre millions de personnes chaque année, et cause entre 1 500 et 2 000 décès, principalement parmi les personnes de plus de 65 ans. Le vaccin contre la grippe a une faible efficacité en raison de la variabilité des souches grippales. L'Organisation Mondiale de la Santé (OMS) décide en février de la composition du vaccin à utiliser pour la campagne de vaccination d'octobre. Ensuite, le vaccin est fabriqué en fonction des souches circulantes, mais certaines souches peuvent muter. Cela s'est produit en France durant l'hiver 2014-2015, lorsque la grippe a causé plus de 18 000 décès parmi les personnes vaccinées contre la grippe. Des mesures préventives doivent être prises par les autorités de santé publique pour prévenir (avant que le vaccin soit trouvé) ou pour compléter l'utilisation du vaccin (quand le vaccin existe). Selon l'OMS, la réduction de l'intensité de contact par confinement à domicile (isolement et quarantaine) et la distanciation sociale est très efficace pour réduire l'incidence de la grippe, en particulier aux premiers stades de la pandémie (Chao et al, 2010 ; Kelso et al., 2009 ; Milne et al, 2008). Pourtant, le confinement à domicile est peu utilisé en France en cas d'épidémie de grippe. Le confinement à domicile consiste à recommander aux personnes susceptibles d'être infectées et à leurs familles de rester à la maison pendant sept jours (Haber et al., 2007). Sept jours correspondent à la durée recommandée par le Centre de contrôle et de prévention des maladies (2007). Les personnes confinées peuvent seulement être en contact avec les membres de leur famille. Pendant le confinement, une aide médicale, c'est-à-dire des soins à domicile, peut également être fournie. Quelle attitude adopteraient les Français si cette mesure était mise en place ? Cette mesure est-elle économiquement rentable ?

Pour répondre à ces questions, nous interrogeons 200 français âgés de 18 à 72 ans entre mars et avril 2014. En guise d'introduction au questionnaire, nous leur expliquons à la fois

que le confinement à domicile consiste à rester à la maison avec pour seul contact les autres membres de leur famille et à la fois les caractéristiques de la grippe (symptômes, durée ...). Nous plaçons ensuite les participants dans une situation hypothétique où une épidémie aurait été signalée et où ils auraient été en contact avec une personne infectée. Nous leur demandons de choisir le nombre maximum de jours pendant lesquels ils seraient prêts à se confiner chez eux. Par la suite, nous leur posons la même question en ajoutant l'intervention d'une assistance médicale, une visite d'un professionnel de la santé qui vérifie l'état de santé du participant pendant le confinement. Cette situation nous permet de mettre en évidence l'effet du suivi médical. Puis, nous leur posons la même question que précédemment, en modifiant la situation initiale par le fait qu'ils n'ont pas été en contact avec des personnes infectées. Cette situation nous permet d'analyser l'impact du risque de contamination sur la décision du participant. Demander le nombre de jours, et non pas directement si le participant se conformerait au confinement à domicile, est un moyen d'éviter le biais d'ancrage. Cela permet d'évaluer la durée pendant laquelle les participants seraient volontairement disposés à rester chez eux en supprimant l'aspect d'efficacité de la mesure sanitaire. Ainsi, nous évitons une déviation de comportement si cette mesure devait être appliquée en cas d'épidémie. Pour l'analyse de nos résultats, nous transformons les réponses de nos participants sur le nombre de jours en une nouvelle variable binaire représentant la participation au confinement. Nous considérons que le participant participe s'il choisit un nombre de jours supérieur ou égal à sept et ne participe pas s'il choisit un nombre de jours inférieur.

A partir d'une analyse descriptive des réponses au questionnaire, nous observons que plus des trois quarts des participants sont prêts à se confiner à domicile en cas d'épidémie de grippe. Les personnes âgées (de plus de 64 ans) sont plus disposées à s'y soumettre que les adultes (de 18 à 64 ans). De plus, le suivi médical pendant le confinement à domicile rassure les participants et les incite à se confiner. L'assistance médicale est l'assurance d'être pris en charge en cas de développement de la maladie. Nous trouvons également qu'un plus grand nombre de personnes âgées indique qu'elles respecteraient le confinement à domicile lorsqu'elles n'ont pas été en contact avec une personne contaminée. Les personnes âgées vérifient l'effet de certitude de Kahneman et Tversky (1979). Elles préfèrent éliminer le risque plutôt que de le réduire. Enfin, dans notre étude, le fait d'avoir été en contact avec une personne infectée rend les participants moins susceptibles de se confiner. Le comportement égoïste est ainsi mis en évidence.

A partir d'un modèle Probit et du test du khi-deux, nous étudions, respectivement, les déterminants de la probabilité de respecter le confinement à domicile, et le lien entre le fait que le participant ait déjà expérimenté des mesures de prévention contre les épidémies (masque, isolation...) et le respect du confinement à domicile [2]. Nous trouvons que les participants ont plus tendance à respecter le confinement à domicile lorsqu'ils sont plus âgés et ont un foyer

2. Le test du khi-deux est utilisé pour déterminer s'il existe une différence significative entre les fréquences attendues et celles observées dans une ou plusieurs catégories. Toutes les méthodes économétriques citées dans cette synthèse : modèle Probit, modèle de régression des moindres carrés, modèle de logistique multinomiale et modèle de panel à effets aléatoires sont détaillées dans le livre de Greene (2017).

plus nombreux. En revanche, les participants ont tendance à moins respecter le confinement à domicile lorsqu'ils font partie des personnes les plus aisées. De plus, nous obtenons que contrairement à Blendon et al (2006), il n'y a aucun lien entre le fait d'avoir expérimenté des mesures de prévention et le choix de respecter le confinement à domicile.

Afin de déterminer le rapport coût-efficacité du confinement à domicile, nous identifions, mesurons et évaluons les coûts (directs, indirects et intangibles avec la mesure de la valeur statistique de la vie humaine qui représente le bénéfice pour la Société d'éviter une mort) de la grippe et ceux du confinement à domicile en France. Nous utilisons les données détaillées sur la prévalence [3], l'incidence de la maladie [4] et le taux d'incidence [5] de 2005 à 2014 fournis par le réseau Sentinelles [6]. Néanmoins, par manque de données, nous ne pouvons pas construire un modèle mathématique sur la réduction de l'incidence de la grippe avec une politique de confinement à domicile. Longini et al. (2005) et Haber et al. (2007) ont pu faire des modèles de simulation stochastique des épidémies de grippe dans des pays qui ont déjà appliqués cette mesure. Cela n'est pas le cas de la France. Nous calculons alors le seuil de réduction de l'incidence à partir duquel le confinement à domicile est économiquement rentable. Nous trouvons qu'en comparant nos résultats avec ceux de Longini et al. (2005) et Haber et al. (2007), et en considérant les conclusions de notre questionnaire, la mesure de prévention de confinement à domicile serait économiquement rentable. En conséquence, le confinement à domicile est une piste intéressante de prévention contre les épidémies de grippe qui mériterait d'être approfondie avec un modèle épidémiologique pouvant déterminer son impact exact en France.

Le travail décrit a donné lieu à la publication d'un article intitulé : ***People's perception and cost-effectiveness of home confinement during an influenza pandemic : evidence from the French case*** **dans European Journal of Health Economics en 2018.** Il comble un manque de la littérature en épidémiologie en étudiant les perceptions et les comportements individuels face à la mise en place du confinement à domicile pour limiter les épidémies de grippe (Zhu et al, 2017). De plus, il complète la littérature traitant de l'analyse coût-efficacité des mesures de prévention des maladies infectieuses (Achonu et al, 2005 ; Adda, 2016 ; Gupta et al, 2005 ; Mubayi et al, 2010) en la réalisant sur le confinement à domicile pour les épidémies de grippe.

Passons maintenant à un risque environnemental, avec l'étude de l'utilisation des bouteilles d'eau en plastique. Les bouteilles d'eau en plastique sont utilisées partout dans le monde. Aujourd'hui, 89 milliards de litres d'eau sont embouteillés avec des emballages plastiques et consommés chaque année dans le monde. Les français sont les troisièmes plus grands consommateurs de bouteilles d'eau en plastique derrière les italiens et les américains. Selon TNS

3. La prévalence est le nombre de cas de maladies enregistrés à un moment donné pour une population déterminée et englobant aussi bien les nouveaux cas que les anciens cas.

4. L'incidence dénombre le nombre de cas de maladie apparus pendant une année au sein d'une population.

5. Le taux d'incidence est le nombre d'individus ayant contracté une maladie pour 1000 personnes exposées au risque de cette maladie. Il se calcule en général pour une année.

6. Ce réseau de recherche et de veille français collecte des données épidémiologiques en temps réel auprès des médecins généralistes et des pédiatres en France.

Sofres, 85% des Français boivent de l'eau dans des bouteilles en plastique. Pourtant, l'emballage plastique produit une quantité importante de déchets et est très résistant à la biodégradation environnementale (environ 500 ans pour se biodégrader dans la nature). Selon Azzarello et Van Vleet (1987), Derraik (2002), Moore (2008), Saido (2014) et Sazima et al. (2002) les déchets de plastique créent une menace directe pour la faune et la flore aussi bien dans les zones terrestres que marines. L'utilisation des bouteilles d'eau en plastique est donc un risque environnemental. Plusieurs questions apparaissent alors : les consommateurs se préoccupent-ils des répercussions environnementales de leur consommation de bouteilles d'eau en plastique ? Quelles politiques environnementales pourraient être proposées ? Comment les politiques environnementales modifient les décisions d'achat des consommateurs ?

Afin de répondre à ces questions, nous interrogeons 148 français âgés de 18 à 79 ans en février 2014, sur les quatre types de plastique existants sur le marché : PET (recyclable), r-PET (recyclé et recyclable), PLA (biologique et biodégradable) et PEF (biologique et recyclable), avec un questionnaire en ligne. Les participants sont tous des acheteurs et consommateurs de bouteilles d'eau en plastique. Le questionnaire est le suivant : d'abord, un texte aide les participants à comprendre le but de cette étude. Aucune information n'est donnée sur les différents types de plastique. Ensuite, les participants remplissent un questionnaire d'entrée sur leur comportement de consommation de bouteille d'eau en plastique et sur leurs caractéristiques sociodémographiques. Enfin, ils reçoivent un premier message leur indiquant le prix moyen d'un pack de six bouteilles d'eau en plastique de 1.5L sur le marché, puis sept messages consécutifs ayant pour objet de les informer sur les dangers et les bénéfices de chacun des plastiques [7]. Après chaque message, nous demandons aux participants leur consentement à payer, c'est à dire, combien ils seraient prêts à payer au maximum pour un pack de six bouteilles d'eau en plastique de 1.5L fabriqué avec chacun des quatre types de plastique.

A partir de l'analyse descriptive des données récoltées, nous obtenons que l'information modifie les consentements à payer des participants. Une information portant sur un impact négatif sur l'environnement aura plus d'effet sur le consentement à payer qu'une information positive. Nous retrouvons le résultat de la théorie des perspectives de Kahneman et Tversky (1979). A partir d'une régression des moindres carrés sur les consentements à payer regroupés et d'une autre sur les primes d'utiliser un plastique au lieu d'un autre regroupées, nous observons que les participants valorisent le plastique recyclé (r-PET) et le plastique biologique et biodégradable (PLA). Néanmoins, l'information sur le manque de capacité de recyclage du plastique biologique et biodégradable fait diminuer leur consentement à payer pour celui-ci de façon significative.

Contrairement à l'arbitrage entre produits conventionnels et biologiques pour lequel le régulateur choisit de soutenir les produits biologiques car ils sont plus sains pour la santé et leur production réduit les dommages sur l'environnement, la question des emballages plastiques est plus technique et complexe. Aucun consensus scientifique ne valorise un plastique

7. Les messages sont détaillés dans l'appendice de cet article, se trouvant dans le recueil des travaux de recherche. Le déroulement du questionnaire est précisé dans la Figure 1.

par rapport à l'autre. Différentes politiques de protection de l'environnement peuvent alors être proposées : une campagne d'information (basée sur les messages que nous avons fournis) afin de sensibiliser les personnes aux dommages causés par les bouteilles en plastique sur l'environnement ; une politique valorisant les plastiques biologiques fabriqués à partir de ressources renouvelables (PLA et PEF) ; une politique valorisant les plastiques biodégradables (PLA) ; et une politique valorisant les plastiques recyclables (PET, r-PET et PEF). Pour les trois dernières politiques, trois instruments de régulations sont avancés : une taxe, une subvention ou une norme (interdiction). Nous constatons que du point de vue du surplus du consommateur, la réglementation est efficace avec une subvention sur les plastiques biologiques, sur les plastiques recyclages et sur ceux biodégradables. Nous observons que la campagne d'information, la taxe sur les plastiques non biologiques, la norme sur les plastiques biologiques, la norme sur les plastiques recyclables et les trois instruments de la politique sur les plastiques biodégradables ont conduit de nombreux consommateurs à quitter le marché des bouteilles d'eau en plastique. Cela nous permet donc de comprendre que la politique et le choix des outils du régulateur ne sont pas évidents. Cela dépendra de ses priorités (réduction des émissions de CO_2, réduction des déchets, réduction de la toxicité, augmentation du surplus du consommateur, diminution de la consommation de bouteilles d'eau en plastique) et des pressions des lobbies.

Cependant, d'autres pistes peuvent être explorées pour limiter l'impact des bouteilles d'eau en plastique sur l'environnement. Par exemple, celles de la substitution en utilisant le verre, qui peut également être un polluant pour l'environnement selon Ferrara et Plourdes (2003), ou en buvant l'eau du robinet. Par ailleurs, ce travail peut être un moteur d'innovation pour les entreprises fabriquant des emballages de bouteilles en plastiques. Une bouteille en plastique comportant les trois propriétés (biologique, recyclable et biodégradable) répondrait à la fois à une demande des consommateurs et à celle de la protection de l'environnement.

Le travail exposé dans cette partie a donné lieu à la publication d'un article co-écrit avec deux étudiants du Mastère spécialisé 'Management des risques sanitaires alimentaires et environnementaux' (ALISEE) d'AgroParisTech-Université Paris-Saclay-Université Paris 1 Panthéon-Sorbonne, Université Paris Desccartes, Nicolas Barret et Aurélien Lemaire, intitulé : ***How consumers of plastic water bottles are responding to environmental policies ?*** **dans Waste Management en 2017.** Il contribue à la littérature qui examine l'interaction entre le consentement à payer et l'acquisition d'information (Bernard et Bernard, 2009 ; Bougherara et Combris, 2009 ; Disdier et al, 2013 ; Marette et al, 2012 ; Marette et Millet, 2014 ; Yue et al., 2009) en examinant l'impact précis de l'information sur le consentement à payer des consommateurs pour les bouteilles d'eau en plastique et en analysant les primes pour les bouteilles d'eau en plastique organique, recyclé et biodégradable. De plus, il participe à la littérature en économie écologique sur la réduction de la pollution et des déchets sur l'environnement qui présente de grandes avancées du point de vue des producteurs (Da Cruz et al., 2012, 2014 ; Hage, 2007 ; Mayers, 2007 ; Numata, 2009 ; Palmer et Walls, 1997) mais qui n'a pas étudié cette question sous l'angle des consommateurs.

Finalement, nous traitons un risque qui peut être à la fois sanitaire et à la fois environnemental, l'usage de véhicules à fortes émissions de gaz à effet de serre. De nombreuses actions ont été menées en France pour réduire les impacts négatifs des moyens de transport, tels que les taxis ou les voitures diesel, sur la qualité de l'air. Ces actions visaient à encourager les personnes à utiliser des véhicules à faibles émissions de gaz à effet de serre, en particulier les transports publics et les voitures électriques. De nombreuses études sur les effets néfastes de la pollution de l'air sur la santé et sur l'environnement ont été réalisées (Air Parif, 2016 ; Douglas et al, 1993 ; Krewski et al, 2004). Malgré cela les français continuent d'utiliser les transports à fortes émissions de gaz à effet de serre. Pourquoi continuent-ils ? Sont-ils conscients des impacts négatifs de la pollution de l'air sur la santé et l'environnement ? Comment les conduire à utiliser des véhicules à faibles émissions ?

Pour répondre à ces questions, nous interrogeons 342 français âgés de 20 à 80 ans, en février 2015, sur leur mode de transport pour effectuer le trajet du centre de Paris (Métro Châtelet, Paris) à l'aéroport de Paris Charles de Gaulle, avec un questionnaire en ligne. Les modes de transport étudiés sont : le taxi et la voiture personnelle (véhicules à fortes émissions de gaz à effet de serre), la voiture électrique de location et les transports publics (véhicules à faibles émissions). Le trajet dure 30 minutes avec chacun des transports et est distant de 33km par l'autoroute A_1 Saint Denis. Ce trajet est utilisé tous les jours pour les loisirs et les voyages d'affaires. Par conséquent, même les Français qui ne résident pas à Paris peuvent avoir effectué ce voyage. De plus, l'autoroute A_1 Saint Denis est l'une des portions de route les plus polluées de France. Nous divisons nos participants en deux groupes sélectionnés en utilisant la méthode des quotas. Chacun des groupes reçoit un questionnaire. Les deux questionnaires ne différent que par l'ordre des sept messages reçus. [8]. Le premier groupe est composé de 177 participants et reçoit d'abord quatre messages sur l'impact négatif de la pollution de l'air sur la santé et ensuite deux sur l'environnement. Le deuxième groupe est composé de 165 participants et reçoit d'abord deux messages sur l'impact négatif sur l'environnement puis quatre sur la santé. Le texte introductif et le premier message, qui indique le prix du marché pour chacun des transports, sont communs aux deux questionnaires. Après chaque message, les participants doivent donner le prix maximum qu'ils seraient prêts à payer pour effectuer le trajet avec chacun des transports. Puis des questions de contrôle sur le comportement et les caractéristiques socio-professionnelles sont posées.

A partir de l'analyse descriptive, nous trouvons que l'information modifie les consentements à payer des individus et leur choix pour les transports. En revanche, l'ordre dans lequel les messages sont donnés n'a aucun impact. Les messages fournis ne parviennent pas à diminuer les préférences et le choix des participants pour la voiture personnelle. À partir de cette étude, nous avons alors une meilleure compréhension de la non-adoption des véhicules à faibles émissions malgré de nombreuses campagnes de sensibilisation. En effet, dans les deux groupes,

8. Les messages sont détaillés dans l'appendice de cet article se trouvant dans le recueil des travaux de recherche. Le déroulement du questionnaire est précisé dans la Figure 1 et l'objectif des messages dans le Tableau 4.

au fur et à mesure que les messages sont diffusés, les participants augmentent en moyenne leur consentement à payer pour la voiture personnelle.

Avec un modèle de panel à effets aléatoires, nous montrons que susciter l'intérêt pour l'indice de pollution de l'air et rassurer les voyageurs sur la fiabilité des recommandations données concernant la pollution de l'air augmenterait leur consentement à payer pour les moyens de transport à faibles émissions de gaz à effet de serre. Avec un modèle de logistique multinomiale, nous vérifions que le fait de rassurer les voyageurs sur la fiabilité des recommandations serait un bon moyen pour les amener à choisir des moyens de transport à faibles émissions plutôt que des moyens de transport à fortes émissions. En effet, donner l'assurance aux voyageurs que les recommandations données concernant la pollution de l'air sont fiables augmenterait le consentement à payer des voyageurs pour les transports publics, puis augmenterait la probabilité que les voyageurs choisissent un moyen de transport à faibles émissions par rapport au transport à fortes émissions. En outre, nous montrons que les voyageurs qui attachent une grande importance au confort sont moins susceptibles que ceux qui valorisent plus le prix de choisir des véhicules à faibles émissions. L'intérêt individuel peut alors prévaloir sur l'intérêt collectif vérifiant ainsi la théorie de la tragédie des communs. Ainsi, améliorer le confort, notamment dans les transports en commun, pourrait être un moyen d'encourager les voyageurs à les utiliser.

Nous testons par la suite différentes options d'interventions réglementaires pour encourager les voyageurs à utiliser des véhicules à faibles émissions. Nous proposons tout d'abord une campagne d'information (basée sur les messages que nous avons fournis), puis une taxation des moyens de transport à fortes émissions de gaz à effet de serre (taxi et voiture personnelle), une subvention pour les moyens de transport à faibles émissions (véhicules électriques de location et transports publics) et enfin une norme imposant l'utilisation de véhicules à faibles émissions. Nous analysons ensuite les impacts de ces quatre interventions réglementaires sur les décisions des participants. Nous notons que les recommandations dépendent des différents objectifs du régulateur : augmentation du surplus du voyageur, augmentation du nombre de voyageurs pour les moyens de transport à faibles émissions et diminution pour les moyens de transport à fortes émissions, diminution du nombre de voyageurs ne prenant aucun des moyens de transport. Deux des politiques sont de bonnes alternatives et satisfont les différents objectifs : une campagne d'information associée avec une subvention des véhicules à faibles émissions, et uniquement une subvention des véhicules à faibles émissions. Ce résultat soutient et aide les politiques actuelles de réduction de la pollution de l'air mise en place par le maire de Paris.

L'étude décrite dans cette partie a donné lieu à la publication d'un article intitulé : ***How do travellers respond to health and environmental policies to reduce air pollution ?*** **dans Ecological Economics en 2019**. Il contribue à la littérature sur le consentement à payer (Baidoo et Nyarko, 2015 ; Hensher, 1994 ; Kotchena et al, 2013 ; Kroes et Sheldon, 1988 ; Louviere et al, 2000 ; Petrik et al, 2016 ; Suna et al, 2016 ; Wanga et al, 2016 ; Wardman, 1988) en étudiant le consentement à payer des voyageurs pour quatre moyens de transport à faibles et fortes émissions de gaz à effet de serre en France. Il participe également à la littérature sur la réduction de

la pollution de l'air (Agostinia et Jiménez, 2015 ; Bollena et Brink, 2014 ; Montag, 2015 ; Naqvi et Zwickl, 2017) en étudiant l'impact des politiques publiques de santé et environnementales sur le comportement du voyageur quant à son moyen de transport.

Les résultats fournis par le Baromètre IRSN chaque année sur la perception des risques par les Français ne sont pas assez précis pour permettre d'aider à la décision de politiques ou mesures de réduction de risques pour un risque spécifique. Pourtant, il est nécessaire d'étudier la perception et le choix des individus pour la mise en place d'une politique efficace. Les études empiriques présentées dans cette partie répondent à cette exigence. Les méthodes de préférences déclarées permettent de définir le comportement des individus et de calibrer les instruments de régulation qui conduiront à l'objectif prioritaire des régulateurs. Les outils économétriques aident à mieux comprendre ce qui caractérise les choix des individus. Ainsi, le régulateur peut cibler et inciter les individus vers son objectif en agissant sur leurs caractéristiques individuels ou psychologiques. Par ailleurs, ce type d'étude rend possible une meilleure compréhension de l'échec de certains programmes de réduction du risque déjà testés. Finalement, ces études permettent de faire un lien entre la théorie économique et le comportement réel des individus. L'effet de certitude et la théorie des perspectives de Kahneman et Tversky (1979) ainsi que la tragédie des communs ont ainsi été vérifiés dans le comportement des individus étudiés.

Après avoir exposé des études analysant les comportements individuels face à différents risques sanitaires et/ou environnementaux, cette synthèse présente les choix d'investissement, d'acquisition d'information et de communication des entreprises dans un contexte d'incertitude.

1.2 Investissements des firmes innovantes

Lorsqu'une firme investit dans un produit innovant, elle a une connaissance initiale limitée sur ses futurs profits. Elle doit anticiper ses bénéfices et pertes en tenant compte des caractéristiques du marché (concurrence, nouvelle demande) et des dommages potentiels sur la santé et l'environnement que sa production peut générer. Les politiques environnementales récentes favorisent le principe «pollueur-payeur», qui souligne *la responsabilité financière de la firme en cas d'incident éventuel induit par sa production*, et le principe de précaution, qui stipule qu'*à la suite d'une évaluation de l'information scientifique disponible, si il existe des motifs raisonnables de préoccupation quant à la possibilité d'effets indésirables mais où l'incertitude scientifique persiste, des mesures provisoires et proportionnées de gestion des risques basées sur des analyses coûts-avantages, en donnant la priorité à la santé humaine et l'environnement, peuvent être adoptées en attendant que d'autres informations scientifiques soient disponibles* (Von Schomberg, 2006).

Dans ce contexte, l'entreprise doit déterminer son niveau d'investissement pour les pro-

duits innovants. Celui-ci peut-être irréversible (trop coûteux, irrécupérable) ou réversible (une partie de l'investissement peut être récupérée). Elle peut également acquérir de l'information, en faisant par exemple de la recherche. Cela lui permet à la fois de réduire l'incertitude sur la dangerosité de son projet et de limiter les dommages potentiels sur la santé des êtres humains et sur l'environnement. L'acquisition de l'information peut ainsi être considérée comme un effort de précaution. Elle est définie comme un effort coûteux pour la firme qui est associé à un degré de précision de l'information (Sinclair-Desgagné et Gozlan, 2003). Plus un effort est important plus l'information est précise. L'acquisition d'information permet également à la firme de réviser ses croyances, en particulier, elle peut décider de prématurément arrêter le projet afin de limiter les dommages potentiels en cas d'accident. De plus, dans leurs efforts pour influer sur la réglementation, les entreprises développent des stratégies spécifiques pour exploiter l'incertitude scientifique. Elles peuvent ainsi décider d'embaucher et de financer des scientifiques dissidents qui produisent et publient des résultats scientifiques favorables afin de montrer que leur activité n'est pas nuisible pour la santé et l'environnement.

Dans nos travaux, nous supposons que les entreprises sont rationnelles, au sens où elles déterminent leurs stratégies en maximisant un objectif (en général en termes de profit) sous des contraintes (financières ou techniques). Les entreprises traitent l'information de manière bayésienne, c'est à dire qu'une distribution a priori est associée aux différents états de la nature et est révisée suite à l'arrivée d'informations suivant la formule de Bayes. Les préférences des entreprises dans l'incertain sont représentées par le modèle d'espérance subjective d'utilité de Savage (1954). Pour une meilleure prise en compte de l'ambiguïté et de l'attitude vis-à-vis de l'ambigüité, nous utilisons aussi le modèle de Klibanoff et al (2005). Dans le modèle de Klibanoff et al (2005), la vision que le décideur se fait de l'ambiguïté est exprimée à travers ses croyances subjectives qui sont représentées par une distribution de second ordre sur ses croyances. Les préférences du décideur prennent la forme d'une espérance à deux niveaux différenciant ainsi l'attitude vis à vis du risque de celle vis à vis de l'ambiguïté. Le choix de ce modèle s'est basé sur le fait qu'il présente une analogie avec le modèle d'espérance d'utilité en reprenant la représentation (à travers une fonction concave) de l'aversion pour le risque pour l'aversion pour l'ambiguïté.

Le dirigeant d'une entreprise (pouvant représenter un ensemble d'actionnaires ou un comité d'administration) peut avoir différentes préférences. En effet, il existe de nombreuses interactions entre le dirigeant et les actionnaires d'une firme, qui sont soumis à des objectifs différents et ne tiennent pas forcément compte de l'horizon de temps de la même manière. Le dirigeant peut être plus intéressé par la performance quotidienne de son entreprise, alors que les actionnaires peuvent avoir une vision à long terme de son développement. De tels conflits peuvent avoir un impact sur les décisions, et un comportement incohérent dans le temps d'un dirigeant. Le dirigeant peut être alors caractérisé par différents types de préférences : cohérentes dans le temps, avec une actualisation hyperbolique, et avec une actualisation hyperbolique et une maitrise de ses décisions.

Commençons par étudier l'acquisition d'information selon ces différents types de préférences. Dans article co-écrit avec Sophie Chemarin, intitulé : ***Innovation and information acquisition under time inconsistency and uncertainty*** et publié dans **Geneva Risk and Insurance Review en 2011**, nous étudions l'impact des préférences sur la décision d'acquisition d'information du dirigeant. Bien qu'acquérir de l'information permette au dirigeant de réduire l'incertitude et que ce dernier a la possibilité de prématurément arrêter le projet afin de limiter les dommages potentiels en cas d'accident, décide-il toujours de le faire ?

Pour répondre à cette question, nous utilisons la théorie des options réelles. L'acquisition d'information est à la fois coûteuse et est définie comme un droit, pas comme une obligation pour la firme. Cette option lui permet à la fois de réduire l'incertitude (Tallon et Vergnaud, 2005), d'arrêter son projet et de récupérer une partie de son investissement initial. Cela contraste avec la littérature où l'investissement est irréversible et le flux de l'information est exogène (Arrow-Fisher, 1974 ; Brocas et Carrillo, 2000, 2004 ; Henry, 1974). Cette approche théorique quantifie la valeur de la flexibilité de la gestion dans un monde d'incertitude. Il contribue ensuite à ajouter une nouvelle dimension grâce à l'introduction de l'information endogène. Par ailleurs, nous examinons la littérature reposant sur les préférences avec actualisation hyperbolique (Bénabou et Tirole, 2002, 2004 ; Carrillo et Mariotti, 2000) afin d'expliquer la raison pour laquelle des firmes peuvent ignorer l'information qui leur est fournie (l'exemple de l'amiante en est une bonne illustration, Henry, 2003). Pour formaliser les préférences avec une actualisation hyperbolique, nous nous appuyons sur la forme fonctionnelle de Phelps et Pollack (1968). Nous considérons que les préférences d'un dirigeant changent au fil du temps pour des motifs psychologiques, tels que l'anxiété, la confiance, ou l'impatience (Akerlof, 1991 ; Ainslie, 1992 ; Bénabou et Tirole, 2002 ; Masson, 2002 ; O'Donoghue et Rabin, 1999). Cela signifie que ce qu'un dirigeant décide aujourd'hui peut être discordant avec ce qu'il décidera demain. Ce dirigeant est considéré comme étant composé de nombreux 'lui-même' différents neutres au risque avec des buts conflictuels (Strotz, 1956). Chaque 'lui-même' représente le dirigeant à un moment différent.

Ainsi, nous étudions trois types de préférences pour un dirigeant. Premièrement, les préférences cohérentes dans le temps qui supposent que la décision optimale est maintenue lorsque les circonstances changent avec le temps, et ainsi que ses futurs 'lui-même' agissent selon les préférences de son 'lui-même' actuel. En d'autres termes, un dirigeant cohérent dans le temps donne le même poids à la période actuelle et qu'à celle futur. Les préférences avec une actualisation hyperbolique, considèrent que le 'lui-même' futur choisit des stratégies qui lui conviennent dans le futur, même si ces stratégies sont sous-optimales du point de vue du 'lui-même' présent. Enfin nous analysons également les préférences avec une actualisation hyperbolique et le contrôle de ses 'lui-même' futurs. Un dirigeant avec ce type de préférence, donne un plus grand poids au présent, mais considère que les périodes futures ont le même poids l'une par rapport à l'autre. Ainsi, dans le futur, il agit comme s'il avait des préférences cohérentes dans le temps.

Nous trouvons tout d'abord qu'un dirigeant ayant des préférences avec une actualisation hyperbolique peut rester ignorant si le degré de la précision de l'information n'est pas assez

élevé pour rendre l'information pertinent pour lui, alors que celui ayant des préférences cohérentes acquerrait l'information. D'autre part, quand un dirigeant a des préférences avec une actualisation hyperbolique, il acquiert moins d'information que celui qui a des préférences cohérentes dans le temps. En effet, l'actualisation hyperbolique souligne une préférence pour les bénéfices immédiats plutôt que pour ceux futurs. De plus, si nous introduisons la possibilité que le dirigeant puisse avoir des préférences avec une actualisation hyperbolique mais se comporte comme un dirigeant avec des préférences cohérentes sur les actions futures, nous obtenons que ce dirigeant sera plus enclin à rester ignorant. Ce dirigeant a besoin d'une information plus précise pour être pertinente pour lui. Ainsi, ignorer l'information ne dépend pas seulement du coût de celle-ci mais également du degré de précision que cette information est capable de fournir. La précision de l'information joue un rôle essentiel dans la décision d'acquisition d'informations des agents hyperboliques.

Toutes les entreprises sont contraintes par un cadre juridique dans lequel des règles de responsabilité spécifient comment allouer les dommages en cas d'accident. Le régime de responsabilité sans faute considère que *si les victimes peuvent démontrer un lien de causalité entre les dommages et l'activité de l'entreprise ou le produit vendu, le dirigeant est entièrement responsable et doit payer pour les dommages causés par son activité*. Le régime de responsabilité avec faute estime que *le dirigeant ne peut être tenu responsable des dommages subis par les victimes que s'il ne prend pas des mesures minimums pour éviter les dommages* (Miceli, 1997 ; Shavell, 1980). Par exemple, acquérir un certain degré d'information. Nous analysons l'impact de ces deux règles de responsabilité sur la décision d'acquisition d'information du dirigeant. Nous trouvons que le régime de responsabilité sans faute ne semble pas être un outil utile pour inciter le dirigeant, quelles que soient ses préférences, à obtenir de l'information. En revanche, le régime de responsabilité avec faute se révèle efficace car le dirigeant sait qu'en faisant le minimum de recherche requise il ne sera pas responsable des coûts des potentiels dommages. Il choisit donc d'acquérir ce minimum d'information qui rend son projet plus rentable pour lui.

Rajoutons maintenant à la décision d'acquisition d'information, la décision d'investissement du dirigeant. Considérons que le dirigeant est neutre au risque, a des préférences cohérentes dans le temps et que l'investissement qu'il souhaite réaliser est irréversible. L'approche la plus commune pour analyser l'investissement irréversible dans un contexte d'incertitude consiste à déterminer si la décision optimale est d'investir aujourd'hui ou d'investir demain (Dixit et Pindyck, 1994 ; Epstein, 1980 ; Henry, 1974). Cependant, dans la course aux nouvelles technologies, le dirigeant peut ne pas vouloir retarder l'investissement. Il doit décider le montant à investir aujourd'hui, même s'il manque de connaissances scientifiques sur les dommages sur la santé humaine et l'environnement de son activité. Quelles sont les conséquences de la réglementation, telle que le principe de précaution, sur cette décision ? L'investissement sera-t-il freiné comme le suggère Sunstein (2002-2003) ?

Dans l'article intitulé : ***Innovation and the precautionary principle*** **publié en 2014 dans Economics of Innovation and New technology**, nous constatons que le principe de précau-

tion peut conduire le dirigeant à ne pas investir dans l'activité alors qu'il l'aurait fait sans réglementation ou avec une réglementation moins exigeante. Dans cette situation, le principe de précaution peut alors être considéré comme un obstacle à l'innovation. En 1995, l'hypothèse de Porter souligne que correctement conçue la réglementation environnementale peut déclencher une innovation qui peut partiellement ou plus que compenser les coûts liés à son respect. L'Hypothèse de Porter suggère l'existence de la situation « gagnant-gagnant », dans laquelle la société et les entreprises privées pourraient être les deux gagnantes suite à l'introduction d'une réglementation environnementale. Nos résultats ne vérifient pas l'hypothèse de Porter. Le principe de précaution paraît trop strict et coûteux au dirigeant qui préfère ne pas investir alors qu'il aurait investi sans cette réglementation environnementale. Avec une approche numérique basée sur les données de l'entreprise Monsanto de 2008 à 2009, nous obtenons que le profit de la firme diminue lors de l'application du principe de précaution.

Afin de respecter le principe de précaution, le dirigeant peut payer pour acquérir de l'information sans en tenir compte et continuer son activité alors qu'il sait que celle-ci est dangereuse. Pour éviter cela, des subventions stimulant l'innovation tout en imposant un certain niveau de dommages considéré comme acceptable pour la Société peuvent être proposées. Néanmoins, l'approche numérique basée sur l'entreprise Monsanto, nous montre qu'une concurrence agressive pour l'innovation entre les pays pourrait conduire à une réglementation moins prudente (avec un niveau requis de précision pour la recherche et de dommages acceptable pour la santé et l'environnement moins élevé) pouvant en plus nécessiter de colossales subventions. Ainsi, exiger un même niveau de sécurité pour de nouvelles activités et les mêmes réglementations pour l'ensemble des pays devrait bénéficier à la protection de la santé et de l'environnement, à l'innovation et aux dépenses publiques (réduction voire annulation des subventions).

Les caractéristiques du marché peuvent également influencer la décision d'investissement irréversible d'un dirigeant. Dans l'article intitulé : ***Irreversible investment, uncertainty, and ambiguity : the case of bioenergy sector*** co-écrit avec Pierre-André Jouvet et Elodie Le Cadre, et publié dans **Energy Economics en 2012**, nous analysons le niveau de production et d'investissement d'un dirigeant neutre au risque sur un marché dont la demande et la concurrence sont incertaines. Nous prenons comme exemple le marché des biocarburants. La nouveauté de ce marché engendre que le dirigeant ne peut pas avoir une connaissance parfaite du nombre d'acheteurs avant de commencer sa production. Cette incertitude sur la demande affecte alors sa perception de la moyenne des prix. De plus, l'effet de la concurrence d'autres ressources énergétiques sur le prix de la biomasse prétraitée est également méconnu. Ainsi, l'incertitude sur la concurrence affecte sa perception de la moyenne des prix mais également celle de la variance du prix. L'investissement du dirigeant est considéré comme un coût d'entrée et représente un coût irrécupérable dû au fait que la torréfaction de la biomasse est spécifique et chère. Cela soulève naturellement la question de l'effet des deux types d'incertitude et de l'irréversibilité sur le niveau d'investissement et de production. De plus, sur le marché de l'énergie, l'instabilité de l'économie peut conduire le dirigeant à avoir des incertitudes quant à son évaluation

de la variance du prix de son produit. Nous utilisons le terme « ambiguïté » pour indiquer les situations dans lesquelles les occurrences d'un événement incertain ne sont pas précisément connues. En d'autres termes, une situation dans laquelle il y a une incertitude sur l'incertitude (Camerer, 1999 ; Ellsberg, 1961 ; Etner et al, 2012 ; Fellner, 1961, 1965 ; Gollier, 2006 ; Slovic et Tversky, 1974). Pour formaliser l'aversion à l'ambiguïté, nous utilisons la modélisation de Klibanoff et al (2005). Nous considérons que la « vraie » valeur de la probabilité associée à la croyance du dirigeant est représentée non pas comme une seule mesure de probabilité sur l'ensemble d'états mais par un ensemble de mesures de probabilité. Une nouvelle question se pose : comment un dirigeant qui a de l'aversion à l'ambiguïté se comporte-t-il quand il prend ses décisions concernant l'investissement et la production ?

En utilisant une approche analytique et une analyse numérique basée sur la base de données des industries françaises de prétraitement de la biomasse, nous trouvons que chacune des incertitudes (demande, effet de la concurrence) implique que le dirigeant perçoit un prix inférieur (supérieur) à celui réalisé quand le prix réalisé est élevé (bas). Cela a un impact direct sur le niveau de production, qui diminue lorsque le prix espéré est inférieur à celui réalisé et augmente lorsque le prix espéré est plus haut que celui réalisé. De plus, produire plus conduit le dirigeant à choisir un niveau d'investissement en capital qui réduit son coût de production unitaire. Combiner les deux incertitudes amplifie ces résultats avec une production encore plus faible (forte) lorsque le dirigeant perçoit un prix inférieur (supérieur) à celui réalisé et un investissement en capital moins (plus) important lorsqu'il pense qu'une augmentation du capital augmente (diminue) le coût d'une unité supplémentaire. Finalement, l'aversion pour l'ambiguïté concernant l'effet de concurrence conduit le dirigeant à réduire son investissement en capital et sa production. En fait, cela ajoute au dirigeant une nouvelle dimension d'incertitude et le décourage d'investir et de produire. L'aversion pour l'ambiguïté restreint alors l'investissement et la production. Cela peut avoir des conséquences drastiques sur le développement de processus émergents.

Ce travail contribue à la littérature sur les investissements irréversibles (Elder et Serletis, 2009, 2010 ; Henry, 1974 ; Kulatilaka et Perotti, 1998 ; Murto, 2006 ; Murto et al., 2004 ; Sarkar, 2000 ; Sutton, 1991 ; Trigeorgis, 1996) en considérant deux types d'incertitude (incertitude sur la demande et sur l'effet concurrentiel) qui affectent les prix de manières différentes : la perception de la moyenne et la variance du prix. De plus, cet article montre la nécessité de réduire les effets de l'ambiguïté dans la politique européenne cadre qui encourage le développement de la production des énergies renouvelables. L'introduction de contrats à long terme pourrait contribuer à les réduire. En effet, ces contrats pourraient être définis comme des accords entre un producteur de biomasse prétraité (vendeur) et un propriétaire de générateur d'énergie renouvelable (acheteur) pour l'achat de biomasse torréfiée. En se couvrant contre la volatilité du prix, ces contrats réduiraient l'ambiguïté de l'effet de la concurrence.

Finalement, nous pouvons également nous interroger sur les stratégies spécifiques qu'un dirigeant peut adopter pour exploiter l'incertitude scientifique et influencer la réglementation.

En effet, des affaires comme celles des producteurs de tabac ou de Monsanto ont montré que les firmes pouvaient embaucher et financer des scientifiques dissidents afin de produire et publier des résultats scientifiques qui leur étaient favorables en dissimulant leur implication dans une recherche biaisée. Cet effort des entreprises, visant à influencer les perceptions des citoyens, peut être définie comme un effort de communication.

Dans l'article intitulé : ***Manufacturing Doubt*** co-écrit avec Yann Bramoullé publié **en 2018 dans Journal of Environmental Economics and Management**, nous étudions l'interaction entre l'incertitude scientifique, la communication des entreprises et les politiques publiques. Nous considérons que le régulateur est bienveillant, et est soit technocrate (maximisant le bien-être social perçu par les scientifiques), soit populiste (maximisant le bien-être social perçu par les citoyens), soit indépendant (maximisant le bien-être social avec des perceptions mises à jour par les scientifiques). L'entreprise est neutre au risque et sa production génère des émissions de gaz à effet de serre. Elle peut décider de produire des rapports coûteux pour montrer que son activité n'est pas nuisible. En recevant cette information, les citoyens actualisent leur croyance sans être conscients que celle-ci peut-être falsifiée. En effet, cette hypothèse est compatible avec la preuve de la dissimulation de résultats scientifiques défavorables par l'industrie du tabac et Monsanto et avec la tendance des scientifiques financés par l'industrie de cacher leur source de financement (Bero, 2013 ; Proctor, 2011 ; Waldman et al, 2017). Cela aide à expliquer pourquoi les citoyens ont des croyances erronées sur de nombreuses questions importantes (Flynn et al, 2017).

Nous montrons d'abord que l'effort de communication de l'entreprise est une fonction non monotone et discontinue des croyances scientifiques. Plus les scientifiques sont convaincus que l'activité est nuisible, plus l'entreprise consacre de ressources pour rassurer les citoyens. Cependant, quand la croyance des scientifiques atteint un seuil critique, contrer le consensus scientifique devient trop coûteux et l'entreprise s'arrête brusquement de communiquer. Ce résultat est robuste aux types d'instrument de régulation utilisé tels que les normes ('command and control') et les taxes sur les émissions.

Nous identifions une condition qui conduit l'entreprise a plus communiquer avec une taxe sur les émissions qu'avec 'command and control'. Ce résultat contribue à la littérature sur le choix des instruments de régulation environnementale. Étant donné que le bénéfice de la firme est inférieur lorsque l'on met en place une taxe sur les émissions, en raison de la charge fiscale supplémentaire par rapport au 'command and control', la firme a plus à gagner à influencer l'opinion publique et la réglementation.

Nous montrons, par la suite, que l'écart entre les croyances des scientifiques et celles des citoyens lié à la communication de la firme, a des implications importantes sur le financement de la recherche. Nous analysons les incitations des différentes institutions (technocrate, populiste et indépendante) à soutenir la recherche. Étant donné qu'un gouvernement populiste se soucie du bien-être perçu, son bien-être augmente lorsque les citoyens sont rassurés par la communication de l'entreprise. Cela peut conduire à un alignement partiel d'intérêts entre le gouvernement et l'industrie. Ainsi, nous constatons qu'un gouvernement populiste peut soutenir la recherche

des scientifiques et permettre à l'entreprise de communiquer plus efficacement. Nous montrons que pour limiter les effets préjudiciables de la communication des entreprises, il faudrait établir une agence de financement indépendante, semblable à la National Science Foundation et au Conseil européen de la recherche. Notre analyse fournit une nouvelle justification pour l'établissement des agences scientifiques.

Notre travail contribue à la littérature liant l'économie politique et l'incertitude scientifique (Baron, 2005 ; Laussel et van Ypersele, 2012 ; Petrova, 2012 ; Shapiro, 2016 ; Yu, 2005) en adoptant une représentation de la science pouvant accumuler et rapprocher progressivement les scientifiques de la vérité. Cela nous permet d'analyser la communication des entreprises en fonction du niveau d'incertitude scientifique et l'impact de la communication sur le financement de la recherche. Ce travail enrichit également la littérature étudiant les implications des croyances erronées des citoyens (Pollak, 1998 ; Portney, 1992 ; Salanié et Treich, 2009 ; Viscusi et Hamilton, 1999) en considérant que ces croyances sont formées de manière endogène et sont affectées par le progrès scientifique et par la communication de l'entreprise. De plus, nous participons à la littérature explorant l'effet de l'incertitude sur l'environnement (Baker, 2005 ; Boucher et Bramoullé, 2010 ; Bramoullé et Treich, 2009 ; Finus et Pintassilgo, 2013 ; Gollier et al, 2000 ; Heal et Kriström, 2002 ; Nordhaus, 1994 ; Stern, 2007 ; Ulph, 2004 ; Weitzman, 2009) en nous intéressant à l'impact des perceptions erronées induites par la communication de l'entreprise en présence d'incertitude sur l'environnement.

A travers ces travaux, les choix d'investissement, d'acquisition de l'information et de communication d'une firme innovante ont été éclairés. Ces études peuvent s'appliquer aux entreprises pharmaceutiques, de nanotechnologies, d'agro-alimentaires (OGM, pesticides...) et d'innovation. La modélisation utilisée est celle de l'espérance d'utilité. Néanmoins, d'autres modèles se basant sur l'économie expérimentale et comportementale pourront être appliqués dans de futurs travaux. Le paradoxe expérimental d'Allais (1953) qui remet en cause la pertinence du modèle d'espérance d'utilité et de son évaluation linéaire des probabilités, est à l'origine du modèle d'espérance d'utilité avec dépendance au rang. Ce modèle généralise le modèle d'espérance d'utilité avec probabilité objective en considérant que le décideur mesure d'abord la satisfaction associée au résultat minimum, puis ajoute les surcroits successifs de satisfaction engendrés par les éventuels gains supplémentaires et pondérés par les probabilités transformées correspondantes. Citons également le modèle de MaxMin de Wald est un modèle décisionnel non probabiliste selon lequel les décisions sont classées en fonction de leurs résultats les plus défavorables. La décision optimale est celle qui a le moins mauvais résultat. En découle le modèle αMaxMin de Arrow et Hurwicz qui incorpore à la fois le plus favorable et le plus défavorable résultat. La décision optimale est celle qui a la meilleure combinaison des résultats pondérés par un coefficient α fixé, dont la valeur est comprise entre 0 et 1. α représente une mesure du pessimisme du décideur selon la situation étudiée. Vient ensuite, le critère de regret de Savage qui vise à éviter les regrets pouvant résulter d'une décision non optimale. Il compare pour chaque action la différence de gain entre le meilleur gain possible et le gain

réalisé de chaque état. Puis, il choisit l'action qui minimise la somme de ces différences. De cette manière, il minimise le regret. Ces modèles sont utiles pour représenter le comportement des agents économiques face au risque.

D'autres modèles s'intéressent à représenter le comportement des agents économiques en présence d'incertitude. Le paradoxe expérimental d'Ellsberg (1961) qui remet en cause la pertinence du modèle d'espérance d'utilité et de son traitement additif des vraisemblances subjectives, est à l'origine du modèle d'espérance d'utilité à la Choquet. Ce modèle généralise le modèle d'espérance d'utilité avec probabilité subjective en considérant que le décideur mesure d'abord la satisfaction associée au résultat minimum, puis ajoute les surcroits successifs de satisfaction engendrés par les éventuels gains supplémentaires et pondérés par les vraisemblances subjectives non-additives correspondantes. La Théorie des perspectives de Kahneman et Tversky (1979) généralise ce modèle en introduisant deux capacités [9], l'une pour les événements correspondant aux gains, et l'autre, pour ceux correspondants aux pertes [10].

Mes travaux de recherche sont complémentaires de mes activités d'enseignement. Dans la partie suivante, je présente le lien entre mes activités d'enseignement et de recherche et les encadrements d'étudiants qui en découlent.

2 Enseignement, recherche et encadrement

A AgroParisTech, les enseignements sont destinés à des étudiants ingénieurs et de l'université à partir du niveau Master. Les premiers sont en priorité intéressés par des enseignements très appliqués, et les seconds privilégient des enseignements plus fondamentaux, avec un contenu théorique plus important. Enseigner à ces deux profils me permet de faire aisément des passerelles entre les théories économiques et leurs applications. Ainsi, la modélisation et l'application sont devenues très complémentaires dans ma recherche et dans mes enseignements.

Depuis mon recrutement, je dirige de nombreux projets de première année d'ingénieur (sept à huit par an), j'encadre également les ingénieurs de deuxième et troisième année pour leur stage court (trois mois), leur Certificat d'Expérience à l'International (CEI) d'un an [11], et leur stage de fin d'étude (six mois), ce qui représente trois à six étudiants par an. De plus, je propose des stages de trois mois aux étudiants du Master 'Economie de l'Environnement, de l'Energie et des Transports (EEET)' d'AgroParisTech-Université Paris-Saclay-Université Paris Nanterre

9. Une capacité est une caractérisation des croyances par une fonction d'ensemble croissante et non nécessairement additive.

10. Les différentes théories ont été présentées et illustrées dans les article de Etner et al (2012), Gayant (1998), Gilboa et Marinacci (2013), Jeleva et Tallon (2016), et Machina et Sinischalchi (2014).

11. Le CEI est une formation accessible aux étudiants d'AgroParisTech disposant d'un niveau Master 1 validé dans une formation Master ou d'ingénieur de l'école. Cette année est encadrée par un enseignant et comporte des mises en situations professionnelles, et des séquences de formation en interne ou en externe, à l'étranger ou en France.

(un à deux par an). Un des stages a d'ailleurs conduit à un document de travail intitulé : ***Willingness to pay for switching from polluting energies to green energies ?*** avec deux étudiants de Master 1, Frédéric Pinto da rocha et Marc Siari. Ce travail a pour but d'étudier l'impact de l'information et des politiques publiques de santé et environnementales (taxe, subvention et norme) sur les décisions d'achat de produits économes en énergie (chaudière, pack électroménagers et isolation). La méthode utilisée est la méthode d'évaluation du consentement à payer avec un questionnaire en ligne et en face à face. Ce projet est en cours de réalisation. Je propose de plus d'encadrer de projets de recherche et de stages du mastère spécialisé ALISEE d'AgroParisTech (trois à quatre étudiants par an). Un de ces projets a donné lieu à la publication Orset et al (2017) qui a été présentée dans la synthèse des travaux. Les encadrements de stage sont une source d'inspiration pour mes recherches et mes enseignements.

En 2012, une réforme a conduit AgroParisTech à partitionner son enseignement de deuxième année d'ingénieur entre quatre domaines : domaine 1 : productions, filières, territoires pour le développement durable ; domaine 2 : ingénierie des aliments, biomolécules et énergie ; domaine 3 : gestion et ingénierie de l'environnement ; et domaine 4 : Ingénierie et santé : homme, bioproduits, environnement. Bien que n'ayant initialement aucune formation dans le domaine de la santé, je me suis investie dans le domaine 4 pour faire un lien entre santé et environnement. Je fais actuellement partie de la Commission de suivi de ce domaine. J'ai ainsi développé un cours de 48h en économie de la santé pour les ingénieurs de deuxième année. Ce cours présente aux étudiants l'offre et la demande de santé, l'économie du risque et de l'incertitude (avec les asymétries d'information, aléa moral, sélection...), l'économie de l'assurance, les expériences économiques liant santé et environnement, et santé et alimentation, et des interventions extérieures comme celle de Claire Huault (Directrice Etudes et Projets Stratégiques à Etablissement Français du Sang). Cet enseignement m'a ouvert une porte vers l'économie de la santé et m'a conduite à écrire un premier travail sur ce thème, Orset (2018) présenté dans la synthèse de recherche. De plus, de nombreux étudiants, ayant suivi cette unité d'enseignement, me demandent de les encadrer pour leur stage court de deuxième année et leur CEI.

Dans la commission du domaine 4, je représente le département des Sciences Economiques, Sociales et de Gestion (SESG). Les autres membres viennent des autres départements : Sciences et ingénierie agronomiques, forestières, de l'eau et de l'environnement ; Sciences de la vie et santé ; Sciences et procédés des aliments et bioproduits ; et Modélisation mathématique, informatique et physique. Les échanges entre les collègues sont très riches et vont au-delà de la Commission. Des projets de recherche ont ainsi commencé à émerger. Ma collègue, Valérie Camel (Professeur de chimie analytique, AgroParisTech), m'a proposé de participer au livre ***Risques chimiques dans les aliments : Principes et applications*** édité par **Lavoisier** dont la sortie est **prévue en octobre 2018**, en écrivant un chapitre sur l'apport de l'économie du risque dans la gestion des risques chimiques dans les aliments.

Par ailleurs, une autre collaboration est née de cette commission, avec mes deux collègues, Jean-François Huneau (Professeur en nutrition, AgroParisTech) et François Mariotti (Profes-

seur en nutrition, AgroParisTech), sur la substitution partielle de protéines animales en protéines végétales dans l'alimentation humaine. Je contribue à ce travail avec Pascal Leroy (Ingénieur de recherche, INRA-ALISS) et Louis-Georges Soler (Directeur de recherche, INRA-ALISS) en étudiant trois impacts. L'impact économique à travers les dépenses des consommateurs en utilisant les prix de la base de données KANTAR [12]. L'impact de santé en estimant le nombre de morts prématurées évitées avec le modèle PRIME [13]. Et pour finir, l'impact environnemental exprimé en kgCO_2-eq/kg d'aliments à l'aide des données européennes de 2016 publiées dans Hartikaiinen et Pulkkinen (2016) et des coefficients d'analyse de cycle de vie décrits par Bertoluci et al. (2016). Ce travail a permis le co-encadrement avec François Mariotti du stage de fin d'étude de six mois de Marjorie Perrimon, étudiante de la dominante d'AgroParisTech METATOX (troisième année d'ingénieur). Ce travail sera également un chapitre de la thèse d'Erwan de Gavelle, doctorant codirigé par Jean-François Huneau et François Mariotti, qui est un ancien élève du mastère spécialisé ALISEE que j'ai encadré pour son stage de fin d'étude. Cette étude est intitulée : ***Rearrangements of protein food intake with simple changes in portion sizes to increase nutrient adequacy : Impacts on sustainability parameters***. Elle a été de nombreuses fois présentée et devrait être soumise début septembre 2018 dans une revue de nutrition.

Finalement, depuis novembre 2016, je codirige, avec l'accord de l'Université de Lorraine qui m'a attribuée l'Autorisation à Codiriger les Thèses (ACT), la thèse de Camille Tevenart avec Marielle Brunette (Chargée de recherche, INRA-BETA). Camille Tevenart travaille sur les freins à l'adoption de mesures d'atténuation dans l'agriculture en introduisant le rôle de l'aversion pour le risque et pour l'ambiguïté. Il a déjà deux documents de travail et un travail préliminaire en cours. Nous avons également, co-écrit une info-débat pour la Chaire du Climat (qui finance la thèse de Camille Tevenart) intitulée : ***Freins à l'adoption de mesures d'atténuation des gaz à effet de serre dans l'agriculture. Quels rôles pour l'aversion au risque et l'aversion à l'ambiguïté ?*** publiée dans **Climate Economics Chair en 2017**. Avec Marielle Brunette, nous avons conduit Camille Tevenart a postulé à l'EIR-A (Ecole Internationale de Recherche d'Agreenium) qui propose un parcours doctoral d'excellence validé par le label Agreenium (L'Institut agronomique, vétérinaire et forestier de France dont AgroParisTech et l'INRA font parties) afin qu'il puisse avoir une expérience à l'étranger durant sa thèse. Camille Tevenart l'a obtenu ce qui lui a permis de partir à l'Université de Californie à Santa Barbara (Etats-Unis) de février à juin 2018 pour collaborer avec Andrew Plantinga (Professeur, Bren School of Environmental Science and Management). Pour que son séjour se passe dans les meilleures conditions, nous avons demandé des financements supplémentaires à AgroParis-

12. KANTAR est une base de données comportant le plus vaste panel de consommateurs existant actuellement sur le marché. De nombreuses informations sur les prix des produits et le comportement d'achat, le profil démographique mais aussi la consommation média ou le mode de vie des consommateurs sont fournies.

13. Le modèle épidémiologique PRIME (Preventable Risk Integrated ModEl) de Scarborough et al. (2014) est adapté à la population française et permet de déterminer l'impact santé de la modification de la consommation alimentaire.

Tech et à l'INRA, ce qui m'a donné une première expérience de montage de projet de recherche (à petite échelle) pour obtenir un financement.

3 Bilan et perspectives de recherche

Je suis maître de conférences à AgroParisTech depuis près de dix ans. Je me suis beaucoup investie dans le collectif de l'école et j'exerce déjà de nombreuses responsabilités telles que responsable d'UFR d'Économie Générale et Appliquée, membre du conseil des enseignants, membre du conseil de l'école doctorale ABIES (Voir Curriculum Vitae). Néanmoins, il me semble aujourd'hui important de devenir Professeur afin de pouvoir assurer d'autres fonctions comme celles de responsable de Master ou de Mastère spécialisé. De plus, nous allons prochainement rejoindre les autres écoles d'ingénieurs et universités formant l'Université Paris-Saclay, sur le Plateau de Saclay. Ce sera une opportunité pour créer une nouvelle dynamique de recherche autour de sujets traitants de l'économie du risque et de l'incertitude. Être Professeur est un atout pour former une équipe, monter des projets de recherche et demander des financements pour des stages, des post-doctorats et des thèses. Candidater à un poste de Professeur est ainsi une des motivations de mon passage de l'Habilitation à Diriger des Recherches (HDR).

Avoir l'HDR, a également une importance pour l'encadrement de futures thèses. En effet, je ne peux demander qu'une seule fois l'ACT. Je souhaiterais pouvoir proposer et encadrer de nouvelles thèses car collaborer avec d'autres personnes me stimule. Je souhaite que mes futurs projets de recherche favorisent l'interaction et les échanges car trouver une problématique qui engendrent une collaboration entre plusieurs personnes n'est pas toujours aisé. Cela m'a d'ailleurs conduite à écrire seule pour ne pas laisser mes questionnements sans réponse.

Peu de thèses ont été écrites sur les investissements et les comportements stratégiques des entreprises innovantes. Proposer ce type de sujet de thèse et continuer mes recherches sur ce thème font partie de mes intentions. Un projet de recherche est d'ailleurs déjà initié avec Julien Jacob (Maitre de conférences, Université de Strasbourg-BETA). En utilisant la théorie des options réelles et les méthodes bayésiennes, nous allons analyser comment (et dans quelle mesure) la responsabilité civile et pénale aident le processus de contrôle des autorisations en incitant l'entreprise à investir dans la recherche pour acquérir de l'information afin de réduire l'incertitude et à diminuer la communication biaisée de ses résultats.

Ensuite, je vais rajouter à mes études sur le comportement individuel en présence de risque sanitaire et environnemental, le volet risque alimentaire. Pour cela, je vais poursuivre avec François Mariotti, le travail déjà initié avec Erwan de Gavelle. Cependant, au lieu de partir d'un modèle de nutrition vers une analyse des impacts économiques, nous proposerons une politique de santé et nous analyserons la diminution des risques sanitaires liés à l'amélioration du régime alimentaire. Ce travail s'intégrera dans le projet de mon laboratoire de recherche Economie Publique, AgroParisTech, INRA, Université Paris-Saclay (EcoPub) financé pendant

trois ans par l'Agence Nationale de la Recherche (ANR), DietPlus qui a débuté en janvier 2018. Ce projet est coordonné par Stephan Marette (Directeur de recherche, INRA-EcoPub) et traite des effets des changements de régimes alimentaires sur l'équilibre des marchés, le partage de la valeur dans les filières, la santé publique, l'environnement et l'usage des sols. Ce projet comporte trois WorkPackages, et je participe au WorkPachage 3 qui examine la politique optimale qui pourrait améliorer la qualité globale des régimes alimentaires. Un stage de fin d'étude de six mois que nous co-encadrerons, avec François Mariotti, sera proposée.

En conséquence, le montage de projet de recherche, l'encadrement de doctorants et post-doctorants et la responsabilité d'une équipe de recherche et de formation sont amenés à prendre de plus en plus de place dans mes activités. Le passage de l'HDR est ainsi nécessaire pour mon projet professionnel.

4 Liste des travaux et références bibliographiques

Liste des travaux

1. Orset, C. (2019), *How travellers are responding to environmental policies for reducing air pollution?*, Ecological Economics, 156 : 68–82.
2. Bramoullé, Y., Orset, C. (2018), *Manufacturing doubt*, Journal of Environmental Economics and Management, 90 : 119-133.
3. Orset, C. (2018), *People's perception and cost-effectiveness of home confinement during an influenza pandemic : evidence from the French case*, European Journal of Health Economics, 1-16.
4. Orset, C., Barret, N., Lemaire, A. (2017), *How consumers of plastic water bottles are responding to environmental policies ?*, Waste Management, 61, 13-27.
5. Orset, C. (2014), *Innovation and the precautionary principle*, Economics of Innovation and New Technology, 23(8) : 780-801.
6. Jouvet, P.A., Le Cadre, E., Orset, C. (2012), *Irreversible investment, uncertainty, and ambiguity : the case of bioenergy sector*, Energy Economics, 34(1) : 45-53.
7. Chemarin, S., Orset, C. (2011), *Innovation and information acquisition under time inconsistency and uncertainty*, Geneva Risk and Insurance Review, 36(2) : 132-173.

Références bibliographiques

1. Achonu, C., Laporte, A., Gardam, M.A. (2005), *The financial impact of controlling a respiratory virus outbreak in a teaching hospital : lessons learned from SARS*, Canadian Journal of Public Health, 96 : 52-54.
2. Adda, J. (2016), *Economic Activity and the Spread of Viral Diseases : Evidence from High Frequency Data*, Quaterly journal of economics, 131(2) : 891-941.
3. Agostinia, C.A., Jiménez, J. 2015, *The distributional incidence of the gasoline tax in Chile*, Energy Policy, 85 : 243-252.
4. Air Parif (2016), *Surveillance et information sur la qualité de l'air en île de France-Bilan année 2015*.
5. Ainslie, G. (1992), *Picoeconomics : The Strategic Interaction of Successive Motivational States within the Person*, Cambridge University Press, New York.
6. Akerlof, G.A. (1991), *Procrastination and obedience*, American Economic Review, 81(2) : 1-19.
7. Allais, M. (1953), *Le comportement de l'homme rationnel devant le risque : critique des postulats et axiomes de l'école américaine*, Econometrica, 21(4) : 503-546.

8. Arrow, K.J., Fisher, A.C. (1974), *Environmental preservation, uncertainty, and irreversibility*, Quaterly Journal of Economics, 88(2) : 312-319.

9. Azzarello, M.Y., Van Vleet, E.S (1987), *Marine birds and plastic pollution*, Marine Ecology, 37 : 295-303.

10. Baker, Erin. (2005), *Uncertainty and Learning in a Strategic Environment : Global Climate Change*, Resource and Energy Economics, 27 : 19-40.

11. Baidoo, I.K., Nyarko, E. (2015),*Stated Preference Modeling for a Preferred Transportation Mode*, Mathematical Theory and Modeling.

12. Baron, David P. (2005), *Competing for the Public through the News Media*, Journal of Economics and Management Strategy, 14(2) : 339-376.

13. Bénabou, R., Tirole, J. (2002), S*elf confidence and personal motivation*, Quarterly Journal of Economics, 871-913.

14. Bénabou, R., Tirole, J. (2004), *Willpower and personal rules*, Journal of Political Economy, 112(4).

15. Bernard, J. C., Bernard, D. J. (2009), *What is it about organic milk ? An experimental analysis*, American Journal of Agricultural Economics, 91 : 826-836.

16. Bertoluci, G., Masset, G., Gomy, C., Mottet, J., Darmon, N. (2016), H*ow to build a standardized country-specific environmental food database for nutritional epidemiology studies*, PloS one, 11(4).

17. Bero, Lisa A. (2013), *Tobacco Industry Manipulation of Research*, Ch.17 dans Late Lessons from Early Warnings : Science, Precaution, Innovation. EEA Report n. 1/2013.

18. Blendon, R., DesRoches, C.M., Cetron, M.S., Benson, J.M., Meinhardt, T., Pollard, W. (2006), *Attitudes toward the use of quarantine in a public health emergency in four countries*, Health Affairs, 25(2) : 15-25.

19. Bollena, J., Brink, C. (2014), *Air pollution policy in Europe : Quantifying the interaction with greenhouse gases and climate change policies*, Energy Economics, 46 : 202-215.

20. Boucher, V., Bramoullé, Y. (2010), *Providing Global Public Goods under Uncertainty*, Journal of Public Economics, 94 : 591-603.

21. Bramoullé, Y., Treich, N. (2009), *Can Uncertainty Alleviate the Commons' Problem ?*, Journal of the European Economic Association, 7(5) : 1042-1067.

22. Bougherara, D., Combris, P. (2009), *Eco-labelled food products : what are consumers paying for ?*, European Review of Agricultural Economics, 36 (3) : 321-341.

23. Brocas, I., Carrillo, J.D. (2000), *The value of information when preferences are dynamically inconsistent*, European Economics Review, 44 : 1104-1115.

24. Brocas, I., Carrillo, J.D. (2004), *Entrepreneurial boldness and excessive investment*, Journal of Economics and Management Strategy, 13(2) : 321-350.

25. Camerer, C. (1999), *Ambiguity-Aversion and Non-Additive Probability : Experimental Evidence, Models and Applications*, chapter Uncertain Decisions : Bridging Theory and Experiments, 53–80, Kluwer Academic Publishers.

26. Carrillo, J.D., Mariotti, T. (2000), *Strategic ignorance as a self disciplining device*, Review of economic studies, 67 : 529-544.

27. Chao, D.L., Halloran, M.E., Obenchain, V.J., Longini, I.M. (2010), *FluTE, a publicly available stochastic influenza epidemic simulation model*, PLoS Computational Biology, 6.

28. Centre de contrôle et de prévention des maladies, Centers for Disease Control and Prevention (CDC) (2007), *Interim pre-pandemic planning guidance : community strategy for pandemic influenza mitigation in the United States*.

29. Cobanoglu C., Warde B. et Moreo P. (2001), *A comparison of mail, fax, and Web-based survey methods*, International Journal of Market Research, 43(4) : 405-410.

30. Couper, M.P. (2000), *Web surveys : A review of issues and approaches*, The Public Opinion Quarterly, 64(4) : 464-494.

31. Da Cruz, N.F., Simoes, P., Marques, R.C. (2012), *Economic cost recovery in the recycling of packaging waste : the case of Portugal*, Journal of Cleaner Production, 37 : 8-18.

32. Da Cruz, N.F., Ferreira, S., Cabral, M., Simoes, P., Marques, R.C. (2014), *Packaging waste recycling in Europe : Is the industry paying for it ?*, Waste Management, 34(2) : 298-308.

33. Derraik, J.G.B. (2002), *The pollution of the marine environment by plastic debris : A review*, Marine Pollution Bulletin, 44(9) : 842-852.

34. Disdier, A-C., Marette, S., Millet, G. (2013), *Are consumers concerned about palm oil ? Evidence from a lab experiment*, Food Policy, 43 : 180-189.

35. Dixit, A.K., Pindyck, R.S. (1994), *Investment Under Uncertainty*, Princeton University Press.

36. Douglas, W., Dockery, C., Pope, A., Xu, X., Spengler, J.D, Ware, J.H., Fay, M.E., Ferris, B.J., Speizer, F.E. (1993), *An Association between Air Pollution and Mortality in Six U.S. Cities*, The New England Journal of Medecine, 329 : 1753-1759.

37. Elder, J., Serletis, A. (2009), *Oil price uncertainty in canada*, Energy Economics, 31(6) : 852-856.

38. Elder, J., Serletis, A. (2010), *Oil price uncertainty*, Journal of Money, Credit, and Banking, 42(6) : 1137–1159.

39. Ellsberg, D. (1961), *Risk, Ambiguity, and the Savage Axioms*, Quarterly Journal of Economics, 75(4) : 643-669.

40. Epstein, L.G. (1980), *Decision making and the temporal resolution of uncertainty*, International economic review, 21(2) : 269-283.

41. Etner, J., M. Jeleva, Tallon, J-M. (2012), *Decision Theory Under Ambiguity*, Journal of Economic Surveys, 26(2) : 234-270.

42. Fellner, W. (1961), *Two propositions in the theory of induced innovations*, The Economic Journal, 71(282) : 305–308.

43. Fellner, W. (1965), *Probability and Profit*, Yale University.

44. Finus, M., Pintassilgo, P. (2013), *The Role of Uncertainty and Learning for the Success of International Climate Agreements*, Journal of Public Economics, 103 : 29-43.

45. Flynn, D.J., Nyhan, B., Reifler, J. (2017), *The Nature and Origins of Misperceptions : Understanding False and Unsupported Beliefs About Politics*, Advances in Political Psychology, 38(1) : 127-150.

46. Fricker S., Galesic M., Tourangeau R., Yan T. (2005), *An experimental comparison of Web and telephone surveys*, The Public Opinion Quarterly, 69(3) : 370-392.

47. Gollier, C. (2006), *Does ambiguity aversion reinforce risk aversion ? applications to portfolio choices and asset prices*, Dans le Séminaire d'Economie Théorique : Université de Toulouse 1 Sciences Sociales.

48. Greene W.H. (2017), *Econometric Analysis*, Pearson (8th edition).

49. Gayant, J-P (1998), *L'apport des modèles non-additifs en théorie de la décision dans le risque et l'incertain*, Revue française d'économie, 13(1) : 199-227.

50. Gilboa, I., Marinacci, M. (2013), *Ambiguity and the Bayesian Paradigm*, in D. Acemoglu, M. Arellano et E. Dekel (éds), Advances in Economics and Econometrics : Theory and Applications, Tenth World Congress of the Econometric Society, New York : Cambridge University Press.

51. Gollier, C., Jullien, B., Treich, N. (2000), *Scientific Progress and Irreversibility : an Economic Interpretation of the Precautionary Principle*, Journal of Public Economics, 75 : 229-253.

52. Gupta, A.G., Moyer, C.A., Stern, D.T. (2005), *The economic impact of quarantine : SARS in Toronto as a case study*, Journal of Infection, 50 : 386-393.

53. Haber, M.J., Shay, D.K., Davis, X.M., Patel, R., Jin, X., Weintraub, E., Orenstein, E., Thompson, W.W. (2007), *Effectiveness of interventions to reduce contact rates during a simulated influenza Pandemic*, Emerging Infectious Diseases, 13(4).

54. Hage, O. (2007), *The Swedish producer responsibility for paper packaging : an effective waste management policy ?*, Resources, Conservation and Recycling, 51(2) : 314-344.

55. Hartikaiinen, H., Pulkkinen, H. (2016), *Summary of the chosen methodologies and practices to produce GHGE-estimates for an average European diet*.

56. Heal, G., Kriström, B. (2002), *Uncertainty and Climate Change*, Environmental and Resource Economics, 22 : 3-39.

57. Heerwegh D., Loosveldt, G. (2008), *Face-to-face versus Web surveying in a high-Internet coverage population : differences in response quality*, The Public Opinion Quarterly, 72(5) : 836-846.

58. Henry, C. (1974), *Investment decisions under uncertainty : the irreversibility effect*, American Economic Review, 64(6) : 1006-1012.

59. Henry, C. (2003), *Séminaire sur le "Principe de Précaution et Risque Environnemental*, Chaire de développement durable EDF-Polytechnique, 16^{th} of June 2003.

60. Hensher, D. A. (1994), *Stated preference analysis of travel choices : The state of practice*, Transportation, 21(2) : 107-133.

61. Jeleva, M., Tallon, J-M. (2016), *Ambiguïté, comportements et marchés financiers*, L'Actualité économique, Revue d'analyse économique, 92 (1-2), mars-juin 2016.

62. Kahneman, D., Tversky, A. (1979), *Prospect theory : an analysis of decision under risk*, Econometrica, 47, 263-291.

63. Kelso, J.K., Milne, G.J., Kelly, H. (2009), *Simulation suggests that rapid activation of social distancing can arrest epidemic development due to a novel strain of influenza*, Public Health, 9.

64. Klibanoff, P., M. Marinacci et S. Mukerji (2005), *A Smooth Model of Decision Making Under Ambiguity*, Econometrica, 73(6) : 1849-1892.

65. Knight, F. H. (1921), *Risk, Uncertainty and Profit*, New York : Hart, Schaffner and Marx.

66. Kotchena, M.J., Boylec, K.J., Leiserowitza, A.A. (2013), *Willingness-to-pay and policy-instrument choice for climate-change policy in the United States*, Energy Policy, 55 : 617-625.

67. Kreuter, F., Presser, S., Tourangeau, R. (2008), *Social desirability bias in CATI, IVR, and Web surveys : The effects of mode and question sensitivity*, The Public Opinion Quarterly, 72(5) : 847-865.

68. Krewski, D., Burnett, R.T., Goldberg, M.S., Hoover, K., Siemiatycki, J., Abrahamowicz, M., White, W.H. (2004), *Validation of the Harvard Six Cities Study of particulate air pollution and mortality*, The New England Journal of Medecine 8 ;350(2) : 198-9.

69. Kroes, E.P., Sheldon, R.J. (1988), *Stated Preference Methods : An Introduction*, Journal of Transport Economics and Policy, 22(1) : 11-25.

70. Kulatilaka, N., Perotti, E. (1998), *Strategic growth options*, Management Science, 44, 1021-1031.

71. Laussel, D., van Ypersele, T. (2012), *When the Squeakiest Wheel Gets the Most Oil : Exploiting One's Nuisance Power*, European Economic Review, 56 : 1593-1306.

72. Longini I.M.Jr., Nizam, A., Xu, S., Ungchusak, K., Hanshaoworakul, W., Cummings, D.A.T, Halloran, M.E. (2005), *Containing Pandemic Influenza at the Source*, Science, 309(12).

73. Louviere, J.J., Hensher, D.A., Swait, J.D. (2000), *Stated Choice Methods, Analysis and Applications*, Cambridge University Press.

74. Lusk, J.L. (2003), *Effects of cheap talk on consumer willingness to pay for golden rice*, American Journal of Agricultural Economics, 85(4) : 40-856.

75. Machina, M. J., Siniscalchi, M. (2014), *Ambiguity and Ambiguity Aversion*, Handbook of the Economics of Uncertainty, 1 : 729-807.

76. Marette, S., Messéan, A., Millet, G. (2012), *Consumers' willingness to pay for eco-friendly apples under different labels : Evidences from a lab experiment*, Food Policy, 37 : 151-161.

77. Marette, S., Millet, G. (2014), *Economic benefits from promoting linseed in the diet of dairy cows for reducing methane emissions and improving milk quality*, Food Policy, 46 : 140-149.

78. Masson, A. (2002), *Risque et horizon temporel : quelle typologie des consommateurs - épargnants ?*, Risques, 49.

79. Mayers, C.K. (2007), *Strategic, financial, and design implications of extended producer responsibility in Europe ? A producer case study*, Journal of Industrial Ecology, 11(3) : 113-131.

80. McDonald, H., Adam, S. (2003), *A comparison of online and postal data collection methods in marketing research*, Marketing Intelligence and Planning, 21(2) : 85-95.

81. Miceli, T. (1997), *Economics of the law*, Oxford university Press, New York.

82. Milne, G.J., Kelso, J.K., Kelly, H.A., Huband, S.T., McVernon, J. (2008), *A small community model for the transmission of infectious diseases : comparison of school closure as an intervention in individual-based models of an influenza pandemic*, PLoS One, 3.

83. Montag, J. (2015), *The simple economics of motor vehicle pollution : A case for fuel tax*, Energy Policy, 85 : 138-149.

84. Moore, C. J. (2008), *Synthetic polymers in the marine environment : A rapidly increasing, long-term threat*, Environmental Research, 108(2) : 131-139.

85. Mubayi, A., Zaleta, C.K., Martcheva, M., Castillo-Chávez, C. (2010), *A cost-based comparison of quarantine strategies for new emerging diseases*, Mathematical Biosciences and Engineering, 7 : 687-717.

86. Murto, P. (2006), *Timing of investment under technological and revenue-related uncertainties*, Journal of Economic Dynamics and Control, 31(5), 1473-1497.

87. Murto, P., Näsäkkälä, E., Keppo, J. (2004), *Timing of investments in oligopoly under uncertainty : A framework for numerical analysis*, European Journal of Operational Research, 157(2), 486-500.

88. Naqvi, A., Zwickl, K. (2017), *Fifty shades of green : Revisiting decoupling by economic sectors and air pollutants*, Ecological Economics, 133 : 111-126.

89. Nordhaus, William D. (2015), *Climate Clubs : Overcoming Free-riding in International Climate Policy*, American Economic Review, 105(4) : 1339-1370.

90. Numata, D. (2009), *Economic analysis of deposit-refund systems with measures for mitigating negative impacts on suppliers*, Resources, Conservation and Recycling, 53(4) : 199-207.

91. O'Donoghue, T., Rabin, M. (1999), *Doing it now or later*, American Economic Review, 89(1) : 103-124.

92. Palmer, K., Walls, M. (1997), *Optimal policies for solid waste disposal taxes, subsidies, and standards*, Journal of Public Economics, 65(2) : 193-205.

93. Petrova, M. (2012), *Mass Media and Special Interest Groups*, Journal of Economic Behavior and Organization, 84(1) : 17-38.

94. Petrik, O., de Abreu e Silva, J., Moura, F. (2016), *Stated preference surveys in transport demand modeling : disengagement of respondents*, International Journal of Transportation Research, 8(1) : 13-25.

95. Pollak, R. A. (1998), *Imagined Risks and Cost-Benefit Analysis*, American Economic Review, 88(2), 376-380.

96. Portney, P. R. (1992), *Trouble in Happyville*, Journal of Policy Analysis and Management, 11(1) : 131-132.

97. Proctor, R. N. (2011), *Golden Holocaust. Origins of the Cigarette Catastrophe and the Case for Abolition*, Berkeley and Los Angeles : University of California Press.

98. Phelps, E. S., Pollack, R. A. (1968), *On second-best national saving and game-equilibrium growth*, Review of Economic Studies, 35(2) : 185-199.

99. Saido, K. (2014), *Ocean Contamination Generated from Plastics*, Reference Module in Earth Systems and Environmental Sciences, Comprehensive Water Quality and Purification, 1 : 86-97.

100. Salanié, F., Treich, N. (2009), *Regulation in Happyville*,Economic Journal, 119 : 665-679.

101. Sarkar, S. (2000), *On the investment-uncertainty relationship in a real options model*, Journal of Economic Dynamics and Control, 24(2) : 219-225.

102. Savage, L. J. (1954), *The Foundations of Statistics*, New York : John Wiley & Sons.

103. Sazima, I., Gadig, O.B., Namora, R.C., Motta, F.S. (2002), *Plastic debris collars on juvenile carcharhinid sharks (Rhizoprionodon lalandii) in southwest Atlantic*, Marine Pollution Bulletin, 44(10) : 1149-51.

104. Scarborough, P., Harrington, R. A., Mizdrak, A., Zhou, L. M., Doherty, A. (2014), *The preventable risk integrated ModEl and its use to estimate the health impact of public health policy scenarios*, Scientifica.

105. Shapiro, J.M. (2016), *Special Interests and the Media : Theory and an Application to Climate Change*, Journal of Public Economics, 144 : 91-108.

106. Shavell, S. (1980), *Strict liability versus negligence*, Journal of Legal Studies, 9(1) : 1-25.

107. Sinclair-Desgagné, B., Gozlan, E. (2003), *A theory of environmental risk disclosure*, Journal of Environmental Economics and Management, 45(2) : 377-393.

108. Slovic, P., Tversky, A. (1974), *Who accepts savage's axiom ?*, Behavioral Science, 19 : 368-373.

109. Stern, N. (2007), *The Economics of Climate Change*, Cambridge University Press.

110. Sutton, J. (1991), *Sunk costs and Market structure*, MIT Press.

111. Strotz, RH. (1956), *Myopia and inconsistency in discounting utility maximization*, Review of Economic Studies, 23(3) : 165-180.

112. Suna, C., Yuana, X., Yaoa, X. (2016), *Social acceptance towards the air pollution in China : Evidence from public's willingness to pay for smog mitigation*, Energy Policy 92 : 313-324.

113. Sunstein, C. R. (2002-2003), *The Paralyzing Principle : Does the Precautionary Principle Point us in any Helpful Direction ?*, Regulation : Winter, The Cato Institute.

114. Tallon, J-M., Vergnaud, J-C. (2005), *Incertitude et information en économie de l'environnement*, Programme Sciences Economiques et Environnement, Rapport final.

115. Trigeorgis, L. (1996), *Real Options*, MIT Press.

116. Ulph, A. (2004), *Stable Environmental International Agreements with a Stock Pollutant, Uncertainty and Learning*, Journal of Risk and Uncertainty, 29 : 53-73.

117. Viscusi, W.K., Hamilton, J.T. (1999), *Are Risk Regulators Rational ? Evidence from Hazardous Waste Cleanup Decisions*, American Economic Review, 89(4) : 1010-1027.

118. Von Schomberg, R. (2006), *The precautionary principle and its normative challenges*, dans E. Fisher, J. Jones and R. von Schomberg. (eds) (2006), Implementing the Precautionary Principle : Perspectives and Prospects, Cheltenham, UK and Northampton, MA, US : Edward Elgar, chapter 2 : 19-42.

119. Waldman, P., Stecker, T., Rosenblatt, J. (2017), *Monsanto was its own Ghostwriter for some Safety Reviews*, Bloomber Businessweek.

120. Wanga, Y., Mingxing, S., Yanga, X., Yuanc, X. (2016), *Public awareness and willingness to pay for tackling smog pollution in China : a case study*, Journal of Cleaner Production, 112 : 1627-1634.

121. Wardman, M.A. (1988), *Comparison of Revealed Preference and Stated Preference Models of Travel Behaviour*, Journal of Transport Economics and Policy, 22(1) : 71-91.

122. Weitzman, M. (2009), *On Modeling and Interpreting the Economics of Catastrophic Climate Change*, Review of Economics and Statistics, 91(1) : 1-19.

123. Yu, Z. (2005), *Environmental Protection : A Theory of Direct and Indirect Competition for Political Influence*, Review of Economic Studies, 72 : 269-286.

124. Yue, C., Alfnes, F., Jensen, H.H. (2009), *Discounting spotted apples : investigating consumers ? willingness to accept cosmetic damage in an organic product*, Journal of Agricultural and Applied Economics, 41 : 29-46.

125. Zhu, G., Chen, G., Fu, X. (2017), *Effects of active links on epidemic transmission over social networks*, Physica A, 468 : 614-621.

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2002 **Master 1 d'Econométrie** – Toulouse School of Economics (TSE).

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Expériences professionnelles

2017-2018	**Expert** pour le projet EFS 2035, Etablissement Français du Sang
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2004-2006	**Vacataire** – Toulouse School of Economics (TSE).
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Enseignements

* **Introduction à la Microéconomie**, Mastère spécialisé ALISEE "Management des risques sanitaires alimentaires et environnementaux", AgroParisTech, Université Paris-Saclay, Université Paris 1 Panthéon-Sorbonne, Université Paris Descartes (2010-), Cursus ingénieur AgroParisTech (1ère année, 2008-2010; 2ème année, 2008-2009).

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* **Economie du risque, de l'incertitude et de l'assurance (en français et en anglais)**, Mastère spécialisé ALISEE (2009-), Master 2 EEET (2009-2011), Master 2 BCPP "Biologie cellulaire, physiologie et pathologie", Université Paris Diderot (2013), Master 2 ARSA "Analyse des risques sanitaires liés à l'alimentation Université", AgroParisTech, Université Paris-Saclay, Université Paris-Est Créteil, (2015-), Cursus ingénieur AgroParisTech (1ère année, 2008-2010 ; 2ème année, 2008-2009/2015-; 3ème année, 2008-), Master 1 EEET (2010-2013).
* **Economie de la santé**, Cursus ingénieur AgroParisTech (1ère année, 2010- ; 2ème année, 2012- ; 3ème année, 2016-).
* **Histoire de la pensée économique**, Mastère spécialisé ALISEE (2011-), Cursus ingénieur AgroParisTech (3ème année, 2008-2011).
* **Economie de l'innovation**, Cursus ingénieur AgroParisTech (3ème année, 2016-).
* **Théorie des contrats**, Mastère spécialisé ALISEE (2014-), Cursus ingénieur AgroParisTech (2ème année, 2014).
* **Economie de l'environnement**, Cursus ingénieur AgroParisTech (2ème année, 2008-2011 ; 3ème année, 2008-2011).
* **Economie des ressources naturelles**, Cursus ingénieur AgroParisTech (2ème année, 2010-2012.
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Responsabilités

2017-	**Responsable de l'UFR** Economie Générale et Appliquée.
2016-	**Membre élue** du conseil des enseignants d'AgroParisTech.
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2012-	**Membre de la commission** du domaine 4 'Santé', AgroParisTech.
2015-	**Responsable de l'unité d'enseignement** 'Gestion et communication des risques sanitaires et environnementaux', dans la dominante METATOX 'De l'évaluation à la gestion des risques toxicologiques pour la santé des écosystèmes et de l'Homme', 3ème année d'ingénieur, AgroParisTech.
2011-	**Responsable de l'unité d'enseignement** 'Economie de la santé et gestion des risques sanitaires liés à l'alimentation et à l'environnement', 2ème année d'ingénieur, AgroParisTech.
2010-	**Responsable de l'unité d'enseignement** 'Stratégies de management des risques' du mastère spécialisé ALISEE**.**
2015-2017	**Responsable de l'option '**Alimentation, Santé et biotechnologie', dans la dominante GIPE 'Gestion, innovation et performances des entreprises du vivant, 3ème année d'ingénieur, AgroParisTech.
2010-2012	**Responsable de l'unité d'enseignement** 'Économie des ressources naturelles', 2ème année d'ingénieur, AgroParisTech.
2009-2011	**Responsable de l'unité d'enseignement** 'Gestion du risque et de l'incertain : applications', du Master 2 EEET.
2008-2010	**Responsable de l'unité d'enseignement** 'Grands problèmes économiques', 1ère année d'ingénieur AgroParisTech.
2008-2009 et 2010-2011	**Responsable de l'unité d'enseignement** 'Économie de l'environnement et des ressources naturelles', 2ème année d'ingénieur AgroParisTech.

2015- **Membre de l'équipe pédagogique** de la dominante de 3ème année d'ingénieur AgroParisTech, METATOX.
2010- **Membre de l'équipe pédagogique** du Mastère spécialisé ALISEE.
2012-2017 **Membre de l'équipe pédagogique** de la dominante de 3ème année d'ingénieur AgroParisTech, GIPE.
2009- **Membre de jury de sélection** du mastère spécialisé ALISEE.
2008- **Membre de jury de mémoire** du mastère spécialisé ALISEE et des Masters 1 et 2 EEET.

2009-2011 **Responsable du séminaire** de l'UMR Economie Publique, AgroParisTech, INRA, Université Paris Saclay.

Publications dans des revues à comité de lecture

1. Orset, C. (2019), How travellers are responding to environmental policies for reducing air pollution ?, Ecological Economics, 156 : 68–82. (HCERES A, CNRS Rang 1, Impact factor : 3.895)
2. Bramoullé, Y., Orset, C. (2018), Manufacturing doubt, Journal of Environmental Economics and Management, 90 : 119-133. (HCERES A, CNRS Rang 1, Impact factor : 2.305)
3. Orset, C. (2018), People's perception and cost-effectiveness of home confinement during an influenza pandemic: evidence from the French case, European Journal of Health Economics, 1-16. (HCERES A, CNRS Rang 2, Impact factor : 2.500)
4. Orset, C., Barret, N., Lemaire, A. (2017), How consumers of plastic water bottles are responding to environmental policies?, Waste Management, 61, 13-27. (Impact factor : 4.030)
5. Orset, C. (2014), Innovation and the precautionary principle, Economics of Innovation and New Technology, 23(8) : 780-801. (HCERES A, CNRS Rang 2, Impact factor : 1.100)
6. Jouvet, P.A., Le Cadre, E., Orset, C. (2012), Irreversible investment, uncertainty, and ambiguity: the case of bioenergy sector, Energy Economics, 34(1) : 45-53. (HCERES A, CNRS Rang 2, Impact factor : 3.199)
7. Chemarin, S., Orset, C. (2011), Innovation and information acquisition under time inconsistency and uncertainty, Geneva Risk and Insurance Review, 36(2) : 132-173. (HCERES A, CNRS Rang 2, Impact factor : 1.480)

Chapitre de livre

* Orset, C., *L'apport de l'économie du risque dans la gestion des risques*, Chapitre 3.3, dans Risques chimiques dans les aliments : Principes et applications, Lavoisier (sortie prévue en octobre 2018).

Autre publication

* Tevenart, C., Brunette, M., Orset, C. (2017), *Freins à l'adoption de mesures d'atténuation des gaz à effet de serre dans l'agriculture. Quels rôles pour l'aversion au risque et l'aversion à l'ambiguïté ?*, Climate Economics Chair, Informations et débats, n° 51.

Documents de travail

* Dessy, S., Orset C., *The Scourge of Human Trafficking: Why A Coordinated Global Effort Is a Hard Sell.*
* de Gavelle, E., Perrimon, M., Leroy, P., Huneau, J-F., Orset, C., Soler, L-G., Mariotti F., *Rearrangements of protein food intake with simple changes in portion sizes to increase nutrient adequacy: Impacts on sustainability parameters.*
* Orset, C, Pinto da rocha, F., Siari, M., *Willingness to pay for switching from polluting energies to green energies?*
* Jacob, J., Orset C., *Innovation, information, lobby and tort law under uncertainty.*

Conférences et séminaires

2018 * Journées Internationales du Risque (JIR), Juin, Niort (France).

2017 * The 23th Annual Conference of the European Association of Environmental and Resource Economists' (EAERE), Juin, Athènes (Grèce).
* Conférence annuelle de la French Association of Environmental and Resource Economists (FAERE), Septembre, Nancy (France).
* Séminaire Invitée, Economie Publique-ALISS, AgroParisTech, INRA, Université Paris-Saclay, Paris (France)
* Workshop Invitée, Régulation des (nouveaux) risques : enjeux et perspectives, Nancy (France).

2016 * The 22th Annual Conference of the European Association of Environmental and Resource Economists' (EAERE), Juin, Zurich (Suisse).
* Journées de microéconomie appliquée (JMA), Juin, Besançon (France).
* Séminaire Invitée, Economie Publique, AgroParisTech, INRA, Université Paris-Saclay, Paris (France).

2015 * 9ème Journées de Recherches en Sciences Sociales (SFER), Décembre, Nancy (France).
* Séminaire Invitée, UMR INRA-AgroCampus Ouest, SMART, Rennes (France).

2014 * Séminaire Invitée, UMR INRA-AgroParisTech, LEF, Nancy (France).

2013 * 2013 North American Summer Meeting of the Econometric Society', Juin, Los Angeles, (Etats-Unis).
* The 20th Annual Conference of the European Association of Environmental and Resource Economists (EAERE), Juin, Toulouse (France).
* The 47th Annual Conference of the Canadian Economics Association (CEA), Juin, Montréal (Canada).

2011 * The 18th Annual Conference of the European Association of Environmental and Resource Economists (EAERE), Juin-Juillet, Rome (Italie).
* The 10th edition of the Days Louis-André Gérard-Varet (LAGV10), Juin, Marseille (France)
* The 45th Annual Conference of the Canadian Economics Association (CEA), Juin, Ottawa (Canada).

2010 * The 4th World Congress of Environmental and Resource Economists (WCERE 2010), Juin, Montreal (Canada).
* World Risk and Insurance Economics congress, Juillet, Singapore (Singapore).
* 59ème congrés de l'Association Française de Science Économique' (AFSE), Septembre, Paris Ouest-Nanterre La Défense (France).

2009 * The 24th edition of the Jornadas de Economía Industrial (JEI2009), Septembre, Vigo (Espagne).
* The 13th Annual Conference of the Asia-Pacific Risk and Insurance Association (APRIA), Juillet, Pekin (Chine).
* The 17th Annual Conference of the European Association of Environmental and Resource Economists (EAERE), Juin, Amsterdam (Pays-Bas).
* Séminaire Invitée, Economie Publique, AgroParisTech, INRA, Université Paris-Saclay, Paris (France).

2008 * The 33rd Symposium of economic analysis, Decembre, Zaragoza (Espagne).
* 2008 North American Summer Meeting of the Econometric Society, Juin, Pittsburgh (Etats-Unis).
* The 42nd Annual Meeting of the Canadian Economics Association (CEA), Juin, Vancouver (Canada)
* Le 48e Congrès de la Société canadienne de science économique (SCSE), Mai, Montebello (Canada).
* Les journées doctorales de l'ADRES, Janvier, Université Toulouse 1 (France).
* Séminaire Invitée, Université Laval CIRPEE, Québec (Canada).

2007 * The 34th Seminar of the European Group of Risk and Insurance Economists (EGRIE), Septembre, Cologne (Allemagne).
* Conference of the French Economic Association on behavioral economics and experimental economics, Mai, Lyon (France).
* The 4th International Finance Conference, March, Hammamet (Tunisie).

2006 * International Conference on Economics Turkish Economic Association, Septembre, Ankara (Turquie).
* Annual conference of IAREP-SABE on behavioural economics and economic psychology, Juillet, Paris (France).
* The 4th International seminary of doctoral students in economic integration, Juin, Bordeaux (France).
* The Spring 2006 Midwest International Economics and Economic Theory meetings, Avril, Michigan University (Etats-Unis).
* Séminaire International des doctorants, Toulouse (France).

Encadrement thèse

2016- Camille Tevenart en co-encadrement avec Marielle Brunette (BETA, Nancy).

Encadrement Ingénieurs AgroParisTech, Master EEET et Mastère spécialisé

Depuis 2008

* 7 à 8 Ingénieurs 1ère année par an
* 2 à 4 Ingénieurs 2ème année par an
* 1 à 2 Ingénieurs 3ème année par an
* 1 à 2 Etudiants en Master 1 et 2 EEET par an
* 3 à 4 Etudiants en Mastère spécialisé ALISEE par an

Divers

* Prix et distinctions : Lauréate de la bourse Robert Solow 2008-2009, Lauréate de la bourse Lavoisier 2008-2009.
* Appartenance à des sociétés savantes : Membres de European Economic Association (EEA), Econometric society (ES), Canadian Economics Association (CEA), European Association of Environmental and Resource Economists (EAERE), French Association of Environmental and Resource Economists (FAERE).
* Rapporteur pour Resource and Energy Economics, Contemporary Economic Policy et Waste management.
* Jury concours de recrutement AgroParisTech MC (2015).
* Jury concours de recrutement de L'Ecole Nationale Vétérinaire de Toulouse recrute un Maître de Conférences en Economie de la santé animale MC (Prévu pour décembre 2018).
* Formation en Economie expérimentale organisée par l'INRA à Montpellier (2015).
* Langues : Français (langue maternelle), Anglais (lu, parlé, écrit), et Espagnol (notion).

Travaux et publications

Table des matières

Orset, C. (2019), *How travellers are responding to environmental policies for reducing air pollution?*, Ecological Economics, 156 : 68–82.

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How Do Travellers Respond to Health and Environmental Policies to Reduce Air Pollution?☆

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ABSTRACT

Despite the various measures taken to reduce air pollution in France, the French continue to use high-emission vehicles. We propose to evaluate the Willingness To Pay (WTP) for four means of transport: two high-emission vehicles (diesel taxi and diesel personal vehicle) and two low-emission vehicles (rented electric vehicle and public transport). Successive messages revealing the effects of air pollution on health and the environment are provided to individuals in a different order. The information conveyed changes both of the WTP of individuals and of their choices. However, the use of high-emission vehicles has not diminished, personal vehicles remain the most popular. Using data collected from our survey, a multinomial logit model is used to determine individual choices. We find that improving individuals' confidence in air pollution recommendations would be a good way to lead them to choose low-emission rather than high-emission means of transport. Moreover, these estimates also indicate that individuals who attach great importance to comfort are less likely to choose low-emission vehicles than those who value price above other factors. Individual interest can therefore prevail over collective interest, thus verifying the theory of the tragedy of the commons. Different policies (taxes, subsidies, or standard) to encourage people to adopt low-emission vehicles are then tested.

1. Introduction

Many actions have been conducted in France to reduce the negative impact of means of transport, such as taxis or diesel vehicles, on air quality. These actions were aimed at encouraging people to use low-emission vehicles, in particular public transport and electric vehicles. Actually, many studies about the adverse effects of air pollution on health have been conducted. Douglas et al. (1993) and Krewski et al. (2004) found a consistent and statistically significant association between long-term exposure to fine particles with a diameter of 2.5 μm ($PM_{2.5}$) coming from fossil fuels in vehicles and the risk of mortality. Using the fifty-one cities from the American Cancer Society study, Pope et al. (2009) reported that wide reductions in $PM_{2.5}$ concentration between 1980 and 2000 were strongly associated with an increase in life expectancy. In 2015, according to a French Senate committee, once the cost of all measures to fight air pollution has been deducted, the net health benefit for France of combating air pollution would be over 11 billion e per year.

Moreover, air pollutants have also a negative impact on the environment.[1] When fossil fuels are burned, it may create acid rain, which damages trees, buildings and makes the water unsuitable for wildlife. In addition, vehicles contribute to eutrophication, which stimulates blooms of algae and causes fish death and loss of plant and animal diversity. Air pollution from high-emission vehicles also increases haze. Air pollution can also damage crops and trees in reducing growth and survivability of tree seedlings and increasing plant susceptibility to disease. In addition, air pollution is responsible for greenhouse gases, which is a cause of global climate change. In 2015, the French Senate committee estimates the cost of air pollution in France to > 100 billion e per year.

So why do the French continue to use high-emission vehicles? Are they aware of the negative impact of air pollution on health and the environment? How to lead them to use low-emission vehicles? We built a questionnaire in which we informed respondents about these negative impacts. We consider two groups of respondents that receive two different questionnaires. The questionnaires only differ by the information order received by the respondents. Group 1 first receives information on the negative impact on health and then on the environment of air pollution, while Group 2 first receives information on the negative

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[1] See the US Environmental Protection Agency (EPA) for more details.

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impact on the environment and then on health. In order to characterize the respondents' preferences for each means of transport, we use the Willingness To Pay method (WTP). Policy-makers are faced with difficult choices when implementing air pollution reduction measures. Understanding people's preferences for these measures allows policy-makers to choose the best health and environmental policies.

Our approach relies on two building blocks. First, our paper is linked to the literature that examines the interaction between the WTP and information acquisition. The WTP approach is a stated preference method. Kroes and Sheldon (1988) and Louviere et al. (2000) present and develop the use of this method in diverse fields. This method has been notably used for estimating the individual preferences for means of transport (Baidoo and Nyarko, 2015, for a study in Accra central (Republic of Ghana); Hensher, 1994, for a review on the application of stated preference models in the transportation market; Petrik et al., 2016, for a study in Portugal; Wardman, 1988, for a study in the United Kingdom). Moreover, the WTP approach has also been used in air pollution issues. Kotchena et al. (2013) have studied the WTP for climate change policies in the United States, Suna et al. (2016) and Wanga et al. (2016) have focused on the WTP for smog mitigation in China. Our paper contributes to this literature by investigating the WTP for four means of transport (low-emission vehicles: public transport and rented electric vehicle, and high-emission vehicles: taxi and personal vehicle) in France. We find that people have a strong preference for personal vehicles, which are one of the high-emission means of transport. We introduce the precise impact of information on the travellers' WTP for the different means of transport. We then conduct an analysis to elicit the WTP for different means of transport with increasing levels of information on the negative impact of air pollution on health and the environment. We observe that information matters but the order of information does not. Indeed, the information caused changes both of the WTP of travellers and their choices. However, the use of high-emission vehicles has not diminished and the personal vehicle is still the preferred mean of transport. Using data collected from our survey, a multinomial logit model was used to determine individual choices. We observe that improving travellers' confidence in air pollution recommendations would be a good way to lead them to choose low-emission rather than high-emission means of transport. Moreover, these estimates indicate that travellers who attach great importance to comfort are less likely necessarily to choose low-emission vehicles than those who value price. Individual interest can therefore prevail over the collective interest, thus verifying the theory of the tragedy of the commons.[2]

Furthermore, we contribute to economics literature on the reduction of air pollution. There is a consensus on the harmful consequences on health and the environment of air pollution due to high-emission vehicles. We then test health and environmental policies: an information campaign on the consequences on health and the environment of air pollution, a tax policy in which high-emission vehicles are taxed, a subsidy policy in which low-emission vehicles are subsidised, and finally, a standard under which high-emission vehicles are forbidden. We also analyse combined policies (tax and subsidy, information campaign and the other tools, standard and subsidy). Some works have analysed the impact of air pollution policies on the structural changes at sectorial level and on energy use (Bollena and Brink, 2014; Naqvi and Zwickl, 2017). Others consider that the volume of pollution produced by an automobile is determined by drivers' behaviour vis–vis three criteria (vehicle selection, kilometres driven, and on-road fuel economy) and they study the optimal policies which could change the driver's behaviour (Montag, 2015). Agostinia and Jimnez (2015) have focused on the gasoline tax as the best instrument of climate policy. Nevertheless, none of these works has studied the impact of health and environmental policies on travellers' behaviour concerning their choice of means of transport. We find that choosing between these health and environmental policies will depend on regulator's priorities. However, two of these policies seem to be good alternatives, namely subsidizing low-emission vehicles with or without information campaign.

The paper is organized as follows. Section 2 details the study. Section 3 presents the results with a descriptive analysis and the determinants of travellers' WTP. Section 4 shows the welfare analysis, the determinants of travellers' choices and regulatory advice. Finally, Section 5 concludes.

2. The Study

According to Avem,[3] pollution related to transport has increased by over 30% in 20 years, the main cause being the increase in vehicle traffic. Indeed, urban congestion contributes to 75% of photochemical pollution and 40% of acid deposition. We then propose to analyse French travellers' Willingness To Pay in order to reduce air pollution related to transport.

2.1. Target Respondents

During February 2015, we conducted the study through Marketest.[4] We asked Marketest to create two groups of respondents. Each group was selected by using the quota method, i.e., the same proportions of gender, age and socioeconomic status (income and occupation) criteria in the group of respondents as in the census report of the French population by the Institut national de la statistique et des ´etudes conomiques (INSEE) in 2013. We had prepared specifically for this study two questionnaires, one for each group, to be posted online. The two questionnaires only differed by the order in the information received by the respondents. Group 1 first received information on the negative impact of air pollution, first on health and then on the environment. Group 2, on the other hand, first received information on the negative impact on the environment and then on health. Group 1 target respondents consists of 177 French people aged between 20 and 65. Group 2 target respondents are 165 French people aged between 20 and 80.

Table 1 presents the socioeconomic characteristics (gender, age, income, and occupation) of the respondents. Differences between the two groups and INSEE data are tested using the Pearson chi-squared test. A P-value (against the null hypothesis of no difference) of $< 5\%$ is considered significant. The results in the last three columns of Table 1 suggest that the three groups are not significantly different.

Through informational questions on the respondents, we understand that for 41.8% of Group 1 respondents and 34.6% of Group 2 respondents, price is the first criterion for selecting their means of transport. 29.4% of Group 1 respondents and 36.9% of Group 2 respondents take into account primarily travel time, and 28.8% of Group 1 respondents and 28.5% of Group 2 respondents the well-being during the ride. Only 33.3% of Group 1 respondents and 33.9% of Group 2 respondents are directly or indirectly (through family) affected by air pollution health issues such as asthma, respiratory disorders or allergies. Finally, 56.5% of Group 1 respondents and 65.5% of Group 2 respondents take into account the recommendations when a pollution peak is announced. Therefore, the majority of respondents in both groups' trusts the air pollution recommendations.

[2] The tragedy of the commons describes a situation in a shared resource system where individual users acting independently for their own benefit behave in a way that is contrary to the common good of all users by depleting or degrading that resource through their collective action. In our study, the common resource is the air, which is a shared resource, and the degradation is due to the pollution created by high-emission transports.

[3] See: http://www.avem.fr/index.php?page=pollution.

[4] For more details on Marketest see: http://www.marketest.co.uk/.

Table 1
Socioeconomic characteristics of respondents. 177 respondents (Group 1) and 165 respondents (Group 2).

Description	Group 1 (%)	Group 2 (%)	INSEE (%)	Chi2 test P-value between Group 1 and Group 2	Chi2 test P-value between Group 1 and INSEE	Chi2 test P-value between Group 2 and INSEE
Gender						
Female	50.3	53.3	51.5	0.58	0.83	0.74
Male	49.7	46.7	48.5			
Age						
[20–24]	13.6	17.0	16.0	0.28	0.68	0.14
[25–59]	75.7	67.9	75.8			
60 ≤	10.7	15.1	8.1			
Monthly net income of the household (€)						
< 1000	11.9	12.1	10.0	0.75	0.63	0.10
[1000–1500)	20.9	13.9	20.0			
[1500–2500)	23.1	30.3	20.0			
2500 ≤	44.1	43.7	50.0			
Professional groups						
Farmer	0.6	0	1.0	0.19	0.24	0.07
Craftsman	3.4	3.6	3.0			
Self-employed and executive	28.8	21.8	22.6			
Employee and worker	33.9	35.2	29.2			
Retired person, unemployed person, and homemaker	33.3	39.4	44.2			

2.2. Means of Transport

We have chosen to focus on the journey from the center of Paris (the Châtelet Paris Metro station) to the Paris Charles de Gaulle Airport (around 33 km (20 miles) using the A_1 Highway by vehicle, public transport also follows this route, with a 30-minute travel time for each means of transport). This journey is used every day for leisure and business trips. Therefore, even French people who do not live in Paris can have made this trip. Moreover, the A_1 Highway between Paris and Charles de Gaulle Airport, peculiarly around the suburb of Saint-Denis, is one of the most polluted road sections in France. Table 2 shows that standards are often exceeded on this particular road section.

We propose to respondents four means of transport for the journey: a taxi (TAXI), a personal vehicle (PV), a rented electric vehicle (REV), and public transport (PT) (bus, subways…).[5] These means of transport emit very different levels of pollutants. Table 3 sums up for each transport, the ride cost, the level of vehicle on dioxide (CO_2), the level of vehicle on monoxide (CO), the level of nitrogen oxide (NO_x) which is the sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2), and the level of particles (PM_{10} and $PM_{2.5}$) for the total journey.[6]

According to the World Health Organization (WHO), CO can cause poisoning, resulting in headaches and dizziness or even coma or death from prolonged exposure. The limit value from a health protection perspective is 10,000 µg/m^3 on average over 8 h. Its oxidation results in the formation of CO_2, which is a greenhouse gaz. CO_2 emissions affect climate in the short and long terms. From a certain concentration in the air, the CO_2 is dangerous or fatal. The exposure limit is 3% over a period of 15 min. At 25% CO_2 in air, respiratory arrests can occur, resulting in death. NO_x does not have direct health effects. However, NO_2 can cause respiratory tract inflammation, an increase of bronchitis symptoms and reduced lung function. Moreover, NO_x contributes to the phenomenon of acid rain that depletes the environment (soil and vegetation). The particles (PM_{10} and $PM_{2.5}$) have adverse effects on health. Chronic exposure helps increase the risk of contracting cardiovascular and respiratory diseases, and lung cancers. The annual limit value to protect health is 40 µg/m^3 annual average for PM_{10} and 25 µg/m^3 for $PM_{2.5}$. Through the hugely dominant effect of particles is on human health, they also have a harmful effect on the environment. They degrade buildings. They have an impact on climate by absorption and scattering of solar radiation as well as the formation of clouds.

Therefore, it seems important to propose the use of low-emission means of transport because they have the least negative impacts on health and the environment. According to Table 3, we see that rented electric vehicle and public transport are low-emission means of transport while taxi and personal vehicle are high-emission means of transport. Note that we have informed the respondents that we consider diesel taxis and diesel personal vehicles. Actually, in Paris, diesel taxis represent 99.9% of the taxi fleet and diesel personal vehicles, 62.2% of the personal vehicle fleet.[7]

2.3. Experimental Design and Information Revealed

In each questionnaire, successive messages emphasizing health and environmental impacts of air pollution are delivered to survey respondents. Means of transport are a source of air pollutants. According to the Paris air pollution measurement agency Airparif,[8] the transport sector represents 24.3% of the CO_2 emissions, 57% of the NO_x emissions, 32% of the PM_{10} emissions, 38% of the $PM_{2.5}$ emissions in Île-de-France (Greater Paris administrative area, in which the journey from

[5] These means of transport were and are still the only ones proposed to make this journey. A taxi corresponds to a Parisian taxi or to a privately driven transport vehicle.

[6] The price for a ride for each mean of transport is the market price in February 2015. For the taxi: http://www.parisaeroport.fr/en/passengers/access/paris-charles-de-gaulle/taxi/paris-cdg-taxi; For the personal vehicle: from ViaMichelin (which considers fuel and highway fees); For the rented electric vehicle: from Autolib, https://www.autolib.eu/fr/; for the public transport: from RATP. Moreover, we have chosen to present these pollutants because they are the ones selected by VEHICLE LABELLING ADEME, which imposes no-claims bonus to vehicles. For Public transport: CO_2: RATP-GETTING AROUND-TIMETABLE, NO_x and Particles: Airparif (http://www.airparif.fr/calculateur-emissions/), and CO: CITEPA (http://www.citepa.org/fr/airetclimat/analyse-sectorielle/transports); for Taxi, Personal Vehicle, Rented Electric Vehicle: CO_2, CO: VEHICLE LABELLING ADEME (mean of diesel vehicles for Taxi and Personal Vehicle, and mean of electric vehicles for rented electric vehicle), NO_x: Airparif (http://www.airparif.fr/calculateur-emissions/) and Particles: average between data from Airparif (http://www.airparif.fr/calculateur-emissions/) and Timmers and Achten (2016) for a weight at 1120 kg for a rented electric vehicle and 1600 kg for taxi and personal vehicle.

[7] http://www.paris.fr/taxis#subventions-taxis-propres$_3$ and http://www.ccfa.fr/IMG/pdf/cpparcfrance2016ok.pdf.

[8] For more details see: http://www.airparif.asso.fr/etat-air/air-et-climat-quelques-chiffres.

Table 2
Situation of different pollutants regulated in relation to air quality standards on A_1 Highway in 2015.
From Airparif (2016).

Polluting	Limit value	Target value	Quality goal
PM_{10}	Exceeded		Exceeded
$PM_{2.5}$	Exceeded	Exceeded	Exceeded
NO_x	Complied with		
CO	Complied with		

Table 3
Costs and levels of pollution for each kind of transports and for the total journey.

Means of transport	Cost (€)	CO_2 (g)	CO (g)	NO_x (g)	Particles (g)
Taxi	50	5620	9.874	19.4	2.8
Personal vehicle	3.7	5620	9.874	19.4	2.8
Rented electric vehicle	13.5	0	0	0	1.4
Public transport	10	108	0.047	0	0.3

the center of Paris (Châtelet Metro station) to the Paris Charles de Gaulle Airport is realized).

We want to raise respondents' awareness about health and environmental issues related to their decisions on means of transport. In order to characterize their preferences for each means of transport, we use the Willingness To Pay method (WTP). WTP is elicited after each message with the following question: *How much would you be willing to pay as a maximum fare for a trip from the center of Paris* (*Châtelet Metro station*) *to the Paris Charles de Gaulle Airport by taxi, public transport, rented electric vehicle and personal vehicle*? The study is divided into several stages as described in Fig. 1.[9]

The sequence of information revealed differs between both groups. Group 1 first received information on the negative impact of air pollution on health and then on the environment, while Group 2 first received information on the negative impact on the environment and then on health. Each questionnaire was given to respondents as follows. First, a text helps respondents understand the purpose of the study: *This study is conducted by economists working in academia without any link to government. This survey focuses on different means of transport that may be used to make the journey from the center of Paris* (*Châtelet Metro station*) *and Roissy Charles De Gaulle airport. The travel time is 30* min *whatever means of transport you choose*. We do not give more information to limit framing effect and anchoring bias.[10] Then, respondents fill a questionnaire with informational and socio-demographic characteristics questions. We needed this information in order to analyse the WTP and choices determinants. Finally, based on different types of information revealed to respondents, seven messages of WTP elicitation are successively determined.

We have decided to divide the set of information into air pollution impact on health and air pollution impact on the environment. Table 4 describes the messages and the respondents' behaviours expected.

3. Results

3.1. Descriptive Analysis

Figs. 2 and 3 present, with boxplots, the distributions of the WTP for each means of transport and the information (message) provided for Group 1 and for Group 2, respectively. For each boxplot, we indicate the means with a cross and the median with a line.

We understand that the dispersion for the WTP for personal vehicles and public transport is not affected by the messages while that of rented electric vehicles and taxis tend to increase. Therefore, the succession of messages seems to create more divergence between the respondents' WTP for these two means of transport.

We then observe that Messages 3, 6 and 7 have on average an unexpected consequence on the respondents' WTP for taxi, public transport and rented electric vehicle. Indeed, Message 3 decreases on average the respondents' WTP for public transport and rented electric vehicles.

Moreover, Message 6 decreases on average the respondents' WTP for rented electric vehicles while Message 7 increases the respondents' WTP for taxis. On the other hand, only Message 6 has the expected consequence on the respondents' WTP for personal vehicles, which is an average decrease respondents' WTP for their personal vehicle. Therefore, the expected goal of the different messages on respondents' preferences concerning personal vehicles is on average not reached.

We understand that the dispersion for the WTP for personal vehicles and for public transport is not affected by the messages while that of rented electric vehicles and taxis tend to increase, just as for Group 1.

We then see that Messages 3, 4 and 7 have on average an unexpected consequence on the respondents' WTP for taxi, public transport and rented electric vehicle. However, no message achieves the expected objective with regard to the preferences of respondents on average for their personal vehicle.

Therefore, for both groups, it appears that the information campaign messages fail to decrease respondents' preferences for their personal vehicle. They even lead to an increase. In addition, if we focus on all other means of transport except personal vehicles, we note that Messages 3, 4, 6 and 7 may not achieve the expected goal for respondent preferences. Only Messages 2 and 5 have the expected effects.

We now test, for each group of respondents, the significance of the average WTP differences linked to the information revelation with the Wilcoxon test for paired samples.[11] We consider the significance of the differences at the 5% level. The test is made as follows: we compare the average WTP before and after each message. This allows us to measure the impact of information revelation on the average respondents' WTP for a given means of transport. Table 5 sums up the results. We note in the table 'Decrease' when the difference significantly decreases, and 'Increase' when the difference significantly increases from a message to another.

Table 5 strengthens the previous results. Moreover, we note that message 4 does not affect any of the groups significantly. Table 5 also shows that respondents from both groups are not significantly affected by the same messages. However, when they are affected, it is in the same way.

Finally, we observe that 17.5% of Group 1 respondents and 22.4% of Group 2 respondents have the same WTP before and after receiving all the messages. Therefore, informing these respondents on the damages on health and the environment of air pollution does not change their preferences for a means of transport. In fact, either individuals prefer to ignore information even if there is potential damage to health and the environment because this behaviour maximizes their own well-being (Chemarin and Orset, 2011), or they already have information about it.

3.2. Econometric Estimations: Willingness-To-Pay

We now investigate the determinants of WTP through estimations.

[9] Messages are given in Appendix A.

[10] Framing effect is the tendency to be influenced by the way a problem is presented. The anchoring bias is the tendency unduly to use information as a reference.

[11] The Wilcoxon test is a nonparametric average comparison test of two independent or matched samples. For more details, see Chapter 7 of Tanizaki (2004).

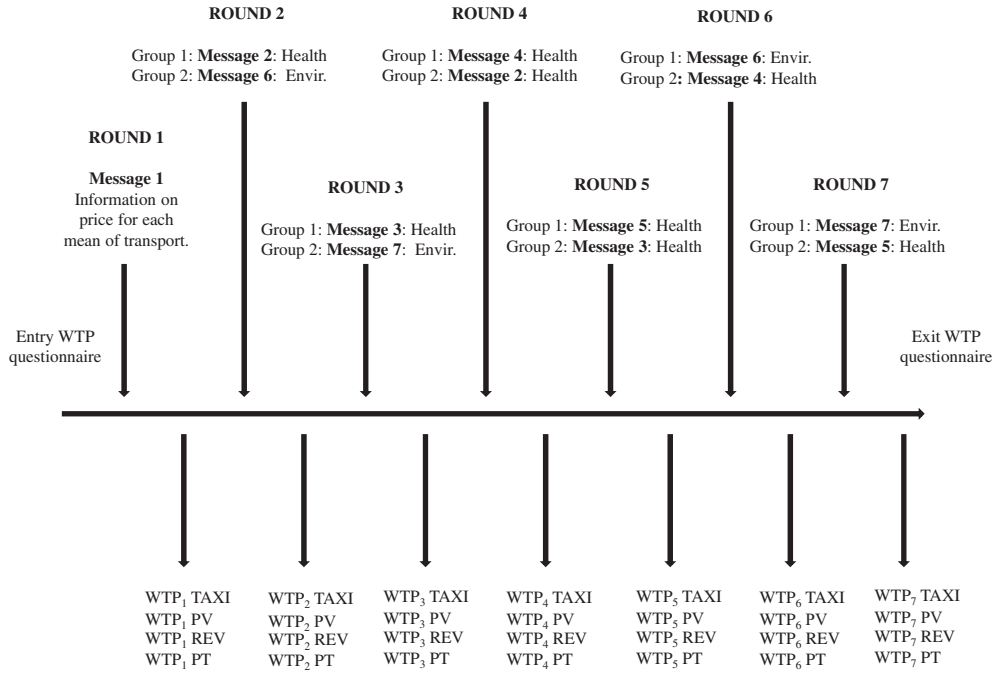

Fig. 1. Questionnaire design.

Table 4
Description of the messages and respondents' behaviour expected.

Message	Category	Description	Behaviour expected	Comment
Message 1		Prices of a ride on each means of transport.		Cheap talk as Lusk (2003) suggests limiting hypothetical bias. The hypothetical bias refers to the fact that the situation presented is described as hypothetical, and therefore the WTP may differ from the actual WTP.
Message 2	Health	Consequences of air pollution on the number of premature deaths (more than 2 million) each year worldwide.	Decrease of WTP for taxi and personal vehicle. Increase of WTP for public transport and rented electric vehicle.	Focus on global pollution.
Message 3	Health	Consequences of air pollution on the number of premature deaths (400,000 in Europe, 42,000 in France, 1,400 in Paris) each year.	Decrease of WTP for taxi and personal vehicle. Increase of WTP for public transport and rented electric vehicle.	Focus on local pollution.
Message 4	Health	Data on actual and recommended level of fine particules and on the impact of fine particles on the life expectancy of parisians and persons from the suburbs.	Decrease of WTP for taxi and personal vehicle. Increase of WTP for public transport and rented electric vehicle..	More technical focus. See whether people are sensitive to data.
Message 5	Health	Health costs of air pollution in France.	Decrease of WTP for taxi and personal vehicle. Increase of WTP for public transport and rented electric vehicle.	Economics focus. See whether people are sensitive to the health costs of air pollution.
Message 6	Environment	Air pollution impact on buildings.	Decrease of WTP for taxi and personal vehicle. Increase of WTP for public transport and rented electric vehicle.	Urban preservation focus.
Message 7	Environment	Consequences of air pollution on climate change and ecosystem.	Decrease of WTP for taxi and personal vehicle. Increase of WTP for public transport and rented electric vehicle.	Ecological focus.

We use a Random effects panel model on pooled data.[12] This model allows us to analyse the effect of each determinant on the dependent variable, here travellers' WTP. The random effects model can be written

[12] According to the Breusch-Pagan test, which tests the null hypothesis that the pooled OLS estimator is adequate against the random effects alternative, we obtain that the random effects model is favourable. Then, we make the Hausman test, which tests the null hypothesis that the random effects model is preferable to fixed effect model. We obtain that the test counts against the fixed effects model and in favour of random effects. See Chapter 11 of Greene (2017).

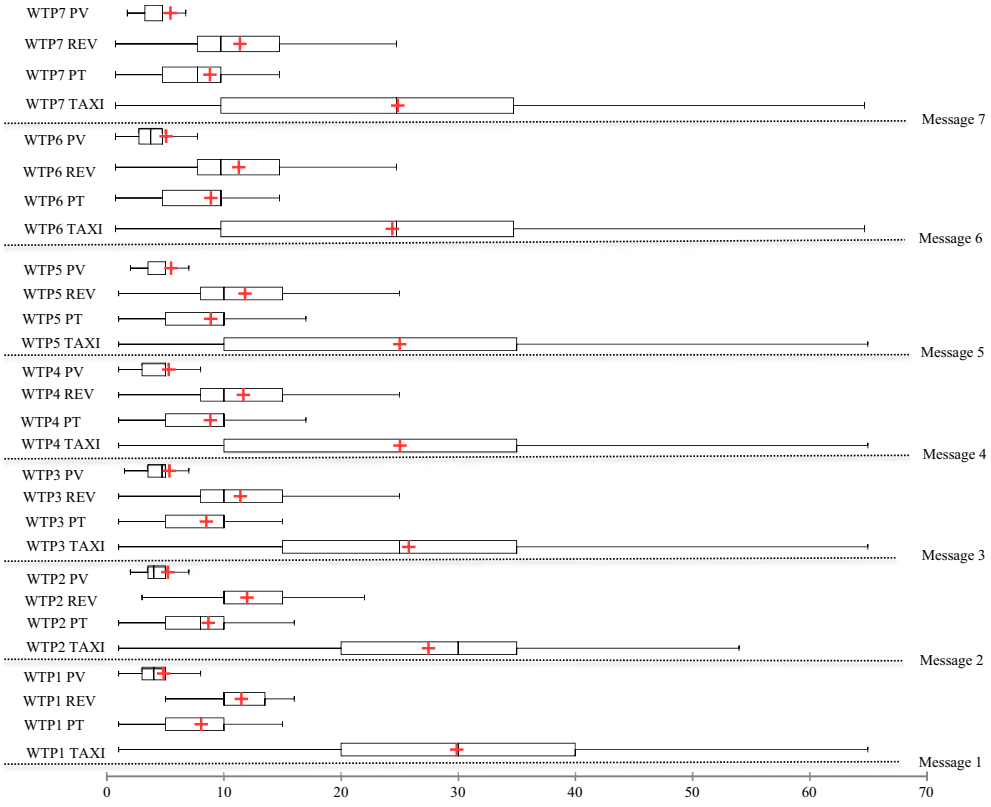

Fig. 2. Distribution of the Willingness-To-Pay for each mean of transport in euro for Group 1.

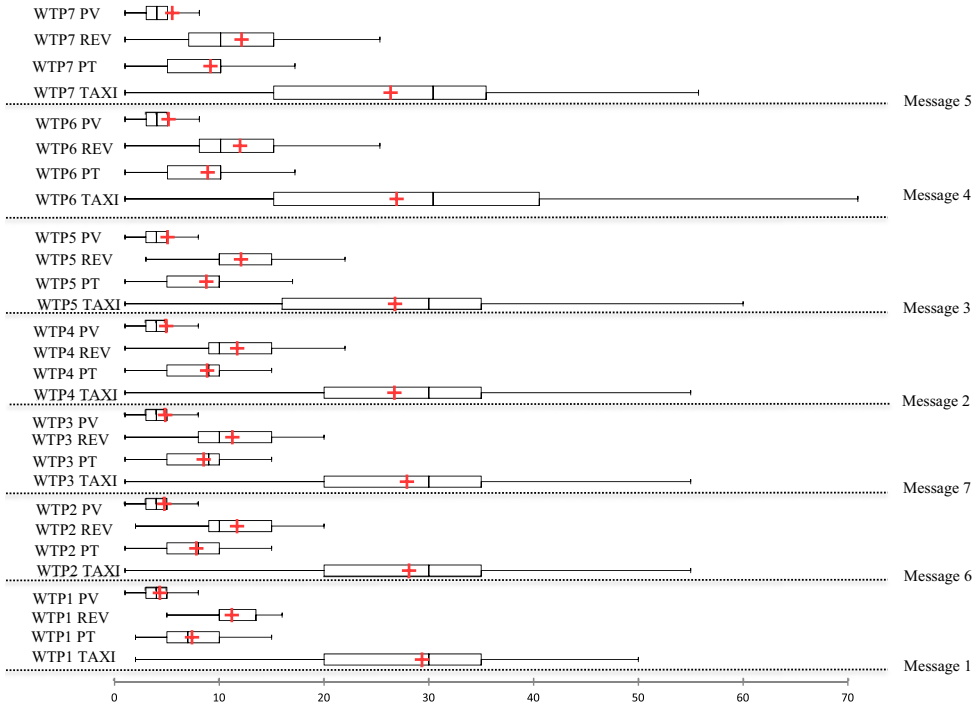

Fig. 3. Distribution of the Willingness-To-Pay for each mean of transport in euro for Group 2.

as

$$y_{it} = \alpha + x_{it}'\beta + z_i'\gamma + c_i + u_{it},$$

for $t = 1 \ldots T$ and $i = 1, \ldots, N$ with $N = 2394$ observations and $T = 7$ time periods, where y_{it} is the dependent variable observed for individual i at time t, that is the individual i's WTP for one of the mean of transport at time is a 8-dimensional row vector of time-varying explanatory variables; we have dummies for the type of information Health or Environment (Information on Environment: 0 for no and 1 for yes), for the order of the received message (Information on Environment received first: 0 for no and 1 for yes), for available information at the moment of the WTP elicitations (Message X: 0 for no and 1 for yes);

Table 5
Results from the Wilcoxon test.

Between	Taxi		PV	
	Group 1	Group 2	Group 1	Group 2
Messages 1 and 2	Decrease	Decrease	Increase	
Messages 2 and 3	Decrease			
Messages 3 and 4				
Messages 4 and 5			Increase	
Messages 5 and 6			Decrease	
Messages 6 and 7			Increase	

Between	REV		PT	
	Group 1	Group 2	Group 1	Group 2
Messages 1 and 2		Increase	Increase	
Messages 2 and 3	Decrease			
Messages 3 and 4				
Messages 4 and 5				
Messages 5 and 6			Increase	
Messages 6 and 7				Increase

z_i is a 18-dimensional row vector of timeinvariant explanatory variables excluding the constant, that is: having one's health impacted by air pollution (asthma, respiratory disorders, allergies), the individual importance attached to the air pollution index, the individual's confidence on air pollution recommendations, gender, income, age, professional groups, individual's localisation in the Île-de-France area, and their criteria of selection between price and comfort. Having one's health impacted by air pollution is a dummy variable (0 for no and 1 for yes); Individual importance attached to air pollution is divided into four variables (Importance attached to air pollution index-0: none; Importance attached to air pollution index-1: weak; Importance attached to air pollution index-2: high; Importance attached to air pollution index-3: very high), the individual's confidence on air pollution recommendations is divided into four variables (Confidence on recommendation-0: none; Confidence on recommendation-1: weak; Confidence on recommendation-2: high; Confidence on recommendation-3: very high). Age is a quantitative variable and gender is a dummy variable (1 for woman and 0 for man). We have divided income into four variables (Income-0: $1000_{¡}$; Income-1: [1000, 1500]; Income-2: [1500, 2500]; Income-3: $2500 \leq$), professional groups into five variables (SPC-0: Farmer; SCP-1: Craftsman; SCP-2: Self-employed and executive; SCP-3: Employee and worker; SCP-4: Retired person, unemployed person and homemaker), an individual's localisation in the Île-de-France area (IDF) is a dummy variable (1 for yes and 0 for no), and the individual's criteria for selecting between price and comfort is a dummy variable (1 for Comfort and 0 for Price); α is the intercept; β is a 8-dimensional column vector of parameters; γ is a 18-dimensional column vector of parameters; c_i is an individual-specific effect and u_{it} is an idiosyncratic error term. We note that with a random effects model, the individual-specific effect is a random variable, which is uncorrelated with the explanatory variables. In the model, Importance attached to the air pollution index-0, Confidence on recommendation-0, Income-0 and SCP-0 are reference modalities. Table 6 presents the estimations results.[13]

All the regressions are significant and the R^2 varies between 4.2% and 8.3%. We understand that providing information on the environment significantly decreases the WTP for a taxi by €2.18. In addition, providing Message 2, which is a message on health explaining the consequences of air pollution on deaths worldwide, significantly decreases the WTP for a taxi by €3.06 while it increases the WTP for public transport by €0.61. Finally, providing Message 3, which is a message on health explaining the consequences of air pollution on death in Europe, significantly decreases the WTP for a taxi by €0.84. Therefore, Messages 2 and 3 respond to the goal to decrease travellers' preferences for a taxi, and message 2 does the same for public transport. This strengthens the previous results. These messages showing the number of deaths due to air pollution and its impact on the environment could be given to travellers in order to decrease their preferences for a high-emission means of transport and increase the ones for low-emission. However, as shown in the descriptive part, these messages could also increase the preferences for a personal vehicle. Therefore, the use of these messages must be taken vehicle fully.

Moreover, having one's health impacted by air pollution significantly increases the WTP for the taxi by €2.73. Respondents who have a high or a very high interest for the air pollution index increase significantly their WTP for the rented electric vehicle by €1.95 and €1.83 related to respondents who do not vehicle about the pollution index, respectively. Moreover, travellers who highly believe to air pollution recommendation increase their WTP for public transport by €1.10 related to those who do not have such confidence. Therefore, giving confidence to respondents would be useful for convincing them to use public transport, which is one of the low-emission means of transport. Finally, the WTP for rented electric vehicle decreases by €0.05 with age, surely due to a lack of knowledge about the means of electric transport and/or ingrained habits in elderly people.

4. Welfare and Regulation

In this section, based on elicited WTP for the means of transport, we deduce the individual's choices. We then investigate the welfare impact of various health and environmental policies (information campaign, tax, subsidy, and standard) on these choices. We assume that all means of transport (taxi, public transport, personal vehicle and electric rented vehicle) are available on the market.

4.1. Demand and Supply of Means of Transport

Fig. 4 shows the ordered WTP of the set of respondents (Group 1 and Group 2) for the four means of transport before and after information about the consequences on health and environment of the use of means of transport. The cumulative number of respondents (equivalent to one used means of transport per participant) is represented on the X-axis and the ordered WTP (in Euros) corresponding to the cumulative number of respondents is represented on the Y-axis in decreasing order. In each graph, the curves represent travellers' demands for the means of transport before (solid line) and after information (dotted line).[14] The price paid by travellers for a ride (€50 for taxi, €3.7 for a personal vehicle, €13.5 for a rented electric vehicle, and €10 for public transport), that is the market price, is in a dashed line. We define the traveller surplus for a means of transport as the difference between what travellers are willing to pay for a means of transport relative to its market price.[15] The four graphs thus allow us to analyse the information impact on the demand, and therefore on the traveller surplus.

The left sides (right sides) of each graph show that, for relatively high-values (low-values) of WTP, the WTPs before information are significantly lower (higher) than the WTPs after information. In all four graphs, it is consistently observed that information leads to a rightward shift in the cumulative distribution function except for low WTP values. Based on the descriptive result, it appears that information about the

[13] We only keep in Table 6 the significant results. See in Appendix A for the complete table.

[14] Note that the WTP in all the curves is ordered, which means that a given number on the X-axis indicates the ranking of WTP related to each curve and not a specific participant.

[15] Here, as we are considering a situation of travel, we will use the term traveller surplus instead of consumer surplus as in the economics literature.

Table 6
Results from random effects panel model about pooled WTPs in levels. *P < 0.1; **P < 0.05; ***P < 0.01. Standard errors in parentheses.

Endogenous variable *Model: Random effects model*	*Pooled Willingness To Pay for Taxi in €*	*Pooled Willingness To Pay for Personal Vehicle in €*	*Pooled Willingness To Pay for Rented Electric Vehicle in €*	*Pooled Willingness To Pay for Public Transport in €*
Constant	**26.551**** (13.279)	2.368 (4.211)	14.324 (5.633)	**7.511*** (4.174)
Information on Environment (1/0)	**−2.185***** (0.667)	0.104 (0.215)	−0.428 (0.325)	−0.041 (0.265)
Message 2	**−3.059***** (0.590)	0.293 (0.190)	0.248 (0.288)	**0.607***** (0.234)
Message 3	**−0.845*** (0.469)	0.129 (0.151)	−0.119 (0.229)	−0.127 (0.186)
Having its health impacted by air pollution (1/0)	**2.731*** (1.537)	−0.457 (0.487)	−0.613 (0.652)	0.394 (0.483)
Importance attached to the air pollution index-2 (-0)	0.201 (2.252)	0.285 (0.714)	**1.953**** (0.955)	0.749 (0.707)
Importance attached to the air pollution index-3 (-0)	2.445 (1.705)	0.555 (0.540)	**1.829**** (0.723)	0.488 (0.536)
Confidence on recommendation-2 (-0)	0.308 (2.347)	0.912 (0.744)	−1.302 (0.995)	**1.100*** (0.737)
Age	0.070 (0.051)	−0.559 (0.454)	**−0.049**** (0.022)	−0.010 (0.016)
Observations	2.394	2.394	2.394	2.394
R^2	0.083	0.045	0.049	0.042
Log-likelihood	−9626.102	−6883.724	−7640.004	−6975.327

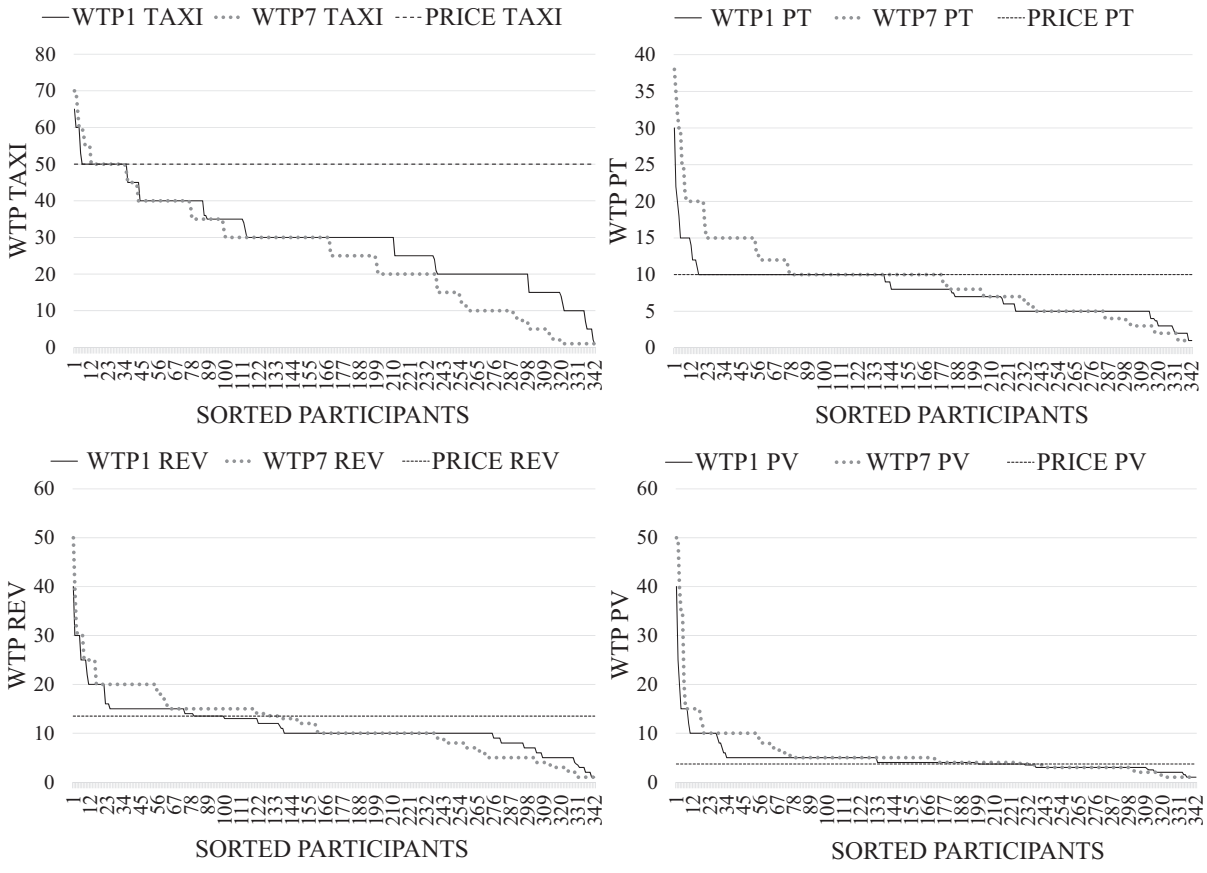

Fig. 4. Observed demand functions of the set of 342 respondents (in euro) before (solid line) and after information (dotted line), and the market price (dashed line) for the four means of transport.

consequences of means of transport on health and the environment leads to a welfare (surplus) increase for travellers.

Now, we assume that each respondent would choose the means of transport with the highest traveller surplus, which is the largest difference between its WTP and the market price. This choice is inferred because the real choice is not observed in the study, which only elicits WTP. Despite this limitation, this methodology is useful for estimating ex ante individuals' reactions to regulatory instruments. We consider the number of travellers for a means of transport as an equivalent to the number of respondents who decide to use this means of transport for the journey. We introduce the possibility that more than one means of transport can lead to the highest traveller surplus. In this situation, we assume that a traveller chooses these means of transport with the same probability. We then obtain an expected number of travellers for each means of transport. For example, if traveller i has their highest traveller surplus for taxi and for public transport, then we consider that the expected number of travellers for taxi is one half, for public transport is one half and it is equal to zero for rented electric vehicles and personal vehicles. Moreover, we consider that if for all the means of transport, the traveller has a negative traveller surplus, that is if their WTP were lower than the market price for all means of transport, then the traveller would not choose anything and the trip would not be made. In this

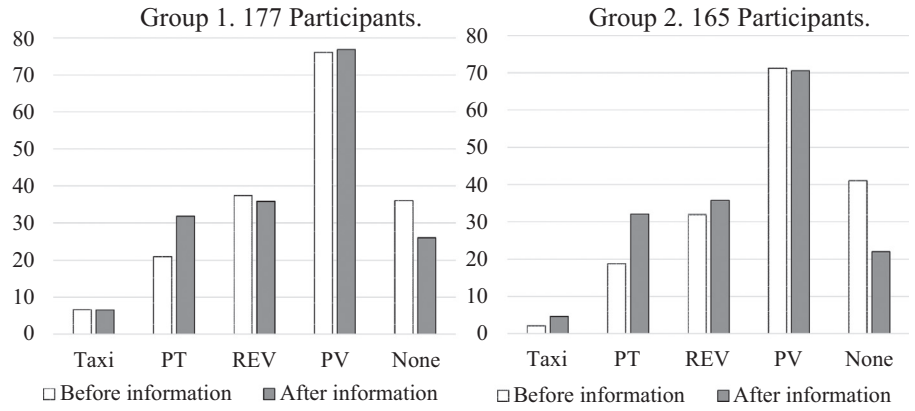

Fig. 5. Expected number of travellers over the 177 (Group 1) and 165 (Group 2) respondents for the five possible choices before and after information (Round 1 and Round 7).

Table 7
Results from a multinomial logistic regression about pooled travellers' choices for the mean of transport. *P < 0.1;**P < 0.05; ***P < 0.01. Standard errors in parentheses.

Class value Model: Multinomial logistic regression	High-emission means of transport	Low and high-emission means of transport	No means of transport
Information on Environment (1/0)	−0.061 (0.258)	**−1.744***** (0.676)	−0.132 (0.327)
Information on Environment First (1/0)	−0.065 (0.236)	**−1.528***** (0.519)	−0.034 (0.288)
Message 2	−0.210 (0.230)	**−2.147***** (0.573)	**−0.502*** (0.289)
Having its health impacted by air pollution (1/0)	**0.260**** (0.104)	−0.132 (0.355)	**−0.263*** (0.147)
Importance attached to the air pollution index-2 (-0)	**−0.552***** (0.155)	0.256 (0.467)	−0.162 (0.203)
Importance attached to the air pollution index-3 (-0)	**−0.468***** (0.117)	**−1.176***** (0.393)	**−0.473***** (0.160)
Confidence on recommendation-1 (-0)	**0.373**** (0.188)	**1.181**** (0.483)	**−0.437*** (0.247)
Confidence on recommendation-2 (-0)	**0.333**** (0.164)	**−1.317***** (0.484)	−0.120 (0.201)
Confidence on recommendation-3 (-0)	**0.682***** (0.168)	**−1.585***** (0.554)	0.089 (0.206)
Income-2 (-0)	0.213 (0.172)	**1.467*** (0.814)	0.309 (0.231)
Income-3 (-0)	**0.473***** (0.163)	**1.451*** (0.806)	**0.479**** (0.222)
Age	**0.021***** (0.003)	0.001 (0.012)	**0.012***** (0.004)
IDF (1/0)	**0.359***** (0.127)	−0.177 (0.495)	**0.370**** (0.169)
1Comfort as selection criteria instead of price (1/0)	0.047 (0.098)	**−1.003***** (0.352)	0.028 (0.130)

Observations: 2394; Nagelkerke's R^2: 0.124; Log-likelihood: −2500.499.

context, we note the traveller's choice as NONE, and we consider that the traveller surplus is equal to zero.[16] Fig. 5 represents, for each group, the expected number of travellers after and before information for all the possible choices (Taxi, PT, REV, PV and NONE) given to respondents.

We first observe that personal vehicles are the most chosen means of transport. Moreover, we see that information changes the expected number of travellers in the different categories. Using the Mann-Whitney-*U* test,[17] we investigate whether the two groups of respondents are initially similar, i.e., whether the choices (Taxi, PT, REV, PV and NONE) expressed in the first round are statistically similar between the two groups. The test result suggests no significant difference at the 5% level. In addition, using the Mann-Whitney-*U* test, we show that the choices after information are not significantly different between Groups 1 and 2. Therefore, the order of information (environmental versus health) does not seem crucial for the traveller choices. Then, in the next sections, we pool the two groups for studying the impact of regulatory interventions on the travellers' choices.

Now, we investigate the determinants of travellers' choices of means of transport through estimations. We use a multinomial logistic model on pooled data (2394 observations). This model allows us to understand the effect of a series of variables on an unordered qualitative response variable (a variable that can take more than two values).[18] With this model, we estimate the probability of belonging to an individual category (class). We consider here that the response variable is the traveller choice for a means of transport. We propose four class values for travellers' choices: low-emission means of transport (public transport or/and rented electric vehicle); high-emission means of transport (taxi or/and personal vehicle); low and high-emission means of transport, which corresponds to the case in which the traveller has the same preference for at least one low-emission means of transport and at least one high-emission means of transport; No means of transport, which means that the traveller does not choose any means of transport. With the multinomial logit model, each category of the variable of interest will be compared to the reference mode. We take as reference the low-emission means of transport class value. Then, we consider the same independent variables as for Table 6. Table 7 presents the results of these estimates.[19]

Travellers are likely to choose high-emission transport rather than

[16] However, for the calculation of the number of travellers, we were careful to differentiate the traveller surplus equal to zero because the price was higher than the WTP and that because the price was equal to the WTP. In the latter case, the traveller may choose the mean of transport.

[17] In statistics, the Mann-Whitney-*U* test is a nonparametric test that tests the hypothesis that the distribution of data is the same in two groups.

[18] The multinomial logit model is a generalization of the logit model when the response variable has more than two categories. A logit model measures the relationship between the qualitative dependent variable and one or more independent variables by estimating probabilities using a logistic function, which is the cumulative logistic distribution.

[19] We only keep in Table 7 the significant results. See in Appendix A the complete table.

low-emission transport according to the following probabilities: 1.297 ($e^{0.260}$) less likely when their health has been impacted by air pollution than when it has not been; 0.576 and 0.626 times more likely when they have a high or very high interest in the air pollution index, respectively, than travellers who have no interest; 1.452, 1.395, and 1.978 times less likely when they have low, high, and very high trust on the recommendation, respectively, than travellers who do not; 1.605 times less likely when they are part of the highest salary bracket than the travellers who are part of the lowest; 1.021 times less likely when their age increases by one year; 1.432 times less likely when they live in the IDF area than when they do not live there.

Travellers hesitate between low-emission transport and high-emission transport rather than choosing low-emission transport with the following likelihood: 0.175 ($e^{-1.744}$) times more likely when information that they first received relates to the environment rather than health; 0.217 times more likely when the information that they first received relates to the environment rather than to health; 0.117 times more likely when they received Message 2 than when they did not; 0.309 times more likely when they have a very high interest in the air pollution index than travellers who have no interest; 3.258 times less likely when they have low confidence for recommendations, and 0.268 and 0.205 times more likely when they have high and very high confidence, respectively, as opposed to travellers who do not have such confidence; 4.336 and 4.267 times less likely when they belong to the second and the first salary bracket, respectively, than when they belong to the lowest; 0.367 times more likely when they take more into account comfort to make their decision than when they consider price first.

Travellers prefer not to take any means of transport rather than choosing low-emission transport with the following likelihoods: 0.605 ($e^{-0.502}$) times more likely when they received Message 2 than when they did not; 0.769 times more likely when their health has been impacted by air pollution than when it has not been; 0.623 times more likely when they have a very high interest in the air pollution index as opposed to travellers who have no interest; 0.646 times more likely when they have low confidence for recommendations as opposed to travellers who do not have such confidence; 1.614 times less likely when they belong to the first salary bracket, respectively, than when they belong to the lowest; 1.012 times less likely when their age increases by one year; 1.448 times less likely when they live in the IDF area than when they do not live there.

4.2. Regulatory Interventions

In France, the measures implemented for reducing air pollution are aimed at encouraging the use of low-emission vehicles. We postulate different regulatory intervention options for testing whether this goal is reached. We first suggest an information campaign, then a taxation of the high-emission means of transport (taxi and personal vehicle), a subsidy for the low-emission means of transport (rented electric vehicle and public transport), and finally a standard imposing the use of low-emission vehicles (rented electric vehicle and public transport). In fact, if a traveller chooses to take a taxi, the introduction of a tax on high-emission means of transport may change their choice. Indeed, the price of a taxi and of the use of a personal vehicle will increase by reducing the traveller surplus for the taxi and the personal vehicle to a level that may be lower than the traveller surplus for the low-emission means of transport. If instead of taxing, a subsidy on low-emission means of transport is implemented, the price of public transport and the rented electric vehicle will decrease. The traveller will have a higher surplus for these two means, which can exceed the surplus with the taxi. We then analyse the impacts of these four regulatory interventions on the respondents' decisions.

4.2.1. Information Campaigns

We suppose that the regulator makes a complete information campaign on air pollution impacts on health and on the environment. For the moment, in France, information only concerns the level of pollution induced by the means of transport and not their health and environmental consequences. CO_2 labelling of passenger vehicles was made compulsory in 2006 for new vehicles. It aims to educate buyers about vehicle emissions. Moreover, since October 1, 2013, passenger transport providers are required to provide information on the amounts of CO_2 produced as a result of their services. The French law on Energy transition towards green growth, adopted on 17 August 2015, extends the mandatory CO_2 information to all greenhouse gases. Here, we consider that public intervention consists in a very intense information campaign, perfectly understood by all travellers and revealing information on the damages of air pollution on health and the environment, which leads to round 7.

Following this information campaign, travellers are perfectly informed. Travellers directly internalize all information provided by the campaign. Traveller i can choose between five outcomes: Taxi at price P (TAXI), public transport (PT) at price P(PT), rented electric vehicle (REV) at price P(REV), personal vehicle (PV) at price P(PV), or none of those. All prices are in Euros. We consider that choices on means of transportation are determined by traveller i's WTP for Taxi, PT, REV, and PV given by $WTP_{i7}TAXI$, $WTP_{i7}PT$, $WTP_{i7}REV$ and $WTP_{i7}PV$, respectively. We assume that travellers may choose one means of transport if their WTP is higher than the price observed on the market. They thus choose to take the means of transport generating the highest utility (with a utility of non-used normalized to zero). Because complete information is perfectly internalized by travellers, no other tool can improve welfare. The per-unit surplus and welfare for participant $i \in N$ is as follows:

$$W_i^L = \max\{0, WTP_{i7}k - P(k); k \in \{TAXI, PT, REV, PV\}\}. \quad (1)$$

4.2.2. A per-Unit Tax

The public intervention consists in the adoption of a per-unit tax τ for the high-emission means of transport, which is taxi and personal vehicle. In France, the bonus malus system was implemented. It allows participating in the significant reduction in average CO_2 emissions by subsidizing for low-emission transport and by taxing high-emission vehicles, which fell from 149 CO_2 g/km in 2007 to 113 CO_2 g/km in 2014. The amounts and thresholds are periodically revised to improve device performance. Since April 1, 2015, in the framework of the law on the energy transition to green growth, the schedule of bonus was reduced to 60 CO_2 g/km, favouring electric vehicles and public transport.

To simulate the tax scenario, we consider that travellers have no precise knowledge about the consequences of air pollution on health and the environment, which corresponds to the situation of round 1. Traveller i can choose between five outcomes: Taxi at price $P^\tau(TAXI) = P(TAXI) + \tau$ euro, public transport (PT) at price $P^\tau(PT) = P(PT)$ euro, rented electric vehicle at price $P^\tau(REV) = P(REV)$ euro, personal vehicle at price $P^\tau(PV) = P(PV) + \tau$ euro, or neither. They take their mean of transport decision based on their surplus maximization, which is equal to:

$$W_i^\tau(\tau) = \max\{0, WTP_{i1}k - P^\tau(k)\}. \quad (2)$$

where $i \in N$ and $k \in \{TAXI,PT,REV,PV\}$.

The regulator also considers the possible tax income coming from each respondent. The tax is only paid by travellers using a mean of transport with high-emission level (Taxi or Personal Vehicle). We note

$$\mathbb{1}_{[k,i]} = \begin{cases} 1 \text{ if traveller } i \text{ chooses a mean of transport } k \text{ with high} \\ \quad - \text{ emission level (Taxi or PV);} \\ 0 \text{ otherwise.} \end{cases}$$

We note n_i the additional number of mean of transport associated to the highest traveller i surplus. That is if l means of transport are associated to the highest traveller i surplus, then $n_i = l - 1$; if only one

mean of transport is associated to the highest traveller i surplus, then $n_i = 0$; if none of the means of transport is associated with a positive traveller i surplus, then $n_i = 0$. The optimal tax τ^* is chosen by the regulator and is given by trial and error, maximizing the expected average welfare $\sum_{i=1}^{N}(W_i^{\tau}(\tau) + ((\sum_k \tau * \mathbb{1}_{[k,i]})/(n_i + 1)))/N$ over the $N = 342$ respondents with $k \in \{TAXI,PT,REV,PV\}$.

4.2.3. A per-Unit Subsidy

The public intervention consists in the adoption of a per-unit subsidy, s, for the low-emission means of transport that is public transport and rented electric vehicles. To simulate the subsidy scenario, we assume that travellers have no precise knowledge about the consequences of air pollution on health and the environment, which corresponds to the situation of round 1. Traveller i can choose between five outcomes: Taxi at price $P^s(TAXI) = P(TAXI)$ euro, public transport (PT) at price $P^s(PT) = P(PT) - s$ euro, rented electric vehicle at price $P^s(REV) = P(REV) - s$ euro, personal vehicle at price $P^s(PV) = P(PV)$ euro, or neither. They choose their mean of transport based on their surplus maximization, which is equal to:

$$W_i^s(s) = \max\{0, WTP_{i1}k - P^s(k)\}. \quad (3)$$

where $i \in N$ and $k \in \{TAXI,PT,REV,PV\}$.

The regulator also considers the possible subsidy expense. The subsidy only reduces the price paid by travellers who use a low-emission means of transport (Public Transport or Rented Electric Vehicle). We note:

$$\mathbb{1}_{[k,i]} = \begin{cases} 1 \text{ if traveller } i \text{ chooses a mean of transport } k \text{ with low} \\ \quad - \text{ emission level (PT or REV);} \\ 0 \text{ otherwise.} \end{cases}$$

We note n_i the additional number of means of transport associated to the highest surplus for traveller i. The optimal subsidy s^* is chosen by the regulator and is given by trial and error, maximizing the expected average welfare $\sum_{i=1}^{N}(W_i^s(s) + ((\sum_k s * \mathbb{1}_{[k,i]})/(n_i + 1)))/N$ over the $N = 342$ respondents with $k \in \{TAXI,PT,REV,PV\}$.

4.2.4. A Standard

To simulate the standard scenario, we also assume that travellers have no precise knowledge about the consequences of air pollution on health and the environment, which corresponds to the situation of Round 1. Public intervention consists of leading people to use low-emission means of transport, that is to say public transport or rented electric vehicles. The City of Paris has organized a Day Without Polluting Vehicles every year since 2015. In addition, since January 23, 2017, an 'Air Quality Certificate' classifies vehicles into five categories according to age and therefore pollution level. This measure is meant to allow the regulator to incentivize traffic to one or more categories of transport. In such a situation, traveller i's means of transport decision is based on their surplus maximization, which is equal to:

$$W_i^S = \max\{0, WTP_{i1}k - P(k)\} \quad (4)$$

where $i \in N$, and with $k \in \{PT,REV\}$.

4.2.5. Welfare Analysis

To perform the welfare analysis, we consider a baseline scenario in which the four means of transport are used without any additional regulation. This baseline welfare is defined by (2) with $\tau = 0$. We compare the welfare effects of the different environmental policies.

We note N the number of respondents, therefore $N = 342$. We define the average variation in traveller surplus by $\Delta W_N^L = \Sigma_{i=1}^{N}[W_i^L - W_i^{\tau}(0)]/N$ for the information campaign. Then, we define the average variation in traveller surplus by $\Delta W_N^{\tau}(\tau^*) = \Sigma_{i=1}^{N}[W_i^{\tau}(\tau^*) - W_i^{\tau}(0)]/N$ for a tax τ^*, and $\Delta W_N^s(s^*) = \Sigma_{i=1}^{N}[W_i^s(s^*) - W_i^{\tau}(0)]/N$ for a subsidy s^*, and $\Delta W_N^S = \Sigma_{i=1}^{N}[W_i^S - W_i^{\tau}(0)]/N$ for the mandatory standard. Finally, we compute the variation in expected number of travellers as the difference between the expected number of travellers for regulatory interventions and the expected number of travellers in the baseline scenario.

Our calculations use the market price observed for the different means of transport in February 2015, that is P(TAXI) = €50 for taxi, P(PT) = €10 for public transport (PT), P(REV) = €13.5 for rented electric vehicle (REV), and P(PV) = €3.7 for personal vehicle (PV).[20]

Fig. 6 presents the average variation in traveller surplus and the variation in expected number of travellers according to information campaigns, a per-unit tax, a per-unit subsidy, and a standard as described in the previous sections. We add to these regulatory interventions a new one, a tax-subsidy system.[21] For the tax-subsidy system, we consider that traveller i can choose between five outcomes: Taxi at price $P^{\tau\&s}(TAXI) = P(TAXI) + \tau$ euro, public transport (PT) at price $P^{\tau\&s}(PT) = P(PT) - s$ euro, rented electric vehicle at price $P^{\tau\&s}(REV) = P(REV) - s$ euro, personal vehicle at price $P^{\tau\&s}(PV) = P(PV) + \tau$ euro, or neither. They take their means of transport decision based on their surplus maximization, which is equal to:

$$W_i^{\tau\&s}(\tau, s) = \max\{0, WTP_{i1}k - P^{\tau\&s}(k)\} \quad (5)$$

where $i \in N$ and $k \in \{TAXI,PT,REV,PV\}$.

The regulator also considers the possible tax income coming from each participant and the subsidy expense. We note:

$$\mathbb{1}_{[k,i,\tau]} = \begin{cases} 1 \text{ if traveller } i \text{ chooses a mean of transport } k \text{ with high} \\ \quad - \text{ emission level (Taxi or PV);} \\ 0 \text{ otherwise.} \end{cases}$$

and

$$\mathbb{1}_{[k,i,s]} = \begin{cases} 1 \text{ if traveller } i \text{ chooses a mean of transport } k \text{ with low} \\ \quad - \text{ emission level (PT or REV);} \\ 0 \text{ otherwise.} \end{cases}$$

We note n_i the additional number of means of transport associated with the highest traveller i surplus. The optimal tax-subsidy system (τ^*, s^*) is chosen by the regulator and is given by trial and error, maximizing the expected average welfare, which is equal to: $\sum_{i=1}^{N}(W_i^{\tau\&s}(\tau, s) + (\sum_k (\tau * \mathbb{1}_{[k,i,\tau]} - s * \mathbb{1}_{[k,i,s]})/(n_i + 1)))/N$ over the $N = 342$ respondents with $k \in \{TAXI,PT,REV,PV\}$.

We could obtain several solutions for the optimal tax subsidy system (τ^*,s^*). We have selected here the one which combined the positive expected impact of a per-unit tax and a perunit subsidy policy on traveller surplus (an increase) and the expected number of travellers (a decrease for high-emission means of transport, TAXI and PV, and an increase for low-emission means of transport, PT and REV). This allows us to show that a tax-subsidy system may be an interesting regulatory intervention. We define the average variation in traveller surplus by $\Delta W_N^{\tau\&s}(\tau^*,s^*) = \Sigma_{i=1}^{N}[W_i^{\tau\&s}(\tau^*,s^*) - W_i^{\tau}(0)]/N$ for a tax τ^* and a subsidy s^*.

We first observe that information campaigns, a per-unit subsidy at e0.29 and the tax-subsidy system all lead to an increase in traveller surplus. In addition, all the regulatory interventions increase the number of travellers for low-emission means of transport but only information campaigns also increase high-emission ones. Finally, information campaigns and a per-unit subsidy at e0.29 decreases the number of travellers who will not choose any means or does not affect that number.

Next, we propose to analyse regulatory interventions after information campaigns, which is to say we combine information campaigns with the other regulatory interventions. Then, to simulate these

[20] For more details, see footnote 6.

[21] We have analysed a standard-subsidy system. However, we did not obtain a positive optimal subsidy combined with a standard.

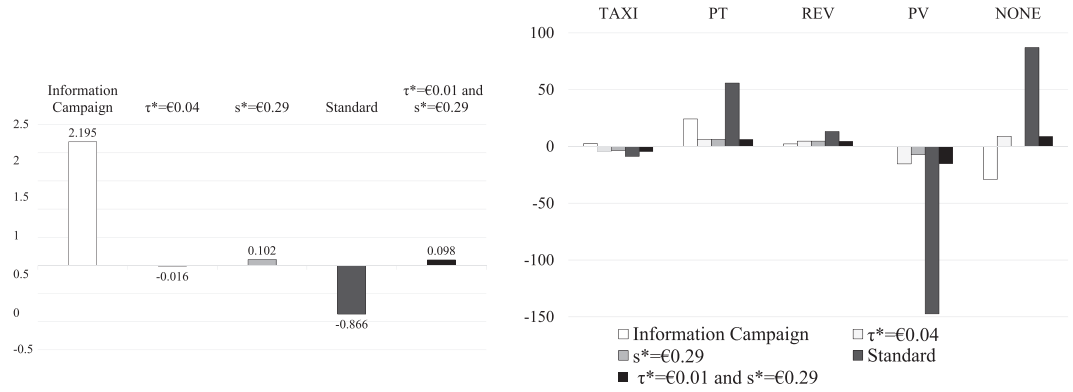

Fig. 6. Average variation in traveller surplus in Euros (on the left) and variation in expected number of travellers (on the right) according to five regulatory interventions. 342 respondents (Group 1 and Group 2).

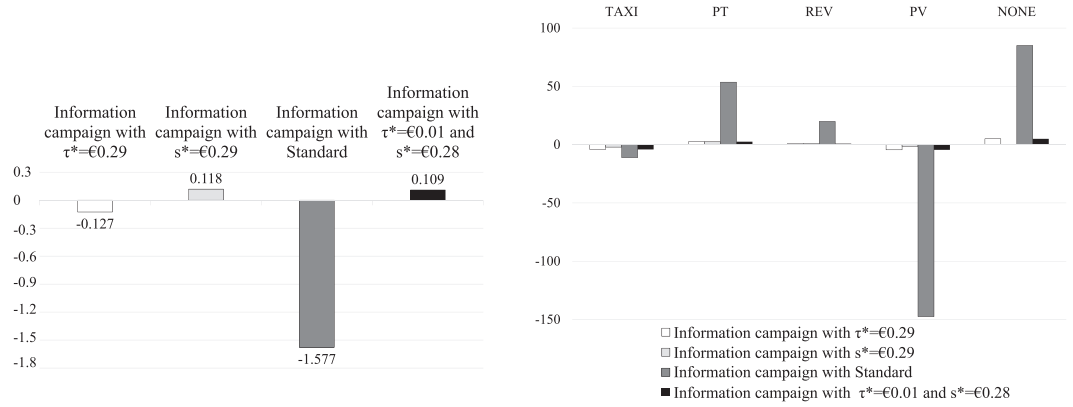

Fig. 7. Average variation in traveller surplus in euro (on the left) and variation in expected number of travellers (on the right) according four regulatory interventions. 342 respondents (Group 1 and Group 2).

Table 8
Overview of the recommended policies.

Point of view of	Policy recommended
Traveller Surplus	* Information Campaign * A per-unit subsidy at €0.29 * A per-unit tax at €0.01 and a per-unit subsidy at €0.29 * Information Campaign with a per-unit subsidy at €0.29 * Information Campaign with a per-unit tax at €0.01 and a per-unit subsidy at €0.28
Increasing the number of travellers for low-emission means of transport and decreasing the number of travellers for high-emission means of transport	* A per unit tax at €0.04 * A per-unit subsidy at €0.29 * A standard * A per-unit tax at €0.01 and a per-unit subsidy at €0.29 * Information Campaign with a per-unit tax at €0.29 * Information Campaign with a per-unit subsidy at €0.29 * Information Campaign with standard * Information Campaign with a per-unit tax at €0.01 and a per-unit subsidy at €0.28
Reducing the number of travellers who do not take any means of transport	* Information campaign * A per-unit subsidy at €0.29 * Information Campaign with a per-unit subsidy at €0.29

scenarios, we assume that the regulator makes a complete campaign of information on air pollution impacts on health and on the environment and one of the regulatory interventions (tax, subsidy and standard). Following this information campaign, travellers are perfectly informed, which corresponds to the situation of Round 7. Therefore, traveller i's mean of transport decision is based on its surplus maximization, which is obtained by changing WTP_{i1} to WTP_{i7} in (2) for a per-unit tax, (3) for a per-unit subsidy, (4) for a standard, and (5) for a tax-subsidy system. The calculation of the optimal taxes and subsidies also takes into account the change. Fig. 7 presents the average variation in traveller surplus and the variation in expected number of travellers according to the combined regulatory interventions.

The tax-subsidy system follows the same criteria of selection as previously.

Information campaigns with a subsidy at e0.29 and information campaigns with a taxsubsidy system both increase the traveller surplus. All the combined regulatory interventions lead to an increase in the expected number of travellers for low-emission means of transport and a decrease for high-emission ones. However, only information campaigns with a subsidy at e0.29 does not change the number of travellers who do not choose any means of transport.

4.2.6. Summary

It is to be noted that the recommendations depend on the point of view that is adopted. From the traveller surplus point of view, we recommend to the health and the environmental regulator the policy, which leads the traveller surplus to increase with its implementation. From the point of view of the number of travellers, we recommend the policy, which increases the number of travellers for high-emission means of transport and decreases that number for high-emission means of transport. Finally, from the point of view of the number of travellers who do not take any means of transport, we recommend the policy that avoids the eviction of travellers on the means of transport market. In other words, we recommend the policy, which leads all travellers to choose at least one of the means of transport proposed. Table 8 sums up our results.

Choosing between these policies will depend on regulators' priorities. However, we observe that with our survey a per-unit subsidy at e0.29 and an information campaign combined with a per-unit subsidy at e0.29 are recommended from every point of view under consideration.

5. Conclusion

In this paper, we have analysed travellers' for their means of transport. This is useful for choices by public authorities (health and environmental policies). While information matters, the order in which it is given does not. The information conveyed changes both travellers' Willingness To Pay and their choices. However, the use of high-emission vehicles has not diminished. Actually, it appears that the information campaign messages fail to decrease respondents' preferences for their personal vehicles. They can even lead them to increase that preference. From this study, we have then a better understanding of the non-adoption of low-emission vehicles after awareness campaigns. Actually, in our two groups, through the information campaign, the respondents increase on average their WTP for the personal vehicle. With a random effects model, we have analysed the determinants of the WTP for each means of transport. We have found that creating an interest for the air pollution index and giving more confidence to travellers in air pollution recommendations would increase the travellers' WTP for low-emission means of transport.

We have then analysed travellers' choices. We have seen that the personal vehicle is the most popular means of transport, before and after the information campaign. We have studied the determinants of traveller choice with a multinomial logit model. We have observed that improving travellers' confidence in air pollution recommendations would be a good way to lead travellers to choose low-emission transport rather than high-emission means. First, it would increase the WTP for public transport; second, it would increase the likelihood of travellers choosing a low-emission means of transport over high-emission transport. In addition, we show that users who attach great importance to comfort are less likely than those who value the price to choose low-emission vehicles. Individual interest can then prevail over the collective interest, thus verifying the theory of the tragedy of the commons. Improving comfort, especially in public transport, could be a way to encourage travellers to use low-emission means of transport.

Finally, concerning regulatory discussions, we have tested different policies (taxes, subsidies, standards and a tax-subsidy system with and without information campaign) to encourage people to adopt low-emission vehicles. Choosing between these policies will depend on regulator's priorities. However, two of these policies seem to be good alternatives: the subsidy of lowemission vehicles with and without information campaigns. This result supports the actual policies taken on the reduction of air pollution by the mayor of Paris.

Although this study may be replicated, our paper presents some limitations. First, as in all WTP approaches, there might be a hypothetical bias in our study. As suggested by Lusk (2003), we have tried to reduce this bias with a cheap talk detailing to respondents the means of transport we were presenting to them and explaining to them the goal of the study. Second, we did not consider controversies or incorrect messages leading to respondents' confusion or misunderstanding. To correct this, we would introduce a probability of being wrongly informed δ, namely a probability of having respondents misunderstand information regarding means of transport, such that the average variation in traveller surplus for information campaign would become $\Sigma_{i=1}^{N}[(1-\delta)W_i^L - \delta W_i^r(0)]/N$. This assumption would decrease the traveller surplus.

Third, the way to collect data might be discussed. We have used an online study. Cobanoglu et al. (2001), Couper (2000), and McDonald and Adam (2003) highlight that online studies allow to save time and efforts in collecting data. Moreover, Fricker et al. (2005), Kreuter et al. (2008) and Heerwegh and Loosveldt (2008) show that online studies make it possible to obtain higher quality answers with fewer 'Don't know' and unanswered questions than telephone surveys and personal interview surveys. Therefore, on the quality of data collection, online studies do not seem to present more disadvantages than other kinds of surveys. Finally, for further research, it might be interesting for this subject to be treated with other experimental methods such as discrete choice theory.

Appendix A

Message 1: *A ride from the center of Paris* (*Châtelet Metro station*) *to Roissy Charles de Gaulle Airport by taxi costs about €50, €10 by public transport, €13.50 in a rented electric vehicle* (*Autolib type*) *and €3.70 in a personal vehicle.*

Message 2: *According to the WHO* (*World Health Organization*): '*Breathing clean air is considered essential for health and well-being of man. However, the air pollution continues to pose a major threat in terms of health around the world.* […] *More than 2 million premature deaths each year can be attributed to the effects of outdoor air pollution in cities* […] *worldwide.*'

Message 3: *In France, 42,000 premature deaths, including 1400 in Paris in 2011 are attributed to pollution. According to the latest report of the European Environment Agency, nearly 400,000 deaths in Europe related to air pollution.*

Message 4: *If fine particles levels were in compliance with WHO quality targets* (10 $\mu g/m^3$ *as an annual average*), *Parisians and persons from the suburbs would gain six months of life expectancy. In 2013, the average fine particle levels were* 26 $\mu g/m^3$, *more than double of what is recommended.*

Message 5: *The Ministry of Ecology, Sustainable Development and Energy estimated in 2012 that health costs of air pollution outdoors in France rose annually by 20 to 30 billion €, which corresponds to about 400 to 500 €/year/person.*

Message 6: *Air pollution induced corrosion due to sulphur dioxide, blackening and crusts of buildings by dust from the combustion of petroleum products, as well as various changes in combination with the gel, moisture and microorganisms.*

Message 7: *Air pollution is caused by the emission of components of different kinds into the atmosphere. While they are issued locally (at a city for example), these pollutants have consequences both at local, regional and global ('acid rain', which alter ecosystems, contributing to the effect greenhouse and global warming).*

Table 9
Results from random effects panel model about pooled WTPs in levels. *P < 0.1;**P < 0.05; ***P < 0.01. Standard errors in parentheses. Complete table.

Endogenous variable *Model: Random effects model*	*Pooled Willingness To Pay for Taxi in €*	*Pooled Willingness To Pay for Personal Vehicle in €*	*Pooled Willingness To Pay for Rented Electric Vehicle in €*	*Pooled Willingness To Pay for Public Transport in €*
Constant	**26.551**** (13.279)	2.368 (4.211)	14.324 (5.633)	**7.511*** (4.174)
Information on Environment (1/0)	**−2.185***** (0.667)	0.104 (0.215)	−0.428 (0.325)	−0.041 (0.265)
Information on Environment First (1/0)	−0.373 (1.536)	−0.226 (0.488)	−0.207 (0.664)	−0.577 (0.500)
Message 2	**−3.059***** (0.590)	0.293 (0.190)	0.248 (0.288)	**0.607***** (0.234)
Message 3	**−0.845*** (0.469)	0.129 (0.151)	−0.119 (0.229)	−0.127 (0.186)
Message 4	−0.489 (0.469)	−0.013 (0.151)	0.013 (0.229)	0.190 (0.186)
Message 5	−0.087 (0.447)	0.170 (0.144)	0.047 (0.218)	0.037 (0.177)
Message 6	1.395 (0.849)	−0.060 (0.273)	0.496 (0.414)	0.333 (0.337)
Message 7	0.143 (0.469)	0.236 (0.151)	−0.166 (0.229)	0.292 (0.186)
Having its health impacted by air pollution (1/0)	**2.731*** (1.537)	−0.457 (0.487)	−0.613 (0.652)	0.394 (0.483)
Importance attached to the air pollution index-1 (-0)	−1.624 (4.027)	0.887 (1.277)	2.450 (1.708)	−0.794 (1.265)
Importance attached to the air pollution index-2 (-0)	0.201 (2.252)	0.285 (0.714)	**1.953**** (0.955)	0.749 (0.707)
Importance attached to the air pollution index-3 (-0)	2.445 (1.705)	0.555 (0.540)	**1.829**** (0.723)	0.488 (0.536)
Confidence on recommendation-1 (-0)	−0.954 (2.701)	0.297 (0.856)	−0.942 (1.145)	1.559 (0.848)
Confidence on recommendation-2 (-0)	0.308 (2.347)	0.912 (0.744)	−1.302 (0.995)	**1.100*** (0.737)
Confidence on recommendation-3 (-0)	−0.771 (2.379)	0.744 (0.754)	−0.999 (1.009)	0.329 (0.747)
Gender (1/0)	−0.176 (1.404)	−0.462 (0.445)	0.041 (0.595)	−0.126 (0.441)
Income-1 (-0)	0.017 (2.662)	−0.097 (0.844)	−0.923 (1.129)	0.088 (0.836)
Income-2 (-0)	−2.916 (2.548)	−1.267 (0.808)	−1.618 (1.081)	0.222 (0.800)
Income-3 (-0)	3.117 (2.429)	−0.883 (0.770)	−1.285 (1.030)	0.045 (0.763)
Age	0.070 (0.051)	−0.559 (0.454)	**−0.049**** (0.022)	−0.010 (0.016)
SPC-1 (-0)	−8.141 (13.342)	1.621 (4.231)	−1.750 (5.659)	−0.848 (4.192)
SPC-2 (-0)	−3.601 (12.840)	1.975 (4.072)	1.017 (5.446)	0.220 (4.035)
SPC-3 (-0)	−1.841 (12.837)	1.495 (4.071)	0.564 (5.445)	−0.314 (4.034)
SPC-4 (-0)	−2.386 (12.849)	1.782 (4.075)	0.253 (5.450)	−0.261 (4.037)
IDF (1/0)	1.151 (1.837)	0.816 (0.582)	−0.610 (0.779)	−0.482 (0.577)
Comfort as selection criteria instead of price (1/0)	1.443 (1.432)	-0.014 (0.016)	0.273 (0.607)	0.076 (0.450)
Observations	2.394	2.394	2.394	2.394
R^2	0.083	0.045	0.049	0.042
Log-likelihood	−9626.102	−6883.724	−7640.004	−6975.327

Table 10
Results from a multinomial logistic regression about pooled travellers' choices for the mean of transport. *P < 0.1;**P < 0.05; ***P < 0.01. Standard errors in parentheses. Complete table.

Class value Model: Multinomial logistic regression	High-emission means of transport	Low and high-emission means of transport	No means of transport
Constant	−2.045 (161609)	0.709 (360670)	24.691 (118396)
Information on Environment (1/0)	−0.061 (0.258)	**−1.744***** (0.676)	−0.132 (0.327)
Information on Environment First (1/0)	−0.065 (0.236)	**−1.528***** (0.519)	−0.034 (0.288)
Message 2	−0.210 (0.230)	**−2.147***** (0.573)	**−0.502*** (0.289)
Message 3	0.037 (0.172)	0.191 (0.596)	0.023 (0.236)
Message 4	−0.112 (0.172)	−0.058 (0.575)	−0.083 (0.236)
Message 5	0.124 (0.164)	0.309 (0.525)	0.079 (0.224)
Message 6	−0.134 (0.325)	1.374 (0.880)	−0.115 (0.414)
Message 7	0.095 (0.173)	−0.440 (0.570)	−0.096 (0.232)
Having its health impacted by air pollution (1/0)	**0.260**** (0.104)	−0.132 (0.355)	**−0.263*** (0.147)
Importance attached to the air pollution index-1 (-0)	−0.388 (0.272)	−21.855 (15494)	0.228 (0.357)
	−0.552*** (0.155)	0.256 (0.467)	−0.162 (0.203)
	−0.468*** (0.117)	**−1.176***** (0.393)	**−0.473***** (0.160)
Importance attached to the air pollution index-2 (-0)	**0.373**** (0.188)	**1.181**** (0.483)	**−0.437*** (0.247)
	0.333** (0.164)	**−1.317***** (0.484)	−0.120 (0.201)
Importance attached to the air pollution index-3 (-0)	**0.682***** (0.168)	**−1.585***** (0.554)	0.089 (0.206)
	0.086 (0.096)	−0.116 (0.290)	−0.087 (0.128)
Confidence on recommendation-1 (-0)	0.163 (0.179)	0.871 (0.841)	0.152 (0.241)
Confidence on recommendation-2 (-0)	0.213 (0.172)	**1.467*** (0.814)	0.309 (0.231)

(*continued on next page*)

Table 10 (*continued*)

Class value Model: Multinomial logistic regression	High-emission means of transport	Low and high-emission means of transport	No means of transport
Confidence on recommendation-3 (-0)	**0.473***** (0.163)	**1.451*** (0.806)	**0.479**** (0.222)
Gender (1/0)	**0.021***** (0.003)	0.001 (0.012)	**0.012***** (0.004)
Income-1 (-0)	1.762 (161609)	−2.134 (360670)	−24.570 (118396)
Income-2 (-0)	0.852 (161609)	−2.289 (360670)	−25.867 (118396)
Income-3 (-0)	0.801 (161609)	−0.837 (360670)	−25.624 (118396)
Age	1.019 (161609)	−3.153 (360670)	−25.312 (118396)
SPC-1 (-0)	**0.359***** (0.127)	−0.177 (0.495)	**0.370**** (0.169)
SPC-2 (-0)	0.047 (0.098)	−**1.003***** (0.352)	0.028 (0.130)
SPC-3 (-0)			
SPC-4 (-0)			
IDF (1/0)			
Comfort as selection criteria instead of price (1/0)			

Observations: 2394; Nagelkerke's R^2: 0.124; Log-likelihood: −2500.499.

References

Agostinia, C.A., Jimnez, J., 2015. The distributional incidence of the gasoline tax in Chile. Energy Policy 85, 243–252.

Airparif, 2016. Surveillance et information sur la qualité de l'air en Île de France - Bilan année 2015.

Baidoo, I.K., Nyarko, E., 2015. Stated Preference Modeling for a Preferred Transportation Mode. Mathematical Theory and Modeling.

Bollena, J., Brink, C., 2014. Air pollution policy in Europe: quantifying the interaction with greenhouse gases and climate change policies. Energy Econ. 46, 202–215.

Chemarin, S., Orset, C., 2011. Innovation and information acquisition under time inconsistency and uncertainty. Geneva Risk Insur. Rev. 36, 132–173.

Cobanoglu, C., Warde, B., Moreo, P., 2001. A comparison of mail, fax, and web-based survey methods. Int. J. Mark. Res. 43 (4), 405–410.

Couper, M.P., 2000. Web surveys: a review of issues and approaches. Public Opin. Q. 64 (4), 464–494.

Douglas, W., Dockery, C., Pope, A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.J., Speizer, F.E., 1993. An association between air pollution and mortality in six U.S. cities. N. Engl. J. Med. 329, 1753–1759.

Fricker, S., Galesic, M., Tourangeau, R., Yan, T., 2005. An experimental comparison of web and telephone surveys. Public Opin. Q. 69 (3), 370–392.

Greene, W.H., 2017. Econometric Analysis, 8th edition. Pearson.

Heerwegh, D., Loosveldt, G., 2008. Face-to-face versus web surveying in a high-internet coverage population: differences in response quality. Public Opin. Q. 72 (5), 836–846.

Hensher, D.A., 1994. Stated preference analysis of travel choices: the state of practice. Transportation 21 (2), 107–133.

Kotchena, M.J., Boylec, K.J., Leiserowitza, A.A., 2013. Willingness-to-pay and policy instrument choice for climate-change policy in the United States. Energy Policy 55, 617625.

Kreuter, F., Presser, S., Tourangeau, R., 2008. Social desirability bias in CATI, IVR, and web surveys: the effects of mode and question sensitivity. Public Opin. Q. 72 (5), 847–865.

Krewski, D., Burnett, R.T., Goldberg, M.S., Hoover, K., Siemiatycki, J., Abrahamowicz, M., White, W.H., 2004. Validation of the Harvard Six Cities Study of particulate air pollution and mortality. N. Engl. J. Med. 350 (2), 198–199.

Kroes, E.P., Sheldon, R.J., 1988. Stated preference methods: an introduction. Journal of Transport Economics and Policy 22 (1), 11–25.

Louviere, J.J., Hensher, D.A., Swait, J.D., 2000. Stated Choice Methods, Analysis and Applications. Cambridge University Press.

Lusk, J.L., 2003. Effects of cheap talk on consumer willingness to pay for golden rice. Am. J. Agric. Econ. 85 (4), 840–856.

McDonald, H., Adam, S., 2003. A comparison of online and postal data collection methods in marketing research. Mark. Intell. Plan. 21 (2), 85–95.

Montag, J., 2015. The simple economics of motor vehicle pollution: a case for fuel tax. Energy Policy 85, 138–149.

Naqvi, A., Zwickl, K., 2017. Fifty shades of green: revisiting decoupling by economic sectors and air pollutants. Ecol. Econ. 133, 111–126.

Petrik, O., de Abreu e Silva, J., Moura, F., 2016. Stated preference surveys in transport-demand modeling: disengagement of respondents. Int. J. Transp. Res. 8 (1), 13–25.

Pope, C.A., Ezzati, M., Dockery, D.W., 2009. Fine-particulate air pollution and life expectancy in the United States. N. Engl. J. Med. 360, 376–386.

Suna, C., Yuana, X., Yaoa, X., 2016. Social acceptance towards the air pollution in China: evidence from public's willingness to pay for smog mitigation. Energy Policy 92, 313–324.

Tanizaki, H., 2004. Computational Methods in Statistics and Econometrics. CRC Press.

Timmers, V.R.J.H., Achten, P.A.J., 2016. Non-exhaust PM emissions from electric vehicles. Atmos. Environ. 134, 10–17.

Wanga, Y., Mingxing, S., Yanga, X., Yuanc, X., 2016. Public awareness and willingnessto pay for tackling smog pollution in China: a case study. J. Clean. Prod. 112, 1627–1634.

Wardman, M.A., 1988. Comparison of revealed preference and stated preference models of travel behaviour. JTEP 22 (1), 71–91.

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Manufacturing doubt☆

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ABSTRACT

In their efforts to affect regulations, firms have developed specific strategies to exploit scientific uncertainty. They have manufactured doubt by hiring and funding dissenting scientists, by producing and publicizing favorable scientific findings and by generally concealing their involvement in biased research. We propose a new model to study the interplay between scientific uncertainty, firms' miscommunication and public policies. The government is benevolent but populist, and maximizes social welfare as perceived by citizens. The industry can produce costly reports showing that its activity is not harmful. Citizens are unaware of the industry's miscommunication. We first characterize the industry's optimal miscommunication policy. The industry notably ceases miscommunicating abruptly when scientists' belief reaches a critical threshold. We identify a natural condition under which miscommunication is stronger under a tax on emissions than under command and control. We then analyze research funding. A populist government may support research to enable firms to falsely reassure citizens. Establishing an independent research agency helps limit the welfare losses induced by populist policies.

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1. Introduction

Many important government regulations have to be adopted under significant scientific uncertainty. In their efforts to affect regulations, firms have developed specific strategies to exploit this uncertainty. For instance, tobacco producers vigorously denied the adverse effects of active smoking in the 1950s and 1960s and of second-hand smoke exposure from the 1970s through the 1990s (Bero, 2013).[1] They spent large amounts of money on hiring and funding dissenting scientists, generating and publicizing favorable scientific findings, and shaping the public's perceptions through large-scale communication campaigns (Proctor, 2011). Throughout this time, the industry tried hard to conceal its involvement in biased research (Bero, 2013, p.157–158). The extent of this involvement only became known after the forced release of confidential corporate documents, as

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[1] For instance, a 1978 report prepared for the Tobacco Institute states that "The strategic and long-run antidote to the passive smoking issue is, as we see it, developing and widely publicizing clear-cut, credible medical reports that passive smoking is not harmful to the non-smoker's health." see Bero (2013, p.154).

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part of the 1998 tobacco master settlement agreement. [2] On climate change, special interest groups have long exploited scientific uncertainties to promote inaction (Hoggan and Littlemore, 2009). Communication strategies outlined in a leaked 1998 memo by the American Petroleum Institute are remarkably similar to those documented for tobacco (Cushman, 1998; and Walker, 1998). Objectives included "Identifying and establishing cooperative relationships with all major scientists whose research in this field supports our position" and "Providing grants for advocacy on climate science, as deemed appropriate." Oreskes and Conway (2010) document how, as announced in this memo, a handful of scientists were coopted by industrial lobbies. Concealing their industry ties and exploiting their scientific stature, they played an effective role in science-denying communication campaigns. On tobacco and climate change, firms have deliberately manufactured doubt in order to avoid, weaken or postpone regulations. These unscrupulous practices likely yield first-order welfare losses.[3] Economic analysis of this subject is still underdeveloped, however, and our analysis aims to fill this gap.

In this paper, we propose a new model to study the interplay between scientific uncertainty, firms' miscommunication and public policies. We assume that firms' economic activity generates uncertain damage, and that this uncertainty can be reduced through scientific research. Firms can miscommunicate by producing favorable reports that resemble independent scientific evidence. Citizens are unaware of firms' miscommunication and do not distinguish between industry-generated information and scientific knowledge. The government is benevolent but populist: it maximizes social welfare as perceived by citizens. It regulates firms' activity either by imposing a maximal level of emissions or through a tax on emissions.

We analyze a sequential game with the following timing. First, either the government or an independent research agency decides how much research to finance. Scientists then run experiments and form their belief. Second, the industry miscommunicates. Scientific knowledge and the industry's communication determine the citizens' belief. Third, the government regulates firms' activity. We develop our analysis in two stages. For a given scientific belief, we characterize the industry's optimal miscommunication and its impact on citizens' beliefs, regulations and welfare. We study how these outcomes depend on the type of environmental regulation implemented. We then analyze how firms' miscommunication affects research funding under different institutions.

Our analysis yields novel insights. We first show that the industry's miscommunication effort is a non-monotonic and discontinuous function of scientific belief. As scientists become increasingly convinced that the activity is harmful, the industry first devotes more and more resources to falsely reassuring the citizens. This yields increasingly large welfare losses. When scientists' belief reaches a critical threshold, however, countering the scientific consensus becomes too costly and the industry abruptly ceases its miscommunication. This qualitative pattern is robust to the type of instrument used (command and control or tax on emissions).

This result sheds light on some documented tendencies. It is consistent with the large time lags typically observed between when scientists reach a consensus on the need for regulation and when an effective public policy is implemented.[4] It can help explain people's persistent underestimation of the scientific consensus on climate change (Ding et al., 2011). Our finding helps explain sudden reversals in the official positions of special interest groups, as observed in the past on tobacco and recently on climate change. It also helps explain episodes of abrupt awakening to the dangers posed by some industrial activity.

We then look at the impact of the type of environmental regulation implemented. We identify a natural condition that leads to more industry miscommunication under a tax on emissions than under command and control. Since the industry's payoff is lower under a tax on emissions, due to the added fiscal burden relative to command and control, the industry has more to gain from influencing public opinion and regulation.

Next, we show that the wedge driven by the industry between scientists' and citizens' beliefs has important implications for research funding. We analyze different institutions' incentives to support research. Since a populist government cares about perceived welfare, its utility increases when citizens are falsely reassured. This may lead to a partial alignment of interests between the government and the industry. We find that a populist government may support research to allow the industry to miscommunicate more effectively. We show that a partial answer to this problem is to establish an independent funding agency, not unlike the current National Science Foundation and European Research Council. Interestingly, the independent agency may decide to provide more or less research funding than under the first-best. Either strategy may provide the best way to limit the damaging effects of firms' miscommunication. Our analysis thus provides a new rationale for the establishment of independent scientific agencies.

A key assumption is that citizens are unaware of the industry's involvement in biased research. This assumption is consistent with evidence of dissimulation of negative scientific findings by the tobacco industry and with the documented tendency of industry-funded scientists to conceal their funding sources (Bero, 2013; Proctor, 2011). The many scandals in the medical sector brought to light this concealment, leading to the adoption of disclosure rules by academic journals. These rules do not appear to be very effective, however, and corporate-funded ghostwriting is still suspected of being a major problem in biomedical research (Bero et al., 2005; PLoS Medicine Editors, 2009; Thacker, 2014).[5] This may help explain why citizens hold incorrect beliefs on

[2] These documents can be consulted at https://www.industrydocumentslibrary.ucsf.edu/tobacco/.

[3] Proctor (2011) argues that early doubt manufactured by the tobacco industry on the link between smoking and cancer caused an excess 8000 billion smoked cigarettes and 8 million premature deaths.

[4] See European Environment Agency (2013), which notably shows that 'false positives', where preventive actions undertaken due to early scientific warnings turn out to be unnecessary, are much less frequent than 'false negatives', where no action is taken despite early warnings that are confirmed ex-post.

[5] Relatedly, Monsanto has recently been accused of ghostwriting scientific articles vouching for the safety of its Roundup herbicide, see Waldman et al. (2017).

many important issues (Flynn et al., 2017).

Our analysis contributes to several literature. It first advances understanding of the political economy of scientific uncertainty. It contributes to a growing literature on indirect lobbying, where special interest groups try to affect voters' beliefs, see e.g. Laussel and van Ypersele (2012), and Petrova (2012). In Yu (2005), an industrial and an environmental lobby compete for political influence directly and through communication campaigns. However, scientific progress plays no role in his analysis. Baron (2005) and Shapiro (2016) model competition between special interests to seek political influence through the news media. They adopt a coarse representation of science where evidence is either uninformative or fully informative. By contrast, we consider a single lobby and voters who are not aware of the lobby's miscommunication.[6] We adopt a rich representation of science where evidence can accumulate and bring scientists progressively closer to the truth. This allows us to analyze how firms' miscommunication depends on the level of scientific uncertainty and how, in turn, this miscommunication affects research funding.

Second, our paper contributes to a literature studying the implications of the fact that citizens often hold incorrect beliefs. Researchers have long debated the normative consequences of citizens' misperceptions: should a benevolent government respect citizens' incorrect beliefs and assuage fears? Or should it use scarce resources where they are really needed, for instance, to save lives?[7] Salanié and Treich (2009) analyze optimal regulations for two types of governments, and we adopt some of their terminology. In this literature, citizens' and experts' beliefs are typically taken as given. By contrast, these beliefs are formed endogenously in our framework, and are affected by scientific progress and by industry miscommunication. This raises new questions, such as how misperceptions depend on the economy's fundamentals and the determination of scientific policies.

Third, a large and growing literature explores the effect of uncertainty on environmental outcomes. Most studies in this literature consider a benevolent social planner with no misperception.[8] Recently, researchers have started to study uncertainty in strategic contexts, such as free-riding between countries.[9] Here, we focus on a new channel through which uncertainty may affect the environment: citizens' misperceptions induced by firms' miscommunication in the presence of scientific uncertainty. We provide a systematic analysis of this channel and show that it may have a first-order impact on environmental and scientific outcomes.

Our paper also contributes to the literature on the choice of environmental policy instruments. We show that a tax on emissions (or a market for permits with permits auctioned) may lead to more miscommunication than command and control (or a market for permits with permits freely allocated).

The remainder of the paper is organized as follows. Section 2 introduces our model. We develop models of scientific progress and of belief formation, and characterize the industry's optimal miscommunication in Section 3. The level of research is endogenized in Section 4. We conclude in Section 5.

2. Model

We consider a society composed of four groups of agents: firms, scientists, citizens and the government. The firms' economic activity generates pollution, which may be harmful to health and to the environment. The government has to decide on the degree of regulation of this pollution. The impacts of the pollution and the extent of harm it might cause are uncertain. Scientists can do research to reduce this uncertainty. Both firms and scientists communicate about the economic activity's impacts. Citizens then form beliefs about these effects, and the government considers public opinion when adopting regulations.

Formally, firms' benefits from emitting emissions e are equal to $B(e) = be_0e - \frac{1}{2}be^2$ with b, $e_0 > 0$.[10] In the absence of regulation, benefits are maximized by emitting $e = e_0$, the "business as usual" level of pollution. The government regulates emissions, and can do so in different ways. Let $e^* \leq e_0$ be the target level of regulated emissions. Under command and control, the government directly imposes this maximal level. Alternatively, the government can tax emissions at rate t. Firms choose emissions to maximize $B(e) - te$, which yields $B'(e) = t$. The government then sets $t = B'(e^*) = b(e_0 - e^*)$. Firms' payoffs are equal to $B(e^*) = be_0e^* - \frac{1}{2}b(e^*)^2$ under command and control and to $B(e^*) - te^* = \frac{1}{2}b(e^*)^2$ under a tax on emissions. In either case, firms' payoffs decrease as e^* decreases, giving them an incentive to be as little regulated as possible.[11]

Emissions may generate damage. For simplicity, we assume that scientific uncertainty takes a binary form. Either pollution is indeed harmful, and overall damage is equal to $D(e) = d_0e + \frac{1}{2}de^2$ with $d_0, d \geq 0$. We further assume that $d_0 < be_0$. The marginal benefit from the first unit of emission exceeds its marginal damage. Or pollution is not harmful. Scientists believe that pollution

[6] Some studies consider Bayesian voters who are fully aware of the lobbies' actions, see Baron (2005) and Stone (2011). However, their results and insights may not carry over to an economy with effective concealment and systematic misperceptions.

[7] See, in particular, Pollak (1998), Portney (1992), and Viscusi and Hamilton (1999).

[8] See, e.g., Gollier et al. (2000), Heal and Kriström (2002), Weitzman (2009) and studies based on integrated assessment models like Nordhaus (1994) and Stern (2007).

[9] As in Baker (2005), Boucher and Bramoullé (2010), Bramoullé and Treich (2009), Finus and Pintassilgo (2013) and Ulph (2004).

[10] Quadratic functional forms have been widely used in environmental economics (e.g. Nordhaus, 2015). They allow researchers to maintain tractability while capturing key economic features, such as the property that marginal abatement cost is increasing in abatement.

[11] The government could also regulate emissions through tradeable permits. Let r be the price on the market for permits. If permits are initially auctioned, firms' payoffs are equal to $B(e) - re$. If permits are initially freely allocated, firms' payoffs are equal to $B(e) - re + re^*$. In either case, this yields $B'(e) = r$ and hence $r = B'(e^*) = t$. Firms' payoffs under command and control and under freely allocated permits are then equal. They are also equal under a tax on emissions and under auctioned permits.

is harmful with probability p. The expected social welfare is thus equal to[12]:

$$W(p, e) = B(e) - pD(e).$$

Say that a government is *technocratic* when it maximizes social welfare computed with up-to-date scientific knowledge. A technocratic government sets the emissions level to optimally balance social benefits and social costs. This means that $B'(e) = pD'(e)$, which yields:

$$e(p) = \frac{be_0 - pd_0}{b + pd}. \tag{1}$$

This corresponds to the first-best outcome, which can be equivalently reached through command and control or through a tax on emissions. Note that e is decreasing and convex in scientific belief p.[13]

Citizens' beliefs may differ from scientists' beliefs. Firms are organized in a communication lobby, which tries to affect public opinion on the effects of pollution.[14,15] Citizens' beliefs, q, then depend both on scientific beliefs and on the industry's miscommunication effort. Say that a government is *populist* when it maximizes social welfare as perceived by citizens: $W(q, e) = B(e) - qD(e)$. The level of regulation chosen by a populist government is then equal to $e(q)$. When citizens are less worried about the impacts of pollution than scientists, $q < p$ and $e(q) > e(p)$. A populist government then underregulates with respect to the first-best. This provides incentives for the industry to try to falsely reassure citizens on the effects of its activity.

We assume that the government is populist in Section 3. We consider an exogenous level of research and characterize the industry's optimal communication policy. In Section 4, we endogenize the level of research under various institutional arrangements.

3. Exogenous science

In this section, we consider an exogenous level of research. We first develop a simple Bayesian model of scientific progress. We then build on it to model industry miscommunication and opinion formation. Finally, we characterize the industry's optimal communication policy. We contrast outcomes under command and control and under a tax on emissions.

3.1. Scientific and popular beliefs

Consider the following model of scientific progress. Scientists can do research to reduce their uncertainty on the effects of pollution. They have prior beliefs p_0 that pollution is harmful. They may run n experiments to learn about pollution's impact. Each experiment provides a noisy signal on the true state of the world, and there is a probability $\frac{1}{2} < P < 1$ of its findings being correct. Denote by k the number of experiments indicating that pollution is harmful. Applying Bayes' rule, we see that scientists' ex-post belief is equal to

$$p = \frac{p_0 \binom{n}{k} P^k (1-P)^{n-k}}{p_0 \binom{n}{k} P^k (1-P)^{n-k} + (1-p_0) \binom{n}{k} P^{n-k} (1-P)^k}.$$

Let $\alpha = P/(1-P) > 1$ denote the relative accuracy of experimental findings. This yields:

$$p(p_0, k, n) = \frac{p_0 \alpha^k}{p_0 \alpha^k + (1-p_0)\alpha^{n-k}}. \tag{2}$$

Note that $p \geq p_0 \Leftrightarrow k \geq n/2$. More generally, this formula embodies key features of Bayesian updating. For instance, if experiments are run in several stages the final belief does not depend on their ordering. Formally, $p(p(p_0, k_1, n_1), k_2, n_2) = p(p_0, k_1 + k_2, n_1 + n_2)$ for any $k_1 \leq n_1$ and $k_2 \leq n_2$.

Thus, scientists' belief is a discrete stochastic variable $\widetilde{p}$, such that $\widetilde{p} = p(p_0, k, n)$ with probability $p_0 \binom{n}{k} P^k (1-P)^{n-k} + (1-p_0) \binom{n}{k} P^{n-k} (1-P)^k$ for any integer k between 0 and n. We can check that the expectation of scientists' belief is equal to their prior: for any n, $E(\widetilde{p}) = p_0$. As n increases, $\widetilde{p}$ puts more and more probability mass on beliefs farther and farther away from p_0. As

[12] Under a tax on emissions, we assume that tax revenues are redistributed in a lump-sum manner to citizens. Citizens' utility is then equal to $te - pD(e)$ and overall welfare is equal to $B(e) - pD(e)$, as under command and control.

[13] The assumption that $be_0 > d_0$ guarantees that $e(p) > 0$. By contrast if $be_0 \leq d_0$, $e(p) = 0$ if $p \geq be_0/d_0$. This introduces a kink in the optimal regulation, which complicates the analysis without affecting the insights obtained.

[14] For instance, in 1954 US tobacco companies formed the Tobacco Industry Research Committee, which later became the Council for Tobacco Research. "The industry stated publicly that it was forming the TIRC to fund independent scientific research to determine whether there was a link between smoking and lung cancer. However, internal documents from Brown & Williamson Tobacco Company have shown that the TIRC was actually formed for public relations purposes, to convince the public that the hazards of smoking had not been proven.", see Bero (2013, p.156).

[15] We abstract away from issues of formation and stability of the communication lobby and, more generally, from strategic interactions between firms in the industry.

$n \to \infty$, we show in the Appendix that $\widetilde{p}$ converges in probability towards the distribution $p_\infty = 0$ with probability $1 - p_0$ and 1 with probability p_0. As the number of experiments becomes arbitrarily large, scientific knowledge converges to the truth.

Citizens' beliefs may differ from scientists' beliefs. At cost c, the industry can produce a report indicating that pollution is not harmful. Citizens are unaware of the industry's miscommunication and treat the information produced by the industry as independent scientific evidence. [16,17] Under this assumption, the citizens' belief is equal to

$$q = \frac{p_0\alpha^k}{p_0\alpha^k + (1-p_0)\alpha^{n-k+m}}$$

where m denotes the industry's communication effort, i.e. the number of reports it has produced. In fact, q can be expressed as a function of scientists' belief p and of communication effort m[18]:

$$q(p,m) = \frac{p}{p + (1-p)\alpha^m}. \tag{3}$$

We assume in what follows that m can take continuous values, $m \in \mathbb{R}_+$. This helps simplify computations and the expressions for the main results without affecting our main insights.

We next clarify how the citizens' belief varies with p and m. We compute q's various derivatives in the Appendix. We see, first, that $\partial q/\partial p > 0$ and $\partial^2 q/\partial p^2 > 0$. The marginal impact of scientists' belief on citizens' belief is positive and increasing. Then, observe that $\partial q/\partial m < 0$: q is decreasing in m from $q(p,0) = p$ to $q(p,\infty) = 0$. Interestingly, its curvature may vary: $\partial^2 q/\partial m^2 < 0$ if $q > \frac{1}{2}$ and $\partial^2 q/\partial m^2 > 0$ if $q < \frac{1}{2}$. Two cases emerge. Suppose first that $p \leq \frac{1}{2}$. Then, q is convex in m. In that case, the marginal impact of industry's miscommunication on citizens' belief is decreasing in absolute value. By contrast if $p \geq \frac{1}{2}$, q is first concave in m for $q \geq \frac{1}{2}$, which happens for $m \leq \ln(p/(1-p))/\ln(\alpha)$, and convex when $m \geq \ln(p/(1-p))/\ln(\alpha)$ and $q \leq \frac{1}{2}$. Therefore, when scientists think that pollution is likely to be harmful, miscommunication initially has an increasing marginal impact, in absolute value, on citizens' belief. These increasing returns capture a well-known property of Bayesian updating: extra information has the largest effect when the agent is most uncertain. In addition, the impact of extra information decreases as the agent becomes more certain. We will see below that this feature plays an important role in determining the optimal communication policy.

3.2. Firms' optimal communication

We now derive our first main result. We characterize the industry's optimal communication policy, uncovering three domains. When p is low and scientists believe that pollution is unlikely to be harmful, the benefits from miscommunication are too low and the industry does not try to change the citizens' beliefs. When p takes intermediate values, and scientists are more uncertain about the effects of the pollution, the industry engages in miscommunication and targets a specific level of citizens' belief. As p increases, the target is unchanged and communication efforts first increase continuously. When p reaches a critical threshold, the costs of miscommunication become too high and the industry abruptly ceases its efforts. Optimal miscommunication is therefore non-monotonic and discontinuous in scientists' belief.

Formally, the industry's objective is to maximize its payoff with respect to m:

$\pi_c(m) = be_0 e(q(p,m)) - \frac{1}{2}be(q(p,m))^2 - cm$ under command and control and $\pi_t(m) = \frac{1}{2}be(q(p,m))^2 - cm$ under a tax on emissions. We provide an in-depth analysis of these payoff functions in the Appendix. Let m_c^* (m_t^*) be a solution to the problem of maximizing π_c (π_t) over $[0, +\infty[$.

Theorem 1. *Under command and control, there exists $\overline{c}_c > 0$ such that if $c \geq \overline{c}_c$, then $m_c^* = 0$. If $c < \overline{c}_c$, there exist a target popular belief q_c^* and a threshold scientific belief $p_c^* > q_c^*$ such that $m_c^* = 0$ if $p \leq q_c^*$ or $p \geq p_c^*$. If $q_c^* \leq p \leq p_c^*$, then $q(m_c^*, p) = q_c^*$ and*

$$m_c^* = \frac{1}{\ln(\alpha)}\left[\ln\left(\frac{p}{1-p}\right) - \ln\left(\frac{q_c^*}{1-q_c^*}\right)\right].$$

Miscommunication under a tax on emissions has a similar shape, with thresholds $\overline{c}_t$, q_t^* and p_t^*.

We provide a sketch of the proof here. See the Appendix for details and for characterizations of the threshold values $\overline{c}_c$, q_c^*, p_c^* and $\overline{c}_t$, q_t^*, p_t^*.[19] We start by examining the second derivatives of the payoff function. Two cases emerge. On the one hand, if p is low enough, π_c is concave everywhere. Since the payoff becomes negative when m is large enough, the solution is then obtained by analyzing the sign of $\partial\pi_c/\partial m(0)$. We show that $\partial\pi_c/\partial m(0) < 0$ if $p < q_c^*$, which implies that $m_c^* = 0$ in that case. In contrast, $\partial\pi_c/\partial m(0) > 0$ if $p > q_c^*$ and m_c^* then solves $\partial\pi_c/\partial m(m_c^*) = 0$. We can express $\partial\pi_c/\partial m$ as a function of q, and this

[16] By contrast, we assume that the government and the research agency are aware of the industry's miscommunication.

[17] Miscommunication costs are not included in the welfare computations. Proposition 1 below is robust to including them. Numerical simulations indicate that welfare effects may be further amplified when accounting for these costs.

[18] In the absence of miscommunication, citizens' belief is equal to scientists' belief. Thus, we abstract away from frictions and costs in knowledge dissemination and from the role played by various media (TV, press, internet) in this process. We discuss these issues further in the Conclusion.

[19] For clarity, we sometimes omit subscripts in what follows. We may for instance write q^* when the argument applies both to q_c^* and q_t^*.

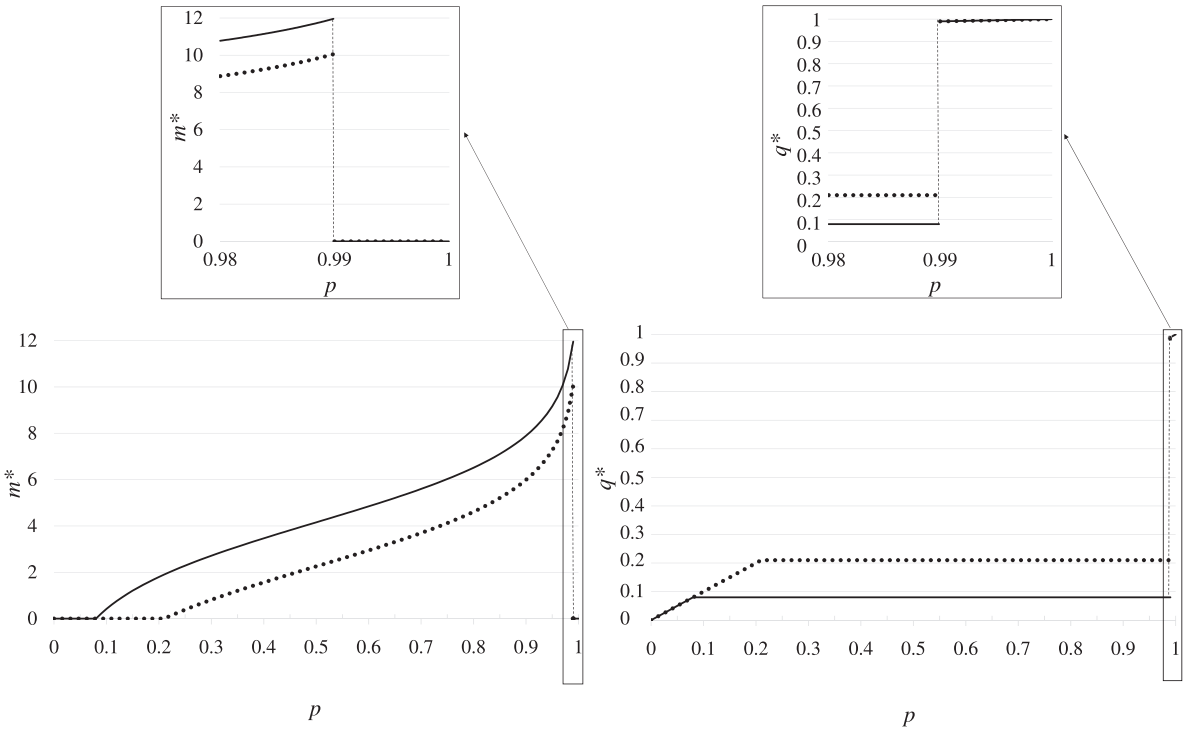

Fig. 1. Firms' miscommunication and citizens' beliefs under tax on emissions (Solid line) and under command and control (Dotted line).

equation then defines the target belief q_c^*. On the other hand, if p is high enough, π_c is first convex and then concave. When p is high, the industry's payoff first displays increasing returns on communication effort. We show that in this case, the solution is either to reach the target q_c^* or to set $m_c^* = 0$. We compare the payoffs obtained from these two actions and show that there exists a critical threshold p_c^* above which q_c^* leads to less payoff than no communication.[20] This discontinuity in the solution is induced by the presence of convexities in payoffs. We then analyze properties of π_t, firms' payoff under a tax on emissions. We show that it displays similar qualitative features and leads to a solution with a similar shape.

We next analyze how the type of environmental regulation affects firms' miscommunication.

Theorem 2. *Suppose that* $be_0 \geq 2d_0 + de_0$ *. Then,* $m_t^* \geq m_c^*$ *with a strict inequality if* $m_t^* > 0$.

This result means that if marginal damages at zero are not too high, firms always miscommunicate more under a tax on emissions than under command and control. This notably implies that $\overline{c}_c < \overline{c}_t$ and if $c < \min(\overline{c}_c, \overline{c}_t)$, $q_t^* < q_c^* < p_c^* < p_t^*$. Observe that with both instruments, firms obtain lower profits because of the lower level of emissions: $B(e) < B(e_0)$. Under a tax on emissions, firms face an additional fiscal burden and see their profits further reduced by the amount of the tax paid to the government. This gives them an extra incentive to influence regulation relative to command and control.[21]

We illustrate Theorems 1 and 2 in Fig. 1. Parameter values are set as follows: $d_0 = 9.9$, $d = 0.01$, $e_0 = 10$, $b = 2$, $c = 4.3$, and $P = 0.64$. From our characterizations in the Appendix, we compute the thresholds: $\overline{c}_c \approx 4.31$, $q_c^* \approx 0.21$, $p_c^* \approx 0.99$ and $\overline{c}_t \approx 11.27$, $q_t^* \approx 0.08$, $p_t^* \approx 0.99$.

Here, the costs of miscommunication are quite low compared to the benefits, and effort is positive over a large range of scientific beliefs, under both types of regulation. We depict in Fig. 1 how m^*, in the Left panel, and $q(m^*, p)$, in the Right panel, vary with p under a tax on emissions and under command and control. Note that citizens' belief also varies discontinuously with p. It stays at the target level q^* as long as the industry engages in miscommunication and then jumps back to p when the

[20] At $p = p_c^*$, the industry is indifferent between playing $m_c^* = 0$ or reaching q_c^*. The problem of maximizing π_c has two solutions.

[21] The condition $be_0 \geq 2d_0 + de_0$ guarantees that $e(p) \geq (d_0 + de_0)/(b + d)$ and the first-best level of emissions is bounded from below. When this condition is not satisfied, emissions can get arbitrarily close to zero. The fiscal burden also gets arbitrarily close to zero and miscommunication incentives may be higher under command and control in some situations.

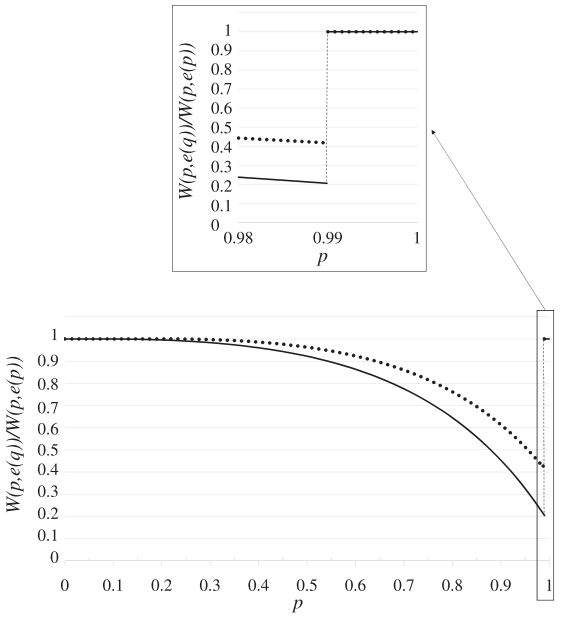

Fig. 2. Welfare loss induced by firms' miscommunication under tax on emissions (Solid line) and under command and control (Dotted line).

industry ceases to miscommunicate.

The combination of citizens' industry-induced misperceptions and of populist policies can lead to significant welfare losses. Note that $W(p, e(q)) - W(p, e(p)) = -\frac{1}{2}(b + pd)[e(p) - e(q)]^2 < 0$. This loss increases in absolute value as q decreases and moves farther away from p. In Fig. 2, we depict the ratio of the level of welfare under the populist policy over the first-best level of welfare (technocratic policy), $W(p, e(q))/W(p, e(p))$, for the same parameter values as in Fig. 1.

We see that relative welfare loss first increases as scientific belief, and hence firms' miscommunication and the induced distortion in citizens' belief, increases. When scientific belief becomes high enough, however, the industry stops miscommunicating and welfare jumps back to its first-best value. In addition, welfare losses are larger under a tax on emissions, due to the increased miscommunication.

From our characterization of firms' communication policy, we can further derive some potentially interesting comparative statics. Consider, for instance, the impact of the accuracy of experimental findings under command and control. An increase in α has two countervailing effects. On the one hand, scientists converge more quickly towards the truth when α is higher. The variance in scientific beliefs tends to be higher when α is higher and, in the absence of industry miscommunication, this applies to citizens' beliefs as well. On the other hand, we see that $\overline{c}_c$ is increasing in α and we show in the Appendix that q_c^* is decreasing while p_c^* is increasing in α. Because citizens do not differentiate between information provided by the industry and by scientists, *a higher* α makes the industry's miscommunication more effective.[22] Industry miscommunication thus emerges for higher values of communication costs and over a larger range of scientific beliefs. This runs counter to the first effect and tends to slow down the convergence of citizens' beliefs towards the truth.[23]

4. Endogenous science

In this section, we analyze the level of research chosen in three different setups: when the government is technocratic; when the government is populist and decides on both research funding and environmental regulation; and when the government is populist but research funding is decided by an independent agency. Throughout the section, we analyze a sequential game with three steps. (1) First, the institution setting the research policy decides how many experiments n to finance. These experiments are then run and scientists form their belief p. (2) Second, the industry observes scientific belief and chooses a level of miscommunication effort m. Citizens then form their belief q. (3) Third, the government regulates the industry's activity. Finally, benefits and costs are realized.

[22] Similarly, the amount of communication needed to reach a fixed target of popular belief is lower when α is higher.

[23] This negative impact of experimental accuracy is reminiscent of findings in Edmond (2013). In a context of information manipulation and political regime change, the accuracy of signals received by citizens may actually help autocratic regimes stay in power.

As in Stackelberg competition, the institution deciding scientific research funding takes its decision before the industry miscommunicates. We analyze the subgame perfect equilibria of this sequential game through backwards induction. (2) Conditional on scientists' realized belief p, the industry chooses its optimal level of miscommunication as described in Theorem 1. (1) The government or the research agency chooses the level of scientific research funding, rationally anticipating the industry's subsequent miscommunication.

4.1. Welfare

We first determine the welfare ranking of these three institutional arrangements. Recall, $W(p, e) = B(e) - pD(e)$ denotes welfare computed once research is done but before the state of the world is revealed. We now consider expected welfare computed *ex-ante*, before the results from research are known. Assume that each experiment costs C.[24] A technocratic government chooses the level of research funding by maximizing expected welfare:

$$W_{tech}(n) = E[W(\widetilde{p}, e(\widetilde{p})) \mid n] - Cn$$

and let W^*_{tech} denote its maximal value.

By contrast, a populist government maximizes expected *perceived* welfare, computed with potentially false popular beliefs:

$$\Pi_{pop}(n) = E[W(\widetilde{q}, e(\widetilde{q})) \mid n] - Cn$$

In general, $\Pi_{pop}(n)$ differs from the expected welfare computed with unbiased scientific belief $E[W(\widetilde{p}, e(\widetilde{q})) \mid n] - Cn$. Denote by W^*_{pop} the expected welfare induced by a populist choice of research funding level.[25]

Finally, consider an independent research agency deciding on the level of research funding before firms miscommunicate and the populist government regulates emissions. Assume that this agency is benevolent and computes welfare based on up-to-date scientific knowledge. It seeks to maximize

$$W_{indep}(n) = E[W(\widetilde{p}, e(\widetilde{q})) \mid n] - Cn.$$

and let W^*_{indep} denote its maximal value.

We show next that welfare can be unambiguously ranked across the three institutions.

Proposition 1. $W^*_{pop} \leq W^*_{indep} \leq W^*_{tech}$.

To see why Proposition 1 holds, note first that W^*_{tech} corresponds to the first-best - and hence highest - level of welfare attainable in the economy. Therefore, $W^*_{pop}, W^*_{indep} \leq W^*_{tech}$. Then, observe that the independent agency maximizes welfare under populist environmental regulation. Therefore, W^*_{indep} is the highest level of welfare attainable when $e = e(q)$, which implies that $W^*_{indep} \geq W^*_{pop}$. Populist policies thus entail welfare losses even when research funding is endogenous. Moreover, these losses are partially offset when research funding is controlled by a technocratic agency which is independent from the government.

4.2. Scientific policies

We now analyze the scientific policies adopted under the different institutions. The institutions' optimization problems involve non-convexities and discrete jumps, and we could not characterize scientific policies analytically. Our objective in this section is accordingly more modest: to illustrate the variety of potential outcomes and to explore the main forces at work.

Consider the technocratic benchmark first. The government anticipates that research will change the ex-post distribution of scientific beliefs. Since $W(p, e(p)) = B(e(p)) - pD(e(p))$ is convex in p,[26] $E[W(\widetilde{p}, e(\widetilde{p})]$ is higher when the distribution of scientific beliefs $\widetilde{p}$ is more dispersed. Expected welfare gross of the costs of experiments is highest when $n = \infty$ and scientists have converged to the truth: $\widetilde{p} = 0$ with probability $1 - p_0$ and 1 with probability p_0. As n increases, scientists get increasingly closer to the truth. Extensive numerical simulations show that expected gross welfare generally increases at a decreasing rate in n.[27] In this case, the optimal level of research funding can be characterized by a standard marginal condition. It should be set at the level where the marginal gain from an additional experiment is approximately equal to its marginal cost C. To sum up, *a technocratic government trades the welfare benefits from uncertainty reduction against the research costs.* Note that this classic incentive also affects the decisions of a populist government and an independent agency. These two institutions are, in addition, affected by firms' miscommunication.

Next, consider a populist government. A key new motive appears in its objective function. Observe that $W(q, e(q))$ increases when q decreases. Perceived welfare is decreasing in actual citizens' belief that emissions are harmful. *A populist government*

[24] These costs may notably include opportunity costs of public funds. We introduce explicit budget considerations in Section 5.

[25] Since $q \leq p$, $\Pi_{pop}(n) \geq E[W(\widetilde{p}, e(\widetilde{q})) \mid n] - Cn$. Undue reassurance increases perceived welfare by decreasing perceived expectations of future harm.

[26] By the envelope theorem, the first derivative is equal to $-D(e(p))$. The second derivative is then equal to $-e'(p)D'(e(p)) \geq 0$.

[27] However, simulations also indicate that $E[W(\widetilde{p}, e(\widetilde{p})]$ may be non-monotonous and non-concave in n in some circumstances. For instance, when p_0 is close to 0 or 1 and α is close to 1, expected gross welfare is often initially convex in n.

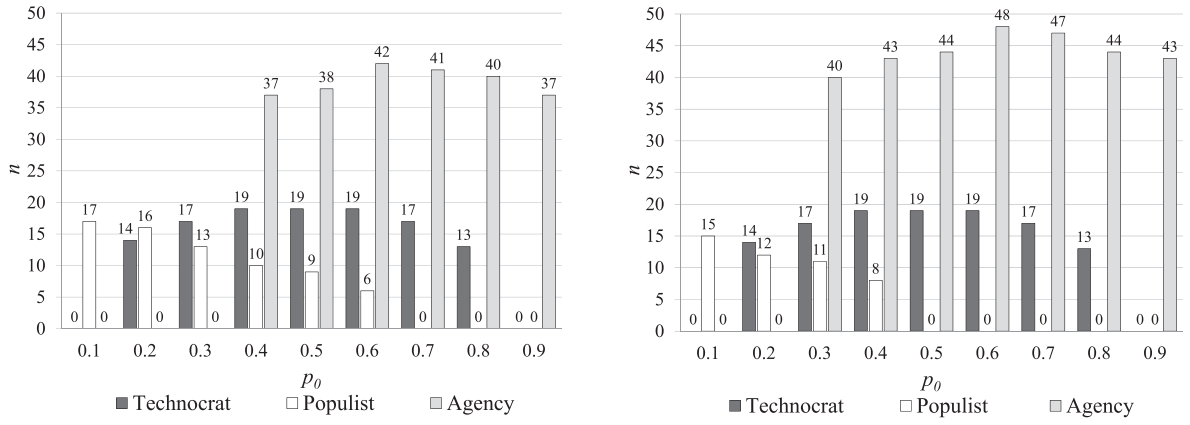

Fig. 3. Research funding under three institutional arrangements. Command and control (on the left) and tax on emissions (on the right).

would therefore like citizens to be falsely reassured. This is precisely what doubt manufacturing does, and hence the interests of a populist government may be partly aligned with those of the industry.[28] Note, then, that doubt manufacturing only occurs when $\widetilde{p}$ takes on moderate values. From Theorem 1, we know that $m^* = 0$ and $q = p$ if $p \leq q^*$ or $p \geq p^*$ while $m^* > 0$ and $q = q^*$ if $q^* < p < p^*$. A populist government may then choose an amount of research ensuring that scientific belief likely takes on moderate values. This, in turn, is partly determined by the position of the initial scientific belief p_0 with respect to the domain of effective miscommunication $[q^*, p^*]$. If $p_0 \in [q^*, p^*]$, public opinion is biased by industry's efforts even when there is very little research. Expected citizens' belief $E(\widetilde{q})$ may then be increasing in n and a populist government may not want to support scientific activities. By contrast, if $p_0 < q^*$ or $p_0 > p^*$, $E(\widetilde{q}) = p_0$ when $n = 0$. In that case $E(\widetilde{q})$ is typically non-monotonic in n, reaching a minimum for some positive value n. This level of research allows the industry to most effectively miscommunicate in expectation, and hence may be preferred by a populist government.

Finally, consider an independent research agency which anticipates the actions of the industrial lobbies and their impact on environmental regulations. In contrast to a populist government, this independent agency tries to counter the negative impact of the industry's miscommunication. This may lead the agency to provide more or less research funding than a technocratic government.

We illustrate these effects in Figs. 3 and 4. We depict in Fig. 3 how scientific policies set by the three institutions vary with initial belief p_0, for the same parameters as in Fig. 1 and for $C = 0.1$.

The left bars in dark grey correspond to the first-best levels of funding, in the absence of citizens' misperceptions. Support for research first increases and then decreases as p_0 increases. A technocratic government only cares about the direct benefits and costs of reducing scientific uncertainty. These benefits are highest when uncertainty is strongest. Here funding reaches a maximum at $p_0 = 0.5$, and research is not funded when initial scientific uncertainty is very low ($p_0 = 0.1$) or very high ($p_0 = 0.9$).

The middle bars in white depict the scientific policies chosen by a populist government. When scientists have initial suspicions that harm is not unlikely, the government provides less funding for research than under the first-best. Too much research would decrease perceived welfare by reducing the ability of firms to reassure citizens. By contrast, when initial belief is low ($p_0 = 0.1$ or 0.2 under command and control; $p_0 = 0.1$ under a tax), *the populist government provides more support for research than in the first-best*. Remember that here $q_c^* \approx 0.21$ and $q_t^* \approx 0.08$. As n increases, a portion of the distribution of scientific beliefs shifts to the right of p_0, and may then fall into the miscommunication range. Firms can thus better miscommunicate, in expectation, for some intermediate value of n. This generates an extra incentive for a populist government to support research.

In addition, we see that populist support for research is stronger under command and control than under a tax on emissions. The reason, paradoxically, is that the miscommunication range is smaller under command and control: $[q_c^*, p_c^*] \subset [q_t^*, p_t^*]$. Reaching this range, and thus better reassuring citizens in expectations, therefore requires more research.

This intuition is confirmed by looking at the expected level of firms' miscommunication, $E(\widetilde{m})$, and at the expected level of popular beliefs, $E(\widetilde{q})$ in Fig. 4.

We see that under a populist government, firms increase their communication effort continuously with scientists' initial belief.[29] This miscommunication is effective: citizens' belief lies significantly below correct belief represented by the 45-degree line in the Right panel.

Finally, the right bars in light grey in Fig. 3 depict the scientific policies of an independent funding agency. We see that the agency essentially tries to limit the welfare losses induced by populist policies in two opposite ways. When initial beliefs are not too low, the agency provides much more funding than under the first-best. This is a strategy of *scientific overkill*: by doing

[28] In the long-run, belief distortion is of course untenable and reality must eventually assert itself. Due to the electoral cycle, governments tend to have relatively short time horizons. They may well decide to assuage citizens' worries now, without caring about long-term consequences.

[29] If scientists are initially close enough to certainty, firms' communication essentially disappears in expectation. Thus, $E(\widetilde{m})$ collapses when p_0 gets close to 1.

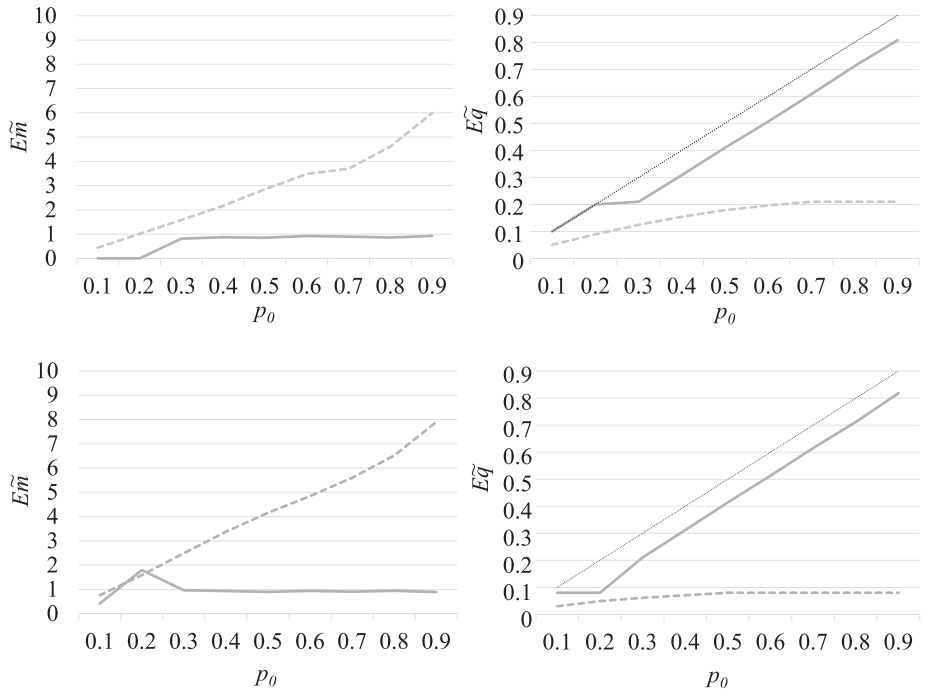

Fig. 4. Expected firm's miscommunication and citizens' belief under populist policy (Dotted line) and agency policy (Solid line). Command and control (Above) and tax on emissions (Below).

lots of research, scientists necessarily get close to the truth and firms then have little leeway to influence public opinion.[30] The benefits from shutting down firms' miscommunication outweigh the added research costs when the likelihood that the activity is harmful is not too low. In addition, scientific overkill starts for a lower level of scientific belief and leads to more research under a tax on emissions than under command and control. Because firms' incentives to miscommunicate are stronger under a tax on emissions, the agency must provide more research funding to counter firms' efforts. This is confirmed by looking at $E(\widetilde{m})$ and $E(\widetilde{q})$ in Fig. 4. When p_0 is not too high, firms' expected communication is much lower than under a populist government. Moreover, $E(\widetilde{m})$ stays more or less constant, leading to a widening gap in expected miscommunication under the two regimes as p_0 increases. Scientific overkill is effective at countering firms' miscommunication. We see in the Right panel of Fig. 4 that in this range, expected citizens' belief, while biased, closely follows the correct beliefs.

By contrast, when initial belief is low, the agency provides no funding. This is a strategy of *deliberate ignorance*, since some research would yield lower welfare than no research. Indeed, firms' expected communication is generally lower than under a populist government, which provides more funding in this range. Relatedly, citizens' expected belief is less biased.

5. Conclusion

We provide one of the first analyses of the interactions between scientific uncertainty, firms' miscommunication and public policies. Characterizing firms' optimal miscommunication, we show that it can yield significant welfare losses and can have a strong impact on scientific research funding. Moreover, miscommunication may be reduced by regulating through command and control.

Our analysis relies on a number of simplifying assumptions. Relaxing them would provide potentially fruitful directions for future research. Since a populist government maximizes perceived welfare, firms do not have an incentive to engage in political lobbying here. Alternatively, the government could maximize a combination of welfare and transfers, as in Grossman and Helpman (1994). Firms would then try to affect regulation both directly through transfers and indirectly via public opinion, and exploring the interaction between direct and indirect lobbying could be interesting. We suspect that Theorem 1 would extend and that the sharp drop in communication effort would be accompanied by a sharp increase in political lobbying.[31] As

[30] That is, there is a low probability that scientists' belief p ends up in the range $[q^*, p^*]$ where firms affect public opinion.

[31] In particular, this could shed new light on the debate on the regulation of political contributions. The introduction of a limit to contributions, for instance, could lead to an increase in miscommunication and, possibly, to a decrease in welfare. We thank Arnaud Dellis for drawing our attention to this implication.

in Yu (2005), it would also be natural to consider interactions between an industrial and an environmental lobby. Competition to affect public opinion would likely increase firms' communication effort and could lead them to abandon miscommunication for lower levels of scientific beliefs.

In our analysis, we assume that firms are organized in a communication lobby which tries to maximize the industry's payoff. In reality, firms within the industry may be tempted to free-ride and to benefit from the lobby's actions without paying their share of the communication costs. Introducing strategic interactions between firms would be an interesting direction for future research. We conjecture that these strategic interactions would generally reduce the effectiveness of the lobby and hence the extent of miscommunication.

Another assumption is that, in the absence of miscommunication, scientific knowledge disseminates widely and with no additional cost to citizens. In reality, knowledge diffusion may be imperfect and costly, and may depend on decisions by other agents such as journalists and media owners (Shapiro, 2016). More generally, misperceptions may have a variety of causes, such as lack of Bayesian rationality.[32] It would be interesting to introduce these considerations in our framework. We suspect that miscommunication would be amplified in some instances and reduced in others. If there is poor diffusion of scientific knowledge, for instance, this likely reduces firms' incentives to produce biased research.

Finally, we have focused our representation of science on the key question of understanding the level of harm induced by the economic activity. In reality, science of course covers a wide variety of issues and questions. Another documented strategy of industrial lobbies has been to fund "distraction research", i.e., legitimate research that does not advance knowledge on this key question and distracts scientists and citizens' attention away from it.[33] Analyzing this elaborate strategy would require developing a richer model of science.

Appendix

Proofs of statements in Section 3.1 We first prove that $\widetilde{p}$ converges in probability to p_∞ as n tends to ∞. Let us first consider even values of n. Introduce $l = k - n/2$ and $\sigma = P(1-P)$. Since $\frac{1}{2} < P < 1$, $\sigma < \frac{1}{4}$. We have: $p(p_0, k, n) = \frac{p_0\alpha^l}{p_0\alpha^l + (1-p_0)\alpha^{-l}} = \widehat{p}(p_0, l)$ with probability $x_{l,n} = \binom{n}{l+n/2}\sigma^{n/2}(p_0\alpha^l + (1-p_0)\alpha^{-l})$ for $l \in \{-\frac{n}{2}, -\frac{n}{2}+1, \dots, -1, 0, 1, \dots, \frac{n}{2}-1, \frac{n}{2}\}$. We show next that $x_{l,n} \to 0$ as $n \to \infty$. That is, keeping l constant, the probability attached to specific belief $\widehat{p}(p_0, l)$ converges to 0 as the number of experiments n becomes arbitrarily large. To see why, note that:

$$\frac{x_{l,n+2}}{x_{l,n}} = \sigma\frac{(n+2)(n+1)}{(\frac{n}{2}+1+l)(\frac{n}{2}+1-l)}.$$

This implies that $\frac{x_{l,n+2}}{x_{l,n}} \to 4\sigma < 1$ as $n \to \infty$. Therefore there exists $K < 1$ such that $\frac{x_{l,n+2}}{x_{l,n}} \leq K < 1$ if n is large enough. This implies that $x_{l,n} \to 0$ as $n \to \infty$.

Next, consider $\widehat{p}$ as a function of l. We see that $\widehat{p}$ is increasing in l and that $\widehat{p}(p_0, l) \to 0$ when $l \to -\infty$ and that $\widehat{p}(p_0, l) \to 1$ when $l \to +\infty$. Take $\varepsilon > 0$. This implies that there exist two threshold values l_1 and l_2 such that:

$$\widehat{p}(p_0, l) \in [\varepsilon, 1-\varepsilon] \Leftrightarrow l_1 \leq l \leq l_2.$$

Importantly, these values l_1 and l_2 do not depend on n. Take $\eta > 0$. Since for any l, $x_{l,n} \to 0$ as $n \to \infty$, there exists $\overline{n}$ such that $n \geq \overline{n} \Rightarrow \sum_{l=l_1}^{l_2} x_{l,n} \leq \eta$. This sum is precisely equal to the probability that belief will end up lying within $[\varepsilon, 1-\varepsilon]$. We showed that $\forall \varepsilon, \eta > 0, \exists \overline{n} : n \geq \overline{n} \Rightarrow \Pr(p(p_0, k, n) \in [\varepsilon, 1-\varepsilon]) \leq \eta$. Since $E(\widetilde{p}) = p_0$, $\widetilde{p}$ must converge in probability to p_∞. The proof for n odd runs along similar lines. QED.

Next, compute the derivatives of $q(p, m)$:

$$\frac{\partial q}{\partial p} = \frac{\alpha^m}{[p + (1-p)\alpha^m]^2}$$

$$\frac{\partial^2 q}{\partial p^2} = \frac{-2\alpha^m(1-\alpha^m)}{[p + (1-p)\alpha^m]^3}$$

$$\frac{\partial q}{\partial m} = -p(1-p)\ln(\alpha)\frac{\alpha^m}{[p + (1-p)\alpha^m]^2}$$

$$\frac{\partial^2 q}{\partial m^2} = -p(1-p)[\ln(\alpha)]^2\alpha^m\frac{p - (1-p)\alpha^m}{[p + (1-p)\alpha^m]^3}$$

QED.

[32] For example, agents may not properly account for the sources of the information they receive when forming their beliefs, as explored in the literature on persuasion bias (DeMarzo et al., 2003) and correlation neglect (Levy and Razin, 2015).

[33] See, in particular, chapter 16 in Proctor (2011).

Proof of Theorem 1. We first obtain some useful formulas. By taking the derivative of (1), we get:

$$\frac{\partial e}{\partial q} = \frac{-b(d_0 + de_0)}{(b + qd)^2}.$$

Then, observe that

$$\frac{q}{1-q} = \frac{p}{1-p}\alpha^{-m}.$$

Taking logs and differentiating with respect to m yields

$$\frac{\partial q}{\partial m} = -\ln(\alpha)q(1-q).$$

Differentiating again and substituting yields

$$\frac{\partial^2 q}{\partial m^2} = -\ln^2(\alpha)q(1-q)(2q-1).$$

We first consider payoff under command and control. We compute the first derivative of π_c with respect to m:

$$\frac{\partial \pi_c}{\partial m} = b(e_0 - e(q))\frac{\partial e}{\partial q}\frac{\partial q}{\partial m} - c$$

$$\Leftrightarrow \frac{\partial \pi_c}{\partial m} = \ln(\alpha)b^2(d_0 + de_0)^2\frac{q^2(1-q)}{(b+qd)^3} - c.$$

Differentiating again and simplifying yields

$$\frac{\partial^2 \pi_c}{\partial m^2} = -\ln^2(\alpha)b^2(d_0 + de_0)^2\frac{q^2(1-q)}{(b+qd)^4}[2b - (3b+d)q].$$

(1) Suppose first that $p < \frac{2b}{3b+d}$. Since $q \le p$, $\frac{\partial^2 \pi_c}{\partial m^2} < 0$ and π_c is concave. Since $\frac{\partial \pi_c}{\partial m}(\infty) = -c$, either $\frac{\partial \pi_c}{\partial m}(0) \le 0$ and the optimal effort is 0 or $\frac{\partial \pi_c}{\partial m}(0) > 0$ and the optimal effort is the unique $m_c^* > 0$ satisfying $\frac{\partial \pi_c}{\partial m}(m_c^*) = 0$. We have:

$$\frac{\partial \pi_c}{\partial m}(0) = \ln(\alpha)b^2(d_0 + de_0)^2\frac{p^2(1-p)}{(b+pd)^3} - c.$$

To understand how $\frac{\partial \pi_c}{\partial m}(0)$ varies with p, study the function $f(p) = \frac{p^2(1-p)}{(b+pd)^3}$. We have:

$$f'(p) = \frac{p[2b - (3b+d)p]}{(b+pd)^4}.$$

This implies that $f' > 0$ if $p \in]0, \frac{2b}{3b+d}[$ and <0 if $p \in]\frac{2b}{3b+d}, 1[$. Therefore, $f(0) = f(1) = 0$ and f is increasing over $[0, \frac{2b}{3b+d}]$, decreasing over $[\frac{2b}{3b+d}, 1]$ and reaches its maximum at $\frac{2b}{3b+d}$. Moreover, $f(\frac{2b}{3b+d}) = \frac{4}{27}\frac{1}{b(b+d)^2}$. Two subcases appear:

(1.1) If $c \ge \bar{c}_c = \frac{4}{27}\ln(\alpha)\frac{b(d_0+de_0)^2}{(b+d)^2}$, then $\frac{\partial \pi_c}{\partial m}(0) \le 0$ and $m_c^* = 0$.

(1.2) If $c < \bar{c}_c$, then there is a unique $q_c^* \in [0, \frac{2b}{3b+d}]$ such that $\frac{\partial \pi_c}{\partial m}(m) = 0$. It satisfies:

$$\frac{q_c^{*2}(1-q_c^*)}{(b+qd)^3} = \frac{c}{\ln(\alpha)b^2(d_0+de_0)^2}$$

Optimal communication is then such that $q = q_c^*$ which implies that

$$m_c^* = \frac{1}{\ln(\alpha)}[\ln(\frac{p}{1-p}) - \ln(\frac{q_c^*}{1-q_c^*})]$$

(2) Suppose, next, that $p > \frac{2b}{3b+d}$. Then π_c is a convex function of m for $q > \frac{2b}{3b+d}$ and a concave function for $q \le \frac{2b}{3b+d}$. The marginal impact of an incremental unit of effort is increasing for $q > \frac{2b}{3b+d}$ and then decreasing when $q < \frac{2b}{3b+d}$. In particular, the optimal effort is such that $q \le \frac{2b}{3b+d}$. We can see that the optimal effort is either 0 or $\widehat{m}_c$ the unique m such that $\frac{\partial \pi_c}{\partial m}(\widehat{m}_c) = 0$ and $q \le \frac{2b}{3b+d}$. Compare the payoffs of these two effort levels:

$$\varphi(p) = \pi_c(0) - \pi_c(\widehat{m}_c) = B(e(p)) - B(e(q_c^*)) + \frac{c}{\ln(\alpha)}[\ln(\frac{p}{1-p}) - \ln(\frac{q_c^*}{1-q_c^*})]$$

Study how φ varies with p. We have:

$$\frac{\partial \varphi}{\partial p} = -\frac{b^2(d_0+de_0)^2}{(b+pd)^3}p + \frac{c}{\ln(\alpha)}(\frac{1}{p} + \frac{1}{1-p})$$

$$\Leftrightarrow \frac{\partial \varphi}{\partial p} = \frac{b^2(d_0 + de_0)^2}{p(1-p)}[f(q_c^*) - f(p)].$$

Note that there is a unique $\overline{q}_c > \frac{2b}{3b+d}$ such that $f(\overline{q}_c) = f(q_c^*)$. From the derivative of function f, we know that $\frac{\partial \varphi}{\partial p}$ is >0 over $]0, q_c^*[$, <0 over $]q_c^*, \overline{q}_c[$ and >0 over $]\overline{q}_c, 1[$. Therefore, φ is increasing over $[0, q_c^*]$, decreasing over $[q_c^*, \overline{q}_c]$ and increasing over $[\overline{q}_c, 1]$. Since $\varphi(q_c^*) = 0$ and $\varphi(1) = +\infty$, there is a unique level $p_c^* > \overline{q}_c > \frac{2b}{3b+d}$ such that $\varphi(p_c^*) = 0$ and $p < p_c^* \Rightarrow \pi_c(0) < \pi_c(\widehat{m}_c)$ and $p > p_c^* \Rightarrow \pi_c(0) > \pi_c(\widehat{m}_c)$.

Next, consider payoff under a tax on emissions. We have:

$$\frac{\partial \pi_t}{\partial m} = be(q)\frac{\partial e}{\partial q}\frac{\partial q}{\partial m} - c$$

$$\Leftrightarrow \frac{\partial \pi_t}{\partial m} = \ln(\alpha)b^2(d_0 + de_0)\frac{q(1-q)(be_0 - qd_0)}{(b+qd)^3} - c.$$

Next, note that

$$\frac{\partial}{\partial q}\left[\frac{q(1-q)(be_0 - qd_0)}{(b+qd)^3}\right] = \frac{h(q)}{(b+qd)^4}$$

with $h(q) = b^2e_0 - 2b(d_0 + e_0(b+d))q + (d_0(3b+d) + dbe_0)q^2$. This implies that

$$\frac{\partial^2 \pi_t}{\partial m^2} = -\ln^2(\alpha)b^2(d_0 + de_0)\frac{q(1-q)h(q)}{(b+qd)^4}.$$

Then, $h(0) = b^2e_0 > 0$ while $h(1) = (b+d)(d_0 - be_0) < 0$. Since h is quadratic, there exists $\overline{p}_t \in]0,1[$ such that $h(\overline{p}_t) = 0$ and $h(q) > 0$ if $0 \le q < \overline{p}_t$ and $h(q) < 0$ if $\overline{p}_t < q \le 1$. Therefore, $\frac{\partial^2 \pi_t}{\partial m^2} < 0$ if $q \in]0, \overline{p}_t[$ and $\frac{\partial^2 \pi_t}{\partial m^2} > 0$ if $q \in]\overline{p}_t, 1[$. As under command and control, there are two cases.

(1) Suppose that $p < \overline{p}_t$. Then π_t is concave. Note that $\frac{\partial \pi_t}{\partial m}(\infty) = -c$ and

$$\frac{\partial \pi_t}{\partial m}(0) = \ln(\alpha)b^2(d_0 + de_0)\frac{p(1-p)(be_0 - pd_0)}{(b+pd)^3} - c,$$

$$\frac{\partial^2 \pi_t}{\partial m \partial p}(0) = \ln(\alpha)b^2(d_0 + de_0)\frac{h(p)}{(b+pd)^4}.$$

Therefore, $\frac{\partial \pi_t}{\partial m}(0)$ is increasing over $[0, \overline{p}_t]$ and decreasing over $[\overline{p}_t, 1]$, and $\frac{\partial \pi_t}{\partial m}(0)$ is maximum for $p = \overline{p}_t$. Introduce

$$\overline{c}_t = \ln(\alpha)b^2(d_0 + de_0)\frac{\overline{p}_t(1-\overline{p}_t)(be_0 - \overline{p}_t d_0)}{(b+\overline{p}_t d)^3}.$$

Then if $c \ge \overline{c}_t$, $\frac{\partial \pi_t}{\partial m}(0) \le 0$ and $m_t^* = 0$. By contrast, if $c < \overline{c}_t$, then define $q_t^* < \overline{p}_t$ such that

$$\ln(\alpha)b^2(d_0 + de_0)\frac{q_t^*(1-q_t^*)(be_0 - q_t^* d_0)}{(b+q_t^* d)^3} = c.$$

If $p \le q_t^*$, then $\frac{\partial \pi_t}{\partial m}(0) \le 0$ and $m_t^* = 0$ while if $p > q_t^*$, then m_t^* is such that $q(m_t^*, p) = q_t^*$.

(2) Suppose that $p > \overline{p}_t$. Then π_t is a convex function of m for $q > \overline{p}_t$ and a concave function for $q \le \overline{p}_t$. Therefore the optimal effort is either 0 or $\widehat{m}_t$ such that $q(\widehat{m}_t, p) = q_t^*$. Compare payoffs:

$$\psi(p) = \pi_t(0) - \pi_t(\widehat{m}_t) = \frac{1}{2}be(p)^2 - \frac{1}{2}be(q_t^*)^2 + \frac{c}{\ln(\alpha)}[\ln(\frac{p}{1-p}) - \ln(\frac{q_t^*}{1-q_t^*})]$$

with derivative

$$\frac{\partial \psi}{\partial p} = b\frac{\partial e}{\partial p}e(p) + \frac{c}{\ln(\alpha)}(\frac{1}{p} + \frac{1}{1-p})$$

$$\Leftrightarrow \frac{\partial \psi}{\partial p} = -b^2(d_0 + de_0)\frac{(be_0 - pd_0)}{(b+pd)^3} + \frac{c}{\ln(\alpha)}\frac{1}{p(1-p)}.$$

Introduce $g(p) = \frac{p(1-p)(be_0 - pd_0)}{(b+pd)^3}$. Note that by definition of q_t^*, $g(q_t^*) = c/[\ln(\alpha)b^2(d_0 + de_0)]$.
This yields

$$\frac{\partial \psi}{\partial p} = \frac{b^2(d_0 + de_0)}{p(1-p)}[g(q_t^*) - g(p)].$$

Since $\partial g/\partial p = h(p)/[(b+pd)^4]$, g is increasing over $[0, \overline{p}_t]$ and decreasing over $[\overline{p}_t, 1]$. Therefore, there is a unique $\overline{q}_t > \overline{p}_t$ such that $g(\overline{q}_t) = g(q_t^*)$ and ψ is increasing over $[0, q_t^*]$, decreasing over $[q_t^*, \overline{q}_t]$ and increasing over $[\overline{q}_t, 1]$. Since $\psi(q_t^*) = 0$ and $\psi(1) = +\infty$, then there exists a unique $p_t^* > q_t^*$ such that $\psi(p_t^*) = 0$. Then $p < p_t^* \Rightarrow \pi_t(0) < \pi_t(\widehat{m}_t)$ and $p > p_t^* \Rightarrow \pi_t(0) > \pi_t(\widehat{m}_t)$. QED.

Proof of Theorem 2. Recall that we have: $\frac{\partial \pi_c}{\partial m} = \ln(\alpha) b^2 (d_0 + de_0)\widetilde{f}(q) - c$ while $\frac{\partial \pi_t}{\partial m} = \ln(\alpha) b^2 (d_0 + de_0) g(q) - c$ with $\widetilde{f}(q) = \frac{(d_0+de_0)q^2(1-q)}{(b+qd)^3}$ and $g(q) = \frac{q(1-q)(be_0 - qd_0)}{(b+qd)^3}$. Then,

$$\frac{g(q)}{\widetilde{f}(q)} = \frac{be_0 - qd_0}{(d_0 + de_0)q} \geq \frac{be_0 - d_0}{d_0 + de_0}$$

where the inequality comes from the fact that $g(q)/\widetilde{f}(q)$ is decreasing with q. Therefore if $be_0 - d_0 \geq d_0 + de_0$, $g(q) > \widetilde{f}(q)$ for any $q \in [0, 1[$ and hence

$$\frac{\partial \pi_t}{\partial m}(m) > \frac{\partial \pi_c}{\partial m}(m)$$

and the marginal impact of effort on payoff is always greater under a tax on emissions than under command and control. Integrate this inequality over $[0, m]$:

$$\pi_t(m) - \pi_t(0) > \pi_c(m) - \pi_c(0).$$

Therefore if 0 is the optimal choice under a tax on emissions, it must also be the optimal choice under command and control. This implies that $\overline{c}_c < \overline{c}_t$ and, if $c < \min(\overline{c}_c, \overline{c}_t)$, $q_t^* < q_c^* < p_c^* < p_t^*$. Moreover, m_t^* is equal to the highest m such that $\frac{\partial \pi_t}{\partial m}(m) = 0$ and $\frac{\partial \pi_t}{\partial m}$ is decreasing above m_t^*, and similarly for $\frac{\partial \pi_c}{\partial m}$. The inequality $\frac{\partial \pi_t}{\partial m} > \frac{\partial \pi_c}{\partial m}$ implies that this last crossing must happen at a larger value for π_t than for π_c. Therefore if $m_t^* > 0$, then $m_t^* > m_c^*$. QED.

Comparative statics. From the characterization of q_c^*, we can write:

$$q_c^*(c) = f^{-1}\left(\frac{c}{\ln(\alpha) b^2 (d_0 + de_0)^2}\right)$$

where f^{-1} is the inverse of f over the range $[0, \frac{2b}{3b+d}]$. Since f is increasing in that range, f^{-1} is also increasing. Since f only depends on d and b, this shows that q_c^* is increasing in c and decreasing in α, d_0 and e_0.

To study the comparative statics of p_c^*, introduce $\lambda(p, c) = B(e(p)) + \frac{c}{\ln(\alpha)} \ln(\frac{p}{1-p})$ such that $\varphi(p, c) = \lambda(p, c) - \lambda(q_c^*(c), c)$. Consider $c_1 < c_2$. Then

$$\lambda(p, c_2) - \lambda(p, c_1) = \frac{c_2 - c_1}{\ln(\alpha)} \ln(\frac{p}{1-p})$$

and this function is increasing in p. Since q_c^* is increasing in c, we have:
$q_c^*(c_2) > q_c^*(c_1)$. Moreover, $q_c^*(c_2) < \frac{2b}{3b+d}$ hence lies in the range where $\lambda(., c)$ is decreasing. Since $p_c^*(c_2) > q_c^*(c_2)$, $\lambda(p_c^*(c_2), c_2) - \lambda(p_c^*(c_2), c_1) > \lambda(q_c^*(c_2), c_2) - \lambda(q_c^*(c_2), c_1)$. This means that $\lambda(p_c^*(c_2), c_2) - \lambda(q_c^*(c_2), c_2) > \lambda(p_c^*(c_2), c_1) - \lambda(q_c^*(c_2), c_1)$. Since $\lambda(p_c^*(c_2), c_2) - \lambda(q_c^*(c_2), c_2) = \varphi(p_c^*(c_2), c_2) = 0$ and $\lambda(q_c^*(c_1), c_1) > \lambda(q_c^*(c_2), c_1)$, we have

$$\lambda(p_c^*(c_2), c_1) - \lambda(q_c^*(c_1), c_1) = \varphi(p_c^*(c_2), c_1) < 0$$

and hence $p_c^*(c_2) < p_c^*(c_1)$. Finally, note that an increase in α has the same impact as a decrease in c. QED.

References

Baker, Erin, 2005. Uncertainty and learning in a strategic environment: global climate change. Resour. Energy Econ. 27, 19–40.
Baron, David P., 2005. Competing for the public through the news media. J. Econ. Manag. Strat. 14 (2), 339–376.
Bero, Lisa A., 2013. Tobacco Industry Manipulation of Research Ch. 17 in Late Lessons from Early Warnings: Science, Precaution, Innovation. EEA Report n. 1/2013.
Bero, Lisa A., Glantz, Stanton, Hong, M.K., 2005. The limits of competing interest disclosures. Tobac. Contr. 14, 118–126.
Boucher, Vincent, Bramoullé, Yann, 2010. Providing global public goods under uncertainty. J. Publ. Econ. 94, 591–603.
Bramoullé, Yann, Treich, Nicolas, 2009. Can uncertainty alleviate the commons' problem? J. Eur. Econ. Assoc. 7 (5), 1042–1067.
Cushman, John H., 1998. Industrial Group Plans to Battle Climate Treaty. New York Times April 26 1998.
DeMarzo, Peter M., Vayanos, Dimitri, Zwiebel, Jeffrey, 2003. Persuasion bias, social influence and unidimensional opinions. Q. J. Econ. 909–968.
Ding, Ding, Maibach, Edward W., Zhao, Xiaoquan, Roser-Renouf, Connie, Leiserowitz, Anthony, 2011. Support for climate policy and societal action are linked to perceptions about scientific agreement. Nat. Clim. Change 1, 462–466.
Edmond, Chris, 2013. Information manipulation, coordination, and regime change. Rev. Econ. Stud. 80, 1422–1458.

European Environment Agency, 2013. Late Lessons from Early Warnings: Science, Precaution, Innovation EEA Report n. 1/2013.
Finus, Michael, Pintassilgo, Pedro, 2013. The role of uncertainty and learning for the success of international climate agreements. J. Publ. Econ. 103, 29–43.
Flynn, D.J., Nyhan, Brendan, Reifler, Jason, 2017. The nature and origins of misperceptions: understanding false and unsupported beliefs about politics. Adv. Polit. Psychol. 38 (1), 127–150.
Gollier, Christian, Jullien, Bruno, Nicolas, Treich, 2000. Scientific progress and irreversibility: an economic interpretation of the Precautionary principle. J. Publ. Econ. 75, 229–253.
Grossman, Gene M., Helpman, Elhanan, 1994. Protection for sale. Am. Econ. Rev. 84 (4), 833–850.
Heal, Geoffrey, Kriström, Bengt, 2002. Uncertainty and climate change. Environ. Resour. Econ. 22, 3–39.
Hoggan, James, Littlemore, Richard, 2009. Climate Cover-up: the Crusade to Deny Global Warming. Greystone Books, Vancouver.
Laussel, Didier, van Ypersele, Tanguy, 2012. When the squeakiest wheel gets the most oil: exploiting One's nuisance power. Eur. Econ. Rev. 56 1593–1306.
Levy, Gilat, Razin, Ronny, 2015. Correlation neglect, voting behavior and information aggregation. Am. Econ. Rev. 105 (4), 1634–1645.
Nordhaus, William D., 2015. Climate clubs: overcoming free-riding in international climate policy. Am. Econ. Rev. 105 (4), 1339–1370.
Nordhaus, William D., 1994. Managing the Global Commons, the Economics of Climate Change. MIT Press.
Oreskes, Naomi, Conway, Erik, 2010. Merchants of Doubt. How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming. Bloosmbury Press, New York.
Petrova, Maria, 2012. Mass media and special interest groups. J. Econ. Behav. Organ. 84 (1), 17–38.
PLoS Medicine Editors, 2009. Ghostwriting: the dirty little secret of medical publishing that just got bigger. PLoS Med. 6 (9), e1000156.
Pollak, Robert A., 1998. Imagined risks and cost-benefit analysis. Am. Econ. Rev. 88 (2), 376–380.
Portney, Paul R., 1992. Trouble in happyville. J. Pol. Anal. Manag. 11 (1), 131–132.
Proctor, Robert N., 2011. Golden Holocaust. Origins of the Cigarette Catastrophe and the Case for Abolition. University of California Press, Berkeley and Los Angeles.
Salanié, François, Treich, Nicolas, 2009. Regulation in happyville. Econ. J. 119, 665–679.
Shapiro, Jesse M., 2016. Special interests and the media: theory and an application to climate change. J. Publ. Econ. 144, 91–108.
Stern, Nicholas, 2007. The Economics of Climate Change. Cambridge University Press.
Stone, Daniel F., 2011. A signal-jamming model of persuasion: interest group funded policy research. Soc. Choice Welfare 37, 397–424.
Thacker, Paul D., 2014. Consumers Deserve to Know Who's Funding Health Research. Harvard Business Review December 2nd 2014.
Ulph, Alistair, 2004. Stable environmental international agreements with a stock pollutant, uncertainty and learning. J. Risk Uncertain. 29, 53–73.
Viscusi, W. Kip, Hamilton, James T., 1999. Are risk regulators Rational? Evidence from hazardous waste cleanup decisions. Am. Econ. Rev. 89 (4), 1010–1027.
Waldman, Peter, Stecker, Tiffany, Joel, Rosenblatt, 2017. Monsanto Was its Own Ghostwriter for Some Safety Reviews. Bloomber Businessweek August 9 2017.
Walker, Joe, 1998. Global Climate Science Communications Action Plan. retrieved on 11/25/2015 from: http://www.euronet.nl/users/e_wesker/ew@shell/API-prop.html.
Weitzman, Martin, 2009. On modeling and interpreting the economics of catastrophic climate change. Rev. Econ. Stat. 91 (1), 1–19.
Yu, Zhihao, 2005. Environmental protection: a theory of direct and indirect competition for political influence. Rev. Econ. Stud. 72, 269–286.

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People's perception and cost effectiveness of home confinement during an influenza pandemic: evidence from the French case

Caroline Orset*

Abstract

In France, home confinement is not a common preventive measure against an influenza pandemic, although it is used around the world. Based on a stated method approach, we analyze the attitude that the French would adopt if this measure were put in place. Next, we propose a cost-benefit analysis to discuss the cost-effectiveness of this measure. We find that over three-quarters of respondents report complying with home confinement. Their choice depends on their individual characteristics, the interaction they may have with an infected person, and home confinement conditions, but not their experience with preventive measures. We find that behaviors such as sensitivity to certainty, selfishness, and altruism emerge. As far as cost-effectiveness is concerned, our study shows that home confinement is a prevention path that should not be neglected and should even be prescribed.

Keywords: people's behavior, cost-benefit analysis, home confinement; epidemics; prevention measures; public health interventions.

JEL Classification: I12; I15; I18; H51; C15.

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1 Introduction

New influenza epidemics have emerged in the past century. Spanish Flu (1918-1920), Asian Flu (1957-1958), Hong Kong Flu (1968-1969), Russian Flu (1977-1978), H_1N_1 Flu Pandemic (2009-2010), avian influenza A (H_7N_9) virus (2013) are examples.[1] These epidemics have a high speed of propagation that generates many victims. The 2009 H_1N_1 epidemic highlighted the importance of the use of home confinement[2] on a large scale to fight against emerging diseases. In March 2009, an influenza pandemic H_1N_1 emerged in Mexico. Since 1^{st} August 2010, more than 214 countries have been affected by this epidemic, which has claimed over 18,449 deaths.[3] As the vaccine has not yet been produced, only non-pharmaceutical interventions have been recommended by the World Health Organization (WHO) (Perez Velasco et al, 2012). One of them is home confinement. Many countries have applied it on a voluntary basis, while others like China have imposed it (Liang et al, 2012).

Home confinement is not a common preventive measure in the face of an influenza pandemic in France. Thus, what attitude the French would adopt if this measure were put in place? Would this measure be economically cost-effective? Based on Haber et al (2007), we define home confinement as the recommendation that infected persons and members of their household stay at home for seven days.[4]

Our approach is based on two building blocks. First, we contribute to the literature in epidemiology by studying perceptions and individual behavior in the face of a home confinement policy to prevent the influenza epidemics. Understanding people's behavior is necessary to define health policy. Indeed, as discussed in Zhu et al (2017), individual behavior within society determines the impact of the epidemic. An individual who does not want to comply with preventive measures would become more and more dangerous to themselves and the rest of society. Therefore, it is necessary to determine in advance individual reactions when deciding on public health policy. The literature lacks data on how individuals will behave in the face of a home confinement policy during an influenza epidemic. This article is the first to fill this gap. We use a stated preference method. Kroes and Sheldon (1988) and Louviere et al (2000) present and develop the use of this method in diverse fields. We then conduct a questionnaire to elicit the preferences of individuals. In the questionnaire, we place respondents in a hypothetical context in which an epidemic has been reported. We put them in different situations: first,

[1] For more details see: http://www.who.int/influenza/en/ and http://www.cdc.gov/flu/index.html.

[2] For the World Health Organization (WHO), the home confinement policy is to separate the infected (isolation) and all members of their household, even if they are in good health (quarantine), from other individuals, asking them to stay at home.

[3] For more details, See: http: // www. Who.int/csr/don/2010 08 06/en/index.html.

[4] A home confinement during seven days for influenza is the recommendation of the Centers for Disease Control and Prevention (2007). See: https://www.cdc.gov/flu/professionals/infectioncontrol/healthcaresettings.html.

they have been in contact with at least one infected person; second, they have been in contact with at least one infected person and medical assistance is provided during home confinement; third, they have not been in contact with infected persons. For each situation, we ask them to choose the maximum number of days they will be willing to stay at home. In fact, asking for the number of days, as opposed to asking directly whether the respondent would comply with home confinement is a way to evaluate the duration that the respondents would voluntarily be willing to stay at home by removing the efficiency aspect of the sanitary measure. Thus, it avoids a deviation of behavior if this measure was to be applied in case of epidemics. From respondents' answers, we elicit the proportion of respondents who are willing to comply with home confinement, which is people who have answered a number of days equal or higher to seven days. We find that more than three quarters of respondents would comply with home confinement. Deciding to be willing to comply with home confinement during an influenza epidemic depends on an individual's characteristics (age, income, composition of the household and professional group), the interaction one can have with an infected person (meeting or not), and the conditions of home confinement (medical assistance or not) but not on having real experience of preventive measures. We discuss the different behaviors that emerge from this study, such as sensitivity to certainty, egoism and altruism.

Second, our paper is linked to the literature dealing with cost-benefit analysis of infectious disease prevention measures. Many studies have been conducted on the impact of a disease using a cost-benefit study. For example, Achonu et al (2005) use a cost-benefit analysis to study the financial impact of combating a respiratory virus epidemic in a teaching hospital. Gupta et al (2005) and Mubayi et al (2010) focus on an emerging infectious disease, SARS, and compare the costs of different quarantine strategies. However, Adda (2016) is the only study that estimated the cost of influenza in France, but its evaluation only concerned the impact on influenza spread of school and public transport closure policies. Focusing on the economic impact of the home confinement policy on influenza is therefore new in economic literature. We try to recognize, identify, evaluate, measure and value the costs of influenza and home confinement in France. We use detailed data on the prevalence, the incidence of the disease and the incidence rate from the French GPs Sentinelles network.[5] These data have the particularity of proposing age groups (children, adults and the elderly), which is very useful given that influenza does not affect people in the same way according to age. However, building a mathematical model on the reduction of the influenza incidence with a home confinement policy in force is difficult largely because of the small amount of occurrences in France and therefore the shortage of data. Because of the difficulties in calculating realistic estimates of the reduc-

[5]The French GPs Sentinelles network is a national system of clinical surveillance that collects real-time epidemiological data from general practitioners and pediatricians in France.

tion of influenza incidence due to home confinement, we focus on the incidence reduction threshold from which home confinement is cost-effective. We find that the measure of home confinement would be a prevention track not to be dismissed. By comparing our results with the existing literature (Longini et al., 2005, and Haber et al., 2007, which have done stochastic simulation models of influenza epidemics in other countries) and the stated method approach, we see that this measure would be cost-effective.

The article is organized as follows. Section 2 presents the study and details the characteristics of the disease and of home confinement policies. Section 3 shows the results on the perception and behavior of the French in the face of home confinement during an epidemic. Section 4 proposes to study the cost-effectiveness of the measure. Section 5 concludes.

2 The study

In this section, we give an overview of the characteristics of the influenza as well as details on home confinement. We then present the survey we analyze.

2.1 2.1 Influenza characteristics and home confinement

We consider one of the major viral diseases: influenza. The principal symptoms of influenza are fever, chills, cough, headaches, diarrhea, sore throat, runny nose, body aches and fatigue. The affected individuals become contagious one day before the onset of the first symptoms and remain so for five days. Symptoms appear one to three days after contamination. The influenza usually lasts one week.[6] In France, influenza affects between 1 and 4 million people each year, and causes between 1,500 and 2,000 deaths, mainly among people over 65.[7]

Influenza viruses are easily transmitted from person to person by air. In the event of a reported epidemic, personal protective measures, such as wearing a mask, are recommended in order to avoid being infected or infecting the others. For influenza, vaccines exist but the immunity is not acquired following vaccination. Moreover, the constant genetic changes in influenza viruses require that the composition of the vaccine be adjusted every year. Indeed, the vaccine for influenza has a low efficacy due to the variability of influenza strains. WHO decides in February on the composition of the vaccine to be used in the October vaccination campaign. Then, the vaccine is manufactured according to the circulating strains, but some strains can mutate. This is what happened in France during the winter 2014-2015, when the flu caused over 18,000 deaths among people who

[6]For more details see: http://www.who.int/influenza/en/.

[7]From the French GPs Sentinelles network and Institute Pasteur in France.

had been vaccinated against the flu.

Preventive measures must be taken by public health authorities to prevent (before the vaccine is found) or to supplement the use of the vaccine (when the vaccine exists). Influenza spreads rapidly, especially when there are high concentrations of populations (public transportation, communities). According to the WHO, reduction of contact intensity by home confinement (isolation and quarantine) and social distancing is highly effective in reducing the incidence of influenza, especially in the early stages of the pandemic (Chao et al, 2010; Halder et al, 2010; Kelso et al, 2009; Milne et al, 2008).

We then focus our analysis on home confinement as a health prevention measure in the case of influenza. This measure consists of recommending to persons infected and their household contacts that they stay at home for seven days. Seven days is the duration recommended by the Center for Disease Control and Prevention (2007). The confined persons only make contacts with their household members. During home confinement, medical assistance, that is to say home care, may also be provided.

Like all countries, France is affected by influenza epidemics. The 2009 influenza pandemic, also known as swine flu or influenza A, reached France in early May 2009. As of April 19, 2016, 77 outbreaks of influenza H_5N_1, H_5N_2 and H_5N_9 have been detected in southwestern France in nine departments.[8] Despite this, home confinement has not been used often in France during influenza epidemics. It seems interesting to analyze the perception of the French population about this preventive measure. This will allow us to see if this measure would be voluntarily followed if recommended by public health authorities.

2.2 Target respondents

To analyze the perception of the French population for home confinement, we use a stated method approach. This method allows us to analyze the choices stated by individuals in order to express individual behavior in relation to a given situation. A questionnaire has been drawn up in which, as an introduction to the respondent, we explain that home confinement consists of staying at home with contact only with the members of one's household and that the characteristics of pandemic flu (symptoms, duration...). We then place the respondent in a hypothetical situation in which an epidemic has been reported and they have been in contact with an infected person (CH Contact). We then ask them to choose the maximum number of days they will be willing to confine themselves to home, i.e., staying at home without outside contact. We ask them the same question by adding the intervention of medical assistance, which is the visit of a health care professional who verifies the state of health of the respondent during home confinement (CH HWV). This

[8]For more details see: http://ec.europa.eu/food/animals/animal-diseases/controlmeasures/avian-influenza/index en.html.

situation allows us to highlight the effect of medical follow-up. We then ask them the same question one last time, modifying the initial situation by the fact that they have not been in contact with infected persons (CH No contact). This situation allows us to analyze the impact of the risk of contamination on the decision of the respondent. In fact, asking for the number of days, not directly whether the respondent would comply with home confinement, that is, staying home for seven days, is a way to avoid the anchorage bias. This makes it possible to evaluate the duration that respondents would voluntarily be willing to stay at home by removing the efficiency aspect of the sanitary measure. Thus, it avoids a deviation of behavior if this measure was to be applied in case of epidemics. Finally, we complete the questionnaire with control questions over respondents' gender, age, income, family composition, professional group and whether they have already experienced preventive measures during periods of epidemics.

After preliminary testing, we conducted the study via Marketest in France from March to April 2014.[9] Marketest selected the French participants using the quota method, i.e., the same proportions of gender, age and socioeconomic status (household composition, occupation, income) as those of the census report of the French population by the Institute National Statistics and Economic Studies (INSEE) in 2013.[10] We specifically prepared the questionnaire to be put online. Target respondents are 200 French people aged 18 to 72 years.[11] Adults were defined as individuals between 18 and 64 years old and Elderly persons as individuals over 64 years old.

Table 1 presents the socio-economic characteristics (gender, age, household composition, income, and occupation) of the respondents. Differences between our panel and the INSEE panel are tested using the Pearson chi-squared test. A P-value (against the null hypothesis of no difference) of less than 5% is considered significant. The results in the last column of Table 1 suggest that the two groups are not significantly different.

[9]For more details on Marketest, see: http://www.marketest.co.uk/.

[10]Influenza can affect everyone, so selecting a sample based on the characteristics of the French population does not present a risk of selection bias.

[11]We do not have the perception of children in this study. In France, interviewing a child requires many administrative procedures. We did not hire them because a child will listen to the decision of their parents, that is, the choice of an adult. As a result, children's behavior is associated with adult behavior.

Table 1: Socio-economic characteristics of respondents. 200 respondents.

Description	Study panel (%)	INSEE (%)	Chi2 test P-value
Gender			
Female	53.0	51.5	0.832
Male	47.0	48.5	
Age			
18-64	82	82	1
>64	18.0	18.0	
People living in the household			
1 person	33.5	34.0	0.953
2 persons	24.5	26.0	
3 persons and more	42.0	40.0	
Monthly net income of the household (€)			
<1000	12.9	10.0	0.129
[1000-1500)	12.9	20.0	
[1500-2500)	33.3	20.0	
[2500-4000)	26.9	30.0	
[4000-6000)	10.5	10.0	
6000 ≤	3.5	10.0	
Professional groups			
Farmer	0	1.0	0.682
Craftsman or trading	3.5	3.0	
Executive and professional	20.0	22.6	
Employee	25.0	29.2	
Retired or looking for a job	25.5	26.5	
Without any professional activity	26.0	17.7	

Based on the control questions, we find that few people practice a medical profession (about 6%). Our panel therefore does not present an over-representation of the medical sector that could be a selection bias.[12] 63% of respondents support a criminal sanction for non-respect of mandatory preventive measures during an epidemic period. Blendon et al (2006) show that in the United States a compulsory home confinement policy is only supported by 42% of the population. Finally, 14% of respondents have already experienced preventive measures such as mask wearing, home confinement etc. for an influenza pandemic, cough or meningitis. The hypothetical bias is reduced for these respondents.

3 Results

We now analyze the answers of respondents. If the number of days chosen is lower than seven days, the respondent is deemed not willing to comply with the home confinement

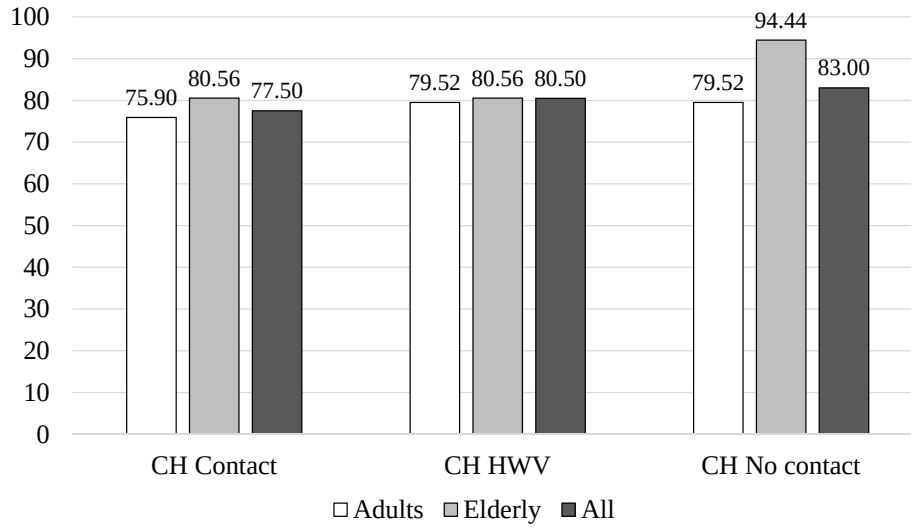
[12] According to the INSEE in 2013, the health sector staff represents 6.5% of the working population.

policy. On the other hand, if it is equal to or higher than seven days, the respondent is willing to do so. We then study the determinants of the respondent's decision to comply or not with home confinement.

3.1 Descriptive analysis

Figure 1 presents the proportion of people who are willing to comply with home confinement, which is people who have answered a number of days equal or higher to seven days. Each situation, that is to say having been in contact with an infected person (CH Contact), having been in contact with an infected person and having the visit of a health professional during home confinement (CH HWV), and not having been in contact with an infected person (CH No contact), is shown.

Figure 1: Proportion of people (in percentage) who comply with home confinement according to the different situations. Adults (166 respondents), Elderly (36 respondents), All (200 respondents).



We first observe that over three quarters of respondents indicate compliance with home confinement. The elderly are more willing to comply with confinement than adults are. We observe that the respondents' decisions are different according to the situations. Indeed, more adults indicate compliance with home confinement when a health professional visits them during home confinement. Medical assistance is the assurance to be taken care of in case of development of the disease. Having a medical follow-up can reassure the respondents about the conditions of their confinement and therefore create an incentive to comply. Moreover, more elderly persons indicate compliance with home

confinement when they have not been in contact with a contaminated person. The elderly verify the certainty effect of Kahneman and Tversky (1979). They prefer to eliminate risk rather than reduce it. The elderly are sensitive to certainty. Finally, selfish behavior by respondents is highlighted. Altruistic behavior would mean that an individual who is more likely to become contaminated and thereby contaminate others, decides to confine themselves to their home to avoid contact with others. In our study, being in contact with an infected person makes respondents (adults and elderly) less likely to confine than not to be in contact. Thus, if the individual risk of being contaminated and therefore of contaminating others is higher, the proportion of respondents in agreement with confinement is lower. This indicates selfish behavior on the part of the respondents.

3.2 Determinants of choice

We now investigate the impacts of the respondents' characteristics (gender, age, number of people living in the household, monthly net income, professional group, and experience (whether the respondent has already experienced prevention measures against epidemics) on the respondent's choice to comply with home confinement. We use a Probit model.[13] An individual i has some propensity to confine to home, y_i^*, linearly related to a vector of observable variables, x_i, and others factors we cannot observe, the error term, ϵ_i:

$$y_i^* = \alpha x_i + \epsilon_i.$$

When y_i^* is greater than zero, the individual i is willing to comply with home confinement. We cannot observe the individual i's propensity to comply with home confinement, only the actual choice, which we will call y_i and yields a value of one when the individual i is willing to comply with home confinement and zero when he is not. The probability that $y_i = 1$ is given by:

$$P(y_i = 1|x_i) = \Phi(x_i^{'}\beta)$$

where Φ is the cumulative density function for the standard normal. Hence, we note y^i the individual i's choice to comply with home confinement (No=0, Yes=1), the quantitative variable Age, x_i^1 , and the qualitative variables, which are Gender (Male=0, Female=1), x_i^2, People living in the household (1 person=1, 2 persons=2, 3 persons and more=3), x_i^3 , Monthly net income of the household in euros ($< 1000 = 1$, [1000-1500)=2, [1500-2500)=3, [2500-4000)=4, [4000-6000)=5, $6000 \leq = 6$), x_i^4, Professional group (Craftsman or trading=1, Executive and professional=2, Employee=3, Retired or looking for a job=4, Without any professional activity=5), x_i^5, and Experience (No=0,Yes=1), x_i^6. Table 2 sums up the results.

[13]Our choice is based on the Probit model because choosing a Logit model would imply a higher probability attributed to extreme events, compared to the choice of a normal distribution.

Table 2: Determinants of choice to comply with home confinement.

Model: *Probit model*

Endogenous variable	*CH Contact*	*CH HWV*	*CH No contact*
Gender	-0.077	0.100	0.059
	(0.201)	(0.217)	(0.221)
Age	0.015***	0.022***	0.017**
	(0.005)	(0.005)	(0.007)
People living in the household	0.171**	0.052	0.026
	(0.079)	(0.082)	(0.086)
Monthly net income of the household	-0.122**	-0.134**	-0.152**
	(0.056)	(0.058)	(0.061)
Professional group	0.061	0.127*	0.068
	(0.067)	(0.071)	(0.095)
Experience	0.568	0.406	0.405
	(0.357)	(0.369)	(0.368)
Observations	200	200	200
McFadden's R^2	0.054	0.078	0.083
Log-likelihood	-100.932	-84.093	-83.637

*p<0.1; **p<0.05; ***p<0.01. Standard errors are in parenthesis.

We first observe that for all proposed situations, the older a respondent is, the more likely they are to be willing to comply with home confinement. Moreover, the lower the respondent's income, the more likely they are to be willing to comply with the recommendations ($e^{-0.122} = 0.885 < 1$, $e^{-0.134} = 0.875 < 1$, and $e^{-0.152} = 0.859 < 1$, respectively).

In addition, in the situation in which the respondent has been in contact with an infected person, the larger the number of family members, the more likely they are to be willing to comply with home confinement ($e^{0.171} = 1.186 > 1$). Finally, in the situation where the respondent has been in contact with an infected person and a health professional visits them during confinement, the higher the index (from 1 to 5) of their professional group, the more likely they are to be willing to comply with home confinement ($e^{0,127} = 1,135 > 1$).

Blendon et al (2006) observe that in regions where people have greater experience of emergency measures, such as Singapore, Taiwan and Hong Kong, the population is less willing to comply with preventive measures like wearing a mask, temperature measurement and quarantine. We then analyze more precisely the link between the choice to comply with home confinement and the individual's experience. In our panel, only 28 over 200 respondents have already experienced preventive measures. Table 3 shows the

contingency tables[14] and the test on independence (Chi-2 test).[15]

Table 3: Link between experience and choice to comply with home confinement.

CH Contact

	No experience	Experience	Total
No home confinement	24.4	10.7	22.5
Home confinement	75.6	89.3	77.5
Total	172	28	

Chi-2 test=2.593 (p-value=0.107)

CH HWV

	No experience	Experience	Total
No home confinement	20.9	10.7	19.5
Home confinement	79.1	89.3	80.5
Total	172	28	

Chi-2 test=1.600 (p-value=0.206)

CH No contact

	No experience	Experience	Total
No home confinement	18.0	10.7	17.0
Home confinement	82.0	89.3	83.0
Total	172	28	

Chi-2 test=0.912 (p-value=0.339)

From Table 3, we find that there is no link between the decision to comply with home confinement and the individual's experience (all the p-values of the Chi2 test are greater than 0.05). In addition, we note that the rates of people with experience who state that they are willing to comply with home confinement and those who state that they are not are identical for all the situations. By analyzing the data, we see that some individuals do not have the same decisions depending on the situations proposed, but that the changes in the decision compensate each other.

Thus, people's behavior changes with culture. In France, having real experience of preventive measures is not a decision-making factor for choosing or not choosing to comply with home confinement. Therefore, it is not necessary to make public health expenditures for simulation exercises addressed to the population.[16]

Respondents may change their behavior according to situations. We then analyze the impacts of the respondents' characteristics (gender, age, people living in the household,

[14]A contingency table is a type of table in a matrix format that displays the (multivariate) frequency distribution of the variables. It provides a basic picture of the interrelation between two variables and can help find interactions between them.

[15]The chi-2 test is used to determine whether there is a significant difference between the expected frequencies and the observed frequencies in one or more categories.

[16]We are not talking here about the importance of simulating an epidemic in a hospital or other medical centers.

monthly net income, socio-professional categories) on the change in decisions in favor of being willing to comply with home confinement between two situations. The independent variables are defined as in Table 2. We use a Probit model again by taking y_i^* the propensity to change one's decision in favor of being willing to comply with home confinement. Table 4 sums up the results.

Table 4: Determinants of choosing to change decision in favor of being willing to comply with home confinement between two situations.

Model: *Probit model*

Endogenous variable	*HC Contact/HC HWV*	*HC Contact/HC No contact*
Gender	-0.458	0.052
	(0.338)	(0.224)
Age	-0.032***	-0.009*
	(0.008)	(0.005)
People living in the household	-0.126	-0.247***
	(0.116)	(0.091)
Monthly net income of the household	0.077	-0.010
	(0.082)	(0.061)
Professional group	-0.101	-0.032
	(0.104)	(0.005)
Observations	200	200
McFadden's R^2	0.021	0.025
Log-likelihood	-32.896	-77.145

*p<0.1; **p<0.05; ***p<0.01. Standard errors are in parenthesis.

If respondents were not willing to comply with home confinement when they have been in contact with an infected person, the younger they are, the more they will change their minds if a health care professional visits them during home confinement or when the interaction with an infected person did not take place. In addition, if respondents were not willing to comply with home confinement when they were in contact with an infected person, the lower the number of family members, the more likely they are to change their minds when the interaction with an infected person did not take place ($e^{-0.247} = 0.781 < 1$).

4 Cost-benefit analysis of home confinement

We propose to make a cost-benefit analysis. No study has been made on the economic efficiency of home confinement policies for reducing the incidence of influenza in France.

We first estimate the cost of influenza in France by age class (Children, < 18 years old; Adults, $18-64$ years old; Elderly, > 64 years old). Adda (2016) has proposed a cost evaluation of influenza in France. We then take this evaluation as a basis and update it with data that are more recent. We obtain Table 5.

Table 5: Costs of influenza per case, in euro.

Children	
GP visit (32% chance)	6.68
Otitis media (0.28% chance)	17.38
Pneumonia (12% chance)	16.45
Hospitalisation (0.07% chance)	2.45
Hospitalisation (sequelae pneumonia 0.7 per 100,000)	3.61
Loss of human capital (3 days off school, 5% return)	92.88
Parent stays home (50% of time, labor market particip. 0.65)	95.70
Value of statistical life	1.3-7.5 million
Probability of death	1.71 per 100,000
Cost of death	22-128
Adults	
Absent from work (2 days of work at average wage)	74
Reduced productivity (0.7 days at 50%)	12.96
GP visit (45% chance)	9.45
Hospitalisation (0.04% chance)	1.80
Value of statistical life	1.3-7.5 million
Probability of death	4.82 per 100,000
Cost of death	63-361
Elderly	
Outpatient visit	219
Hospital	476
Value of statistical life	1.3-7.5 million
Probability of death	205.19 per 100,000
Cost of death	2667-15389

Notes. Data on costs and healthcare use are taken from Prosser et al. (2006) for children, from Nichol (2001) for adults and from Molinari et al. (2007) for the elderly. These studies weight medical costs by the probability of health care usage. Data on mortality from influenza by age group comes from the National Vital Statistics Reports, Vol 65, No 4, June 2016. We have taken the average rate of mortality from 2005 to 2014 by age group. Data on wages are taken from INSEE, "Revenus salariaux médians des salariés de 25 à 55 ans selon le sexe en 2014" (http://www.insee.fr/fr/themes/tableau.asp?reg id=0&ref id=NATnon04146). Labor market participation data comes from OECD skill data set. All US dollars converted into euros with an exchange rate of 0.8. Loss of human capital is costed using a return to schooling of 5 percent, median wages by sex and average labor market participation by sex over a period of 42 years. Net present value numbers are displayed, calculated with a discount factor equal to 0.95.

We note that according to age, different costs are considered and their value differs. For children, the cost is divided between a medical cost (otitis media, pneumonia, hospitalization), the loss of human capital, the loss of parent productivity and the death of children cost. The medical cost is the lowest cost because the probability that influenza

degenerates into otitis media and pneumonia is low. However, the loss of human capital represents a high cost.[17] We take the same assumptions than Adda (2016) but we update the results with more recent data. We assume that sick children miss school for 3 days implying a reduction of about 0.8 percent of their human capital in that year. We assume a return to schooling of 5 percent per year. The net present value of earnings over the life cycle (42 years) is calculated with an annual discount factor equal to 0.95. We consider individuals to live 15 years in retirement. This yields a loss of 92.88 euros per influenza episode. As a child cannot supervise himself, an adult (most often the mother) has to be at home during their illness. This creates a loss of productivity based on the median female income, weighted by the labor market participation of women. This induces a large cost of 95.70 euros. We then use the value of a statistical life (VSL) which quantifies the benefit for the society of avoiding a fatality. Empirical literature evaluates the VSL between 1.3 and 7.5 million euros (Ashenfelter and Greenstone, 2004; Viscusi and Aldy, 2003; Murphy and Topel, 2006). We then use this range of values for our study. For the death rate, we have taken the average death rate from 2005 to 2014 for children. It is very low, about 1.71 per 100,000.[18]

For adults, we consider that on average an adult infected by influenza does not go to work during two days. This implies a loss of productivity due to their absence from work of ca. 74 euros, and an additional loss of productivity when they work at 50 percent of their capacity, around 12.96 euros. For evaluating the cost of death, we adopt the same method than for the children. We get a low risk of death around 4.82 per 100,000. Then, we add medical costs for GP visit and hospitalization. These costs represent a small expenditure compared to the overall cost.[19]

Finally, the costs for the elderly are divided between the medical cost and the cost of death. Medical cost is much higher than for children and adults, at 695 euros. Moreover, the probability of death is large, 205.19 per 100,000, implying a large cost of death.[20] Then, we estimate the cost of home confinement in France. Research on the cost-benefit analysis of prevention measures for infectious diseases has considered different types of cost measures including costs to society, costs to individuals (Coudeville, 2009), quality-of-life measures (Newall et al, 2007), etc. In general, costs can be divided into direct and indirect costs. Direct costs are all expenditures for continuing care, health care providers, certain household expenditures (meal and delivery, home energy), hospitalization, per-

[17] As Smith (1776) states: *The acquisition of ... talents during ... education, study, or apprenticeship, costs a real expense, which is capital in [a] person. Those talents [are] part of his fortune [and] likewise that of society.*

[18] In Adda (2016), the loss of human capital was 99 euros, the loss of productivity was 102 euros, the probability of death was 0.7 per 100,000, and the VSL was between 1.6 and 6 million euros.

[19] In Adda (2016), absent from work was 78.90 euros, reduced productivity was 13.80 euros, the probability of death was 4 per 100,000, and the VSL was between 1.6 and 6 million euros.

[20] In Adda (2016), the probability of death was 102 per 100,000, and the VSL was between 1.6 and 6 million euros.

sonal wage employed for the sanitary measures. Indirect cost is the productivity loss cost due to the absence of the individual to its work, the productivity loss cost due to the closure or the lack of frequentation of public place and the cost of death. We try to recognize, identify, list, measure and value these costs in Table 6.

Table 6: Costs associated with home confinement per case, in euro.

	1 person	2 persons	3 persons	4 persons	5 persons	6 persons
Children						
Loss of human capital (7 days off school. 5% return)		216.72	216.72	433.44	650.16	866.88
Absent from work (7 days of work)		259	518	518	518	518
Reduced productivity (4.9 days at 50%)		45.36	90.72	90.72	90.72	90.72
Personal wage (heathcare worker visit)		252	252	252	252	252
Cost of meals (meal and delivery)		462	693	924	1155	1386
Costs Home Energy		24.36	24.36	48.72	24.36	24.36
Loss of productivity (public place)		252	378	504	630	756
GP visit (32% chance)		6.68	6.68	6.68	6.68	6.68
Otitis media (0.28% chance)		17.38	17.38	17.38	17.38	17.38
Pneumonia (12% chance)		16.45	16.45	16.45	16.45	16.45
Hospitalisation (0.07% chance)		2.45	2.45	2.45	2.45	2.45
Hospitalisation (sequelae pneumonia 0.7 per 100.000)		3.61	3.61	3.61	3.61	3.61
Cost of death		22-128	22-128	22-128	22-128	22-128
Adults						
Loss of human capital (7 days off school. 5% return)		216.72 (26.6%) 0 (73.4%)	216.72	433.44	650.16	866.88
Absent from work (7 days of work)	259	259 (26.6%) 518 (73.4%)	518	518	518	518
Reduced productivity (4.9 days at 50%)	45.36	45.36 (26.6%) 90.72 (73.4%)	90.72	90.72	90.72	90.72
Personal wage (heathcare worker visit)	252	252	252	252	252	252
Cost of meals (meal and delivery)	462	462	693	924	1155	1386
Costs Home Energy	24.36	24.36	24.36	24.36	24.36	24.36
Loss of productivity (public place)	252	252	378	504	630	756
GP visit (45% chance)	9.45	9.45	9.45	9.45	9.45	9.45
Hospitalisation (0.04% chance)	1.8	1.8	1.8	1.8	1.8	1.8
Cost of death	63-361	63-361	63-361	63-361	63-361	63-361
Elderly						
Personal wage (heathcare worker visit)	252	252	252	252	252	252
Cost of meals (meal and delivery)	231	462	693	924	1155	1386
Costs Home Energy	24.36	24.36	24.36	24.36	24.36	24.36
Loss of productivity (public place)	126	252	378	504	630	756
Outpatient visit	219	219	219	219	219	219
Hospital	476	476	476	476	476	476
Cost of death	2667-15389	2667-15389	2667-15389	2667-15389	2667-15389	2667-15389
Weight in France (in %)						
Children	0	15.2	36	32.4	12	4.4
Adult	29.9	28.2	17.8	16	5.9	2.2
Elderly	47.9	45.9	4.6	1.1	0.3	0.2

Notes. Data on costs and healthcare use are taken from Prosser et al. (2006) for children, from Nichol (2001) for adults and from Molinari et al. (2007) for the elderly. These studies weight medical costs by the probability of health care usage. Data on mortality from influenza by age group comes from the National Vital Statistics Reports, Vol 65, No 4, June 2016. We have taken the average rate of mortality from 2005 to 2014 by age group. Data on wages are taken from INSEE, "Revenus salariaux médians des salariés de 25 à 55 ans selon le sexe en 2014" (http://www.insee.fr/fr/themes/tableau.asp?reg id=0&ref id=NATnon04146). Labor market participation data comes from OECD skill data set. All US dollars

converted into euros with an exchange rate of 0.8. Loss of human capital is costed using a return to schooling of 5 percent, median wages by sex and average labor market participation by sex over a period of 42 years. Net present value numbers are displayed, calculated with a discount factor equal to 0.95. Cost of meals (meal and delivery) is given from http://www.dependance-infos.com/maintien-a-domicile/aidehumaine/portage-repas-domicile#portage-prix. Costs Home Energy and the loss of productivity (public place) are taken from INSEE (2014), "Individual energy expenditure" and "Individual consumption expenditure", respectively.

Table 6 displays the costs of home confinement. We have considered the same age group as for the costs of influenza. We take as a reference the age of the infected person. As home confinement concerns all household members including the infected person, we have evaluated the costs for the entire household according to INSEE (2013-2014). In order to calculate the costs of a representative household, we have used the weight that each household composition represents in France from INSEE (2013-2014).

For each age group, we assume the possibility of setting up medical surveillance, i.e., a health care professional coming every day to take health news from the confined. Being confined at home implies that meals must be delivered for each family member as well as an additional cost of energy (power, gas, water ...). Finally, we also factor in the loss of production of shops, museums, movie theaters... due to the absence of consumers.

When a child is infected, a parent must stay at home to watch them. A household of one person cannot include children age group. We assume that a three-person household consists of two adults and one infected child; a four-person household of two adults and two children (including an infected child); a five-person household of two adults and three children (including an infected child); and a six-person household of two adults and four children (including an infected child). We added to the medical costs and the cost of death, the adult costs of absenteeism (absence and loss of productivity) and loss of human capital for each confined child.

When an adult is infected, all costs related to their illness and absence from work have been identified (absence from work and loss of productivity). We assume that a one-person household includes an infected adult; a two-person one 26.6%, one child and one infected adult, or 73.4%, two adults (including one infected adult);[21] a three-person one: two adults (including one infected adult) and one child; a four-person one: two adults (including one infected adult) and two children; a five-person one two adults (including one infected adult) and three children; and a six-person one two adults (including one infected adult) and four children. Home confinement for other family members results in costs: for children, there is a loss of human capital due to their absence from school, and for adults the costs attributable to their absence from work.

[21] From INSEE 2013-2014.

Finally, when an elderly person is infected, we assume that a household of one person includes: an infected elderly person; a two-person one includes two elderly people (including one infected elderly person); a three-person one, three elderly people (including one infected elderly person); a four?persons household four elderly people (including one infected elderly person), a five-person one five elderly people (including one infected elderly person); and finally a six?person household will consist of six elderly people (including one infected elderly person). In France, few elderly people live in a household consisting of more than two people. When that is the case, this means that they share their dwelling with other elderly people (for example in a retirement home). Today, few seniors live with their children.

We now turn to the cost-benefit analysis. For evaluating the incidence and the prevalence of influenza in France, we use the French GPs Sentinelles network, which compiles of large databases on disease prevalence, incidence and incidence rate in France. This network is made up of 1,300 general practitioners (2.2% of all practitioners in France) and about a hundred voluntary, liberal pediatricians. The member physicians are called "Sentinel physicians".[22] In 2017, the network continuously collected information on eight health indicators (seven infectious diseases and one non-infectious indicator).[23] The Institut de Veille Sanitaire (lnVS) implemented this network as a public health surveillance system in 1984.

Figure 2 displays the time series patterns of incidence rates at the national level and on a weekly basis between 2005 and 2014.[24] Each year, we observe recurrent peaks of influenza during the winter season. However, the amplitude of these peaks varies little. It does not appear to diminish or increase over time.

[22]For more details see: https://websenti.u707.jussieu.fr/sentiweb/?page=presentation.

[23]Acute diarrhea, Chickenpox, Herpes zoster, Influenza, Lyme disease, Male urethritis, Mumps and Suicidal attempts.

[24]Actually, data from 1985 exists but we could not access to the age classes.

Figure 2: Weekly incidence rates of influenza, 2005-2014.

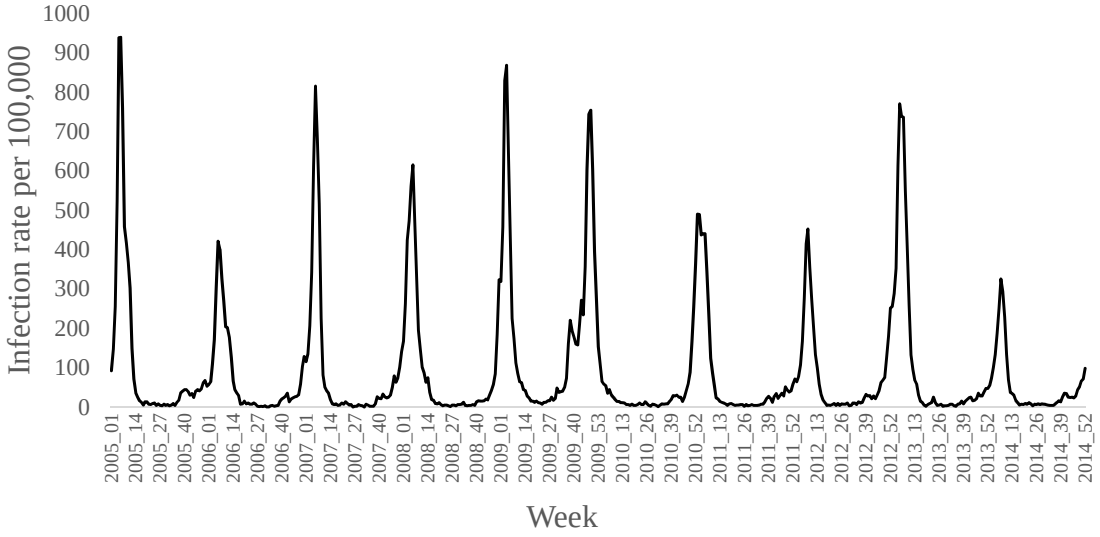


Figure 3 displays the average incidence rates within a year, by calendar month, from January to December. As seen in the previous graph, influenza shows strong seasonal patterns with a peak in winter (in February) and a low incidence between mid-spring and mid-fall (from May to August).

Figure 3: Incidence rates of influenza over calendar year. Average 2005-2014.

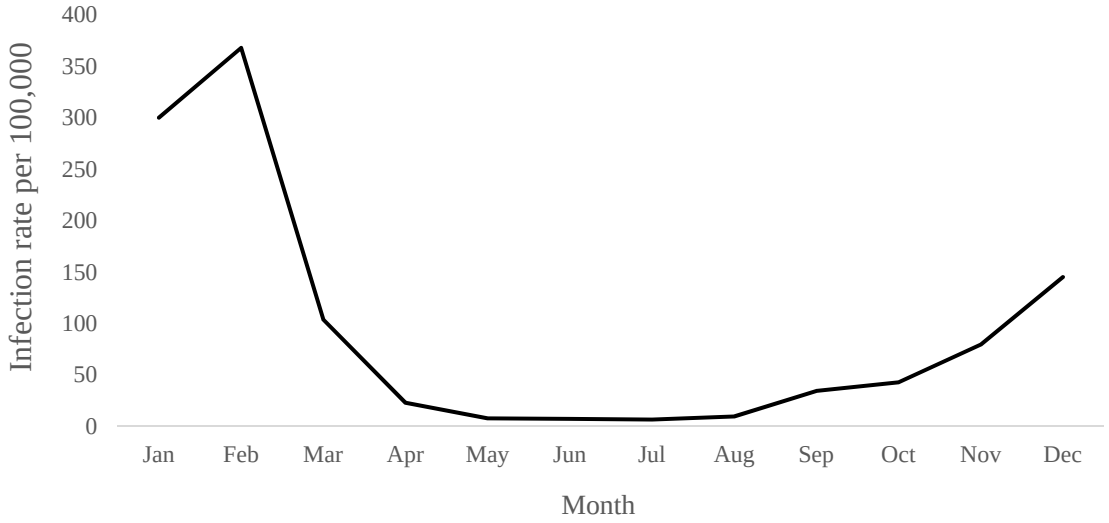
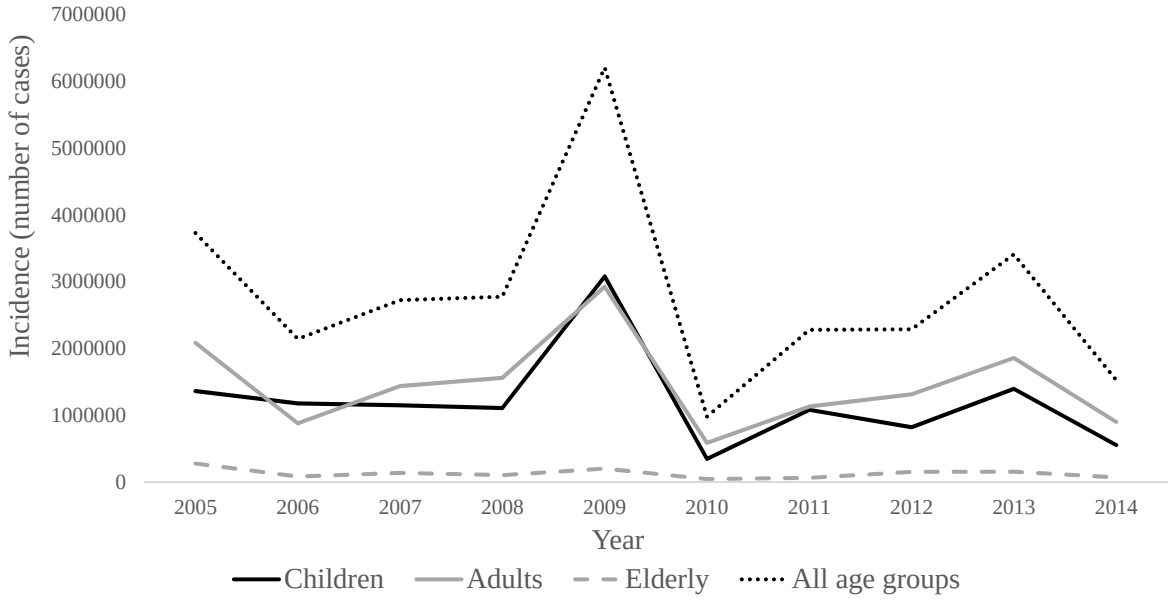


Figure 4 displays the yearly incidence in number of cases, by age group (Children, < 18 years old; Adults, 18-64 years old; Elderly, > 64 years old) from 2005 to 2014. We observe peaks in 2009, 2011 and 2013. The incidence of influenza affects all age groups, but it is predominantly high for adults and children. One reason for this downward trend for the elderly is the increased uptake of vaccination. Actually, the French Health Insurance covers the 100% seasonal flu vaccine for elderly (persons aged 65 and over). This means that in 2013-2014 only 38.3% of adults and children were vaccinated while 51.9% of the elderly were vaccinated.[25]

[25]Data from CNAM-TS, http://invs.santepubliquefrance.fr/Dossiers-thematiques/Maladiesinfectieuses/Maladies-a-prevention-vaccinale/Couverture-vaccinale/Donnees/Grippe.

Figure 4: Yearly incidence of influenza, by age, 2005-2014.



For $i \in \{Children, Adults, Elderly\}$, we define the average annual costs of home confinement in euros, C_{Conf}, and the average annual costs of influenza in euros, C_{Influ}, as, respectively:

$$C_{Conf} = \sum_i \left[(n_d^i + n_{Influ}^i * r_{Conf})(p_{Conf}^i * Cost_{Conf}^i + Cost_{Influ}^i) \right]$$

and

$$C_{Influ} = \sum_i \left[(n_d^i + n_{Influ}^i) * Cost_{Influ}^i \right],$$

with n_d^i, the average of declared cases (infected persons) for the age class i, p_{Conf}^i, the proportion (in percentage) of cases i complying with home confinement, n_{Influ}^i, the average incidence for age class i, $1 - r_{Conf}$, the rate reduction in the incidence due to home confinement, $Cost_{Conf}^i$, costs with home confinement per case for the age class i in euro, $Cost_{Influ}^i$, costs of influenza per case for the age class i in euro. We also define the average annual costs of home confinement for all aggregated age groups in euro, C_{Conf}^{All}, and the average annual costs of influenza for all aggregated age groups in euro, C_{Influ}^{All}, as,

respectively:

$$C_{Conf}^{All} = (n_d^{All} + n_{Influ}^{All} * r_{Conf}^{All})(p_{Conf}^{All} * Cost_{Conf}^{All} + Cost_{Influ}^{All})$$

and

$$C_{Influ}^{All} = (n_d^{All} + n_{Influ}^{All}) * Cost_{Influ}^{All},$$

with n_d^{All}, the average of declared cases (infected persons) without any distinction of age class, p_{Conf}^{All}, proportion (in percentage) of cases (without any distinction of age class) complying with home confinement, n_{Influ}^{All}, the average incidence without any distinction of age class, $1 - r_{Conf}^{All}$, the rate reduction in the incidence due to confinement at home for the aggregated population (without any distinction of age class), $Cost_{Conf}^{All}$, average of the costs with home confinement per case for the children, the adults and the elderly in euro, $Cost_{Influ}^{All}$, average of the costs of influenza per case for the children, the adults and the elderly in euro.[26]

Table 7 presents the set of the parameters used to calculate the cost effectiveness of the confinement measure. We consider the average prevalence and the average incidence from the data of the French GPs Sentinelles network from 2005 to 2014, the costs with home confinement per case from table 6 and the costs of influenza per case from Table 5. For the costs of home confinement, we make a distinction between the presence (With HWV) or not (Without HWV) of a medical assistance during home confinement. The costs are higher with medical assistance.

[26]Although there is a time lag between the occurrence of different patients, the costs are calculated over a period of one year. We then consider that the discount rate is equal to one.

Table 7: Parameters from the data of the French GPs Sentinelles network, from tables 5 and 6 according to different VSL values and the presence or not of medical assistance.

i			Children	Adults	Elderly	All
n^i_d			3737	4489	417	8643
n^i_{Influ}			1,209,151	1,468,697	129,668	2,807,516
$Cost^i_{Conf}$	Without HWV	VSL = 1.3 million €	2296.39	1654.3	3959.51	2636.73
		VSL = 4 million €	2342.79	1784.1	9692.51	4606.47
		VSL = 5 million €	2359.89	1832.3	11552.01	5248.07
		VSL = 7.5 million €	2402.39	1952.3	16681.51	7012.07
	With HWV	VSL = 1.3 million €	2548.39	1906.3	4211.51	2888.73
		VSL = 4 million €	2594.79	2036.1	9944.51	4858.47
		VSL = 5 million €	2611.89	2084.3	11804.01	5500.07
		VSL = 7.5 million €	2654.39	2204.3	16933.51	7264.07
$Cost^i_{Influ}$		VSL = 1.3 million €	257.15	161.21	3362	1260.12
		VSL = 4 million €	303.55	291.01	9095	3229.85
		VSL = 5 million €	320.65	339.21	10954.5	3871.45
		VSL = 7.5 million €	363.15	459.21	16084	5635.45

We consider that home confinement is cost-effective when the average annual costs of home confinement, C_{Conf}, are lower than or equal to the average annual costs of influenza, C_{Influ}, and for the aggregated population, $i = All$, when the average annual costs of home confinement for all aggregated age groups, C^{All}_{Conf}, are lower than or equal to the average annual costs of influenza for all aggregated age groups, C^{All}_{Influ}. Building a mathematical model on the reduction of the influenza incidence with home confinement prevention in France is difficult largely because of the very few occurred cases in France and therefore the shortage of data.[27] In fact, only two cases occurred when at the end of December 2016, residents (66 people) of a retirement home in Moselle (Northeast France) and a retirement home (80 people) in Saint-Gengoux-le-National (Center-East France) were confined to reduce the spread of influenza. Because of the difficulties in calculating realistic estimates of the rate reduction in the incidence due to home confinement, we propose to evaluate the rate reduction threshold in the incidence due to home confinement for which the home confinement policy is cost effective. We then calculate this threshold, $1 - \bar{r}_{Conf}$ when all the age class are differentiated, and $1 - \bar{r}^{All}_{Conf}$ for all aggregated population, such that $C_{Conf} = C_{Influ}$ and $C^i_{Conf} = C^i_{Influ}$, respectively. We consider two options for home confinement: without medical assistance (Without HWV) and with medical assistance

[27] We discussed with the French GPs Sentinelles network to verify whether data were available or whether an epidemiological model had been produced concerning the impacts of home confinement on the incidence of influenza in France. Unfortunately, there is none.

(With HWV). Table 8 presents the results according to the VSL value and the proportion (in percentage) of individuals complying with home confinement.

Table 8: Rates reduction threshold of incidence, $1 - \bar{r}_{Conf}$ and $1 - \bar{r}^{All}_{Conf}$.

	Threshold for VSL= 1.3 million €		Threshold for VSL= 4 million €		Threshold for VSL= 5 million €		Threshold for VSL= 7.5 million €	
Proportion of cases complying with home confinement	$1-\bar{r}_{Conf}$	$1-\bar{r}^{All}_{Conf}$	$1-\bar{r}_{Conf}$	$1-\bar{r}^{All}_{Conf}$	$1-\bar{r}_{Conf}$	$1-\bar{r}^{All}_{Conf}$	$1-\bar{r}_{Conf}$	$1-\bar{r}^{All}_{Conf}$
Without HWV								
10%	36.89%	17.36%	25.45%	12.53%	23.47%	11.98%	19.94%	11.10%
20%	53.94%	29.60%	40.60%	22.27%	38.04%	21.40%	33.27%	19.99%
30%	63.76%	38.69%	50.65%	30.06%	47.96%	29,00%	42.80%	27.27%
40%	70.15%	45.71%	57.81%	36.44%	55.16%	35.27%	49.96%	33.34%
50%	74.64%	51.29%	63.16%	41.76%	60.62%	40.53%	55.54%	38.48%
60%	77.97%	55.84%	67.32%	46.26%	64.90%	45,00%	60,00%	42.88%
70%	80.53%	59.62%	70.63%	50.12%	68.34%	48.84%	63.66%	46.70%
80%	82.57%	62.80%	73.35%	53.46%	71.18%	52.19%	66.70%	50.04%
90%	84.22%	65.52%	75.61%	56.39%	73.55%	55.13%	69.28%	52.99%
100%	85.59%	67.88%	77.51%	58.97%	75.57%	57.73%	71.49%	55.62%
With HWV								
10%	39.65%	18.71%	27.40%	13.12%	25.23%	12.48%	21.34%	11.46%
20%	56.83%	31.54%	43.05%	23.20%	40.32%	22.20%	35.19%	20.56%
30%	66.43%	40.88%	53.16%	31.20%	50.36%	29.98%	44.91%	27.98%
40%	72.56%	47.99%	60.24%	37.69%	57.52%	36.35%	52.10%	34.13%
50%	76.81%	53.58%	65.47%	43.06%	62.89%	41.66%	57.64%	39.32%
60%	79.93%	58.09%	69.50%	47.59%	67.06%	46.16%	62.04%	43.75%
70%	82.32%	61.80%	72.69%	51.45%	70.39%	50.02%	65.62%	47.58%
80%	84.21%	64.92%	75.28%	54.79%	73.12%	53.36%	68.58%	50.93%
90%	85.74%	67.57%	77.42%	57.70%	75.39%	56.29%	71.08%	53.88%
100%	87.00%	69.85%	79.23%	60.26%	77.31%	58.87%	73.22%	56.49%

We first note that the higher the benefit for the society of avoiding a fatality and/or the lower the proportion of individuals complying with home confinement, the lower the rate reduction threshold. Therefore, based on cost-benefit analysis, to implement home confinement, health decision-makers will be more inclined to be less demanding about the level of reduction in the impact of this measure when the benefit to society of avoiding death is high. On the other hand, the more the measure will be respected by more individuals, the more the level of reduction required will be high. We then observe that the increased costs of the measure linked to the medical assistance during home confinement must be offset by an increase of the rate of incidence reduction for the measure to be cost-effective. Finally, we note that the rate reduction threshold of incidence is higher when we differentiate age class than when we consider the aggregated population. Thus, by not differentiating by age classes, the public decision-maker may consider that the measure is cost-effective whereas it is not when differentiation is taken into account. This shows the interest of considering age classes in a study on influenza epidemics.

As we mentioned, in France, there are no epidemiological studies on the reduction of the incidence rate due to home confinement. Nevertheless, some have been made in other countries. Longini et al (2005) show that for 70% of people who follow home confinement in Southeast Asia,[28] the rate reduction in the incidence due to confinement at home is at 99.91% for a basic reproduction number $R_0 = 1.4$, at 99.7% for $R_0 = 1.7$, at 98.5% for $R_0 = 2.1$, at 85% for $R_0 = 2.4$.[29] Moreover, Haber et al (2007) evaluate that for 70% (80%) of people who follow home confinement in a small urban US community, the rate reduction in the incidence due to confinement at home is at 83% (91%) for $R_0 = 2.7$. We can note that the results of these studies are convergent, although the countries considered do not have the same size and the same density of population and although their environmental characteristics differ. Would a home confinement policy be cost-effective if we consider that the reduction of the incidence rate of these studies would apply for the influenza epidemic in France?

We then compare the lines for which the proportion of individuals complying with home confinement is at 70% and 80% in Table 8 and the rate reduction of incidence data from these studies. We observe that whatever the way of calculating the rate reduction threshold of incidence and whatever the pandemic severity level, home confinement would be cost-effective.

From our stated method approach, we have understood the proportion of people who would comply with home confinement (see Figure 1). Children were not questioned in our study. We used the parents' answers for them (Adult category). Three situations were proposed. In order to implement home confinement, we consider that the infected person has been in contact with an infected person (CH Contact); has been in contact with an infected person and will seek medical assistance during their home confinement (CH HWV); or has not been in contact with an infected person. In addition, we assume that if the infected person is willing to comply with home confinement, all household members will be confined with them. We propose to analyze the cost-effectiveness of home confinement from the stated answers of our survey. Table 9 presents the results.

[28] That is, 70% of those infected and their household members agreed to stay confined to home while 30% refused.

[29] The basic reproduction number (R_0) is one of the commonly accepted measures of pandemic severity. R_0 is defined as the average number of secondary infections, produced by a typical infected case in a very susceptible population. From Ferguson et al. (2005), Mills et al. (2004), and Uribe-Sanchez et al (2011), R_0 values for influenza range between 1.4 and 3.9, where $R_0 \leq 1.8$ are considered as of low transmissibility and $2.2 \leq R_0 \leq 3.9$ as of high transmissibility. These studies have been done in Southeast Asia, for reproducing the 1918 pandemic influenza around the world, and in Florida (United States), respectively.

Table 9: Rates reduction threshold of incidence, $1 - \bar{r}_{Conf}$ and $1 - \bar{r}^{All}_{Conf}$. Panel data.

	CH Contact				CH HWV				CH No contact			
	Children	Adults	Elderly	All	Children	Adults	Elderly	All	Children	Adults	Elderly	All
Proportion of cases complying with home confinement	75.90%	75.90%	80.56%	77.50%	79.52%	79.52%	80.56%	80.50%	79.52%	79.52%	94.44%	83.00%
	$1-\bar{r}_{Conf}$			$1-\bar{r}^{All}_{Conf}$	$1-\bar{r}_{Conf}$			$1-\bar{r}^{All}_{Conf}$	$1-\bar{r}_{Conf}$			$1-\bar{r}^{All}_{Conf}$
Threshold for VSL= 1.3 million €	81.86%			62.04%	84.13%			65.05%	82.71%			63.65%
Threshold for VSL= 4 million €	72.52%			52.66%	75.2%			54.93%	73.9%			54.34%
Threshold for VSL= 5 million €	70.34%			51.39%	73.04%			53.51%	71.85%			53.1%
Threshold for VSL= 7.5 million €	65.88%			49.24%	68.52%			51.08%	67.67%			50.96%

As previously, it is worth highlighting the interest of differentiating by age class instead of taking the aggregated population. The rate reduction threshold of incidence varies between 65.88% and 84.13% with differentiated age classes, and between 49.24% and 65.05% with the aggregated population. According to the existing studies carried out in other countries, we observe that a 10% increase in the proportion of people who comply with home confinement strongly increases the incidence reduction rate. For instance, from Haber et al (2007), when 70% of people comply with the measure, the reduction rate is 83% while it is 91% with 80% of people complying. In our stated approach, we find that the level of home confinement stated by respondents is between 75.90% and 94.44%. Hence, taking into account the existing studies, we can estimate that in France, home confinement would be cost effective regardless of the pandemic severity level and the VSL value.

5 Conclusion

This paper aims to support home confinement as a preventive measure in the context of influenza epidemics. We first probe perceptions and attitudes towards complying with home confinement in France. We conclude that knowing the level of voluntary participation for this type of measure is essential. This measure cannot be implemented

if the population decides not to participate. It would seem inconceivable to assign a police officer to each person detected as infected to verify that they comply with confinement. In addition, assessing people's participation also makes it possible to estimate whether the measure will be economically effective from a public health perspective.

We find that over three quarters of respondents indicate compliance with home confinement. Deciding to be willing to comply with home confinement during an influenza epidemic depends on an individual's characteristics (age, income, household composition and professional group), the interaction with an infected person (meeting or not), and the conditions of home confinement (medical assistance or not). However, having real experience of preventive measures does not factor significantly in the decision to comply or not. Moreover, we highlight selfish behavior by respondents. When they are more likely to become contaminated and thereby contaminate others, they are less willing to comply with home confinement. However, this behavior may also be explained by a certainty bias that pushes people to believe that they are taking all necessary measures to avoid contamination. Finally, we also observe that respondents may behave altruistically when dealing with their own family. Indeed, not staying home during an epidemic limits the risk of contamination of next of kin, especially in large families.

When considering preventive measures, the health decision-maker needs to analyze whether the measure is cost-effective. We find that taking into account age may sharpen the analysis. According to the VSL value and the proportion of people who comply with confinement, we assess the level of the incidence reduction rate threshold for which the measure is cost-effective. No epidemiological study has examined or estimated the reduction in influenza incidence following the implementation of home confinement in France. However, estimates from studies in other countries converge to very close values. From our stated method approach and from the existing studies, this allows us to estimate that in France, the home confinement policy would be cost-effective regardless of the pandemic severity. However, the epidemiological model would be useful for determining the exact impact of home confinement in France. We expect that our study will trigger additional research in this direction. Moreover, as influenza epidemics know no borders, it would also be interesting for this work to be extended to other countries. Indeed, our study can easily be replicated in other regions or countries.

Our paper has certain limitations. First, as in all preference approaches, there may be hypothetical biases and controversies or incorrect messages leading to confusion or misunderstanding by participants in our study. As suggested by Lusk (2003), we tried to reduce the hypothetical bias by using "cheap talk"[30] to explain the home confinement policy and the characteristics of pandemic flu (symptoms, duration...) before asking the

[30]Cheap talk refers to process of explaining hypothetical bias to individuals prior to asking a valuation question.

first question to respondents. Second, the data collection method could be discussed. We used an online study. Online studies save time and effort in collecting data (Cobanoglu et al., 2001, Couper, 2000 and McDonald and Adam, 2003) and provide better quality responses with fewer "Do not know" answers (Fricker et al., 2005, Kreuter et al., 2008, and Heerwegh and Loosveld, 2008). Therefore, as far as the quality of the collected data is concerned, online studies do not seem to present more disadvantages than other types of surveys.

References

1. Achonu, C., Laporte, A., Gardam, M.A. The financial impact of controlling a respiratory virus outbreak in a teaching hospital: lessons learned from SARS. *Canadian Journal of Public Health.* 2005;96:52-54.

2. Adda, J. Economic Activity and the Spread of Viral Diseases: Evidence from High Frequency Data. *Quaterly journal of economics.* 2016; 131(2):891-941.

3. Ashenfelter, O., Greenstone, M. Using Mandated Speed Limits to Measure the Value of a Statistical Life. *Journal of Political Economy.* 2004; 112:226-267.

4. Blendon, R., DesRoches, C.M., Cetron, M.S., Benson, J.M., Meinhardt, T., Pollard, W. Attitudes toward the use of quarantine in a public health emergency in four countries. *Health Affairs.* 2006;25(2):15-25.

5. Centers for Disease Control and Prevention (CDC). Interim pre-pandemic planning guidance: community strategy for pandemic influenza mitigation in the United States; 2007.

6. Chao, D.L., Halloran, M.E., Obenchain, V.J., Longini, I.M. FluTE, a publicly available stochastic influenza epidemic simulation model. *PLoS Computational Biology.* 2010;6.

7. Cobanoglu, C., Warde, B., Moreo, P. A comparison of mail, fax, and Web-based survey methods. *International Journal of Market Research.* 2001;43(4): 405-410.

8. Coudeville, L., Van Rie, A., Getsios, D., Caro, J.J., Crpey, P., Nguyen, V.N. Adult vaccination strategies for the control of pertussis in the United States: an economic evaluation including the dynamic population effects. *PLoS One.* 2009;4.

9. Couper, M.P. Web surveys: A review of issues and approaches. *The Public Opinion Quarterly.* 2000;64(4):464-494.

10. Fricker, S., Galesic, M., Tourangeau, R., Yan, T. An experimental comparison of Web and telephone surveys. *The Public Opinion Quarterly.* 2005;69(3):370-392.

11. Gupta, A.G., Moyer, C.A., Stern, D.T. The economic impact of quarantine: SARS in Toronto as a case study. *Journal of Infection.* 2005;50:386-393.

12. Haber, M.J., Shay, D.K., Davis, X.M., Patel, R., Jin, X., Weintraub, E., Orenstein, E., Thompson, W.W. Effectiveness of interventions to reduce contact rates during a simulated influenza Pandemic. *Emerging Infectious Diseases.* 2007;13(4).

13. Ferguson, N.M., Cummings, D.A.T, Cauchemez, S., Fraser, C., Riley, S., Meeyai, A., Iamsirithaworn, S., Burke, D.S. Strategies for containing an emerging influenza pandemic in Southeast Asia. *Nature.* 2005;437:209-214.

14. Halder, N., Kelso, J.K., Milne, G.J. Analysis of the effectiveness of interventions used during the 2009 A/H_1N_1 influenza pandemic. *BioMed Central.* 2010;10.

15. Heerwegh, D., Loosveldt, G. Face-to-face versus Web surveying in a high-Internet coverage population: differences in response quality. *The Public Opinion Quarterly.* 2008;72(5):836-846.

16. Kahneman, D., Tversky, A. Prospect Theory: An Analysis of Decision under Risk. *Econometrica.* 1979;47(2):263-91.

17. Kelso, J.K., Milne, G.J., Kelly, H. Simulation suggests that rapid activation of social distancing can arrest epidemic development due to a novel strain of influenza. *Public Health.* 2009;9.

18. Kreuter, F., Presser, S., Tourangeau, R. Social desirability bias in CATI, IVR, and Web surveys: The effects of mode and question sensitivity. *The Public Opinion Quarterly.* 2008;72(5):847-865.

19. Kroes, E.P., Sheldon, R.J. Stated Preference Methods: An Introduction. *Journal of Transport Economics and Policy.* 1988; 22(1):11-25.

20. Liang, W., Feng, L., Xu, C., Xiang, N., Zhang, Y., Shu, Y., Wang, H., Luo, H., Yu, H., Liang, X., Li, D., Lee, C.K., Feng, Z., Hou, Y., Wang, Y., Chen, Z., Yang, W. Response to the first wave of pandemic (H_1N_1) 2009: experiences and lessons learnt from China. *Public Health.* 2012;126:427-36.

21. Longini I.M.Jr., Nizam, A., Xu, S., Ungchusak, K., Hanshaoworakul, W., Cummings, D.A.T, Halloran, M.E. Containing Pandemic Influenza at the Source. *Science.* 2005; 309(12).

22. Louviere, J.J., Hensher, D.A., Swait, J.D. 2000. Stated Choice Methods, Analysis and Applications. *Cambridge University Press*.

23. Lusk, J.L. Effects of cheap talk on consumer willingness to pay for golden rice. *American Journal of Agricultural Economics*. 2003;85(4): 840-856.

24. McDonald, H., Adam, S. A comparison of online and postal data collection methods in marketing research. *Marketing Intelligence and Planning*. 2003;21(2):85-95.

25. Mills, C.E, Robins, J.M., Lipsitch, M. Transmissibility of 1918 pandemic influenza. *Nature*. 2004; 432, 904-906.

26. Milne, G.J., Kelso, J.K., Kelly, H.A., Huband, S.T., McVernon, J. A small community model for the transmission of infectious diseases: comparison of school closure as an intervention in individual-based models of an influenza pandemic. *PLoS One*. 2008;3.

27. Molinari, N.A.M., Ortega-Sanchez, I.R., Messonnier, M.L., Thompson, W.W., Wortley, P.M., Weintraub, E., Bridges, C.B. The annual impact of seasonal influenza in the US: Measuring disease burden and costs. *Vaccine*. 2007; 25:5086-5096.

28. Mubayi, A., Zaleta, C.K., Martcheva, M., Castillo-Chvez, C.. A cost-based comparison of quarantine strategies for new emerging diseases. *Mathematical Biosciences and Engineering*. 2010;7:687-717.

29. Murphy, K.M., Topel, R. The Value of Health and Longevity. *Journal of Political Economy*. 2006; 114:871-904.

30. Newall, A.T., Beutels, P., Wood, J.G., Edmunds, W.J., MacIntyre, C.R. Cost-effectiveness analyses of human papillomavirus vaccination. *The Lancet Infectious Diseases*. 2007;7:289-96.

31. Nichol, K. L. Cost-Benefit Analysis of a Strategy to Vaccinate Healthy Working Adults Against Influenza. *JAMA Internal Medicine*. 2001; 161:749-759.

32. Pérez Velasco, R., Praditsitthikorn, N., Wichmann, K., Mohara, A., Kotirum, S., Tantivess, S., Vallenas, C., Harmanci, H., Teerawattananon, Y. Systematic review of economic evaluations of preparedness strategies and interventions against influenza pandemics. *PloS One*. 2012.

33. Prosser, L. A., Bridges, C. B., Uyeki, T. M., Hinrichsen, V. L., Meltzer, M. I., Molinari, N.- A. M., Schwartz, B., Thompson, W. W., Fukuda, K., Lieu, T. A. Health Benefits, Risks, and Cost-Effectiveness of Influenza Vaccination of Children. *Emerging Infectious Diseases*. 2006; 12:1548-1558.

34. Smith, A. Recherches sur la nature et les causes de la richesse des nations. 1776.

35. Uribe-Sánchez, A., Savachkin, A., Santana, A., Prieto-Santa, D., Das, T.K. A predictive decision-aid methodology for dynamic mitigation of influenza pandemics. *OR Spectrum*. 2011;33(3):751-786.

36. Viscusi, W.K., Aldy, J.E. The Value of a Statistical Life: A Critical Review of Market Estimates throughout the World. *Journal of Risk and Uncertainty*. 2003; 27:5-76.

37. Zhu, G., Chen, G., Fu, X. Effects of active links on epidemic transmission over social networks. *Physica A*. 2017;468:614-621.

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How consumers of plastic water bottles are responding to environmental policies?

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ABSTRACT

Although plastic induces environmental damages, almost all water bottles are made from plastic and the consumption never stops increasing. This study evaluates the consumers' willingness to pay (WTP) for different plastics used for water packaging. Successive messages emphasizing the characteristics of plastic are delivered to consumers allowing explaining the influence of information on the consumers' WTP. We find that information has a manifest effect on the WTP. We show there is a significant premium associated with recycled plastic packaging and biodegradable bioplastic packaging. As there is no consensus on the plastic which is the most or the least dangerous for the environment, we propose different policies for protecting the environment. We discuss about the impact of these policies on consumer's purchasing decisions: switching one plastic packaging for another, or leaving water plastic bottles market. We present the environmental policies that are effective according to the point of view adopted. Choosing between these policies then depends on the priorities of the regulator and pressure of lobbies.

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1. Introduction

Plastic packaging is widely used everywhere in the world. This kind of packaging produces an important quantity of waste. One of the most common plastic used is polyethylene terephthalate abbreviated PET. This plastic is strong and durable, chemically and thermally stable. It has low gas permeability and is easily processed and handled. This almost unique combination of properties makes PET a very desirable material for a wide range of applications including food and beverage packaging, especially water bottles at a very cost effective price. Globally, 389 billion of PET bottles had been produced in 2010, 46% of them for water packaging (ELIPSO, 2012). But, this stability leads PET to be highly resistant to environmental biodegradation. Biodegradation of one PET bottle left in nature can last around 500 years. Thus, this causes many and varied environmental concerns for both terrestrial and marine areas. Its accumulation is particularly impressive in the world's oceans, where about 10% of global plastic production amass each year (Fitzgerald, 2011). A seafaring scientist named Captain Charles Moore discovered and confirmed the existence of the Great Pacific Garbage Patch in 1997. In 2010, another similar area has been discovered in the Atlantic Ocean: The North Atlantic Garbage Patch. Finally, in 2013, a French expedition named the 7*th* Continent expedition studied the Great Pacific Garbage Patch (Bossy, 2013) and started a new expedition in May 2014 in the North Atlantic Ocean.[1] The vast majority of all those marine debris is plastic materials and many of them are made of PET. According to Azzarello and Van Vleet (1987), Derraik (2002), Moore (2008), Saido (2014), and Sazima et al. (2002) plastic debris create a direct threat to wildlife, with many and varied species documented as being negatively impacted by those small plastic items. As very often concerning highly complex topics, the range of possible solutions for protecting the ecosystem of plastic pollution is wide. In Portugal, face to the continuous growth of waste produced by the population, the waste

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[1] For more details, see: http://expedition-7eme-continent-monsite.com/en/pages/-page.html.

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regulator decided to use the sunshine regulation, based on a set of performances indicators, to measure the operators' efficiency and effectiveness in the provision of their activities. Simões and Marques (2012) have studied the influence of this regulation on the performance of Portuguese urban waste utilities from 2001 to 2008. They have found that productivity declines in the urban waste utilities but the quality of service has improved. Recently on the 13th of March 2014, San Francisco municipality has made a step with an ordinance to ban the sale of PET water bottles on city-owned property (Timm, 2014). On the 2nd July 2014, the European Commission adopted the Packaging and Packaging Waste Directive 94/62/EC, which currently concerns plastic bags. However, as with plastic bags, plastic bottles are the most emblematic plastic waste, this directive could be extended to plastic bottles.

Suppliers are also working on the reduction of plastic waste. The significant environmental drawbacks of plastic disposal via both landfill and incineration are the driving force behind the development of plastic recycling processes (Paponga et al., 2014). PET is now recycled in many countries that are developing specific waste management policies. The recycled PET is named r-PET. In France, this solution has been used 20 years ago. In 2010, 310,000 tons of PET bottles have been collected in France: it represents a recycling rate of 51%. Around 30% of this collected PET can be used in order to produce food grade r-PET quality.[2] Another solution is the development of new plastics like bio-based (plant-derivative) plastics. The two most known biopolymers are polylactic acid (PLA) and polyethylene furanoate (PEF). They are derived from renewable biomass sources. PLA is produced from glucose and it is biodegradable. La Mantia et al. (2012) prove that there is a better impact on environment of PLA compared to PET. However, PLA production is still low because even if PLA is mentioned as biodegradable plastic it needs anaerobic conditions. Its degradation is a source of methane that is a very powerful greenhouse effect gas. In addition, PLA recycling processes are still in progress. Loopla[3] by Galatic uses PLA waste in order to recycle them but their process does not lead to 100% recycling of PLA. In addition, since the introduction of PLA in PET process recycling can lead to problems concerning PET recycling quality, few recycling companies invest in PLA recycling. Hence, in our study, we do not consider the recyclable property of PLA. By contrast, PEF is fully recyclable like PET but it is poorly biodegradable. PEF is made by converting sugars from sugarcane into plastic. Nowadays more than 2.5 billion plastic bottles made of biopolymers are already in use around the world, but this only represents less than 1% of global production. One of the main limiting aspects is the cost.

Today, 89 billion litre of water are bottled and consumed each year worldwide. Overall consumption of bottled water in the world in 2004 was almost double that of 1997.[4] Moreover, annual growth rate for plastic water bottle consumption in the world from 2008 to 2013 is at 6.2%.[5] So we wonder whether consumers care about plastic water bottles' environmental impacts. Which environmental policies could be proposed and which one(s) is(are) optimal? How environmental policies change consumers' purchasing decisions? To address these questions, we propose to study the consumers' perceptions through a willingness-to-pay (WTP) analysis. Indeed, consumers' perceptions are not only essential for packaging companies' choices but they are also for environmental policies.

Our approach relies on two building blocks. First, our paper is linked to the literature that examines the interaction between the WTP and information acquisition. Food experiments constitute some (for instance, on palm oil, Disdier et al., 2013; on milk, Marette and Millet, 2014, and on organic apples, Marette et al., 2012). Our paper contributes to this literature by investigating the precise impact of information on the plastic water bottles consumers' WTP. We believe to be the first study focusing on the consumer perception regarding plastic bottles. We first conduct an analysis to elicit the WTP for different kinds of plastic bottles with increasing levels of information on the use of various plastic bottles, and their environmental impacts. We find that information matters in terms of WTP. Bougherara and Combris (2009), Disdier et al. (2013), Marette et al. (2012), Marette and Millet (2014), and Yue et al. (2009) show that a significant proportion of consumers are willing to pay substantial premiums for environmentally friendly products. We then propose to analyse the premiums for organic, recyclable, and biodegradable plastic water bottles.

Furthermore, we contribute to the ecological economics literature on the reduction of pollution and waste on the environment. Contrary to questions about trade-off between regular and organic products in which regulator chooses to support organic products because they are safer for health and their production reduces damages on the environment, the question of plastic bottles packaging is more technical and complex. Indeed, there is no consensus on the plastic which is the most or the least dangerous for the environment, we propose four policies for protecting the environment: an information campaign on the characteristics of each plastic and their consequences on the environment, an organic policy favouring plastic bottles issued of renewable products, a biodegradable policy favouring biodegradable plastic bottles, and a recycling policy favouring recyclable plastic bottles. A lot of works have been done on the producer side essentially on the producer responsibility regulations based on the Extended Producer Responsibility (EPR) principle[6] to reduce waste and pollution in the environment (Cruz et al., 2012, 2014; Ferreira et al., 2016; Hage, 2007; Marques et al., 2014; Mayers, 2007; Numata, 2009; Palmer and Walls, 1997). Cruz et al. (2012) highlight that the extra cost of recycling is difficult to evaluate implying that the industry may be responsible for the possible cost-inefficiencies of waste management operators. However, from a cost and benefit analysis on recycling system, Marques et al. (2014) study the actual implementation of the EPR principle in Belgium and Portugal. They show that in Belgium, the industry supports all the extra-costs of recycling while in Portugal the industry is not always paying the net financial cost of packaging waste management. This depends whether diverting packaging waste from other treatment operations are taken into account as a benefit or a cost for the local authorities. The same conclusions than the one for the Portugal are obtained by Ferreira et al. (2016) for Italy and Belgium, and by Cruz et al. (2014) for France and Romania. But, none of these works have studied this issue from the consumers' side. In this paper, from the consumers' revealed and estimated preferences on plastic used for water bottles packaging, we analyse the impact of environmental policies on the social welfare. This allows us both to identify the effects of each policy on the consumers' and producers' welfare, and to recommend optimal environmental policies. Cruz et al. (2014) and OECD (2008) suggest that regulation and financial incentives for citizens are essential for habits changing in waste sector. We then discuss about the impact of these policies on consumer's purchasing decisions: switching one plastic packaging for another, or leaving water plastic bottles' market. We see that the environmental policies are effective according to the point of view adopted (consumer surplus, producer surplus, social welfare,

[2] For more details, see ELIPSO (2012).
[3] For more details, see http://www.loopla.org/cradle/cradle.htm.
[4] See: http://www.planetoscope.com/dechets/321-consommation-mondiale-de-bouteilles-d-eau-en-plastique.html.
[5] See: http://www.bottledwater.org/economics/industry-statistics.
[6] According to the Organisation for Economic Cooperation and Development (OECD), *the Extended Producer Responsibility (EPR) is a policy approach under which producers are given a significant responsibility – financial and/or physical – for the treatment or disposal of post-consumer products.*

or number of consumers leaving the plastic water bottles market). Choosing between these policies then depends on the priorities of the regulator and pressure of lobbies.

The paper is organized as follows. Section 2 details the study. Section 3 presents the econometric estimations. From a welfare analysis, Section 4 displays the regulator's choices between different environmental policies. Finally, Section 5 concludes.

2. The study

After an increase by 2% in 2010, the market of plastic water bottles has increased by 6% in 2011 in France with 5.5 billion of litres consumed. In 2014, the consumption of plastic bottles is around 7.7 billion of litres (around 118 L per inhabitant), namely an increase by 28.6% from 2011.[7] Today, French are the third biggest water bottles consumers after Italian and American people. According to Taylor Nelson Sofres, 85% of the French citizen drink water bottles. We then propose to analyse the French consumers' perception on plastic water bottles.

2.1. Target respondents

During February 2014, we conducted the study through Marketest.[8] Marketest had selected French participants by using the quota method, i.e., the same proportions of gender, age and socio-economic status (occupation, household composition, income, education) criteria in the group of respondents as in the census report of French population by Institut national de la statistique et des études économiques (INSEE).[9] We had especially prepared the questionnaire to be posted online. The target respondents consists of 148 French people aged between 18 and 79 (with on average 43 years old, a median at 45 years old, and a standard deviation at 18.3).

Table 1 presents the socio-economic characteristics (gender, age, education, household composition, income, and occupation) of the participants. Differences between our panel and INSEE are tested using the Pearson chi-squared test. A p-value (against the null hypothesis of no difference) of less than 5% is considered significant. The results in the last column of Table 1 suggest that the two groups are not significantly different.

Through informational questions on the respondents, we have selected participants who were both buyers and consumers of plastic water bottles. The price is important for their plastic bottle decisions for 86.5% of them. Plastic bottles use does not create damages on the environment for 19.6% of the participants. Bottle producers' communication campaign on the safety of their product for the environment does not convince 43.2% of the participants while 43.3% of them believe on bottle producers environment friendly engagement to protect the environment. 62.8% of the participants feel up to concerning environmental damages of plastic bottles. The use of recyclable packaging is an important innovation for the water bottle packaging sector for 88.5% of the participants. It is also important for 88.5% of the participants that the packaging be in recyclable material. Finally, 64.2% of the participant are sensitive to the environmental protection.

Table 1
Socio-economic characteristics of participants.

Description	Study panel (%)	INSEE (%)	Chi2 test P-value
Gender			
Female	54.7	51.5	0.518
Male	45.3	48.5	
Age			
<20	14.9	25.0	0.063
[20–64]	65.5	57.0	
>64	19.6	18.0	
Education			
No baccalaureate (BAC)	45.9	59.0	0.062
BAC	21.0	16.0	
3 years after BAC	16.2	11.0	
More than 3 years after BAC	16.9	14.0	
People living in the household			
1 person	29.7	34.0	0.662
2 persons	27.7	26.0	
3 persons and more	42.6	40.0	
Monthly net income of the household (€)			
<1000	12.2	10.0	0.973
[1000–1500)	20.3	20.0	
[1500–2500)	20.3	20.0	
[2500–4000)	29.0	30.0	
[4000–6000)	10.1	10.0	
6000⩽	8.1	10.0	
Socio-professional categories			
Farmers	0.0	1.0	0.987
Craftsman or trading	2.7	3.0	
Executives and professionals	9.5	9.6	
Freelance workers	14.2	13.0	
Employees	16.9	17.0	
Workers	12.8	12.2	
Retired or looking for a job	27.7	26.5	
Without any professional activities	16.2	17.7	

Notes: Baccalaureate is the French high school diploma.

2.2. Products

Our study focuses on plastic water bottles. We consider a pack of six plastic water 1.5 L bottles. Different kinds of plastic are proposed: PET, r-PET, PLA and PEF. PET is currently the most-widely used polyester in bottles. It is petroleum based and 100% recyclable but not biodegradable. r-PET is PET which has been recycled and is 100% recyclable. PLA is a biodegradable plastic. We do not mention its possible recyclable property in this work because since now, only few recycling companies have invested in its recycling and the actual processes do not lead to 100% recycling of PLA.[10] It is derived from renewable resources. PLA is then considered as a bioplastic as well as PEF which is also made from renewable resources. PEF is 100% recyclable but not biodegradable. We have then decided to study these four kinds of plastic because they allow us to compare the demand for bioplastics, recyclable and biodegradable plastics for water bottles packaging.

In average, the observed pack of six water 1.5 L bottles price is at 3.6 euro.[11] In our study, we only focus on the kind of plastic used for water bottles packaging.[12]

2.3. Experimental design and information revealed

In the questionnaire, successive messages emphasizing the plastic bottles characteristics and their environmental impacts are delivered to the survey participants. WTP is elicited after each message with the following question: *What is the maximum price you are willing to pay for a pack of six water 1.5 L bottles with a packaging made of this plastic?* Only PET plastic bottles are presented for the three first messages, then r-PET and biopolymer bottles (PLA

[7] Data from – Canadean 2014: http://www.efbw.eu/fileadmin/user_upload/documents/Publications/EFBW_Industry_Report_2015_02.pdf.
[8] For more details on Marketest see: http://www.marketest.co.uk/.
[9] INSEE is the census bureau in France.
[10] This allows us to separate biodegradable and recycling participants' interest.
[11] This price is estimated from our enquiry at Naturalia and Carrefour market, in November 2013.
[12] We do not mention trademark to participants in order not to influence their decision.

and PEF) are introduced with the fourth message and with the fifth message, respectively. The experiment is divided into several stages as described in Fig. 1.[13]

The sequence of information revealed does not differ between the participants. As pre-tests have showed changing the order of the messages appear difficult to the participant's understanding.[14] Marketest has its own panel of respondents and pays them for replying to questionnaire. The questionnaire is as follows: first, a text helps participants to understand the purpose of this study. No information is given about the different kinds of plastic bottles. Then, participants fill in an entry questionnaire on consumption behaviour and socio-demographic characteristics. Finally, based on different types of information revealed to participants, eight rounds of WTP elicitation are successively determined.

The observed retail price for a pack of six plastic water 1.5 L bottles, 3.6 euro is revealed in message 1, before the first WTP elicitation, allowing us to control the anchorage effect for the first message.[15] Messages 2 and 3 reveal detailed information about the negative consequences of PET bottles on the environment (pollution and non-biodegradability). Messages 4 and 5 introduce the r-PET and biopolymers (PLA and PEF) bottles, respectively. Then in message 6, biopolymers are divided in two categories of plastic, the biodegradable one, PLA, and the non-biodegradable one, PEF. Message 7 gives information on the negative impact of PLA bottles on the environment by clarifying that PLA bottles are non-recyclable. Finally, message 8 informs the participants that PEF is recyclable.[16]

3. Results

3.1. Descriptive analysis

Fig. 2 presents, with boxplots, the distributions of the WTP for a pack of six water 1.5 L bottles according to the type of plastic and the information (message) provided. For each boxplot, we indicate the mean with a red cross and the median with a line. We also show the actual price of a pack of six water 1.5 L bottles (3.6 €) with a vertical green dotted line.

Fig. 2 shows that r-PET and PLA bottles attract the highest WTP for any level of information while PET bottles WTP is the lowest. The reduction of WTPs for PLA and PEF bottles following an information on the negative impact of these products[17] is more important in absolute values than the increase when information specifies that these products do not affect the environment.[18] In their prospect theory, Kahneman and Tversky (1979) observe that the impact of a loss on utility is twice higher than the impact of a symmetric gain on the utility. Our result presents this observation too. In addition, we find that the average and median WTPs are lower than the reference price for a pack, which is 3.6 euro.[19]

In Fig. 3, we make a histogram for each kind of plastic, in which each bar represents the average WTP in euro for one pack of six plastic water 1.5 L bottles expressed by all participants i after each message j with $j = 1, 2, \ldots, 8$ (PET bottles in very light-grey, r-PET bottles in light-grey, PLA bottles in grey, and PEF bottles in black). The standard deviation is reported in parentheses. We test for the significance of the WTP differences linked to the information revelation with the Wilcoxon test (Δ^{**} denotes significant differences at the 5% level). The test is made as follows: between messages j (between bars) for measuring the information revelation impact on the average WTP for a given pack.

We first note that information matters. Indeed, following the revelation of information, in average, participants change their WTP. We observe that, information significantly decreases the WTP for PET (messages 2 and 3, which give the harmful consequences of the PET use on the environment, and message 6, which highlights that there exists biodegradable plastics.) and increases it with message 5 which presents the bioplastics. In addition, we observe that, in average, after message 6, which says that PLA is a biodegradable plastic, the WTP for the other plastic bottles significantly decreases. So participants are sensitive to the biodegradability property of plastic. Moreover, after message 7, which says that the biodegradable plastic (PLA) is non-recyclable, the WTP for PLA and PEF bottles significantly decreases in average. Actually, this information shows to the participants that none of the plastic totally preserves the environment. Participants react to this information by decreasing their WTP for the two biopolymers. Finally, after message 8, which informs the participants on the recycling attribute of PEF, the participants significantly increase their WTP for PEF in average. Hence, participants are also sensitive to the recycling property of plastic.

For each specific message j, we then test for the significance of the WTP differences linked to the information revelation with the Wilcoxon test between two packs made in different plastic. We get that in average, the WTP for PET bottles is significantly lower than the ones for r-PET bottles, PLA bottles and PEF bottles. In average, after message 6, the WTP for PEF bottles is significantly lower than the ones for PLA and r-PET bottles. Then, until message 7, the WTP for PLA is significantly higher than the one for r-PET in average. To sum up, for our panel, in average, WTP PET < WTP PEF $\leqslant$ WTP PLA $\approx$ WTP r-PET.

3.2. Econometric estimations

3.2.1. Willingness-to-pay

We now investigate the determinants of WTP through estimations. We use an ordinary least square regression (OLS) model on pooled data (L = 2960). It includes dummies for the considered plastic bottles, and for available information at the moment of the WTP elicitations. The model also includes six additional control variables: age, sex, income, the individual importance attached to the protection of the environment, the individual's confidence to bottle producers' communication campaign, and the individual's confidence on bottle producers' environment friendly engagement.[20] Age is a quantitative variable and sex is a dummy variable (0 for women and 1 for men). We have divided income in five dummy variables[21] (Income-0: 1000<; Income-1: [1000, 1500); Income-2: [1500, 2500); Income-3: [2500, 4000); Income-4: [4000, 6000); Income-5: 6000$\leqslant$), individual attachment to the protection of the environment in five dummy variables (Importance attached to the protection of environment-0: does not know; Importance attached to the protection of environment-1: none; Importance attached to the protection of environment-2: weak; Importance attached to the protection of environment-3: high; Importance attached to the protection of environment-4: very high), the individ-

[13] Messages are given in Appendix A.

[14] We have first tested our questionnaire on small samples of respondents before sending our questionnaire to Marketest. We call this pre-test.

[15] See Drichoutis et al. (2008) for a discussion on the issue of provision of reference prices prior to the auctions.

[16] See messages in Appendix A.

[17] Message 7 for PLA bottles and message 6 for PEF bottles.

[18] Message 6 for PLA bottles and message 8 for PEF bottles.

[19] On average, our panel reveals that it is not willing to pay 3.6 € for buying a pack of plastic bottles.

[20] Crociata et al. (2015), and Polyzou et al. (2011) have showed the importance of control variables for studying good consumption behaviours, recycling behaviours, and WTP for environmental goods.

[21] For income, individual attachment to the protection of the environment, the individual's confidence on bottle producers' communication campaign, and the individual's confidence on bottle producers' environment friendly engagement, the dummy variable is defined as follows: 1 if the participant has given this response; 0 otherwise.

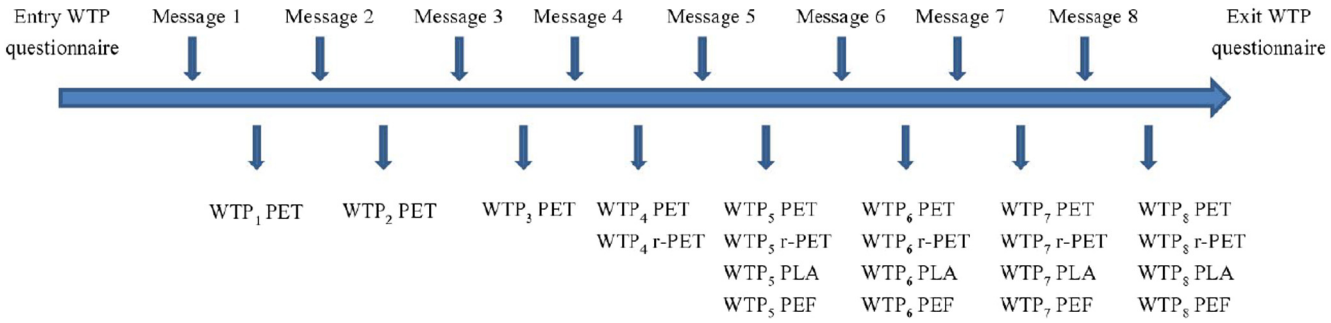

Fig. 1. Questionnaire design.

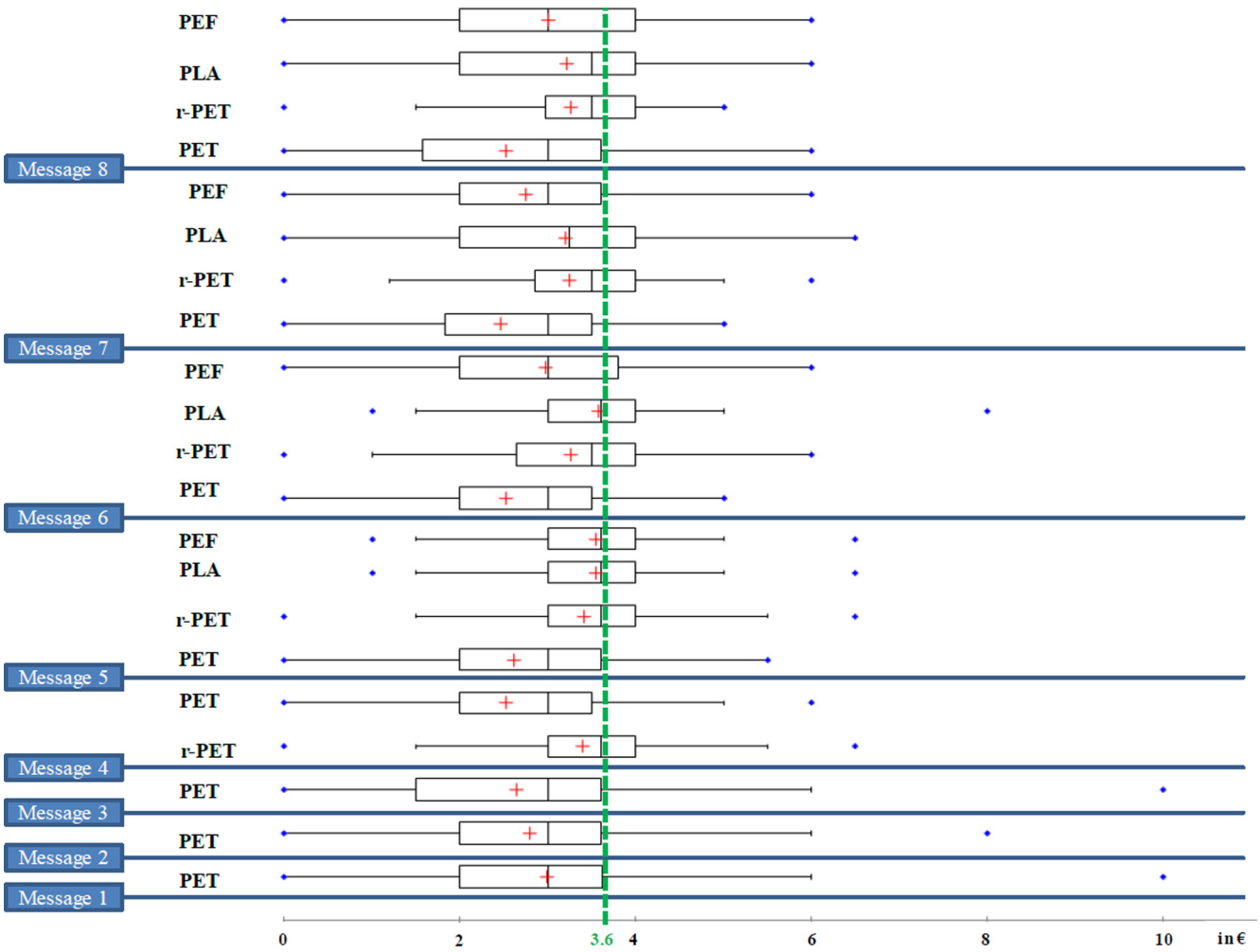

Fig. 2. Boxplot of willingness-to-pay for a pack of six plastic water 1.5 L bottles in euro (Cross: mean, Line: median).

ual's confidence on bottle producers' communication campaign in three dummy variables (Confidence to bottles producers' communication campaign-0: does not know; Confidence to bottles producers' communication campaign-1: yes; Confidence to bottles producers' communication campaign-2: no), and the individual's confidence on bottle producers' environment friendly engagement in three dummy variables (Confidence to bottles producers' environment friendly engagement-0: does not know; Confidence to bottles producers' environment friendly engagement-1: yes; Confidence to bottles producers' environment friendly engagement-2: no). Table 2 presents the estimation results. In the model, PET bottles, Importance attached to the protection of environment-4, Confidence to bottles producers' communication campaign-2, Confidence to bottles producers' environment friendly engagement-2, and Income 5 are reference modalities.

In the model, the R^2 is about 12.2% and the *adjusted* R^2 is about 11.4%.[22] So the model explains around 11.4% of the total variation of pooled WTP.[23] Relative to the PET bottles, the WTPs for the other kinds of plastic bottles are on average higher. The WTPs for PLA bottles and for r-PET bottles are on average the highest. Hence,

[22] The adjusted R^2 is a correction of the R^2, which allows to take into account the number of variables used in the model.

[23] Since the p-value is lower than 0.05, the model is significant.

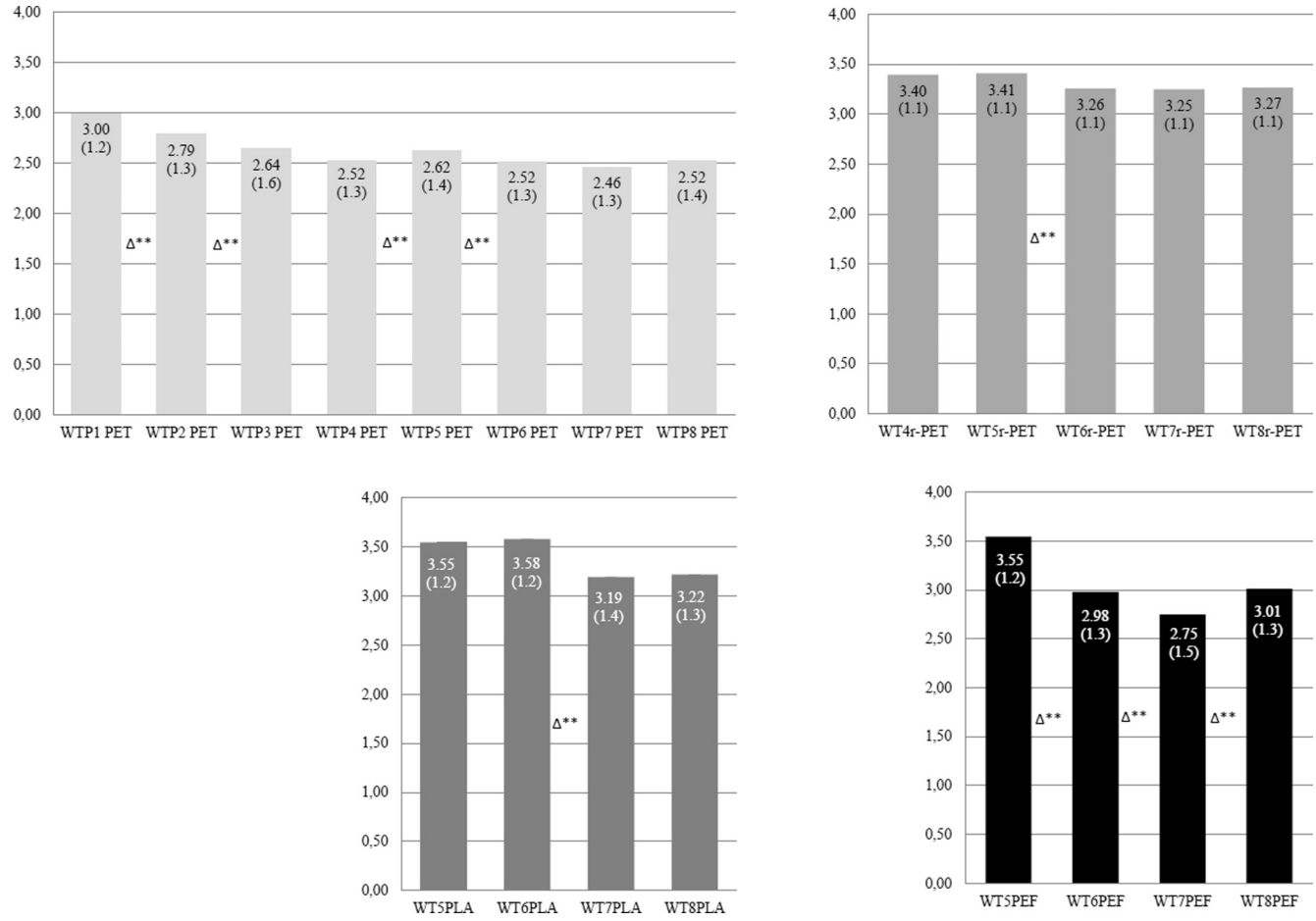

Fig. 3. Average WTP for one pack of six plastic water 1.5 L bottles in euro.

participants have on average a higher valuation for biodegradable bioplastic, and recycled plastic than for recyclable bioplastic.

Providing message 7, on the non-recyclable property of the biodegradable biopolymer, PLA, significantly modifies the WTP, by decreasing the WTP for all the plastic bottles by €0.171. Actually, participants show that for them the recyclable property for a plastic is important.

We find that the youngest participants have a lower WTP for plastic water bottles than the oldest one. The WTP of men for plastic bottles is on average €0.115 higher than women. If we do not take into account participants who have a weak attachment to the protection of environment, participants who do not attach importance to the protection of environment have the highest WTP for plastic water bottles. Indeed, these participants have a higher demand for plastic water bottles than the other participants because they do not affect a high value of preservation of the environment. In addition, being suspicious of producers' messages leads participants to decrease their demands for plastic bottles in comparison to participants who do not know whether they believe or not the producers' messages. Participants who are confident to bottles producers' environment friendly engagement, have the highest WTP for plastic water bottles. Indeed, these participants believe that since producers respect the environment, consuming plastic bottles does not be an issue. Finally, relative to participant with the highest income (more than €6000 per month), the WTP of participants who earn between 4000 € and 6000 € per month is on average €0.370 higher while the WTP of participants who earn between €2500 and €4000 per month is on average €0.367 lower.

3.2.2. Premiums

We now analyse the difference in WTP between two kinds of plastic bottles. Hence, as we examine difference in WTP and not the WTP itself, some differences may be negative. We do not exclude them because a negative premium implies an individual preference for the other plastic bottles. Nevertheless, we do not consider the WTP expressed before message 4 since only PET bottles were available on the market. We define the premium associated with recyclable plastic packaging by the difference between the WTP for recyclable plastic bottles (PET bottles, r-PET bottles, and PEF bottles) and the WTP for non-recyclable plastic bottles (PLA bottles). We then note that the premium associated with biodegradable plastic packaging is exactly the inverse difference. We then define the premium associated with organic plastic packaging by the difference between the WTP for bioplastic bottles (PLA and PEF bottles) and the WTP for non-organic plastic bottles (PET and r-PET bottles). The results are presented in Table 3.

From Table 3, we observe that the premium associated with biodegradable (recyclable) plastic packaging (columns 2, 4 and 5) is always positive (negative) except with the r-PET after message 7. So participants attribute a premium of using biodegradable plastic (PLA) but after receiving all the messages, they favour the r-PET bottles instead of PLA. We get the same conclusions for the premium associated with organic plastic packaging PLA. Concerning the premium associated with organic plastic packaging PEF (columns 3 and 6), we observe it is always positive when we compare PEF and PET, but after message 6, it is always negative when we compare r-PET and PEF. So the premium associated with organic plastic packaging depends on the organic plastic used.

Table 2
Results from OLS regression model about pooled WTPs in levels.

	Coefficient	Standard errors
Endogenous variable: *Pooled Willingness To Pay in €/pack of six water bottles*		
Model: *OLS Estimation*		
Const	2.848	0.168
Age	0.006***	0.001
r-PET (PET)	0.762***	0.064
PLA (PET)	0.755***	0.065
PEF (PET)	0.337***	0.065
Importance attached to the protection of environment-0 (4)	−0.719**	0.293
Importance attached to the protection of environment-1 (4)	0.909***	0.215
Importance attached to the protection of environment-2 (4)	0.000	0.072
Importance attached to the protection of environment-3 (4)	−0.178***	0.069
Confidence to bottles producers' communication campaign-0 (2)	0.141**	0.057
Confidence to bottles producers' communication campaign-1 (2)	−0.015	0.065
Confidence on bottles producers' environment friendly engagement-0 (2)	−0.196**	0.079
Confidence on bottles producers' environment friendly engagement-1 (2)	0.148*	0.076
Sex (0/1)	0.115**	0.048
Income-0 (5)	−0.170	0.109
Income-1 (5)	−0.058	0.098
Income-2 (5)	−0.079	0.102
Income-3 (5)	−0.367***	0.095
Income-4 (5)	0.370***	0.112
Message 2 (0/1)	−0.207	0.145
Message 3 (0/1)	−0.148	0.145
Message 4 (0/1)	−0.063	0.130
Message 5 (0/1)	−0.006	0.098
Message 6 (0/1)	0.048	0.079
Message 7 (0/1)	−0.171**	0.072
Message 8 (0/1)	0.091	0.072
Observations	2960	
R^2	0.122	
Adjusted R^2	0.114	
Log-likelihood	−4840.983	
P-value(F)	$1.07^{*}10^{-65}$	

* p < 0.1.
** p < 0.05.
*** p < 0.01.

We then analyse the determinants of these premiums through an OLS estimation model on pooled data (L = 592–740), dummies for available information, and the same control variables as in Table 2. Table 4 presents the results. In the model, PET bottles, Importance attached to the protection of environment-4, Confidence to bottles producers' communication campaign-2, Confidence to bottles producers' environment friendly engagement-2, and Income 5 are reference modalities.

With the models, the R^2 varies between 5% and 15%, and the *adjusted* R^2 varies between 1.7% and 12.6% So the models explain between 1.7% and 12.6% of the total variation of pooled premiums.[24] The difference between the WTP for r-PET bottles and PET bottles of men is on average €0.381 lower than the one of women, and the difference between the WTP for PLA bottles and PEF bottles of men is on average €0.164 lower than the one of women.

Providing message 6, which specifies that PEF is non-biodegradable while PLA is, implies a positive premium for the use of the other plastic (PET, r-PET, and PLA) instead of PEF. Actually, this result shows that participants give an importance to the biodegradability of plastics. Providing message 7 on the non-recycling property of the biodegradable biopolymer (PLA) and providing message 8 on the recyclable property of the biopolymer PEF decreases the premium for the use of PLA instead of using the other plastics (PET, r-PET and PEF). Participants have then also an interest for the recycling property of the plastic.

Moreover, participants who attach a very high importance to the protection of environment give a higher premium for the use of r-PET instead using PET than the other participants (column 1). Indeed, these participants attribute a higher value to recycled products which have the reputation to protecting the environment. These participants also attribute a higher premium to PLA than the other participants (columns 2 and 5).

In addition, we note that in comparison to participants who are not confident to bottles producers' communication campaign, participants who are confident decrease the premium of using PLA instead of using PET. Actually, these participants believe the comforting message from producers who minimise the negative impacts of PET on the environment. Moreover, relative to the participants who are not confident to bottles producers' communication campaign, participants who do not know whether they are confident decrease the premium for using PEF (recyclable bioplastic) instead of using the other plastics.

Relative to the participants who are not confident to bottles producers' environment friendly engagement, the difference between the WTP for r-PET bottles and PET bottles of participants do not know whether they are confident is on average €0.373 higher.

Finally, participants who earn between €4000 and €6000 per month give a higher premium to organic plastic than participants with the highest income (more than €6000 per month). Moreover, relative to participants with the highest income, participants who earn between €1500 and €4000 per month present a higher premium for recycled plastic (r-PET) in comparison with the same plastic which is not already recycled (PET). In addition, participants who earn between €1000 and €1500 per month make a difference between the organic plastics. Relative to participant with the highest income, they have a higher premium for biodegradable bioplastic (PLA) in comparison with recyclable bioplastic (PEF). Finally, relative to participant with the highest income, participants with the lowest income have a higher premium for recycled plastic (r-PET) and biodegradable bioplastic (PLA) in comparison with PET.

4. Welfare and regulation

Contrary to questions about trade-off between regular and organic products in which regulator chooses to support organic products because they are safer for health and their production reduces damages on the environment, the question of plastic bottles packaging is more technical and complex. Indeed, the regulator cannot have a clear opinion on this issue because there is no consensus on the plastic which is the most or the least dangerous for the environment. We then propose different policies which protect the environment on different way.

First, we suggest a policy which presents to people the different impacts of all kinds of plastic bottles on the environment. The goal of this information campaign is to raise awareness among people to plastic bottles damages on the environment, and specifically among plastic bottles' consumers. Remember that plastic bottles use does not create damages on the environment for 19.6% of the participants of our panel. We will call this policy the *'information policy'*.

The use of plant products from renewable sources is interesting because it helps limit resource depletion. Eerhart et al. (2012) have demonstrated that the carbon footprint of PEF is 50–70% lower than PET. In addition, as PET and r-PET, PEF is 100% recyclable

[24] Since all the p-value are lower than 0.1, the models are significant.

Table 3
Pooled premiums.

	Average premium for r-PET bottles instead of PET bottles	Average premium for PLA bottles instead of r-PET bottles	Average premium for PEF bottles instead of r-PET bottles	Average premium for PLA bottles instead of PET bottles	Average premium for PLA bottles instead of PEF bottles	Average premium for PEF bottles instead of PET bottles
Average premium in%/pack of six water 1.5 L bottles						
Message 4	25.67					
Message 5	23.09	4.09	4.09	35.33	0	35.33
Message 6	22.77	9.91	−8.52	29.73	16.77	15.57
Message 7	24.14	−1.64	−15.40	22.87	13.98	10.33
Message 8	22.84	−1.43	−7.80	21.72	6.46	16.31
Global Mean	23.71	2.28	−10.57	24.77	12.56	14.18
Average premium in €/pack of six water 1.5 L bottles						
Message 4	0.87					
Message 5	0.79	2.62	2.62	3.55	0	3.55
Message 6	0.74	0.32	−0.28	1.06	0.60	0.46
Message 7	0.78	−0.05	−0.50	0.73	0.45	0.28
Message 8	0.75	−0.05	−0.25	0.70	0.21	0.49
Global Mean	0.79	0.07	−0.34	0.83	0.42	0.41

but it is superior gas barrier (10 times PET for O_2 and 5 times for CO_2).[25] From Alpha Packaging,[26] the carbon dioxide transmission rate[27] in $cm^3-mil/m^2/24$ h of PET is 540 while the one of PLA is 201. So, from these indicators, PLA and PEF are less harmful to the environment than PET and r-PET. However, the environmental impact of organic plastics (bioplastics), PLA and PEF, is often debated. Indeed, from Detzel et al. (2013) PLA has advantages over the fossil polymers (PET, r-PET) with respect to climate change and resource consumption and disadvantages with respect to acidification and eutrophication as well as impact categories used to rate toxicity potentials. Moreover, PEF is not biodegradable and may create degradation to the nature if it is thrown. Hence, regulator may support an environmental policy favouring organic plastics bottles (PLA and PEF) if he wants to reduce gas barrier and to promote a production derived from renewable biomass sources. We call this policy the *'organic policy'*.

In addition, biodegradation property allows plastic as PLA to be easily broken down by microorganisms and return to nature. The biodegradation also provides other environmental benefits. It has low toxicity to wildlife and flora, and reduces health risks. However, biodegradation of plastic is slowed down if the environment for microorganisms is not appropriate. For PLA, microorganisms need high oxygen conditions and require a high temperature (more than *55°C* (*131°F*))to be degraded. In addition, methane might be released when there is degradation in an anaerobic landfill environment. So biodegradation may not always solve environmental problem. However, if the regulator wants to reduce toxicity to nature and health risks, and to limit waste, he may support the use of biodegradable plastic for water bottles packaging. We will call this policy the *'biodegradable policy'*.

Finally, recycling of plastic bottles (PET, r-PET and PEF) has environmental and economic advantages over the non-recyclable plastic bottles (PLA). These recyclable plastics reduce land- fills and so the pollution that it causes. Increasing the recycling rate is an interesting way for reducing greenhouse gas emissions, limiting waste, and so for preserving the environment as mentioned in Abbott et al. (2011), Acuff and Kaffine (2013), Kinnaman et al. (2014). Moreover, the recycling also contributes to the economic development of a country by creating new industries (new jobs and tax revenue).[28] However, there are some environmental downsides to recycling. Plastic recycling uses different processes and some of them employ caustic chemicals which create emissions and water pollution. So if regulator wants to reduce landfills, he may support recycling plastics for water bottles packaging. We will name this policy the *'recycling policy'*.

In this section, based on elicited WTP and purchase decisions, we investigate the welfare impact of various environmental policies (information policy, organic policy, biodegradable policy and recycling policy). We assume that all kinds of plastic bottles are available on the market. We first present the elicited and predicted demands for each kinds of plastic bottles.

4.1. Plastic bottles demand

To convert the WTP to demand curves, it is assumed that each participant makes a choice related to the largest difference between his WTP and the market price. This choice is inferred because the real choice is not observed in the study, which only elicits WTP.

Fig. 4 shows the ordered WTP for the four plastic bottles after message 8 (i.e. after receiving all the messages).[29] The cumulative number of participants (equivalent to one purchased pack of six plastic water 1.5 L bottles per participant) is represented on the X-axis and the ordered WTP (in euro) corresponding to the cumulative number of participants is represented on the Y-axis in decreasing order. The black ordered curve is the elicited WTP directly observed from the panel study, the grey curve is the predicted WTP with the classical OLS estimation, and the dotted line is the sale price.[30]

The left sides (right sides) of each graphs shows that, for relatively high-values (low-values) of WTP, the elicited WTPs directly observed from the panel study are significantly higher (lower) than the WTPs predicted. The differences between elicited WTP and the OLS estimations of WTP are not large.

4.2. Regulatory interventions and tools

We now focus on the different tools for implementing the information policy, the organic policy, the biodegradable policy and the

[25] For more details see: http://www.packagingdigest.com/resins/pef-will-not-oust-pet-for-beverage-bottles-anytime-soon140724.

[26] For more details see: http://www.alphap.com/bottle-basics/plastics-comparison-chart.php.

[27] Carbon dioxide transmission is the measurement of the amount of carbon dioxide gas measure that passes through a substance over a given period. The lower the readings, the more resistant the plastic is to letting gasses through.

[28] For more details see: http://www.epa.gov/osw/conserve/tools/localgov/benefits/.

[29] The results after the other messages are available at the Supplemental Material.

[30] Note that the WTP in all the curves is ordered, which means that a given number on the X-axis indicates the ranking of WTP related to each curve and not a specific participant.

Table 4
Results from OLS regression model about pooled premiums in levels.

	Endogenous variable					
	Premium in €/pack of six water 1.5 L bottles for r-PET bottles instead of PET bottles	Premium in €/pack of six water 1.5 L bottles for PLA bottles instead of r-PET bottles	Premium in €/pack of six water 1.5 L bottles for PEF bottles instead of r-PET bottles	Premium in €/pack of six water 1.5 L bottles for PLA bottles instead of PET bottles	Premium in €/pack of six water 1.5 L bottles for PLA bottles instead of PEF bottles	Premium in €/pack of six water 1.5 L bottles for PEF bottles instead of PET bottles
Model: *OLS estimation*						
Const	1.280***	−0.080	−0.181	0.879**	0.128	0.778*
	(0.286)	(0.364)	(0.363)	(0.350)	(0.272)	(0.465)
Age	−0.005	0.004	0.002	−0.002	0.003	−0.004
	(0.003)	(0.004)	(0.004)	(0.004)	(0.003)	(0.005)
Importance attached to the protection of environment-0 (4)	−1.392**	−1.473*	−0.560	−0.894	−0.561	0.019
	(0.591)	(0.762)	(0.759)	(0.733)	(0.569)	(0.972)
Importance attached to the protection of environment-1 (4)	−1.521***	−0.032	0.878	−0.006	−0.533	0.904
	(0.434)	(0.559)	(0.557)	(0.538)	(0.418)	(0.715)
Importance attached to the protection of environment-2 (4)	−1.033***	−0.086	0.220	−0.213	−0.609***	0.093
	(0.145)	(0.186)	(0.186)	(0.179)	(0.139)	(0.238)
Importance attached to the protection of environment-3 (4)	−0.477***	0.006	0.089	−0.021	−0.452***	0.062
	(0.139)	(0.179)	(0.178)	(0.172)	(0.133)	(0.228)
Confidence to bottles producers' communication campaign-0 (2)	−0.072	−0.213	0.370**	−0.141	−0.205*	0.442**
	(0.114)	(0.147)	(0.147)	(0.141)	(0.110)	(0.188)
Confidence to bottles producers' communication campaign-1 (2)	−0.180	0.023	0.175	−0.362**	−0.128	−0.211
	(0.131)	(0.169)	(0.168)	(0.162)	(0.126)	(0.215)
Confidence on bottles producers' environment friendly engagement-0 (2)	0.373**	−0.035	−0.322	0.161	0.232	−0.125
	(0.160)	(0.206)	(0.205)	(0.198)	(0.154)	(0.263)
Confidence on bottles producers' environment friendly engagement-1 (2)	0.185	0.129	0.240	0.161	0.136	0.272
	(0.153)	(0.198)	(0.197)	(0.190)	(0.148)	(0.252)
Sexe (0/1)	−0.381***	−0.037	0.187	−0.166	−0.164*	0.057
	(0.097)	(0.125)	(0.125)	(0.121)	(0.094)	(0.160)
Income-0 (5)	0.781***	0.401	0.013	0.474*	0.189	0.086
	(0.220)	(0.284)	(0.283)	(0.272)	(0.212)	(0.362)
Income-1 (5)	0.034	−0.030	−0.147	−0.070	0.187	−0.187
	(0.198)	(0.255)	(0.254)	(0.245)	(0.190)	(0.325)
Income-2 (5)	0.316	0.048	−0.249	0.339	0.378*	0.041
	(0.206)	(0.266)	(0.265)	(0.256)	(0.199)	(0.339)
Income-3 (5)	0.501***	0.043	−0.377	0.345	0.115	−0.075
	(0.192)	(0.247)	(0.247)	(0.238)	(0.185)	(0.316)
Income-4 (5)	0.765***	0.440	0.631**	0.867***	0.252	1.059***
	(0.226)	(0.291)	(0.290)	(0.280)	(0.217)	(0.371)
Message 4 (0/1)						
Message 5 (0/1)	−0.086					
	(0.146)					
Message 6 (0/1)	−0.045	0.184	−0.417**	0.139	0.600***	−0.461**
	(0.146)	(0.168)	(0.168)	(0.162)	(0.126)	(0.215)
Message 7 (0/1)	0.042	−0.376**	−0.222	−0.334**	−0.154	−0.180
	(0.146)	(0.168)	(0.168)	(0.162)	(0.126)	(0.215)

(*continued on next page*)

Table 4 (*continued*)

	Endogenous variable					
	Premium in €/pack of six water 1.5 L bottles for r-PET bottles instead of PET bottles	Premium in €/pack of six water 1.5 L bottles for PLA bottles instead of r-PET bottles	Premium in €/pack of six water 1.5 L bottles for PEF bottles instead of r-PET bottles	Premium in €/pack of six water 1.5 L bottles for PLA bottles instead of PET bottles	Premium in €/pack of six water 1.5 L bottles for PLA bottles instead of PEF bottles	Premium in €/pack of six water 1.5 L bottles for PEF bottles instead of PET bottles
Message 8 (0/1)	−0.038	0.007	0.245	−0.031	−0.238*	0.207
	(0.146)	(0.168)	(0.168)	(0.162)	(0.126)	(0.215)
Observations	740	592	592	592	592	592
R^2	0.149	0.047	0.093	0.070	0.100	0.067
Adjusted R^2	0.126	0.017	0.064	0.040	0.072	0.038
Log-likelihood	−1209.199	−1049.577	−1047.423	−1026.665	−877.169	−1194.475
P-value(F)	$3.75 * 10^{-16}$	0.061	$7.43 * 10^{-6}$	0.001	$1.34 * 10^{-6}$	0.002

Standard errors are in parenthesis.
* p < 0.1.
** p < 0.05.
*** p < 0.01.

recycling policy. First, we set up an information campaign about the characteristics of each plastic and their consequences on the environment for implementing the information policy. Then, for applying, the organic policy, the biodegradable policy and the recycling policy, we propose either a per-unit tax on product that does not respect the goal of the policy chosen, or a per-unit subsidy on product that reaches the goal of the policy chosen, or a standard which only allows products respecting the policy chosen.

4.2.1. Information campaign

For the information policy, the regulator makes a complete campaign of information on the characteristics of plastic bottles packaging and their impacts on the environment. That is this public intervention consists in a very intense consumer information campaign, perfectly understood by consumers and revealing complete information on plastic bottles issues linked to the environment, which leads to round 8 (after message 8) in our model. Following this campaign, consumers are perfectly informed. Consumers directly internalize all information provided by the campaign. Consumer *i* can choose between five outcomes: one pack of six water 1.5 L PET bottles at price P(PET) euro, one pack of six water 1.5 L r-PET bottles at price P(r-PET) euro, one pack of six water 1.5 L PLA bottles at price P(PLA) euro, one pack of six water 1.5 L PEF bottles at price P(PEF) euro, or none of those. We consider that purchasing decisions are determined by the consumer *i*'s WTP for PET, r-PET, PLA and PEF pack of six water 1.5 L bottles given by WTP_{i8}PET, WTP_{i8}r-PET, WTP_{i8}PLA and WTP_{i8}PEF, respectively. We assume that a consumer may purchase one pack of six water plastic 1.5 L bottles if his WTP is higher than the price observed for this pack in the supermarket. He then chooses to buy the pack of six water plastic 1.5 L bottles generating the highest utility (with a utility of non-purchase normalized to zero). Because complete information is perfectly internalized by consumers, no other tool can improve the welfare. The per-unit surplus and welfare for participant $i \in N$ is as follows:

$$W_i^L = \max\{0, WTP_{i8}k - P(k);\ k \in \{PET, r-PET, PLA, PEF\}\}. \quad (1)$$

4.2.2. A per-unit tax

The public intervention consists in the adoption of a per-unit tax, τ. To simulate the tax scenario, we consider that consumers have no precise knowledge about the concerned plastic bottles, which corresponds to the situation before message 2 for PET bottles, the situation before message 4 for r-PET bottles, and the situation before message 5 for PLA and PEF bottles. Consumer *i* can choose between five outcomes: one pack of six water 1.5 L PET bottles at price P^τ(PET) euro, one pack of six water 1.5 L r-PET bottles at price P^τ(r-PET) euro, one pack of six water 1.5 L of PLA bottles at price P^τ(PLA) euro, one pack of PEF bottles at price P^τ(PEF) euro, or neither. He makes his purchasing decision based on his surplus maximization:

$$W_i^\tau(\tau) = \max\{0, WTP_{ij}k - P^\tau(k)\} \quad (2)$$

where $i \in N$, $k \in$ {PET, r-PET, PLA, PEF}, and

$$j = \begin{cases} 1, & \text{for } k = PET; \\ 4, & \text{for } k = r-PET; \\ 5, & \text{for } k = PLA \text{ and } k = PEF. \end{cases}$$

The regulator also considers the possible tax income coming from each participant. The tax is only paid by consumers purchasing one pack of six water 1.5 L *k* bottles with $k \in$ PET, r-PET} for the organic policy, with $k \in$ {PLA} for the recycling policy, and with $k \in$ {PET, r-PET, PEF} for the biodegradable policy. We note:

$$\mathbb{1}[k,i] = \begin{cases} 1 & \text{if consumer } i \text{ buys the pack of six water 1.5 L k bottles;} \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

So the possible tax income coming from each participant *i* is equal to $\tau^*[k, i]$ with $k \in$ PET, r-PET, PLA, PEF}. The optimal tax τ^* is chosen by the regulator and is given by tatonnement, maximizing the average welfare $\sum_{i=1}^{N}(W_i^\tau(\tau) + \sum_k \tau * 1[k,i])/N$ over the N = 148 participants with $k \in$ {PET, r-PET, PLA, PEF}. Table 5 presents the list of taxes and the prices of each pack of bottles according to the plastic packaging and the policy implemented.

4.2.3. A per-unit subsidy

The public intervention consists in the adoption of a per-unit subsidy, *s*. To simulate the subsidy scenario, we consider that consumers have no precise knowledge about the concerned plastic bottles. Consumer *i* can choose between five outcomes: one pack of six water 1.5 L PET bottles at price P^s(PET) euro, one pack of six water 1.5 L r-PET bottles at price P^s(r-PET) euro, one pack of six water 1.5 L PLA bottles at price P^s(PLA) euro, one pack of six water 1.5 L PEF bottles at price P^s(PEF) euro, or neither. He makes his purchasing decision based on his surplus maximization, which is equal to:

$$W_i^s(s) = \max\{0, WTP_{ij}k - P^s(k)\} \quad (4)$$

where $i \in N$, $k \in$ {PET, r-PET, PLA, PEF}, and

$$j = \begin{cases} 1, & \text{for } k = PET; \\ 4, & \text{for } k = r-PET; \\ 5, & \text{for } k = PLA \text{ and } k = PEF. \end{cases}$$

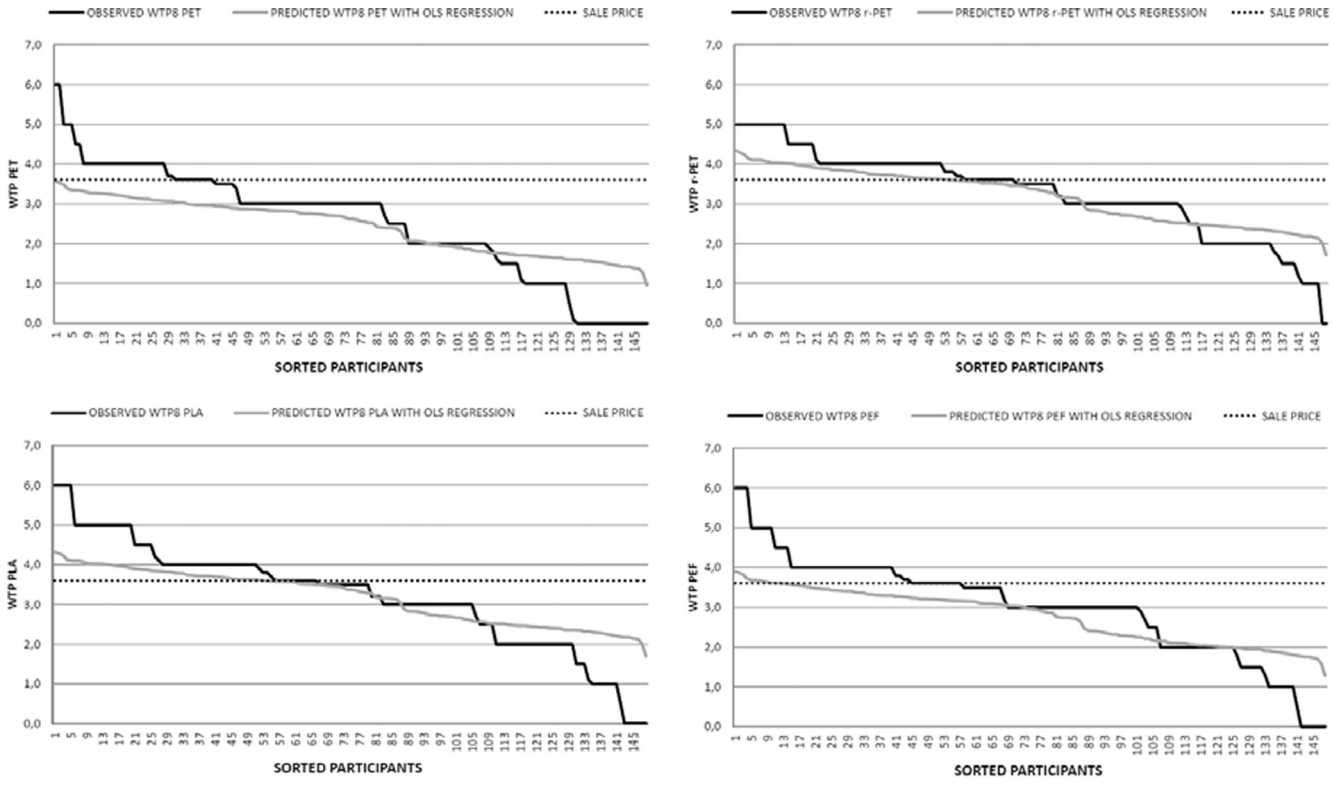

Fig. 4. Observed and predicted demand functions for the four kinds of plastic bottles after message 8 (in euro).

The regulator also considers the possible subsidy he has to give, the subsidy expense. The subsidy only reduces the price paid by consumers purchasing one pack of six water 1.5 L *k* bottles with $k \in \{PLA, PEF\}$ for the organic policy, with $k \in \{PET, r\text{-}PET, PEF\}$ for the recycling policy, and with $k \in \{PLA\}$ for the biodegradable policy. We note:

$$\mathbb{1}[k,i] = \begin{cases} 1 & \text{if consumer } i \text{ buys the pack of six water 1.5 L k bottles;} \\ 0 & \text{otherwise.} \end{cases} \quad (5)$$

So the possible subsidy expense given to each participant *i* is equal to $s^*[k, i]$ with $k \in \{PET, r\text{-}PET, PLA, PEF\}$. The optimal subsidy s^* is given by tatonnement, maximizing the average welfare $\sum_{i=1}^{N}(W_i^s(s) + \sum_k s^* 1[k,i])/N$ over the N = 148 participants with $k \in \{PET, r\text{-}PET, PLA, PEF\}$. Table 6 presents the list of subsidies and the prices of each pack of bottles according to the plastic packaging and the policy implemented.

4.2.4. A standard

To simulate the standard scenario, we also consider that consumers have no precise knowledge about the concerned plastic bottles. Public intervention consists of constraining the purchase of one pack of six water 1.5 L *k* bottles with $k \in \{PET, r\text{-}PET, PLA, and/or PEF\}$. For the organic policy, we constraint the purchase to one pack of six water 1.5 L PLA bottles or PEF bottles; For the recycling policy, we constraint the purchase to one pack of six water 1.5 L PET bottles, r-PET bottles, or PEF bottles; For the biodegradable policy, we constraint the purchase to one pack of six water 1.5 L PLA bottles. The consumer *i*'s purchasing decision then is based on his surplus maximization, which is equal to:

$$W_i^S(s) = \max\{0, WTP_{ij}k - P(k)\} \quad (6)$$

where $i \in N$, and $j = \begin{cases} 1, & \text{for } k = PET; \\ 4, & \text{for } k = r - PET; \\ 5, & \text{for } k = PLA \text{ and } k = PEF. \end{cases}$, with the *k* bottles allowed on the market.

4.3. Welfare analysis

To perform the welfare analysis, we consider a baseline scenario in which the four packs of six plastic water 1.5 L bottles are sold without any additional regulation. The baseline welfare is defined by (2) with $\tau = 0$. We compare the welfare effects of the different environmental policies.

Table 7 presents the results of the welfare analysis for the four policies (information policy, organic policy, biodegradable policy and recycling policy) in percentage, in euro and in number of packs consumed. With a number N = 148, we detail the sum of welfare variations in euro with elicited and predicted values (from the OLS regression model in Table 2) linked to one purchased pack of six plastic water 1.5 L bottles.[31]

We define the average variation in consumer surplus by $\Delta W_N^L = \sum_{i=1}^{N}(W_i^L - W_i^\tau(0))/N$ for the information campaign. Then, we define the average variation in consumer surplus by $\Delta W_N^\tau(\tau^*) = \sum_{i=1}^{N}(W_i^\tau(\tau^*) - W_i^\tau(0))/N$ for a tax τ^*, and $\Delta W_N^s(s^*) = \sum_{i=1}^{N}(W_i^s(s^*) - W_i^\tau(0))/N$ for a subsidy s^*, and $\Delta W_N^S = \sum_{i=1}^{N}(W_i^S - W_i^\tau(0))/N$ for the mandatory standard. We note:

$$\mathbb{1}[k,i,t] = \begin{cases} 1 & \text{if consumer i buys the pack of k bottles under scenario t;} \\ 0 & \text{otherwise.} \end{cases} \quad (7)$$

[31] From the variations in euro, we compute the increase or decrease in percentage for each scenario with respect to the baseline scenario for the variations in percentage.

Table 5
Taxes and price for all the policies.

	Organic policy		Recycling policy		Biodegradable policy	
k	τ	$P^{\tau}(k)$	τ	$P^{\tau}(k)$	τ	$P^{\tau}(k)$
PET	τ_{NO}	$P(PET) + \tau_{NO}$	0	P(PET)	τ_{NB}	$P(PET) + \tau_{NB}$
r-PET	τ_{NO}	$P(r\text{-}PET) + \tau_{NO}$	0	P(r-PET)	τ_{NB}	$P(r\text{-}PET) + \tau_{NB}$
PLA	0	P(PLA)	τ_{NR}	$P(PLA) + \tau_{NR}$	0	P(PLA)
PEF	0	P(PEF)	0	P(PEF)	τ_{NB}	$P(PEF) + \tau_{NB}$

Table 6
Subsidies and price for all the policies.

	Organic policy		Recycling policy		Biodegradable policy	
k	s	$P^{s}(k)$	s	$P^{s}(k)$	s	$P^{s}(k)$
PET	0	P(PET)	s_R	$P(PET)\text{-}s_R$	0	P(PET)
r-PET	0	P(r-PET)	s_R	$P(r\text{-}PET)\text{-}s_R$	0	P(r-PET)
PLA	s_O	$P(PLA)\text{-}s_O$	0	P(PLA)	s_B	$P(PLA)\text{-}s_B$
PEF	s_O	$P(PEF)\text{-}s_O$	s_R	$P(PEF)\text{-}s_R$	0	P(PEF)

where $i \in N$, and $t = \begin{cases} 0, & \text{for the base line scenario;} \\ \tau^*, & \text{for the tax scenario;} \\ s^*, & \text{for the subsidy scenario;} \\ S, & \text{for the standard scenario.} \end{cases}$

The average profit for the *k* bottles' producers under scenario t is defined by:

$$\Pi(k,t) = \frac{1}{N}\sum_{i=1}^{N}(P(k) * 1[k,i,t]) - C_k \quad (8)$$

With C_k the production cost per pack of six water 1.5 L *k* bottles, and $k \in \{PET, r\text{-}PET, PLA, PEF\}$. The average profit variation for *k* bottles' producers under scenario t is so $\Pi(k,t) - \Pi(k,0)$.[32] The average tax income and the average subsidy expense are $\tau^* * \left(\sum_{i=1}^{N}\sum_{k}1[k,i]/N\right)$ and $s^* * \left(\sum_{i=1}^{N}\sum_{k}1[k,i]/N\right)$, respectively. Then, the average social welfare variation is the sum of the average variation in consumer surplus, the average profit variation of all the plastic bottles' producers and the average tax income or average subsidy expense. Finally, we compute the variation in number of packs of bottles consumed as the difference between the number of packs consumed for each policy and the number of pack consumed in the baseline scenario.

Our calculations use the average price observed for the pack of six 1.5 L plastic bottles, namely that is P(PET) = P(r-PET) = P(PLA) = P(PEF) = 3.6 euro.[33]

With the elicited model, giving consumers full information via a communication campaign increases the profit of the r-PET bottles' producers and of the PLA bottles' producers. However, information campaign decreases the profit for the producers of the other kinds of plastic (PET and PEF) bottles, the consumer surplus, and the social welfare. Hence, information policy is beneficial for producers who produce biodegradable bioplastic and those who produce recycled plastic. From the third table, we note that information policy leads many participants to leave the plastic water bottles market. Indeed, after all the messages, the participants know that each plastic presents properties which are harmful for the environment. Some of them may then prefer not using plastic bottle anymore. Other participants have moved their consumption from PET and PEF products to r-PET and PLA products. With the predicted model, consumers only buy packs of six water 1.5 L r-PET bottles. Adding information on the harmfulness of plastic decreases the total number of packs consumed. This implies that with the predicted model, the number of packs of six water 1.5 L r-PET bottles decreases implying a decrease of the profit variation for r-PET bottles' producers instead of increasing it as in the elicited model. Finally, both models show that the consumer surplus and the social welfare decrease with the information policy. So in the market of plastic bottles, information campaign on the plastic damages on the environment is not beneficial for the welfare of consumers and of the society.

Now, we discuss of the impacts of the organic policy on welfares. We note that none of the tools leads to an increase of the social welfare. However, the two models suggest that only a subsidy leads to an increase in consumer surplus and a stable social welfare. All the tools increase the profit of the PEF and PLA bottles' producers and the number of packs of PEF and PLA bottles consumed while they decrease the profits of PET and r-PET bottles' producers and the number of packs of PET and r-PET bottles consumed. With the subsidy, consumers have moved their consumption from PET and r-PET products to PEF and PLA products while with the tax and the standard, they have also left the plastic bottles market.

Now we turn to the recycling policy. We note that only the tax and the subsidy lead to a stable social welfare. We observe that the subsidy increases the consumer surplus and the tax leaves it stable. All the tools decrease the profit for PLA bottles' producers at the benefit of those of the other plastic bottles' producers. We note that consumers have moved their consumption from PLA products to PET, r-PET and PEF products with the subsidy and the tax, while with the standard, they have also left the plastic bottles market.

Then, we analyse the impacts of the biodegradable policy on welfares. We note that none of the tools leads to an increase of the social welfare. Only the subsidy increases the consumer surplus. All the tools increase the profit for PLA bottles' producers at the cost of those of the other plastic bottles' producers. With all the tools, consumers either have moved their consumption from PET, r-PET and PEF products to PLA products, or they have left the plastic bottles market.

We note that the recommendations depend to the point of view taken. For the consumer surplus (producer surplus, or social welfare) point of view, we recommend to the environmental regulator the policy which leads the consumer surplus (producer surplus, or social welfare) to be stable or to increase with the policy. For the participants leaving the plastic bottles market point of view, we recommend the policy which gets a strictly positive number of packs of plastic bottles not consumed. Table 8 sums up our results.

Then, featuring between these policies will depend on regulator's priorities and the pressures of the lobbies.

[32] As we compute variations, we do not need to quantify the production cost C_k.

[33] These prices are estimated from our enquiry at Naturalia and Carrefour market, in November 2013.

Table 7
Welfare analysis in percentage and in euro, and in number of packs over the 148 participants for all the policies.

	Information policy	Organic policy			Recycling policy			Biodegradable policy		
	Information Campaign	Tax	Subsidy	Standard	Tax	Subsidy	Standard	Tax	Subsidy	Standard
Variations in percentage										
Elicited WTP		τ^*_{NO} = 0.10 €	s^*_O = 0.09 €		τ^*_{NR} = 0.01 €	s^*_R = 0.09 €		τ^*_{NB} = 0.10 €	s^*_B = 0.09 €	
Average variation in consumer surplus	−14.23	−2.17	9.49	−17.39	0	12.06	0	−2.17	9.49	−17.39
Average profit variation										
for PET bottles' producers	−4.05	−7.43	−4.05	−10.81	1.35	1.35	4.73	−7.43	−4.05	−10.81
for r-PET bottles' producers	1.35	−8.10	−8.11	−15.55	3.38	3.38	12.83	−8.11	−8.11	−15.55
for PLA bottles' producers	2.70	6.08	6.08	7.44	−20.94	−20.94	−20.94	33.11	32.44	35.81
for PEF bottles' producers	−8.11	6.08	6.08	7.44	16.22	16.22	−20.94	−20.94	−20.94	−20.94
Average social welfare variation	−2.53	−0.92	0	−3.49	0	0	−6.08	−0.92	−0.24	−3.48
Predicted WTP with model OLS		τ^*_{NO} = 0	s^*_O = 0		τ^*_{NR} = 0	s^*_R = 0		τ^*_{NB} = 0	s^*_B = 0	
Average variation in consumer surplus	−43.53	0	0	−1.76	0	0	0	0	0	−1.76
Average profit variation										
for PET bottles' producers	0	0	0	0	0	0	0	0	0	0
for r-PET bottles' producers	−13.61	0	0	−49.44	0	0	0	0	0	−49.44
for PLA bottles' producers	0	0	0	48.89	0	0	0	0	0	48.89
for PEF bottles' producers	0	0	0	0	0	0	0	0	0	0
Average social welfare variation	−3.90	0	0	−0.19	0	0	0	0	0	−0.19
Variations in euro										
Elicited WTP		τ^*_{NO} = 0.10 €	s^*_O = 0.09 €		τ^*_{NR} = 0.01 €	s^*_R = 0.09 €		τ^*_{NB} = 0.10 €	s^*_B = 0.09 €	
Average variation in consumer surplus	−0.07	−0.01	0.05	−0.09	0	0.06	0	−0.01	0.05	−0.09
Average profit variation										
for PET bottles' producers	−0.15	−0.27	−0.15	−0.39	0.05	0.05	0.17	−0.27	−0.15	−0.39
for r-PET bottles' producers	0.05	−0.29	−0.29	−0.56	0.12	0.12	0.45	−0.29	−0.29	−0.56
for PLA bottles' producers	0.10	0.22	0.22	0.27	−0.75	−0.75	−0.75	1.18	1.17	1.29
for PEF bottles' producers	−0.29	0.22	0.22	0.27	0.58	0.58	−0.75	−0.75	−0.75	−0.75
Average tax income/Average subsidy expense		0.01	−0.05		0	−0.06		0.01	−0.05	
Average social welfare variation	−0.36	−0.13	0	−0.50	0	0	−0.88	−0.13	−0.02	−0.50
Predicted WTP with model OLS		τ^*_{NO} = 0	s^*_O = 0		τ^*_{NR} = 0	s^*_R = 0		τ^*_{NB} = 0	s^*_B = 0	
Average variation in consumer surplus	−0.07	0	0	−0.01	0	0	0	0	0	−0.01
Average profit variation										
for PET bottles' producers	0	0	0	0	0	0	0	0	0	0
for r-PET bottles' producers	−0.49	0	0	−1.78	0	0	0	0	0	−1.78
for PLA bottles' producers	0	0	0	1.76	0	0	0	0	0	1.75
for PEF bottles' producers	0	0	0	0	0	0	0	0	0	0
Average tax income/Average subsidy expense		0	0		0	0		0	0	
Average social welfare variation	−0.56	0	0	−0.03	0	0	0	0	0	−0.03
Elicited WTP		τ^*_{NO} = 0.10 €	s^*_O = 0.09 €		τ^*_{NR} = 0.01 €	s^*_R = 0.09 €		τ^*_{NB} = 0.10 €	s^*_B = 0.09 €	
Variation in number of										
packs of PET bottles consumed	−6	−11	−6	−16	2	2	7	−11	−6	−16
packs of r-PET bottles consumed	2	−12	−12	−23	5	5	19	−12	−12	−23
packs of PLA bottles consumed	4	9	9	11	−31	−31	−31	49	48	53
packs of PEF bottles consumed	−12	9	9	11	24	24	−31	−31	−31	−31
packs of plastic bottles not consumed	12	5	0	17	0	0	36	5	1	17
Predicted WTP with model OLS		τ^*_{NO} = 0	s^*_O = 0		τ^*_{NR} = 0	s^*_R = 0		τ^*_{NB} = 0	s^*_B = 0	
Variation in number of										
packs of PET bottles consumed	0	0	0	0	0	0	0	0	0	0
packs of r-PET bottles consumed	−20	0	0	−73	0	0	0	0	0	−73

(*continued on next page*)

Table 7 (*continued*)

	Information policy	Organic policy			Recycling policy			Biodegradable policy		
	Information Campaign	Tax	Subsidy	Standard	Tax	Subsidy	Standard	Tax	Subsidy	Standard
packs of PLA bottles consumed	0	0	0	72	0	0	0	0	0	72
packs of PEF bottles consumed	0	0	0	0	0	0	0	0	0	0
packs of plastic bottles not consumed	20	0	0	1	0	0	0	0	0	1

Table 8
Overview of the recommended policies.

Point of view of	Policy recommended
Consumer surplus	Organic Policy with subsidy at 0.09 € Recycling Policy with tax at 0.01 € Recycling Policy with subsidy at 0.09 € Recycling Policy with standard Biodegradable Policy with subsidy at 0.09 €
Producer surplus	Organic Policy with subsidy at 0.09 € Recycling Policy with tax at 0.01 € Recycling Policy with subsidy at 0.09 €
Social welfare	Organic Policy with subsidy at 0.09 € Recycling Policy with tax at 0.01 € Recycling Policy with subsidy at 0.09 €
Participants who leave the plastic bottles market	Information Policy Organic Policy with tax at 0.10 € Organic Policy with standard Recycling Policy with standard Biodegradable Policy with tax at 0.10 € Biodegradable Policy with subsidy at 0.09 € Biodegradable Policy with standard

5. Conclusion

In this paper, we have analysed the perception and behaviour of the plastic water bottles consumers. This is useful as well for plastic bottles companies' decisions (on production, research and development) as for public authorities' choices (environmental policies).

Currently, there is no consensus on the plastic which is the most or the least dangerous for the environment. It is still difficult to perfectly rank them according to environmental indicators. We have proposed different policies linked to the actual possibilities of plastic bottles. We have found that the recommendations depend to the point of view taken. On the consumer surplus point of view, we recommend the organic policy with subsidy, the three tools of the recycling policy, and the biodegradable policy with subsidy. On the producer surplus point of view, we recommend the organic policy with subsidy, the recycling policy with tax and subsidy. Then, on the social welfare point of view, we recommend the organic policy with subsidy, the recycling policy with tax and with subsidy. Finally, we recommend the information campaign, the organic policy with tax and standard, the recycling policy with standard, and the three tools of the biodegradable policy which lead to the goal that consumers leave the plastic bottle market. Hence, this allows us to understand that the regulator's policy and tool choice are not obvious. This will depend on the regulator's priorities (reduction of emission of CO_2, reduction of landfills, reduction of toxicity, reduction of waste, increasing the consumer surplus, decreasing the plastic water bottles consumption...) and the pressures of the lobbies.

Ferrara and Plourde (2003) have discussed about plastic substitution, for instance by using glass. However, glass has also negative effects on the environment and it is not clear that its use is beneficial in comparison to plastic. Tap water is also an alternative. it is less expensive than water plastic bottles (between 200 and 300 less expensive) and its quality is good in France.[34] This work shows to bottles companies that there is an interest for innovating in a plastic with a better environmental quality (that is biodegradability, recycling, and organic properties). Indeed, by analysing the WTP to participants, we have pointed out their preferences, and so their demands for the different plastic bottles. We have found a significant premium associated with recycled plastic packaging (r-PET) and biodegradable bioplastic packaging (PLA). A plastic bottle with these three properties would have a consumer demand and would increase water companies' production for these kinds of plastic bottles.[35]

Although our work could be reproduced with other samples and/or in other countries, it presents some limitations. First, as in all WTP approaches, there might be a hypothetical bias in our study. As suggested by Lusk (2003), we have tried to reduce this bias with a cheap talk explaining to participants that they should reply as if they would pay for the pack of six 1.5 L plastic bottles. Second, we did not consider controversies or incorrect messages leading to participants' confusion or misunderstanding. To correct this, we would introduce a probability of being wrongly informed δ, namely a probability of having participants with misunderstanding regarding plastic, such that the average variation in consumer surplus for the information campaign would become $\Delta W_N^L = \sum_{i=1}^{N}((1-\delta)W_i^L - \delta W_i^\tau(0))/N$. This assumption would decrease the social benefit of using advertising campaigns. Third, the way to collect data might be discussed. We have used an online study. Cobanoglu et al. (2001), Couper (2000), and McDonald and Adam (2003) highlight that online studies allow to save time and efforts in collecting data. Moreover, Fricker et al. (2005), Kreuter et al. (2008); and Heerwegh and Loosveldt (2008) show that online studies make it possible to get higher quality answers with less 'I do not know' and less unanswered than telephone survey and personal interview survey. So, on the quality data collection, online studies do not look to present more disadvantage than other kinds of surveys.

[34] See: http://www.planetoscope.com/consommation-eau/340-litres-d-eau-en-bouteille-consommes-dans-le-monde.html and http://social-sante.gouv.fr/sante-et-environnement/eaux/article/qualite-de-l-eau-potable.

[35] This study could then motivate more bottles companies to develop the recycling property and process for PLA.

Appendix A

Message 1: *The average price for a pack of six plastic water 1.5 L bottles is 3.6 euro.*

Message 2: *PET plastic used for water bottle is 100% petroleum derived. The average weight of a 1.5 L empty bottle is 32 g: it needs 64 ml of petroleum to produce it (13 coffee spoon).*

Message 3: *Those bottles made with PET needs 500 years to be completely degraded in the nature.*

Message 4: *It is now technologically possible to produce bottles made of 100% of recycled PET. We call then r-PET.*

Message 5: *It is now technologically possible to produce bottles made of 100% of biopolymers, PLA and PEF (derived from sugar or corn, renewable resources, and not from petroleum, fossil resource).*

Message 6: *There are two kinds of biopolymers. The first one, PEF, is not presenting a better biodegradability than PET and r-PET, and has the same negative impact on the environment than PET and r-PET if it is not recycled. The second one, PLA, is biodegradable and can be composted.*

Message 7: *The biodegradable biopolymer, PLA, is a source of methane (powerful greenhouse effect gas).*

Message 8: *As for the non-biodegradable biopolymer, PEF, it is recyclable like the classical polymer.*

References

Abbott, A., Nandeibam, S., O'Shea, L., 2011. Explaining the variation in household recycling rates across the UK. Ecol. Econ. 70, 2214–2223.

Acuff, K., Kaffine, D.T., 2013. Greenhouse gas emissions, waste and recycling policy. J. Environ. Econ. Manage. 65, 74–86.

Azzarello, M.Y., Van Vleet, E.S., 1987. Marine birds and plastic pollution. Mar. Ecol. 37, 295–303.

Bougherara, D., Combris, P., 2009. Eco-labelled food products: what are consumers paying for. Eur. Rev. Agric. Econ. 36 (3), 321–341.

Bossy, D., 2013. L'expédition 7e continent confirme: l'océan est une soupe de plastique. Futura-Sciences.

Cobanoglu, C., Warde, B., Moreo, P., 2001. A comparison of mail, fax, and Web-based survey methods. Int. J. Mark. Res. 43 (4), 405–410.

Couper, M.P., 2000. Web surveys: a review of issues and approaches. Pub. Opin. Quart. 64 (4), 464–494.

Crociata, A., Massimiliano, A., Sacco, P.L., 2015. Recycling waste: does culture matter? J. Behav. Exp. Econ. 55, 40–47.

Cruz, N.F., Simões, P., Marques, R.C., 2012. Economic cost recovery in the recycling of packaging waste: the case of Portugal. J. Clean. Prod. 37, 8–18.

Cruz, N.F., Ferreira, S., Cabral, M., Simões, P., Marques, R.C., 2014. Packaging waste recycling in Europe: is the industry paying for it? Waste Manage. 34 (2), 298–308.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44 (9), 842–852.

Detzel, A., Kauertz, B., Derreza-Greeven, C., 2013. Study of the Environmental Impacts of Packagings Made of Biodegradable Plastics. Federal Environment Agency in Germany.

Disdier, A.-C., Marette, S., Millet, G., 2013. Are consumers concerned about palm oil? Evidence from a lab experiment. Food Policy 43, 180–189.

Drichoutis, A.C., Lazaridis, P., Nayga, R.M., 2008. The role of reference prices in experimental auctions. Econ. Lett. 97, 446–448.

ELIPSO, 2012. Plastic and flexible packaging 14.

Eerhart, A.J.J.E., Faaij, A.P.C., Patel, M.K., 2012. Replacing fossil based PET with bio based PEF; process analysis, energy and GHG balance. Energy Environ. Sci. 5, 6407–6422.

Ferreira, S., Cabral, M., Cruz, N.F., Simões, P., Marques, R.C., 2016. The costs and benefits of packaging waste management systems in Europe: the perspective of local authorities. J. Environ. Plann. Manage., 1–19

Ferrara, I., Plourde, C., 2003. Refillable versus non-refillable containers: the impact of regulatory measures on packaging mix and quality choices. Resour. Policy 29 (1–2), 1–13.

Fitzgerald, E., 2011. Pacific Ocean Plastic Waste Dump.

Fricker, S., Galesic, M., Tourangeau, R., Yan, T., 2005. An experimental comparison of Web and telephone surveys. Pub. Opin. Quart. 69 (3), 370–392.

Hage, O., 2007. The Swedish producer responsibility for paper packaging: an effective waste management policy? Resour. Conserv. Recycl. 51 (2), 314–344.

Heerwegh, D., Loosveldt, G., 2008. Face-to-face versus Web surveying in a high-Internet coverage population: differences in response quality. Pub. Opin. Quart. 72 (5), 836–846.

Kahneman, D., Tversky, A., 1979. Prospect theory: an analysis of decision under risk. Econometrica 47, 263–292.

Kinnaman, T.C., Shinkuma, T., Yamamoto, M., 2014. The socially optimal recycling rate: evidence from Japan. J. Environ. Econ. Manage. 68, 54–70.

Kreuter, F., Presser, S., Tourangeau, R., 2008. Social desirability bias in CATI, IVR, and Web surveys: the effects of mode and question sensitivity. Pub. Opin. Quart. 72 (5), 847–865.

La Mantia, F.P., Botta, L., Morreale, M., Scaffaro, R., 2012. Effect of small amounts of poly(lactic acid) on the recycling of poly(ethylene terephthalate) bottles. Polym. Degrad. Stabil. 97 (1), 21–24.

Lusk, J.L., 2003. Effects of cheap talk on consumer willingness to pay for golden rice. Am. J. Agric. Econ. 85 (4), 840–856.

Marette, S., Messan, A., Millet, G., 2012. Consumers' willingness to pay for eco-friendly apples under different labels: evidences from a lab experiment. Food Policy 37, 151–161.

Marette, S., Millet, G., 2014. Economic benefits from promoting linseed in the diet of dairy cows for reducing methane emissions and improving milk quality. Food Policy 46, 140–149.

Marques, R., Cruz, N.F., Simões, P., Ferreira, S., Cabral, M., De Jaeger, S., 2014. Economic viability of packaging waste recycling systems: a comparison between Belgium and Portugal. Resour. Conserv. Recycl. 85, 22–33.

Mayers, C.K., 2007. Strategic, financial, and design implications of extended producer responsibility in Europe? A producer case study. J. Ind. Ecol. 11 (3), 113–131.

McDonald, H., Adam, S., 2003. A comparison of online and postal data collection methods in marketing research. Market. Intell. Plann. 21 (2), 85–95.

Moore, C.J., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. Environ. Res. 108 (2), 131–139.

Numata, D., 2009. Economic analysis of deposit-refund systems with measures for mitigating negative impacts on suppliers. Resour. Conserv. Recycl. 53 (4), 199–207.

OECD, 2008. Promoting Sustainable Consumption: Good Practices in OECD countries.

Paponga, S., Malakula, P., Trungkavashirakuna, R., Wenununa, P., Chomina, T., Nithitanakulb, M., Sarobolc, E., 2014. Comparative assessment of the environmental profile of PLA and PET drinking water bottles from a life cycle perspective. J. Clean. Prod. 65, 539–550.

Palmer, K., Walls, M., 1997. Optimal policies for solid waste disposal taxes, subsidies, and standards. J. Publ. Econ. 65 (2), 193–205.

Polyzou, E., Jones, N., Evangelinos, K.I., Halvadakis, C.P., 2011. Willingness to pay for drinking water quality improvement and the influence of social capital. J. Socio-Econ. 40, 74–80.

Saido, K., 2014. Ocean contamination generated from plastics, reference module in earth systems and environmental sciences. Compr. Water Qual. Purif. 1, 86–97.

Sazima, I., Gadig, O.B., Namora, R.C., Motta, F.S., 2002. Plastic debris collars on juvenile carcharhinid sharks (Rhizoprionodon lalandii) in southwest Atlantic. Mar. Pollut. Bull. 44 (10), 1149–1151.

Simões, P., Marques, R., 2012. Influence of regulation on the productivity of waste utilities. What can we learn with the Portuguese experience? Waste Manage. 32 (6), 1266–1275.

Timm, J.C., 2014. San Francisco Bans Sale of Plastic Water Bottles on City Property. MSNBC.

Yue, C., Alfnes, F., Jensen, H.H., 2009. Discounting spotted apples: investigating consumers? willingness to accept cosmetic damage in an organic product. J. Agric. Appl. Econ. 41, 29–46.

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Innovation and the precautionary principle

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Recent environmental policies favour the polluter pays principle. This principle points out the pollutant financial liability for the eventual incidents induced by his activities. In this context, we analyse the decision of an agent to invest in new industrial activities, the consequences of which on human health and the environment are initially unknown. It is not possible for him to delay investing, but the agent has the opportunity to acquire information and to reduce the cost of an accident. This allows the agent to reduce uncertainty regarding dangers associated with the project and to limit potential damages that it might cause. However, the agent's chosen level of these actions may be considered as insufficient and not acceptable by society as response in the face of a possible danger. Precautionary state regulation may then be introduced. We appreciate that this regulation may slow down innovation and may favour innovation in countries with less safety requirements. We find that the agent may get around the goal of the regulation by ignoring the information on the dangerousness of its project. We then propose some policy tools which stimulate innovation and impose a certain level of risk considered as acceptable for society to the agent. Finally, we use a numerical analysis based on the Monsanto Company for studying the agent's behaviour with different regulatory frameworks.

Keywords: environment; information acquisition; irreversible investment; the precautionary principle; uncertainty

JEL Classification: D21; D81; D83; H25; O38

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1. Introduction

Investing in new industrial activities, such as pharmaceutical or chemical manufacturing, fertilizer or pesticide processing, or other new technologies, generates uncertainty about the future returns, as well as the costs of damages that such innovations could involve. To reduce this uncertainty, the agent has the opportunity to acquire information on the project's potential consequences on human health and the environment, through basic research activities. Recent health and environmental policies in the European Union (EU) and the United States (USA) favour the polluter pays principle. In international environmental law, the polluter pays principle states that the polluting parties are made liable to pay for the damages they cause. To reduce potential damage costs of an accident, the agent may carry out technological and developmental research into how to reduce the impact by improving, for example, the environmental quality or the safety testing of the product.

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However, the agent's chosen level of these actions may be viewed as insufficient in the face of a possible danger to human health, or to protect the environment. Each country has its own approach of the precautionary principle but all these approaches advocate that evidence of harm to human, animal or plant health, or to the environment, rather than definitive proof of harm, should prompt protecting actions. The strong precautionary principle says that an activity should not proceed if there are potential adverse effects on human health and the environment that are not fully understood, that is, any degree of uncertainty is sufficient to stop an activity. The problem with this interpretation is that there can never be full scientific certainty on anything, and therefore the precautionary principle is sufficient to stop any activity. Furthermore, uncertain damages can occur in both directions. Consider the case of a vaccine that is developed to control the spread of a new virulent strain of flu. The new vaccine could possibly have adverse effects on human health, and hence one might invoke the precautionary principle to block a proposed programme to inoculate the public. But not inoculating the public means that the virulent flu stain might spread, thereby resulting in adverse effects on human health on a global scale. Is it precautionary to inoculate or not to inoculate? In such cases, the strong version of the precautionary principle provides no guidance on what to do. Hence, from the 1992 Rio Declaration,[1] Von Schomberg (2006) has defined a weak precautionary principle for the EU as follows:

> Where, following an assessment of available scientific information, there are reasonable grounds for concern for the possibility of adverse effects but scientific uncertainty persists, provisional risk management measures based on a broad cost/benefit analysis whereby priority will be given to human health and the environment, necessary to ensure the chosen high level of protection in the Community and proportionate to this level of protection, may be adopted, pending further scientific information for a more comprehensive risk assessment, without having to wait until the reality and seriousness of those adverse effects become fully apparent.

By reflecting this weak precautionary approach, precautionary state regulation may be introduced. To a certain extent, information acquisition and cost reduction can be viewed as precautionary efforts in so far as they allow agent under uncertainty to limit potential damages the project could entail and to improve protection of human health and the environment. By invoking the weak precautionary principle, State may require a certain level of information collection and of cost in order to lead the agent to respect a certain level of risk considered as acceptable for society. But what are the consequences of precautionary state regulation on the agent's investment decision? Through examples of the regulation of arsenic in water by the Bush administration, of genetic modification of food, of nuclear power plants and for the trade-off between the protection of marine mammals and military exercises, Sunstein (2002–2003) denounces the possible paralyzing effect of regulation by the precautionary principle. Hence, does the precautionary state regulation slow down innovation as suggested in Sunstein (2002–2003)?

To address these questions, we consider an agent[2] who wants to invest in new industrial activities which cannot be delayed. Indeed, in the race for new technologies, the agent may not be willing to delay investing. For instance, competitive industries, as pharmaceutical industries (medicines, vaccines) and chemical industries (genetically modified organism, GMO), are not willing to delay their investment that could cause them to lose a patent. The agent has a limited initial knowledge on his project's returns, and he has financial liability for eventual incident induced by his activity (the polluter pays principle). He has the opportunity to collect information through basic research, at a cost, and to update his beliefs in a Bayesian way. A degree of information precision is associated with this level of cost: a higher cost

implies a higher precision. Through information acquisition, the agent develops a better understanding of the level of danger associated with his investment project, and can then decide to prematurely stop the project and therefore limit the potential damage to human health and the environment. Moreover, the agent has also the possibility to conduct applied research and experimental development in order to reduce the potential financial costs of the project.[3] Indeed, through applied research and experimental development, the agent limits both financial expenses and the potential damage to human health and the environment in the case of an accident. Using such an approach allows us to consider the problem of managing new activities and to contribute to a better understanding of the issues being faced by the innovator.

We then introduce precautionary state regulation reflecting the precautionary principle. In this paper, precautionary state regulation then consists of imposing a certain level of information collection and of damage cost which lead the agent to respect a certain level of risk considered as acceptable for society. Different regulatory environments may occur. Each state may propose precautionary state regulation. As an example, the EU precautionary regulation on GMOs establishes a case-by-case and step-by-step procedure in which the applier for a GMO release has to demonstrate safety of its product (Von Schomberg 2006). This constrains the applier to identify, through research, and to reduce the ecological or potential health risks attached to its production. This precautionary regulation is specific to Europe and is scientifically justified by the uncertainties about the impacts of the GMOs uses and the lack of scientific information to resolve these uncertainties (Johnston and Santillo 2006).

Our approach relies on two building blocks. First, our paper is linked to the literature that examines the interaction of irreversibility, uncertainty, and information acquisition. Arrow and Kurz (1970) conducted pioneering work on irreversible investments under certainty. Their work was expanded through the introduction of uncertainty (Charles and Munro 1985; Clark, Munro, and Charles 1985; Pindyck 1981; Viscusi 1985).

The role of information in irreversible investment decisions is covered in a large body of work by Arrow and Fisher (1974), Crabbe (1987), Dixit and Pindyck (1994), Fisher (1978), Freeman (1984), Freixas and Laffont (1984), Gollier and Treich (2003), Henry (1974), and Jones and Ostroy (1984). These works propose a conventional 'option value' approach, in which the investment is irreversible (i.e. it cannot be recovered in the future) and investment decisions are made under uncertainty about future returns. An agent can postpone investing in order to be able to acquire more information about the possible future consequences of the project. This leads one to evaluate the option value of waiting in order to get new information. We propose to analyse the irreversible investment decision made in a context of uncertainty about future returns by an agent who does not have the option to postpone his investment. Moreover, we integrate endogenous information in a literature, real option theory (Arrow and Fisher 1974; Dixit and Pindyck 1994; Henry 1974; Schwartz and Trigeorgis 2001), that usually deals with exogenous information, by allowing the agent to initially decide whether or not he will acquire information in the future.

Gollier, Jullien, and Treich (2000), Gollier (2001), and Gollier and Treich (2003) have focused on a precautionary approach to the interaction of irreversibility and uncertainty. Gollier, Jullien, and Treich (2000) propose an economic interpretation of the precautionary principle within the standard Bayesian framework. They consider that more scientific uncertainty should induce society to take stronger prevention measures today. They examine how the prospect of receiving information affects the current prevention effort and show that earlier prevention effort only if prudence is larger than twice absolute risk aversion. Under this condition, they then conclude that scientific uncertainties justify an immediate

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reduction of the consumption of a potentially toxic substance. Gollier (2001) proposes to balance the precautionary principle against the benefits of waiting to learn before we act by using a standard cost–benefit analysis. Finally, Gollier and Treich (2003) investigate how classical economic theory justifies the precautionary principle. They identify conditions so that the precautionary principle is an efficient economic guideline. However, none of these studies has ever specified the precautionary state regulation requirements emerging from the precautionary principle. To the best of our knowledge, we are the first to state them exactly and to analyse with a mathematical formalization their impacts on the irreversible investment, and so on innovation.

Furthermore, our paper is also relied to the literature on the Porter Hypothesis. In its original writings, Porter (1991) suggested that environmental regulation will enhance a country's competitiveness. Jaffe et al. (1995) found evidence that was consistent with Porter's writings. But Brunnermeier and Levinson (2004) and Copeland and Taylor (2004) found evidence which contradicted these writings and supported the pollution haven hypothesis which states that stringent environmental regulation will induce firms to leave the country for less strict regulatory regimes. In other words, the stringent environmental regulation may favour the outsourcing decision.

In 1995,[4] Porter proposed the Porter Hypothesis which states that 'properly designed environmental regulation can trigger innovation that may partially or more than fully offset the costs of complying with them'. The Porter Hypothesis suggests the existence of 'win-win' situation, in which society and private firms could both be winners with the introduction of environmental regulation. This hypothesis is contrary to the traditional paradigm which says that environmental regulation restricts the firm's options and thus reduced their profit. Conflicting theoretical and empirical studies concerning this hypothesis have been written. Oates, Palmer, and Portney (1995) suggest that environmental regulation may increase the firm's payoff by leading them to profitable innovation. However, these are exceptions instead of the rule. Actually, they argue that firms should identify by themselves if there are opportunities to reduce costs and inefficiencies without the need for government intervention. On the other hand, Xepapadeas and Zeeuw (1999) find that environmental regulations have a negative impact on profit.

Three distinct variants of the Porter Hypothesis were presented by Jaffe and Palmer (1997): the 'weak' version in which environmental regulation will stimulate certain kinds of environmental innovations; the 'narrow' version which asserts that flexible environmental policy instruments, such as pollution charges or tradable permits, give firms a greater incentive to innovate than prescriptive regulations, such as technology-based standards; and finally, the 'strong' version which posits that properly designed regulation may induce innovation that more than compensates for the cost of compliance and improves the financial situation of the firm.[5] In general, empirical studies have found strong support for the 'weak' version (Jaffe and Palmer 1997; Lanoie et al. 2011), limited support for the 'narrow' version (Lanoie et al. 2011), and qualified support for the 'strong' version with the studies of Gollop and Roberts (1983), Jaffe et al. (1995), and Lanoie et al. (2011) which contradict this version, and the studies of Alpay, Buccola, and Kerkvliet (2002), Berman and Bui (2001), and Lanoie, Patry and Lajeunesse (2008) which support it. In our paper, we contribute to this literature by analysing the impact of the precautionary state regulation based on the precautionary principle on innovation and competitiveness.

We find that precautionary state regulation may lead the agent to prefer not investing in the project while he would have done without regulation or/and under a less cautious regulation. In this situation, precautionary state regulation may then be considered as an obstacle to innovation. Moreover, in order to respect the regulation, the agent pays for

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acquiring information but he may not use it and stay ignorant about the dangerousness of its project. The agent may get around the goal of the precautionary state regulation to reduce the uncertainty. In order to avoid this kind of pervert effects, we propose some policy tools, subsidies, which stimulate innovation in a country and impose a certain level of risk considered as acceptable for society to the agent.

Using an analytical approach and numerical analysis based on the Monsanto Company, we show that risk perception and the level of uncertainty influence the decision of acquiring information, and so the decision to reduce the uncertainty. Besides, the choice of policy tools has to be taken with caution. Indeed, State may not support the activity when the subsidy that it should give to the company is so large. Finally, we find that the choice of the precautionary state regulation may be decisive for attracting innovators. An aggressive competition between the countries could lead to less cautious regulation, so less safety, and large subsidies in the worst case. We have chosen the Monsanto Company case because this American multinational chemical industry is the world leader of the GMOs. The Monsanto Company was founded in Saint Louis, Missouri, in 1901, by John Francis Queeny (1859–1933). It has a vision of a future with 'Abundant Food and a Healthy Environment'. In 2013, the Monsanto Company was the world's largest supplier of vegetable seeds by value, selling 821m of seed. RoundUp, manufactured by the Monsanto Company, is the world's biggest selling herbicide. However, the Monsanto Company has a long and messy history of manufacturing hazardous chemicals. As examples, in 1929, the Monsanto Company became the largest producer of polychlorinated biphenyls which are one of the deadliest carcinogens and chemicals that can cause immune system disorder, birth defects, cancer, and fatal death. From 1961 to 1971, the Monsanto Company was involved in the production of Agent Orange which has created severe health problems for the Vietnamese citizens as well as the US military. In 1994, the recombinant bovine growth hormone, a genetically engineered hormone manufactured by Monsanto Company under the name of Posilac, is injected in the cows every week to force the cows to produce more milk than their bodies normally would. This causes a number of problems with the milk, among them, raising levels of pus, antibiotics residues and breast, prostate, and colon human cancers.[6]

The remainder of paper is organized as follows. Section 1 introduces the model. Section 2 studies the agent's optimal investment in the project and its optimal expenses on information collection and on damage reduction. Section 3 introduces precautionary state regulation and different policy tools which favour innovation in the country and impose a certain level of risk considered as acceptable for society to the innovator. A numerical illustration based on the Monsanto Company is provided in Section 4. Finally, Section 5 concludes. All proofs are given in the appendix.

2. The model

We consider a three-period model. At period 0, an agent may invest $I \geq 0$ in a project that may cause damage to human health and to the environment. We consider two possible states of the world, H and L associated with different probabilities of damage θ^H and θ^L, respectively. We assume that state H is more dangerous than state L, so:

$$\theta^L < \theta^H.$$

At period 0, the prior beliefs of the agent are p_0 on state H, and $1 - p_0$ on state L. The expected probability of the damage is thus given by

$$E(\theta) = p_0\theta^H + (1 - p_0)\theta^L.$$

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At period 0, the agent may pay $C^a \geq 0$, to undertake applied research and experimental development, specifically technological and development research about how to improve the environmental quality and the safety testing of the product. Getting a better quality and a better safety lead to limit damage given on accident occurs. So C^a is an expense in damage reduction. The agent may also pay $C^b \geq 0$ to undertake basic research for acquiring information at period 1 through a signal $\sigma \in \{h, l\}$ on the true state of the world. C^b is an expense on information collection.

The precision of the signal is defined as the probability the signal corresponds to the state. Here it is represented as an increasing and concave function $f(C^b)$ such that:

$$P(h|H, C^b) = P(l|L, C^b) = f(C^b) \quad \text{and} \quad P(h|L, C^b) = P(l|H, C^b) = 1 - f(C^b)$$

and

$$f(0) = \tfrac{1}{2}.$$

Hence, the information precision depends on the expense on information collection C^b. If the agent does not pay for information acquisition, i.e. $C^b = 0$, then the signal is not informative.[7] On the other hand, a larger expense implies a higher precision.

According to the Bayes' rule, the probability of being in state H given signal h and C^b, and the probability of being in state H given signal l and C^b are, respectively:

$$P(H|h, C^b) = \frac{p_0 f(C^b)}{p_0 f(C^b) + (1 - p_0)(1 - f(C^b))} \quad \text{and}$$

$$P(H|l, C^b) = \frac{p_0 (1 - f(C^b))}{p_0 (1 - f(C^b)) + (1 - p_0) f(C^b)}.$$

At period 1, according to signal $\sigma \in \{l, h\}$, let us define $x_\sigma \in \{0, 1\}$ as the agent's decision to either stop, or to continue his project. We assume that when the agent stops his project $x_\sigma = 0$, while $x_\sigma = 1$ if he continues it.

At period 2, an accident might happen. If the project has been stopped at period 1, then the returns from the project are equal to zero.[8] On the other hand, if the project has continued until period 2, it yields a payoff equal to $R(I) \geq 0$. From this payoff must be subtracted the cost of accident $K(I, C^a) \geq 0$ that occurs with probability θ^H or θ^L depending on the state of the world. This cost is damage – a negative consequence – on human health and the environment, and thus represents an externality. This externality has been fully internalized by some market or economic instrument, which renders this externality equivalent to a private cost. In other word, the agent is strictly liable for damages, as imposed by the polluter pays principle. We assume that R is an increasing concave function such that $R(0) = 0$. K is an increasing convex function with I, while it is a decreasing convex function with C^a, such that $K(0, C^a) = 0$. We also assume that for all $K \geq 0$, $K_{IC^a} < 0$, i.e. the marginal damage of the project, K_I, decreases when additional funds are spent to reduce damages.

We note $\beta \leq 1$ as the discount rate. So the expected payoffs at period 1 and period 0 may be expressed recursively:[9]

$$V_1(x_\sigma, \sigma, I, C^b, C^a) = \beta x_\sigma [P(H|\sigma, C^b)(R(I) - \theta^H K(I, C^a)) + (1 - P(H|\sigma, C^b))(R(I) - \theta^L K(I, C^a))]$$

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and

$$V_0(x_h, x_l, I, C^b, C^a) = -I - C^b - C^a + \beta(p_0 f(C^b) + (1-p_0)(1-f(C^b)))V_1(x_h, h, I, C^b, C^a) + \beta(p_0(1-f(C^b)) + (1-p_0)f(C^b))V_1(x_l, l, I, C^b, C^a).$$

We assume that the maximization problem linked to the expected profit $V_0(x_h, x_l, I, C^b, C^a)$ is always well defined.

3. Optimal decision-making

At period 0, the agent chooses how much he is willing to invest in the project to pay for reducing damage and for acquiring information, knowing that at period 1, he takes decision to stop or to continue the project.

We use the backward induction method in order to characterize the agent's optimal decisions.

3.1. Stopping or continuing the project

For $\sigma \in \{h, l\}$ and $C^b \geq 0$, denote both the equilibrium strategy by x^*_σ and the revised expected probability of damage by $E(\theta|\sigma, C^b) = P(H|\sigma, C^b)\theta^H + (1 - P(H|\sigma, C^b))\theta^L$. For $\sigma \in \{h, l\}$ and for $I, C^b, C^a \geq 0$, agent continues the project if his expected payoff by continuing the project is higher than when he stops it. That is

$$V_1(0, \sigma, I, C^b, C^a) < V_1(1, \sigma, I, C^b, C^a).$$

Conditions under which agent stops or continues his project are: for $\sigma \in \{h, l\}$ and $I, C^b, C^a \geq 0$, if $R(I) > E(\theta|\sigma, C^b)K(I, C^a)$, then the agent continues the project, i.e. $x^*_\sigma = 1$; If $R(I) < E(\theta|\sigma, C^b)K(I, C^a)$, then he stops the project, i.e. $x^*_\sigma = 0$; Finally, if $R(I) = E(\theta|\sigma, C^b)K(I, C^a)$, then he is indifferent between stopping and continuing his project, i.e. $x^*_\sigma \in \{0, 1\}$. So the agent continues his project unless its expected cost exceeds its payoff.

We can easily verify that:

LEMMA 1 *For all* $C^b \geq 0, \theta^L \leq E(\theta|l, C^b) \leq E(\theta) \leq E(\theta|h, C^b) \leq \theta^H$, *and* $E(\theta|h, C^b)$ *is increasing with* C^b *while* $E(\theta|l, C^b)$ *is decreasing with* C^b.

Hence, a higher expense on information collection improves the knowledge of agent on the true state of the world and emphasizes the decision of stopping project when agent receives signal h, i.e. being in the most dangerous state of the world, and the decision of continuing project when the agent receives signal l. In addition, a higher expense in damage reduction strengthens the decision of continuing project and weakens the decision of stopping it.

Moreover, according to Lemma 1, agent is confronted to three strategies. First, he always stops the project whatever the signal. Actually, the agent expects that, in the two states of the world, the consequences of his project will lead him to a negative return. Second, the agent always continues the project whatever the signal. Here, the agent expects that even in the worst state of the word, his project is profitable. Finally, the agent stops the project when he receives signal h (being the most dangerous state of the world), while when he gets signal l he continues it. So the agent considers that its returns will be negative if the state H occurred and if state L occurred, it will be positive.

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3.2. Project investment and expenses on information collection and in damage reduction

We now turn to agent's optimal decisions to invest in the project, to acquire information and to reduce damage. The agent chooses optimally how much he is willing to invest in the project and pay for acquiring information and for reducing damage knowing that he will either always stop the project whatever the signal, or always continue it whatever the signal, or only continue it if he receives signal l.

Define by $I_{x_h x_l}$ the agent's optimal investment in the project, $C^b_{x_h x_l}$, the agent's optimal expense on information collection, $C^a_{x_h x_l}$, the agent's optimal expense in damage reduction, under the strategy $\{x_h, x_l\}$. The agent wants to maximize its expected payoff, he then solves the following problem:

$$\max_{I, C^b, C^a \geq 0} V_0(x_h, x_l, I, C^b, C^a).$$

Let us first study case in which agent anticipates that he will always stop the project, i.e. $\{x_h = 0, x_l = 0\}$. Agent's expected payoff under this strategy is

$$V_0(0, 0, I, C^b, C^a) = -I - C^b - C^a.$$

Since $V_0(0, 0, I, C^b, C^a)$ is decreasing with I, C^b and C^a, then the agent does not invest in the project and does not make any expenses on information collection and in damage reduction. Overall, the optimal decisions are $I_{00} = C^b_{00} = C^a_{00} = 0$.

So when the agent anticipates that he always stops the project in the future, he considers that the project is not profitable for him and does not want to waste money by investing in the project. He is not willing to make expenses in information collection and in damage reduction either.

Let us now study the case in which the agent anticipates that he will always continue the project, i.e. $\{x_h = 1, x_l = 1\}$. Agent's expected payoff under this strategy is

$$V_0(1, 1, I, C^b, C^a) = -I - C^b - C^a + \beta^2(R(I) - E(\theta)K(I, C^a)). \tag{1}$$

Before investing the agent, first check the expected profitability of the project. If he expects that the project is not profitable, i.e. for all $I > 0$ and $C^b, C^a \geq 0$:

$$\beta^2 R(I) < I + C^b + C^a + \beta^2 E(\theta)K(I, C^a),$$

then the agent decides not to invest and not to do any expenses on information collection and in damage reduction, i.e. $I_{11} = C^b_{11} = C^a_{11} = 0$.

On the other hand, if he anticipates that the project is profitable, i.e. if there exists $I > 0$ and $C^b, C^a \geq 0$ such that:

$$\beta^2 R(I) \geq I + C^b + C^a + \beta^2 E(\theta)K(I, C^a),$$

then the agent never acquires information, i.e. $C^b_{11} = 0$, because $V_0(1, 1, I, C^b, C^a)$ is decreasing with C^b. However, he invests in the project $I_{11} > 0$, and makes an expense in damage reduction $C^a_{11} > 0$. So the agent pays for safety and quality measures without paying for the likelihood of an accident. We have assumed that the maximization problem linked to the expected profit $V_0(x_h, x_l, I, C^b, C^a)$ is always well defined. Thus, we consider that $V_0(1, 1, I, 0, C^a)$ is concave. I_{11} and C^a_{11} are then characterized by the first-order

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conditions:

$$\begin{cases} \beta^2 R'(I) - \beta^2 E(\theta) K_I(I, C^a) = 1; \\ \beta^2 E(\theta) K_{C^a}(I, C^a) = -1. \end{cases} \tag{2}$$

Let us turn to case in which agent anticipates to only give up the project if he receives signal h, i.e. $\{x_h = 0, x_l = 1\}$. Agent's expected payoff under this strategy is as follows:

$$\begin{aligned} V_0(0, 1, I, C^b, C^a) = &-I - C^b - C^a + \beta^2(p_0(1 - f(C^b))(R(I) - \theta^H K(I, C^a))) \\ &+ \beta^2((1 - p_0) f(C^b)(R(I) - \theta^L K(I, C^a))). \end{aligned} \tag{3}$$

The agent first verifies the profitability of the project. If for all $I > 0$ and $C^b, C^a \geq 0$

$$\begin{aligned} \beta^2(p_0(1 - f(C^b)) + (1 - p_0) f(C^b)) R(I) < I + C^b + C^a + \beta^2(p_0(1 - f(C^b))\theta^H \\ + (1 - p_0) f(C^b)\theta^L) K(I, C^a), \end{aligned}$$

then the agent decides not to invest and not to make any expenses on information collection and in damage reduction, i.e. $I_{01} = C^b_{01} = C^a_{01} = 0$.

On the other hand, if there exists $I > 0$ such that for all $C^b, C^a \geq 0$

$$\begin{aligned} \beta^2(p_0(1 - f(C^b)) + (1 - p_0) f(C^b)) R(I) > I + C^b + C^a + \beta^2(p_0(1 - f(C^b))\theta^H \\ + (1 - p_0) f(C^b)\theta^L) K(I, C^a), \end{aligned}$$

then the agent invests in the project $I_{01} > 0$, makes an expense on information collection $C^b_{01} > 0$, and makes an expense in damage reduction $C^a_{01} > 0$. We have assumed that the maximization problem linked to the expected profit $V_0(x_h, x_l, I, C^b, C^a)$ is always well defined. Thus, we consider that $V_0(0, 1, I, C^b, C^a)$ is concave. I_{01}, C^a_{01} and C^b_{01} are then characterized by the first-order conditions:

$$\begin{cases} \beta^2(p_0(1 - f(C^b))(R'(I) - \theta^H K_I(I, C^a)) + (1 - p_0) f(C^b)(R'(I) - \theta^L K_I(I, C^a))) = 1; \\ \beta^2(p_0(1 - f(C^b))\theta^H + (1 - p_0) f(C^b)\theta^L) K_{C^a}(I, C^a) = -1; \\ \beta^2(p_0(R(I) - \theta^H K(I, C^a)) - (1 - p_0)(R(I) - \theta^L K(I, C^a))) f'(C^b) = -1. \end{cases} \tag{4}$$

Finally, define I^* as the agent's optimal investment in the project, C^{b*}, the agent's optimal expense on information collection, and C^{a*}, the agent's optimal expense in damage reduction over all the strategies. To determine them, we compare agent's expected payoffs of the three strategies and select I, C^b and C^a that lead to the highest expected payoff. We obtain the next result.

LEMMA 2 *If for* $I_{01}, I_{11} > 0$ *and* $C^a_{01}, C^b_{01}, C^a_{11}, C^b_{11} \geq 0$,

$$\begin{aligned} &\beta^2(p_0(1 - f(C^b_{01})) + (1 - p_0) f(C^b_{01})) R(I_{01}) \\ &\quad \geq I_{01} + C^b_{01} + C^a_{01} + \beta^2(p_0(1 - f(C^b_{01}))\theta^H + (1 - p_0) f(C^b_{01})\theta^L) K(I_{01}, C^a_{01}) \end{aligned} \tag{5}$$

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and

$$
\begin{aligned}
&-I_{11} - C_{11}^{b} - C_{11}^{a} + \beta^2[R(I_{11}) - E(\theta)K(I_{11}, C_{11}^{a})] \\
&\quad \leq -I_{01} - C_{01}^{b} - C_{01}^{a} + \beta^2(p_0(1 - f(C_{01}^{b}))(R(I_{01}) - \theta^H K(I_{01}, C_{01}^{a}))) \\
&\qquad + \beta^2((1 - p_0)f(C_{01}^{b})(R(I_{01}) - \theta^L K(I_{01}, C_{01}^{a}))) \qquad (6)
\end{aligned}
$$

hold, then the agent invests $I^* = I_{01} > 0$, *makes expenses* $C^{b*} = C_{01}^{b} > 0$ *for acquiring information and* $C^{a*} = C_{01}^{a} \geq 0$ *for reducing damage. Then if condition* (6) *does not hold and*

$$
I_{11} + C_{11}^{b} + C_{11}^{a} + \beta^2 E(\theta)K(I_{11}, C_{11}^{a}) \leq \beta^2 R(I_{11}) \qquad (7)
$$

holds, the agent then invests $I^* = I_{11} > 0$, *makes an expense* $C^{a*} = C_{11}^{a} \geq 0$ *for reducing damage but does not make a spending for acquiring information,* $C^{b*} = C_{11}^{b} = 0$; *Finally, if conditions* (5) *and* (7) *do not hold, then the agent does not invest in the project* $I^* = 0$, *nor makes any expenses for acquiring information and for reducing damage,* $C^{b*} = C^{a*} = 0$.

So we denote three behaviours: First, the agent decides not to invest because he anticipates that the project will not be profitable whatever the state of the world which will occur. Second, the agent decides to invest in the project and makes an expense for reducing damages by improving safety and the quality of the product. However, he refuses to make an expense on information collection, he does not decrease the uncertainty. Hence, the agent is more concerned by the potential financial cost of its project than by learning about the potential damages. Third, the agent invests in the project, makes an expense for reducing damage, and for acquiring information which allows him to withdraw the project when there exists a possibility for the worse state to be revealed. This behaviour may be considered as cautious. Indeed, the agent tries to reduce both the uncertainty on the state of the world and the consequences of a potential damages. However, through that, these actions may be judged as not acceptable for society. Indeed, from the precautionary approach, they might be not sufficient to protect health and the environment.

4. Precautionary state regulation

In its strongest forms, the precautionary principle says that an activity should not proceed if there are potential adverse effects on human health and the environment that are not fully understood. In this form, the precautionary principle is literally paralyzing (Sunstein 2003). However, from the 1992 Rio Declaration, a weakest version of the precautionary principle has been suggested implying that a lack of decisive evidence of harm should not be a ground for refusing to regulate. As Sunstein (2003) says, the precautionary principle might be described both in terms of the level of uncertainty that triggers a regulatory response and in terms of the tool that will be chosen in the face of uncertainty (technological requirements). Regarding to this, we propose a precautionary state regulation aims for imposing a certain level of information collection and of damage cost which lead the agent to respect a certain level of risk considered as acceptable for society. The choice of these levels determines the actual standards for health and the environment of a country.

As an example, the US Food and Drug Administration regulation on GMO reflecting the precautionary principle shows a design of a precautionary regulatory framework. Food

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and feed made from GMOs can only be allowed on the market once they have received authorization. Contrary to the EU precautionary regulation on GMOs, there is no a case-by-case procedure. Firms producing GMOs have to demonstrate that their products are not dangerous to health and the environment. This constrains the firm to acquire a certain level of information precision and to improve safety and quality of its product in order to reduce potential damage. If the firm does not respect the level of protection imposed by the regulation, there is no delivery of authorization of selling in USA.

We then analyse the agent's behaviour with the introduction of precautionary state regulation in accordance with the precautionary principle. The government constrains agent to take all appropriate measures to avoid adverse effects of its production on human health and the environment. No respect of this regulation could justify restricted use or a ban of the agent's products. According to the court of Law and the state's policy, the level of risk considered as acceptable for society may be specified by the legal framework in considering an acceptable cost of damage, $\bar{K} \geq 0$ and a sufficient reduction of uncertainty, i.e. a sufficient knowledge, $\underline{f} > \frac{1}{2}$.[10]

Under the precautionary state regulation, let us define $I^R_{x_h x_l}$ the agent's optimal investment in the project, $C^{bR}_{x_h x_l}$, the agent's optimal expense on information collection, $C^{aR}_{x_h x_l}$, the agent's optimal expense in damage reduction under the strategy $\{x_h, x_l\}$. $I^R_{x_h x_l}$, $C^{bR}_{x_h x_l}$, and $C^{aR}_{x_h x_l}$ maximize the agent's expected payoff under precautionary state regulation constraints:

$$\begin{cases} \max_{I \geq 0, C^b \geq 0, C^a \geq 0} V_0(x_h, x_l, I, C^b, C^a). \\ f(C^b) \geq \bar{f}, \\ K(I, C^a) \leq \bar{K}. \end{cases}$$

We do not consider the case in which the agent anticipates that he will always stop his project, i.e. the strategy $\{x_h = 0, x_l = 0\}$. Indeed, in this case, the agent does not undertake the project, so there is no need of regulation. We then only analyse the two other cases: the agent anticipates that he will always continue his project whatever the signal, he then maximizes the expected payoff (1) under the precautionary state regulation constraints $f(C^b) \geq \bar{f}$ and $K(I, C^a) \leq \bar{K}$; And, the agent anticipates that he will only give up the project if he receives signal h, he then maximizes the expected payoff (3) under the precautionary state regulation constraints $f(C^b) \geq \bar{f}$ and $K(I, C^a) \leq \bar{K}$. For each case, if the project is not profitable, i.e. for $x_h \in \{0, 1\}$ and $x_l \in \{1\}$ if for all $I > 0$ and $C^b, C^a \geq 0$, $V_0(x_h, x_l, I, C^b, C^a) < 0$, we get that $I^R_{x_h x_l} = C^{bR}_{x_h x_l} = C^{aR}_{x_h x_l} = 0$. Otherwise, if the project is profitable, I^R_{11}, C^{aR}_{11}, and C^{bR}_{11} are characterized by Equation (2) and the precautionary state regulation constraints $f(C^b) \geq \bar{f}$ and $K(I, C^a) \leq \bar{K}$; and I^R_{01}, C^{aR}_{01}, and $C^{bR} b_{01}$ are characterized by Equation (4) and the precautionary state regulation constraints $f(C^b) \geq \bar{f}$ and $K(I, C^a) \leq \bar{K}$.

Finally, define I^R as the agent's optimal investment in the project, C^{bR}, the agent's optimal expense on information collection, C^{aR}, the agent's optimal expense in damage reduction under regulation over all the cases. To determine them, we compare agent's expected payoffs of the two cases and select I, C^b, and C^a that lead to the highest expected payoff. We obtain the results of Lemma 2 by changing $I_{x_h x_l}$ by $I^R_{x_h x_l}$, $C^b_{x_h x_l}$ by $C^{bR}_{x_h x_l}$, $C^b_{x_h x_l}$ by $C^{aR}_{x_h x_l}$, I^* by I^R, C^{b^*} by C^{bR}, and C^{a^*} by C^{aR}.

Now we analyse the agent's decision to invest in the project. If the agent has decided not to invest in the absence of regulation, in the presence of regulation he will not invest. However, if it is optimal for the agent to invest in the absence of regulation, it might occur that under regulation, it is not optimal anymore. Actually, under regulation the agent gets at

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best the same payoff than in the absence of regulation. Indeed, in the absence of regulation the agent chooses its first best solution. Regulation may be so constraining that the agent's payoff is negative. The project is not profitable anymore and the agent does not invest in it. This does not support the Porter Hypothesis. However, if we only focus on the future payoff (at period 2), the precautionary state regulation may have a positive effect in the long run, in particular with a cost function strongly convex in C^a.

Moreover, in order to respect the regulation, the agent makes an expense on information collection; however, he may not use this information. Indeed, the agent may remain ignorant because its profit with information is lower than without information. Actually, this behaviour has already occurred in the past , for example, the asbestos case. The dangerousness was already known by Greeks and Romans. In 1898, the annual reports of the Chief Inspector of Factories confirmed that asbestos created health risks. However, asbestos industry refused this available information on the asbestos risks. In the 1970s, after many facts revealed the link between cancer and asbestos, the first regulation appeared. The use of asbestos in new construction projects is now banned in many developed countries (Henry 2003).

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In addition, since the countries may have different regulatory environments, a pervert effect of the precautionary regulation might be to decrease innovation in the country with the most cautious regulation. Indeed, since under regulation the agent gets at best the same payoff than in the absence of regulation, agent may decide to move on in another country without (or less) cautious regulation in order to reach its maximum (or a better) payoff. This idea contradicts Porter's original writings and supports the pollution haven hypothesis (here we could call it the risk factor haven hypothesis) which says that the stringent regulation may favour the outsourcing decision. In this context, State might evaluate the acceptable cost of damage, $\bar{K} \geq 0$ and the sufficient reduction of uncertainty, $\underline{f} > \frac{1}{2}$ such that: if at least one country does not have any precautionary regulation, $\bar{K} = K(I^*, C^{a*})$ and $\underline{f} = f(C^{b*})$; otherwise, if all States establish precautionary regulation, $\bar{K} = K(\bar{I}, \bar{C}^a)$ and $\underline{f} = f(\bar{C}^b)$ with $\bar{I}$, $\bar{C}^a$, and $\bar{C}^b$, the investment in the project, the expenses in damage reduction, and on information collection associated to $\bar{V}_0$, the agent's highest expected payoff considering all the precautionary regulations of all the countries in the world, respectively. We note that $\bar{V}_0 \leq V_0(x_h, x_l, I^*, C^{b*}, C^{a*})$. However, this evaluation is not based on the level of risk acceptable by the society, but it only depends on the innovation policy which favours a large number of innovating firms in order to increase the growth and the employment. Precautionary state regulation favouring innovation in a country could be done to the detriment of the security. Hence, precautionary state regulation should not take into account of this evaluation.

So, how both to stimulate innovation in a country and to impose a certain level of risk considered as acceptable for society to the agent? We then propose policy tools which reach these goals.

First, State may promote a funding for compensating the agent's expected payoff loss. We propose subsidies or allocations that the state could give to the agent to lead him both to invest in the project in the country and to respect a certain level of risk considered as acceptable for society.

PROPOSITION 1 (i) *If* $V_0(0, 1, I_{01}^R, C_{01}^{bR}, C_{01}^{aR}) < V_0(1, 1, I_{11}^R, C_{11}^{bR}, C_{11}^{aR}) < \bar{V}_0$, *State may promote a funding to lead the agent to invest in the project in the country*, $\tau_1 \geq 0$, *and a funding to lead him to respect a certain level of risk considered as acceptable for society*, $\tau_2 \geq 0$,

such that:

$$\begin{cases} V_0(1,1,I_{11}^R,C_{11}^{bR},C_{11}^{aR}) + \tau_1 = \bar{V}_0, \\ V_0(0,1,I_{01}^R,C_{01}^{bR},C_{01}^{aR}) + \tau_2 = V_0(1,1,I_{11}^R,C_{11}^{bR},C_{11}^{aR}). \end{cases}$$

(ii) *If* $V_0(1,1,I_{11}^R,C_{11}^{bR},C_{11}^{aR}) \leq V_0(0,1,I_{01}^R,C_{01}^{bR},C_{01}^{aR}) < \bar{V}_0$, *State may promote a funding to lead the agent to invest in the project in the country*, $\tau \geq 0$ *such that*:

$$V_0(0,1,I_{01}^R,C_{01}^{bR},C_{01}^{aR}) + \tau = \bar{V}_0.$$

Second, we propose subsidies or allocations for research that the state could give to the agent to lead him both to invest in the project in the country and to respect a certain level of risk considered as acceptable for society.[11]

PROPOSITION 2 (i) *If* $V_0(0,1,I_{01}^R,C_{01}^{bR},C_{01}^{aR}) < V_0(1,1,I_{11}^R,C_{11}^{bR},C_{11}^{aR}) < \bar{V}_0$, *State may promote a funding for reducing damage, and so a funding for applied research, to lead the agent to invest in the project in the country,* $C_{\tau 1}^a \geq 0$, *and another funding for applied research to lead him to respect a certain level of risk considered as acceptable for society,* $C_{\tau 2}^a \geq 0$, *such that*:

$$\begin{cases} V_0(1,1,I_{11}^R,C_{11}^{bR},C_{11}^{aR} + C_{\tau 1}^a) + C_{\tau 1}^a = \bar{V}_0, \\ V_0(0,1,I_{01}^R,C_{01}^{bR},C_{01}^{aR} + C_{\tau 2}^a) + C_{\tau 2}^a = V_0(1,1,I_{11}^R,C_{11}^{bR},C_{11}^{aR}). \end{cases}$$

(ii) *If* $V_0(1,1,I_{11}^R,C_{11}^{bR},C_{11}^{aR}) \leq V_0(0,1,I_{01}^R,C_{01}^{bR},C_{01}^{aR}) < \bar{V}_0$, *State may promote a funding for reducing damage and for acquiring information, so a funding for applied and basic research,* $C_\tau^a + C_\tau^b \geq 0$. $C_\tau^a \geq 0$ *and* $C_\tau^b \geq 0$ *are characterized by*

$$V_0(0,1,I_{01}^R,C_{01}^{bR} + C_\tau^b, C_{01}^{aR} + C_\tau^a) + C_\tau^b + C_\tau^a = \bar{V}_0. \tag{8}$$

State may choose the combination of (C_τ^a, C_τ^b) *which verifies Equation* (8) *in accordance with its R&D policy.*

From Propositions 1 and 2, we note that when the expected payoff under regulation is lower than the agent's highest expected payoff considering all the precautionary regulation of all the countries in the world, State may give compensation to agent in order to yield him to invest in the country. In addition, if the highest expected payoff under regulation leads the agent to pay for acquiring information but do not use this information, the security is involved. State may give a funding to the agent which incentives him to get and use the information in order to reduce its uncertainty on the project and allows him to stop it. In this context, the agent respects a certain level of risk considered as acceptable for society.

In the period of financial crisis, it might be surprising to propose subsidies. However, in Europe, there already is support to innovation with the Competitiveness and Innovation Framework Programme (CIP). The CIP have run from 2007 to 2013 with an overall budget of 3 billion euros. A new Programme for the Competitiveness of Enterprises and Small- and Medium-sized Enterprises (COSME) will run from 2014 to 2020, with a planned budget of 2.5 billion euros. In the USA, the total of innovating project funding in 2008 was 89$millions, in 2009, 146$millions and in 2010, 46$millions.

Moreover, there also exist funding for research programme. In Europe, there is the Seventh Framework Programme for Research and Technological Development (FP7) which

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has a budget of around 50 billion of euros for 2007–2013. In the USA, funding for research represent 27$billion for basic research, 99$billion for applied and development research in 2008, and 32$billion for basic research, 100$billion for applied and development research in 2009.[12]

5. Numerical analysis

Relying on an analytical approach based on an industry which is faced with scientific uncertainty, we analyse the impact of the introduction of precautionary state regulation in accordance with the precautionary principle on the industry's behaviour.

We propose to simulate the model by specifying the information–precision function, the revenue function and the cost function. These expressions are useful for applications and numerical simulations, and also allow us to obtain more precise information on the optimal investment in the project, on the optimal expenses on information collection and on damage reduction in different contexts.

We assume that:

- $f(C^b) = (C^b + 1)/(C^b + 2)$;
- $R(I) = rI^{\gamma}$ with $r > 0$ and $0 < \gamma < 1$;
- $K(I, C^a) = I^{\kappa_1}(C^a + 1)^{\kappa_2}$ with $\kappa_1 > 1$ and $\kappa_2 < 0$.

We study the chemical industry giant, the Monsanto Company. The Monsanto Company is an American multinational, specializing in the chemical and biotechnology industries. It is considered to be the world leader of the GMOs. The Monsanto Company is notable for its involvement in a number of class action suits, where fines and damages have run into hundreds of millions of dollars, usually over health and environmental issues related to its products.[13]

Actually, GMOs are characterized by uncertainty about future returns as well as monetary damages cost to human health and the environment that could occur. Environmental policies, such as the polluter pays principle is applied to all GMOs. The Monsanto Company then has financial interest to acquire information in order to reduce uncertainty regarding dangers associated with the project and to improve safety and quality products for reducing the cost of potential damages.[14]

The evaluation of the discount rate is an important topic in investment decision theory (Kumbaroglu, Madlener, Demirel 2008). Areas ripe for innovation, such as chemical production, are characterized by a long-term return on investment. A company like the Monsanto Company investing in this kind of project has a low preference for the present, so a discount rate is close to 1 (here, $\beta = 0.90$). Moreover, through the class action suits, the Monsanto Company continues to invest in GMOs so, the Monsanto Company may think that the worst state of the world has a lower probability to occur, we then consider $p_0 = 0.30$ and $p_0 = 0.40$. Finally, we suggest a situation in which the probabilities of damage θ^H and θ^L are close, and another situation in which θ^H is close to 1 and θ^L is close to 0. Table 1 sums up the four studied cases.

Table 2 presents the information precision and the monetary worth of the Monsanto Company, in terms of million euros: investment in the project, expenses on information collection and in damage reduction, return on investment, profit and cost of damages for the years 2008 and 2009.

We then calculate r, γ, κ_1 and κ_2 on the basis of Table 2. Table 3 lists the corresponding values of our coefficients such that the maximization problems linked to the expected profits (1) and (3) are well defined. It also presents the optimal investment in the project,

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Table 1. Studied cases.

Parameter	Case 1	Case 2	Case 3	Case 4
β	0.90	0.90	0.90	0.90
p_0	0.30	0.30	0.40	0.40
θ_H	0.70	0.90	0.70	0.90
θ_L	0.30	0.10	0.30	0.10

Table 2. The Monsanto Company data.

Year	I	C^b	C^a	$R(I)$	V_0	$f(C^b)$
2008	658.09	30.32	674.72	8330.31	2107.57	0.97
2009	638.20	42.09	723.16	8182.16	2119.18	0.98

Year	$K(I, C^a)$ (Case 1)	$K(I, C^a)$ (Case 2)	$K(I, C^a)$ (Case 3)	$K(I, C^a)$ (Case 4)
2008	11754.63	18943.63	3614.61	9552.32
2009	10687.86	17499.66	2870.83	7832.73

Source: The 2009 and the 2010 EU Industrial R&D investment scoreboard, and the science and engineering indicators 2012 (Appendix tables, Tables 4.4–4.6). The cost of damage and the information precision are evaluated by using the model and the parameters values of the studied cases.

Table 3. Simulated coefficients and optimal decisions in million euros in absence of regulation.

	Case 1	Case 2	Case 3	Case 4
κ_1	1.95	1.85	3.19	2.97
κ_2	−0.51	−0.32	−1.92	−1.55
r	187.42	187.42	187.42	187.42
γ	0.58	0.58	0.58	0.58
x_h	1	0	1	1
x_l	1	1	1	1
I^*	344.07	504.41	1634.63	756.07
C^{a*}	590.60	302.45	2887.92	1751.61
C^{b*}	0	67.62	0	0
$V_0(x_h, x_l, I^*, C^{b*}, C^{a*})$	2398.52	2071.59	5066.69	3455.21

the optimal expense on information collection, the optimal expense in damage reduction and the associated profit in the absence of precautionary state regulation.

In all the cases, the project is profitable and the Monsanto Company decides to invest in the project and to pay an expense in order to reduce the cost of a potential accident. Actually, as the company is made liable to pay for the damages it causes, its interest is to find a solution to reduce its financial cost. Then, the polluter pays principle incentives to the Company to make technological and developmental research, and so to make technological change.[15] However, in Cases 1, 3, and 4, the company refuses to acquire information while it acquires it in Case 2. Actually, Case 2 is the most uncertain case in which the company has the lowest prior belief on the realization of the worst state of the world. The company is aware that if it under-evaluates the possibility that the worst state of the world occurs, the financial consequences will be large. Hence, information in order to reduce this uncertainty is useful for it. In the other cases, either the company has the highest prior belief on the

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Table 4. Optimal decisions in million euros with precautionary state regulation.

		Case 1	Case 2	Case 3	Case 4
Situation A	x_h	1	–	0	1
$\underline{f} = 0.97$ and $\bar{K} = 0.001$	x_l	1	–	1	1
	I^R	0.62	0	0.86	1.39
	C_R^a	33.49	0	27.27	62.42
	C_R^b	31.34	0	31.34	31.34
	$V_0(x_h, x_l, I_R, C_R^b, C_R^a)$	49.58	0	23.01	88.92
Situation B	x_h	1	0	1	1
$\underline{f} = 0.97$ and $\bar{K} = 10,000$	x_l	1	1	1	1
	I^R	344.07	381.55	750.14	756.07
	C_R^a	590.59	264.83	1411.68	1751.61
	C_R^b	31.34	57.4	31.34	31.34
	$V_0(x_h, x_l, I_R, C_R^b, C_R^a)$	2367.19	2009.46	4372.82	3423.88
Situation C	x_h	–	–	–	1
$\underline{f} = 0.99$ and $\bar{K} = 0.001$	x_l	–	–	–	1
	I^R	0	0	0	1.39
	C_R^a	0	0	0	62.42
	C_R^b	0	0	0	98
	$V_0(x_h, x_l, I_R, C_R^b, C_R^a)$	0	0	0	22.26
Situation D	x_h	1	0	1	1
$\underline{f} = 0.99$ and $\bar{K} = 10,000$	x_l	1	1	1	1
	I^R	344.07	381.90	750.14	756.07
	C_R^a	590.59	266.25	1411.68	1751.61
	C_R^b	98	98	98	98
	$V_0(x_h, x_l, I_R, C_R^b, C_R^a)$	2300.52	1992.98	4306.16	3357.21

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realization of the worst state of the world and so has less possibility to be surprised in the case of its realization (Cases 3 and 4); or the difference between the financial consequences of the two states of the world are closer (Cases 1 and 3). So information has less interest in those cases for the company which prefers not paying for it ($C^{b*} = 0$).

Now, Table 4 presents the optimal investment in the project, the optimal expense on information collection, the optimal expense in damage reduction and the associated profit levels with the introduction of different precautionary state regulations.

Situations A and B consider a level of information precision, 0.97, similar to the one chosen by the Monsanto Company (see Table 1), while Situations C and D are more cautious with a level of 0.99. In addition, in Situations B and D, 10,000 million euros is an acceptable cost of damage. We note that the cost taken by the Monsanto Company in Cases 3 and 4 in Table 1 are lower than this acceptable cost of damage. However, in Situations A and B, the acceptable cost of damage is more cautious, it is 1000 euros. In those situations, the society may be qualified as more risk averse than in the two other situations. So we can say that Situation C is the most cautious precautionary state regulation, while Situation B is the less one.

There are five important remarks.

Remark 1 From Table 4, we note that a decrease in the level of the acceptable cost of damage decreases more the optimal level of investment in the project than an increase in the level of information precision.

Table 5. Policy tools: subsidies in million euros.

	Subsidy	Case 1	Case 2	Case 3	Case 4
Situation A	τ_1	2348.93	–	–	3366.29
$\underline{f} = 0.97$ and $\bar{K} = 0.001$	τ_2	67.08	–	–	81.51
	τ	–	2071.59	5043.68	–
	$C^a_{\tau 1}$	$+\infty$	–	–	$+\infty$
	$C^a_{\tau 2}$	$+\infty$	–	–	$+\infty$
	C^a_{τ}	–	$+\infty$	$+\infty$	–
	C^b_{τ}	–	$+\infty$	$+\infty$	–
Situation B	τ_1	31.33	–	693.87	31.33
$\underline{f} = 0.97$ and $\bar{K} = 10,000$	τ_2	754.32	–	2307.83	1391.47
	τ	–	62.13	–	–
	$C^a_{\tau 1}$	32.63	–	$+\infty$	32.06
	$C^a_{\tau 2}$	$+\infty$	–	$+\infty$	$+\infty$
	C^a_{τ}	–	109.55 (62.33)	–	–
	C^b_{τ}	–	0 (40.6)	–	–
Situation C	τ_1	–	–	–	3432.95
$\underline{f} = 0.99$ and $\bar{K} = 0.001$	τ_2	–	–	–	81.14
	τ	2398.52	2071.59	5066.69	–
	$C^a_{\tau 1}$	–	–	–	$+\infty$
	$C^a_{\tau 2}$	–	–	–	$+\infty$
	C^a_{τ}	$+\infty$	$+\infty$	$+\infty$	–
	C^b_{τ}	$+\infty$	$+\infty$	$+\infty$	–
Situation D	τ_1	98	–	760.53	98
$\underline{f} = 0.99$ and $\bar{K} = 10,000$	τ_2	720.44	–	2339.90	1339.12
	τ	–	78.61	–	–
	$C^a_{\tau 1}$	111.77	–	$+\infty$	105.56
	$C^a_{\tau 2}$	$+\infty$	–	$+\infty$	$+\infty$
	C^a_{τ}	–	152.92 (105.56)	–	–
	C^b_{τ}	–	0 (100)	–	–

Remark 2 From Tables 3 and 4, the optimal level of investment in the project under precautionary state regulation is always lower or equal to the one without regulation.

Remark 3 Precautionary state regulation may be so cautious that the company may decide not to invest. In this context, the actual standards for health and the environment restrict the innovation.

As Sunstein (2002–2003) proposition, precautionary state regulation may stifle innovation.

Remark 4 The company pays an expense on information collection in order to respect regulation; however, it may not use this information. Indeed, the company remains ignorant because its profit with information is lower than without information.

In this context, the precautionary state regulation partially leads the company to take all recommended precautionary measures. The company may get around the goal of the precautionary state regulation to reduce the uncertainty.

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Remark 5 Except for the case in which the Company voluntarily satisfies the actual standards for health and the environment, the precautionary state regulation restricts the firm's options and thus reduces its profit.

This remark strengthens the traditional paradigm and is in contraction with the Porter Hypothesis which says that environmental regulation increases firm's profit.

So in Table 5, we calculate the subsidies defined in Propositions 1 and 2 which lead the company to invest in the project in the country and to respect a certain level of risk considered as acceptable for society. We consider here that $\bar{V}_0 = V_0(x_h, x_l, I^*, C^{b*}, C^{a*})$, that is the highest expected payoff under precautionary regulation of all countries in the world is equal to the one without regulation. In other words, we suggest that at least one country do not apply precautionary state regulation.[16]

There is one important remark.

Remark 6 State may not support the activity when the subsidy that it should give to the company is so large.

We note that in our example, this situation occurs more often with research subsidies, i.e. subsidies for reducing damage and for acquiring information.

Besides, giving a subsidy for company as the Monsanto Company could also create some arguments. This could be a delicate political and societal topic.

6. Conclusion

The most common approach to irreversible investment under uncertainty consists in determining whether the optimal decision is to invest today or to invest tomorrow (Dixit and Pindyck 1994; Epstein 1980; Henry 1974). However, in the race for new technologies, the agent may not be willing to delay investing. The agent has to decide how much he should invest in these new activities today, even if not enough scientific knowledge is available about the risks for human health and the environment. To reduce this uncertainty, the agent has the option to pay for acquiring information. Indeed, spending some money today for acquiring information enables the agent to withdraw from a project if it is considered too risky. Hence, with information the agent may revise its decision to make the project by stopping it. In addition, the agent is financially liable for the potential damages on health and the environment (polluter pays principle). In order to reduce its potential cost, the agent may improve the quality and the safety of his product at a cost. These two actions may be considered as precautionary measures for protecting health and the environment.

However, the agent's level of these actions may be not sufficiently acceptable for society. Precautionary state regulation has then to be required. We have found that the consequences of precautionary regulation may be harmful for the innovation. Indeed, some new activities may not be undertaken by the agent under regulation while it could have been done without regulation. Precautionary state regulation may then be paralyzing for the innovation.

Moreover, in order to respect the regulation, the agent pays for acquiring information but he may not use it and stay ignorant about the dangerousness of its project. The agent may get around the goal of the precautionary state regulation to reduce the uncertainty.

In addition, we have raised that since the countries may have different regulatory environments, a pervert effect of the precautionary regulation might be to decrease innovation in the country with the most cautious precautionary regulation.

Our work then does not verify the Porter Hypothesis. Actually, as Ambec et al. (2013) suggest the impact of regulation on innovation and competitiveness depends on the type of

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regulation that is implemented. From empirical evidence, the Porter Hypothesis is premised on flexible market-based regulation, not rigid command-and-control regulation. Here, we have used a command-and-control regulation by imposing standards for health and the environment to the innovator. Although, our work deals with precautionary regulation for health and the environment and not about environmental regulation, ours results are in accord with the Porter Hypothesis literature.

We have then proposed some policy tools, subsidies, which could stimulate innovation in a country and impose a certain level of risk considered as acceptable for society to the innovator.

Using an analytical approach and numerical analysis, we have showed that risk perception and the level of uncertainty influence the decision of acquiring information, and so the decision to reduce the uncertainty. The precautionary state regulation constraint on the level of acceptable cost of damage, $\bar{K}$, implies a higher change in the level investment in the project decision than the constraint on the level of information precision, $\underline{f}$. Moreover, the regulated level of investment in the project is always lower or equal to the non-regulated one.

Besides, the choice of policy tools allowing to stimulate innovation in a country and to impose a certain level of risk considered as acceptable for society to the innovator has to be taken with caution. Indeed, State may not support the activity when the subsidy that it should give to the company is so large.

Furthermore, in this world crisis context, countries may be in competition for innovation. The choice of the precautionary state regulation may be decisive for attracting innovators. An aggressive competition could lead to less cautious regulation, so less safety, and large subsidies in the worst case. Currently, developed countries may subsidize research and development, and so may preserve a high safety level of its production and attract innovators. But, how developing countries may bring innovators when they cannot afford subsidy? Do they have to sacrifice their safety? Countries should probably require a same level of safety for new activities and countries should cooperate for applying the same precautionary regulation. In this regards, the cooperation would benefit to health and the environment protection, and would allow to avoid subsidies, so public spending.

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Notes

1. The 1992 Rio Declaration, Principle 15 states that:

> In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

2. The private agent considered in our approach can also be viewed as a firm.
3. As the organization for economic co-operation and development, we define applied research and experimental development as follows:

> The goal is to find possible applications for the results of basic research; to find new solutions making it possible to reach an objective chosen in advance; and to use the knowledge obtained through research or practical experience to undertake, by means of a prototype or pilot installations, to launch new products, establish new processes, or bring about a substantial improvement in existing processes and products.

4. See Porter and Van der Linde (1995).
5. We have taken the description of the three variants of the Porter Hypothesis in Lanoie et al. (2011).
6. For more details on the Monsanto Company history and controversies, see http://www.monsanto.com/Pages/default.aspx and http://www.combat-monsanto.co.uk/spip.php?article233.
7. We do not consider exogenous information, as equivalent to public information. Our interest is the singular initiative of an agent to acquire information and his willingness to pay for it.
8. Without loss of generality, we consider that a stopped project does not yield revenue.
9. We do not take into account to the budget constraint of the agent. We consider that the agent is able to pay for his chosen investment and its chosen expenses on information collection and in damage reduction.
10. See Shavell (1980, 1992) and Miceli (1997) for more details.
11. Actually, we do not include a subsidy for investment because a higher investment will yield to an increase in the damage cost.
12. For more details, see http://ec.europa.eu/cip/eip/innovation/index_en.htm. Data from the science and engineering indicators 2012 (Appendix tables, Tables 4.42 and 4.30).
13. For more details on the Monsanto Company, see http://www.monsanto.com/Pages/default.aspx.
14. For more details on the research and development of the Monsanto Company, see http://www.monsanto.com/products/Pages/monsanto-science-and-research.aspx.
15. See Huergo (2006), Palmberg (2004), and Paraskevopoulou (2012) for interesting discussions on the role of technological management and the implications of regulation and policies on technological change.
16. Otherwise, we would have taken for each case an arbitrary value of $\bar{V}_0$ lower than $V_0(x_h, x_l, I^*, C^{b*}, C^{a*})$.

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References

Alpay, E., S. Buccola, and J. Kerkvliet. 2002. "Productivity Growth and Environmental Regulation in Mexican and U.S. Food Manufacturing." *American Journal of Agricultural Economics* 84 (4): 887–901.

Ambec, S., M. A. Cohen, S. Elgie, and P. Lanoie. 2013. "The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness?" *Review of Environmental Economics and Policy* 7 (1): 2–22.

Arrow, K. J., and A. C. Fisher. 1974. "Environmental Preservation, Uncertainty, and Irreversibility." *Quarterly Journal of Economics* 88 (2): 312–319.

Arrow, K. J., and Kurz, M. 1970. *Public Investment, the Rate of Return, and Optimal Fiscal Policy*. Baltimore: Johns Hopkins University Press for Resources for the Future.

Berman, E., and L. T. M. Bui. 2001. "Environmental Regulation and Productivity: Evidence from Oil Refineries." *Review of Economics and Statistics* 83 (3): 498–510.

Brunnermeier, S. G., and A. Levinson. 2004. "Examining the Evidence on Environmental Regulations and Industry Location." *Journal of Environment and Development* 13 (6): 6–41.

Charles, A. T., and G. R. Munro. 1985. "Irreversible Investment and Optimal Fisheries Management. A Stochastic Analysis." *Marine Resource Economies* 1 (3): 247–264.

Clark, C. W., G. R. Munro, and A. T. Charles. 1985. "Fisheries, Dynamics and Uncertainty." In *Progress in Natural Resource Economies*, edited by Anthony Scott, Tracy R. Lewis, Philip A. Neher, University of British Columbia and Programme in Natural Resource Economics, 99–120. New York: Clarendon Press.

Copeland, B. R., and M. S. Taylor. 2004. "Trade, Growth and the Environment." *Journal of Economic Literature* 42 (1): 7–71.

Crabbe, P. J. 1987. "The Quasi-Option Value of Irreversible Investment: A Comment." *Journal of Environmental Economics and Management* 14 (4): 384–385.

Dixit, A. K., and R. S. Pindyck. 1994. *Investment Under Uncertainty*. Princeton, NJ: Princeton University Press.
Epstein, L. G. 1980. "Decision Making and the Temporal Resolution of Uncertainty." *International Economic Review* 21 (2): 269–283.
Fisher, S. 1978. "Call Option Pricing When the Exercise Price is Uncertain and the Valuation of Index Bonds." *Journal of Finance* 33 (1): 169–176.
Freeman, A. M. 1984. "The Quasi-Option Value of Irreversible Development." *Journal of Environmental Economies and Management* 11 (3): 292–295.
Freixas, X., and J. J. Laffont. 1984. "On the Irreversibility Effect?" In *Bayesian Models in Economic Theory*, edited by Marcel Boyer and Richard Kihlstrom, 105–114. Amsterdam: North-Holland.
Gollier, C. 2001. "Should We Beware of the Precautionary Principle?" *Economic Policy* 16 (33): 301–328.
Gollier, C., B. Jullien, and N. Treich. 2000. "Scientific Progress and Irreversibility: An Economic Interpretation of the Precautionary Principle." *Journal of Public Economics* 75 (2): 229–253.
Gollier, C., and N. Treich. 2003. "Decision-Making Under Scientific Uncertainty: The Economics of the Precautionary Principle." *Journal of Risk and Uncertainty* 27 (1): 77–103.
Gollop, F. M., and M. J. Roberts. 1983. "Environmental Regulations and Productivity Growth: The Case of Fossil-Fueled Electric Power Generation." *Journal of Political Economy* 91 (4): 654–674.
Henry, C. 1974. "Investment Decisions Under Uncertainty: The Irreversibility Effect." *American Economic Review* 64 (6): 1006–1012.
Henry, C. 2003. Seminar on "Principe de Précaution et Risque Environnemental." Chaire de développement durable EDF-Polytechnique, Paris, France, June 16.
Huergo, E. 2006. "The Role of Technological Management as a Source of Innovation: Evidence from Spanish Manufacturing Firms." *Research Policy* 35 (9): 1377–1388.
Jaffe, A. B., and K. Palmer. 1997. "Environmental Regulation and Innovation: A Panel Data Study." *Review of Economics and Statistics* 79 (4): 610–619.
Jaffe, A. B., S. R. Peterson, P. R. Portney, and R. N. Stavins. 1995. "Environmental Regulation and International Competitiveness: What Does the Evidence Tell Us?." *Journal of Economic Literature* 33 (1): 132–163.
Johnston, P., and D. Santillo. 2006. "The Precautionary Principle: A Barrier to Innovation and Progress?" Greenpeace Research Laboratories Discussion Paper, University of Exeter, UK.
Jones, R., and J. Ostroy. 1984. "Flexibility and Uncertainty." *Review of Economic Studies* 51 (1): 13–32.
Kumbaroglu, G., R. Madlener, and M. Demirel. 2008. "A Real Options Evaluation Model for the Diffusion Prospects of New Renewable Power Generation Technologies." *Energy Economics* 30 (4): 1882–1908.
Lanoie, P., J. Laurent-Lucchetti, N. Johnstone, and S. Ambec. (2011). "Environmental Policy, Innovation and Performance: New Insights on the Porter Hypothesis." *Journal of Economics and Management Strategy* 20 (3): 803–842.
Lanoie, P., M. Patry, and R. Lajeunesse. 2008. "Environmental Regulation and Productivity: New Findings on the Porter Hypothesis." *Journal of Productivity Analysis* 30 (2): 121–128.
Miceli, T. 1997. *Economics of the Law*. New York: Oxford University Press.
Oates, E., K. Palmer, and P. R. Portney. 1995. "Tightening Environmental Standards: The Benefit-Cost or the No-Cost Paradigm?" *Journal of Economic Perspectives* 9 (4): 119–112.
Palmberg, C. 2004. "The Sources of Innovations – Looking Beyond Technological Opportunities." *Economics of Innovation and New Technology* 13 (2): 183–197.
Paraskevopoulou, E. 2012. "Non-Technological Regulatory Effects: Implications for Innovation and Innovation Policy." *Research Policy* 41 (6): 1058–1071.
Pindyck, R. S. 1981. "The Optimal Production of an Exhaustible Resource When Price is Exogenous and Stochastic." *Scandinavian Journal of Economies* 83 (2): 277–288.
Porter, M. E. 1991. "America's Green Strategy." *Scientific American* 264 (4): 168.
Porter, M., and C. van der Linde. 1995. "To Ward a New Conception of the Environment-Competitiveness Relationship." *Journal of Economic Perspective* 9 (4): 97–118.
Schwartz, E. S. and L. Trigeorgis. 2001. *Real Options and Investment Under Uncertainty*. Cambridge, MA: The MIT Press.
Shavell, S. 1980. "Strict Liability Versus Negligence." *Journal of Legal Studies* 9 (1): 1–25.

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Shavell, S. 1992. "Liability and the Incentive to Obtain Information About Risk." *Journal of Legal Studies* 21 (2): 259–270.
Sunstein, C. R. 2002–2003. "The Paralyzing Principle: Does the Precautionary Principle Point Us in Any Helpful Direction?" *Regulation* Winter, The Cato Institute. http://object.cato.org/sites/cato.org/files/serials/files/regulation/2002/12/v25n4-9.pdf
Sunstein, C. R. 2003. "Beyond the Precautionary Principle." *University of Pennsylvania Law review* 151 (3): 1003–1056.
Viscusi, W. K. 1985. "Environmental Policy Choice with an Uncertain Chance of Irreversibility." *Journal of Environmental Economics and Management* 12 (1): 28–44.
Von Schomberg, R. 2006. "The Precautionary Principle and Its Normative Challenges." In *Implementing the Precautionary Principle: Perspectives and Prospects*, edited by E. Fisher, J. Jones and R. von Schomberg, chap. 2, 19–42. Cheltenham and Northampton, MA: Edward Elgar Publishing.
Xepapadeas, A., and A. J. Zeeuw. 1999. "Environmental Policy and Competitiveness: The Porter Hypothesis and the Composition of Capital." *Journal of Environmental Economics and Management* 37 (2): 165–182.

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Appendix

LEMMA A.1

Proof We have

$$E(\theta|l, C^b) - E(\theta) = \frac{(1-p_0)p_0(\theta^H - \theta^L)(1-2f(C^b))}{(1-p_0)f(C^b) + p_0(1-f(C^b))}$$

and

$$E(\theta) - E(\theta|h, C^b) = \frac{(1-p_0)p_0(\theta^L - \theta^H)(2f(C^b)-1)}{p_0 f(C^b) + (1-p_0)(1-f(C^b))},$$

which are negative or equal to zero because $\theta^H > \theta^L$, and for all $C^b \geq 0$ we have $f(C^b) \geq \frac{1}{2}$.

$$E(\theta|l, C^b) - \theta^L = \frac{p_0(1-f(C^b))(\theta^H - \theta^L)}{(1-p_0)f(C^b) + p_0(1-f(C^b))}$$

and

$$\theta^H - E(\theta|h, C^b) = \frac{(1-p_0)(1-f(C^b))(\theta^L - \theta^H))}{p_0 f(C^b) + (1-p_0)(1-f(C^b))},$$

which are positive or equal to zero because $\theta^H > \theta^L$, and for all $C^b \geq 0$ we have $f(C^b) \geq \frac{1}{2}$.

We then differentiate $E(\theta|h, C^b)$ with respect to C^b, we obtain

$$\frac{\partial E(\theta|h, C^b)}{\partial C^b} = \frac{(1-p_0)p_0 f'(C^b)(\theta^H - \theta^L)}{[(1-p_0)(1-f(C^b)) + p_0 f(C^b)]^2}$$

which is positive because f is increasing and $\theta^H > \theta^L$.

We now differentiate $E(\theta|l, C^b)$ with respect to C^b, we obtain

$$\frac{\partial E(\theta|l, C^b)}{\partial C^b} = \frac{(1-p_0)p_0 f'(C^b)((\theta^L - \theta^H)}{[p_0(1-f(C^b)) + (1-p_0)f(C^b)]^2},$$

which is negative because f is increasing and $\theta^H > \theta^L$. ■

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Irreversible investment, uncertainty, and ambiguity: The case of bioenergy sector

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ABSTRACT

We analyze production and investment decisions of an agent in industrial activities that are characterized by two forms of uncertainty: demand uncertainty (in terms of number of buyers) and competitive effect uncertainty (in terms of other energy resource). We apply our model on the bioenergy industries. We compare the case of an ambiguity neutral agent with that of an ambiguity averse agent. We show that the investment decision of an agent depends on the effects of both the capital investment and the level of production on the cost and the uncertainty the agent is confronted with. Moreover, we find that ambiguity aversion tends to decrease the agent's optimal levels of production and investment. Our numerical analysis of the French case illustrates the different effects associated with demand uncertainty and competitive effect uncertainty.
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1. Introduction

Investments into renewable technologies will have to develop in order to reach the renewable energy target of 20% fixed by the European Union (EU) for 2020.[2] To reach the future targets set out by the EU, significant amounts of biomass and investments into biomass based technologies will be necessary.[3] Biomass is key to the development of renewable energies, but it must undergo a pretreatment and densification process before it can be transported and stored. Indeed, biomass is a resource that is heterogeneous in quality and is not homogeneously distributed across space. Therefore, the large range of biomass types is not directly usable in some feeding systems and conversion processes. Investment in new pre-treatment facilities is a necessary step in the total biomass supply chain in order to save transport, material, handling costs for users and to reduce investments in transformation facilities.

These pre-treatment processes are still in progress and the biomass market is emerging. Although a potential investor has information about the demand and the competitive effect on the supply market, this information still remains imperfect.

Indeed, due to the novelty of this market, the agent cannot get a perfect knowledge on the number of buyers before starting the production. He will either have to supply a few potential buyers such as heat and electricity producers, needing to replace coal, or a larger number of potential buyers including producers of second generation biofuel and heat and electricity producers. This uncertainty then affects the agent's perception of the average price. Here and hereafter, we define this uncertainty as the demand uncertainty.

Moreover, the competition effect from other energy resource on the price of pretreated biomass is also not well-known by the agent. In fact, the biomass may be sold either to heating or power units as a substitute for coal (the selling price could then be indexed with coal prices) or to Biomass to Liquid (BtL) units as a substitute for fossil fuel and prices could then be indexed with oil prices, which fluctuate even more sharply than coal prices. So, uncertainty about competition affects the agent's perception of the average price and mostly the variance price. We define this uncertainty as the competitive effect uncertainty.

Considering these two kinds of uncertainty and their impact on the selling price, a biomass agent has to decide how much capital investment and produced units he will make in biomass activities. Capital investment, also called in the literature the cost of entry, in

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[1] Climate Economics Chair.
[2] In 2007, the European Commission has fixed the renewable energy target in the EU's overall mix to 20% in the final energy consumption by 2020 regarding 1990. To reach this goal, the member states have adopted the pack energy-climate and renewable energy (European Commission, 2009) in particular which defines the operational measures to develop 20% of renewable energies by 2020.
[3] Currently biomass delivers around 4% of the EU's primary energy (EEA, 2008).

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bioenergy production represents a quasi-sunk cost due to the fact that biomass torrefaction is a specific, and relatively expensive, process. This naturally raises the issue of the effect of both types of uncertainty and of the irreversibility on the investment level and production.

Furthermore, in the energy market, the instability of the economy may lead the agent to have uncertainties about his evaluation of the variance of the output price. We use the term 'ambiguity' to indicate situations in which the odds of an uncertain event are not precisely known. In other words, a situation in which there is an 'uncertainty about uncertainty'.[4] An agent who has doubts about the odds is considered as an ambiguity-averse agent. So a question arises: how an ambiguity-averse agent behaves when he makes his decisions concerning investment and production?

To understand the impact of uncertainty on investment and production in biomass activities, we propose a two-period model in which there is incomplete information about the number of buyers and the competitive effect. Under these uncertainties, an agent has to choose his capital investment for the production of pre-treated biomass units at the following period. We study the cases of an ambiguity-neutral agent and of an ambiguity-averse agent. Following Klibanoff et al. (2005), we extend our work by presenting ambiguity as a second order prior probability distribution over the set of plausible distributions of the competitive effect. This approach allows us to analyze the impact of ambiguity on the investment and production choices.

The standard theory of irreversible investments or quasi sunk cost (Henry, 1974; Sutton, 1991) and options values suggests a negative relation between investment and uncertainty (Dixit and Pindyck, 1994). Empirical studies also confirm this negative relation (Bond et al., 2005; Carruth et al., 2000; Fan and Zhu, 2010). However, (Kulatilaka and Perotti, 1998; Sarkar, 2000) point out that an increase in uncertainty could increase the probability of investing, and thereby has a positive impact on investment. Moreover, Mohn and Misund (2009) argue that any positive impact on investment arising from the fact that greater uncertainty, under certain circumstances, increases the marginal profitability of capital. In all these papers the effect of price uncertainty has been analyzed as the effect of demand uncertainty on capacity choice (Dangl, 1999; Elder and Serletis, 2009, 2010; Isik et al., 2003; Trigeorgis, 1996). Considering real options approach, Murto et al. (2004) are interested with in the timing of investment projects under demand uncertainty and oligopolistic competition. The important characteristic is that the output price is influenced by both exogenous uncertainty and new capacity investments. This paper is closed to our approach with demand uncertainty and competitive effect even if there is no real uncertainty on the competition. Murto (2006) introduces two types of uncertainty by combining effect of technological uncertainty and uncertainty in output price with real options approach. However, no work has been done on the two types of uncertainty (demand uncertainty and competitive effect uncertainty) that affect prices in different ways: the perception of the average and the variance of the price. Concerning ambiguity, we refer to the basic literature on ambiguity with (Ellsberg, 1961) and Fellner (1961, 1965), the empirical investigations by (Slovic and Tversky, 1974) and the recent literature with (Klibanoff et al., 2005) and Gollier (2006) to indicate situations for which the odds of an uncertain event are not precisely known. Determining how an ambiguity-averse agent decides to invest and produce in emerging technologies is an important line of research in entrepreneurial decision-making in BtL.

Using an analytical approach and numerical analysis, we first note that whatever the certainty or uncertainty context, the agent never invests or produces when he thinks that an increase in capital increases the cost of one more unit. Moreover, we show that the agent's capital investment decision depends on the effects of the amount of capital invested, of the level of production on the cost and on the uncertainty to which the agent is confronted. Then, we observe asymmetric effects of demand uncertainty and competitive effect uncertainty on the optimal amount of investment and optimal production. Finally, we find that ambiguity aversion tends to decrease the agent's level of capital investment and production.

The French biomass pre-treatment industry (torrefaction) is taken as an example, and the empirical results show that the model developed here can provide useful advice for pre-treatment biomass investment programs.

The remainder of the paper is organized as follows. Section 2 consists of a description of the model. Section 3 analyzes and compares the optimal investment and production decisions of both an ambiguity neutral agent and an ambiguity averse agent. Section 4 presents a numerical analysis. Finally, Section 5 concludes.

2. Model description

We consider a two period model with a risk-neutral agent. The agent faces two types of uncertainty: demand uncertainty, in terms of number of buyers, and a competitive effect uncertainty. Indeed, whereas the agent knows that he is competing on the market of fuel providers,[5] *i.e.* he is a price taker,[6] he only has a subjective perception of his potential customers and of the severity of the market competition. Both types of uncertainty affect prices in different ways: the demand uncertainty pertains to the perception of the price average while the competition effect uncertainty pertains to the average and mostly the price variance.

We define four possible states of the world: a Low number of buyers and a Weak competition effect (*LW*), a High number of buyers and a Weak competition effect (*HW*), a Low number of buyers and a Strong competition effect (*LS*) and High number of buyer and a Strong competition effect (*HS*). We propose to divide the agent's subjective probabilities on these states in two kinds of beliefs: first, the agent's subjective probabilities are ψ on the low number of buyers, and $(1-\psi)$ on the high number of buyers; second, the agent's subjective probabilities are θ on the strong competition, and $(1-\theta)$ on the weak competition. In addition, we consider that the 'right' value of the probability associated with the competitive effect uncertainty θ may be unknown. In this case, θ is a random variable, and it is called $\tilde{\theta}$. The agent associates a probability distribution $F(\theta)$ on $[\underline{\theta}, \overline{\theta}]$ which measures the subjective relevance of a particular θ probability. The competitive effect is then ambiguous in the sense that his beliefs depend on a probability distribution. Instability in the energy market can cause the agent to become uncertain about the true value of probability θ, which pertains to the variance of the output price. So there may be a great deal of ambiguity associated with the competition based on the output selling price.[7] Following Klibanoff et al. (2005), we describe the agent's behaviour towards ambiguity by a function ϕ. An increasing and concave ϕ means that the agent is ambiguity averse. Similarly, ambiguity neutrality is characterized by the linear function ϕ.

We associate a selling price P_i with each state $i \in \{LW, HW, LS, HS\}$. A larger number of buyers is likely to be able to support a higher

[4] For more details on ambiguity approach, see Camerer (1999); Etner et al. (forthcoming).

[5] Indeed, the agent knows that there already exists substitute of pre-treatment process which could provide the biomass consumers.

[6] The energy price is determined by the total supply of energy and each unit considers the price as given. Then we do not consider the impact of additional capacity on price.

[7] In a context in which there are two uncertainties affecting simultaneously the level and the variability of the price, an agent is more sensitive to the price variability than to the price average. The demand uncertainty affects the perception of the average price while the competitive effect uncertainty affects the perception of the average price and mostly the variance price. Therefore, we assume an ambiguity associated with the competition effect uncertainty.

price, so we get that $P_{HW}>P_{LW}$ and $P_{HS}>P_{LS}$. Moreover, competition between fuel suppliers leads to a lower price, $P_{HW}>P_{HS}$ and $P_{LW}>P_{LS}$.

In period 0, the agent has the opportunity to invest in plant in order to produce pre-treated biomass. Let be $K\geq 0$, the stock of capital and the investment costs $I(K)$. I is an increasing and convex function such that $I(0)=0$. As in Cairns (2009), we assume a sunk capital, *i.e.*, a capital amount that is specific to the firm.

In period 1, if the agent has invested $I(K)$ in period 0, he has to choose his production q which represents the units of torrefied biomass. This yields a pay-off equals to $P_i q$ in state $i\in\{LW, HW, LS, HS\}$. From this pay-off the cost of production $c(q, K)$ which is an increasing and convex function in q and a decreasing and convex function in K must be subtracted. Moreover, we assume that if $q>0$ then $c(q, 0)=\infty$, $c(0, K)=0$ for all $K>0$.

So, with a discount factor $\beta<1$, the agent's expected pay-off $V(K, q; \psi, \theta)$ is expressed as follows:

$$V(K,q;\psi,\theta) = -I(K) + \beta\psi[\theta(P_{LS}q - c(q,K)) + (1-\theta)(P_{LW}q - c(q,K))] + \beta(1-\psi)[\theta(P_{HS}q - c(q,K))) + (1-\theta)(P_{HW}q - c(q,K))].$$

Likewise, considering the KMM ambiguity approach, the agent's expected pay-offs is given by[8]:

$$W(K,q,\psi,\theta) = \phi^{-1}\left(\int_{\underline{\theta}}^{\bar{\theta}} \phi(V(K,q,\psi,\theta))dF(\theta)\right). \quad (1)$$

3. Optimal decision making

3.1. Neutrality to ambiguity

In this section, we consider that the agent is aware of the true value of θ. In other words, there is uncertainty about the price variance and he believes that the probability associated with this uncertainty is relevant. In this case, we consider $W(K, q; \psi, \theta)=V(K, q; \psi, \theta)$.[9] In period 0, the agent has to determine his optimal stock of capital K^* for producing pre-treated biomass. Then, in period 1, he could decide which quantity q^* to produce. By consequence, we propose to solve this model through backward induction.

We define the expected price under demand uncertainty, the expected price under competitive effect uncertainty, and the expected price under both demand and competitive effect uncertainties, respectively, as follows:

$$E_\psi P_m = \psi P_{Lm} + (1-\psi)P_{Hm}, E_\theta P_j = \theta P_{jS} + (1-\theta)P_{jW}, \text{and } E_{\psi\theta}P = \psi E_\theta P_L + (1-\psi)E_\theta P_H.$$

with $j\in\{L, H\}$ and $m\in\{W, S\}$.

So the first order condition on quantity is[10]:

$$\frac{\partial c(q,K)}{\partial q} = c_q = E_{\psi\theta}P. \quad (2)$$

If for all $q>0$ we get $V(K, q; \psi, \theta)\leq 0$, *i.e.*, if the project is never profitable, then the agent does not produce. On the other hand, if there exists $q>0$ such that $V(K, q; \psi, \theta)>0$, the project is profitable for a certain level of production. This relation implies that q is an implicit function of K, $q\equiv q(K)$.

Now, we study the optimal stock of capital K which maximizes the expected pay-off $V(K, q(K); \psi, \theta)$. The condition is given by the solution of the following program:

$$-\frac{dI(K)}{dK} + \beta\frac{dq(K)}{dK}E_{\psi\theta}P - \beta\left(c_q\frac{dq(K)}{dK} + c_K\right) = 0.$$

Using Eq. (2), we obtain,

$$\beta c_K = -\frac{dI(K)}{dK} = -I'(K). \quad (3)$$

If for all $K>0$ we get $V(K, q(K); \psi, \theta)\leq 0$, *i.e.*, if the project is never profitable, then the agent does not invest in it. On the other hand, if there exists $K>0$ such that $V(K, q(K); \psi, \theta)>0$, the project is profitable for certain level of investment.

As already mentioned in McDonald and Siegel (1986) as in Gollier (2007), it is optimal for an agent to invest only if investment value exceeds his cost. Finally, the optimal decisions (q^*, K^*) are defined by Eqs. (2) and (3). We can summarize some static comparative results in the following lemma.

Lemma 1.

(i) A higher price, P_{LW}, P_{HW}, P_{LS}, and/or P_{HS}, always increases the level of production, q^*. That is not the case for the investment K^*, which increases when $\partial^2 c(q^*, K^*)/\partial q\partial K<0$, decreases when $\partial^2 c(q^*, K^*)/\partial q\partial K>0$ and does not vary when $\partial^2 c(q^*, K^*)/\partial q\partial K=0$.

(ii) A higher subjective probability on the realization of a low number of buyers, ψ, and/or a higher subjective probability on the realization of a strong competition effect, θ, always decreases the level of production, q^*. That is not the case for the investment K^* which decreases when $\partial^2 c(q^*, K^*)/\partial q\partial K<0$, increases when $\partial^2 c(q^*, K^*)/\partial q\partial K>0$ and does not vary when $\partial^2 c(q^*, K^*)/\partial q\partial K=0$.

Proof.

Part (*i*)

Increasing any price induces an increase of $E_{\psi\theta}P$. Conditions (2) and (3) imply $q^*\equiv q^*(E_{\psi\theta}P)$ and $K^*\equiv K^*(E_{\psi\theta}P)$. Denoting $\overline{P}$, the price expected value and differentiate (2) and (3), we obtain respectively, if $\partial^2 c(q^*(\overline{P}), K^*(\overline{P}))/\partial q\partial K\neq 0$,

$$\frac{dq^*(\overline{P})}{d\overline{P}} = \frac{1 - c_{qK}\frac{\partial K^*(\overline{P})}{\partial\overline{P}}}{c_{qq}}$$

and

$$\frac{dK^*(P)}{dP} = -\frac{c_{qK}}{\beta c_{qq}c_{KK} - \beta\left[c_{qK}\right]^2 + c_{qq}I''(K)}$$

With cost convexity assumption and the convexity of $I(.)$, we assume $\beta c_{qq}c_{KK} - \beta[c_{qK}]^2 + c_{qq}I''(K)>0$. Then, if $c_{qK}<0$, $\partial K^*(\overline{P})/\partial\overline{P}>0$ and $\partial q^*(\overline{P})/\partial\overline{P}>0$.

Part(*ii*)

Conditions (2) and (3) imply $q^*\equiv q^*(\psi, \theta)$ and $K^*\equiv K^*(\psi, \theta)$. We differentiate Eqs. (2) and (3) with respect to ψ and θ, we obtain respectively, if $\partial^2 c(q^*(\theta, \psi), K^*(\theta, \psi))/\partial q\partial K\neq 0$,

$$\frac{\partial q^*(\theta,\psi)}{\partial\theta} = \frac{\psi(P_{LS}-P_{LW}) + (1-\psi)(P_{HS}-P_{HW}) - c_{qK}\frac{\partial K^*(\theta,\psi)}{\partial\theta}}{c_{qq}}$$

$$\frac{\partial q^*(\theta,\psi)}{\partial\psi} = \frac{\theta(P_{LS}-P_{HS}) + (1-\theta)(P_{LW}-P_{HW}) - c_{qK}\frac{\partial K^*(\theta,\psi)}{\partial\psi}}{c_{qq}}$$

[8] Notice that we are interested by optimal decision and so the ϕ^{-1} has no influence on our results. We thank an anonymous referee for pointing out this property.

[9] More precisely, a neutral agent maximizes the expected pay-off $\phi(V(K, q; \psi, \theta))$ where ϕ is linear function. For notation convenience, we assume ϕ is a scalar equal to 1 when agent is neutral to ambiguity.

[10] Here and hereafter, we will equally use the following notations: $\frac{\partial c(q,K)}{\partial K} = c_K$, $\frac{\partial^2 c(q,K)}{\partial q\partial K} = c_{qK}$, $\frac{\partial^2 c(q,K)}{\partial K^2} = c_{KK}$ and $\frac{\partial^2 c(q,K)}{\partial q\partial q} = c_{qq}$.

and

$$\frac{\partial K^*(\theta,\psi)}{\partial \theta} = -\frac{c_{qK}[\psi(P_{LS}-P_{LW})+(1-\psi)(P_{HS}-P_{HW})]}{c_{qq}c_{KK}-\left[c_{qK}\right]^2+c_{qq}I_{KK}}$$

$$\frac{\partial K^*(\theta,\psi)}{\partial \psi} = -\frac{c_{qK}[\theta(P_{LS}-P_{HS})+(1-\theta)(P_{LW}-P_{HW})]}{c_{qq}c_{KK}-\left[c_{qK}\right]^2+c_{qq}I_{KK}}$$

where $\psi(P_{LS}-P_{LW})+(1-\psi)(P_{HS}-P_{HW})<0$ and $\theta(P_{LS}-P_{HS})+(1-\theta)(P_{LW}-P_{HW})<0$. Then, $\partial q^*(\theta,\psi)/\partial\theta<0$, $\partial K^*(\theta,\psi)/\partial\theta<0$, $\partial q^*(\theta,\psi)/\partial\psi<0$ and $\partial K^*(\theta,\psi)/\partial\psi<0$ if $\partial^2 c(q^*(\theta,\psi),K^*(\theta,\psi))/\partial q\partial K<0$. □

So the opportunity to sell each unit at a higher price, and then getting a higher pay-off, prompts the agent to produce more. This opportunity may come from an increase in the possible selling prices, a lower belief in the realization of a low number of buyers, and/or a lower belief in the realization of a strong competition effect.

Moreover, if the marginal production cost decreases in the capital investment, a higher price, a lower belief in the realization of a low number of buyers, and/or a lower belief in the realization of a strong competition effect increases the optimal level of investment in capital. Besides, if the capital investment has no impact on the marginal production costs then the prices and the two beliefs do not affect the agent's decision concerning the level of investment in capital. For simplicity in the following, we consider $c_{qK}>0$ and we can get that $K^*=0$ and $q^*=0$.

In addition, if the marginal production cost decreases with the capital investment, a higher price, a lower belief in the realization of a low number of buyers, and/or a lower belief on the realization of a strong competition effect prompts the agent to invest and produce.

So the effect of the capital investment on the marginal production cost plays a major role in the agent's decision concerning his investment in capital and production.

It is natural now to compare the situation of certainty with the situations in which there is one type of uncertainty (either demand uncertainty, or competitive effect uncertainty), and with the situation in which there are both types of uncertainty. To do so, we define the marginal rate of substitution associated with the cost as follows:

$$TMSC(q,K) = -\frac{\dfrac{\partial c(q,K)}{\partial q}}{\dfrac{\partial c(q,K)}{\partial K}},$$

which represents the increase in K for which the cost is maintained when the agent produces one more unit. Using relations (2) and (3), we have

$$TMSC(q,K) = -\frac{c_q}{c_K} = \frac{E_{\psi\theta}P}{I'(K)}. \tag{4}$$

The situation of certainty, *i.e.* that in which the agent knows the number of buyers on the market and the severity of the market competition effect, corresponds to $E_{\psi\theta}P=P$. In this case, we denote by q_C^* and K_C^* the optimal quantity and investment.

The cases in which there is only one type of uncertainty: first, demand uncertainty, *i.e.*, the agent has perfect knowledge of the level of the effect of market competition , correspond to $E_{\psi\theta}P=E_{\psi}P_m$ with $\theta=0$ or $\theta=1$. In the case of Demand Uncertainty, we denote by q_{DU}^* and K_{DU}^* the optimal quantity and investment; secondly, the competition effect uncertainty (*i.e.*, the agent does not initially know the effect of competition but he knows the number of buyers of the future market) corresponds to $E_{\psi\theta}P=E_{\theta}P_j$ with $\psi=0$ or $\psi=1$. In the case of Competitive effect Uncertainty , we denote by q_{CU}^* and K_{CU}^* the optimal quantity and investment.

We first note that regardless of the certainty or uncertainty level, the agent never invests nor produces when he thinks that an increase in capital increases the cost of one more unit.

The lack of information on the true level of the price implies that the agent expects a lower value of the price than the realized one when it is high and expects an upper value of the price than the realized one when it is low. This directly impacts on the level of production, which decreases when the expected price is lower than the realized one, and increases when the expected price is higher than the realized one. Even though the level of capital investment is affected by this erroneous evaluation, the agent's decision also takes into account the effect on the cost of both the level of production and the level of capital invested. Actually, producing more leads the agent to choose a level of investment in capital that reduces his unit production cost. Then under uncertainty, the agent makes a lower (higher) investment when the expected price is lower (higher) than the realized one and the increase in capital decreases the cost of one more unit. (Elder and Serletis, 2009, 2010) find empirical evidence that uncertainty about oil prices has tended to depress investment in Canada and United States. Our model could explain their result with considering that the investors expect at once a price that is lower than the true one and that an increase in capital reduces the marginal cost of production.

Moreover, under both uncertainties, the agent produces less when he does not know that the realized price is the highest, *i.e.*, the number of buyers is high and there is little market competition. In this context, he invests less capital when he thinks that an increase in capital increases the cost of one more unit. On the contrary, the agent produces more when he does not know that the realized price is the lowest, *i.e.*, the number of buyers is low and there is a strong market competition effect. Then, he invests more in capital when he thinks that an increase in capital decreases the cost of one more unit.

3.2. Aversion to ambiguity

In this section, we seek to understand how choices concerning capital and capacity investment are affected by ambiguity aversion. We then propose to compare the optimal production and capital investment decisions of an agent who is averse to ambiguity with those of an ambiguity neutral agent. To formalize the aversion to ambiguity, we consider that the 'right' value of the probability associated with the competition severity uncertainty θ may be unknown. The agent's belief, θ, is then represented not as a single probability measure on the set of states but as a set of probability measures. Such a framework is relevant to the decision concerning investment and production; indeed, as quoted in Heath and Tversky (1991): *the ambiguity aversion is particularly strong in cases in which people feel that their competence in assessing the relevant probabilities is low.*

We then extend the model by considering that θ is a random variable. The agent now associates a probability distribution $F(\theta)$ on $[\underline{\theta},\overline{\theta}]$ which measures the subjective relevance of a particular θ probability. Following Klibanoff et al. (2005), we assume that the preferences of the agent indicate smooth ambiguity aversion. So, the agent considers that his expected pay-off is defined by Eq. (1):

$$W(K,q,\psi,\theta) = \phi^{-1}\left(\int_{\underline{\theta}}^{\overline{\theta}}\phi(V(K,q,\psi,\theta))dF(\theta)\right)$$

with $\phi(.)$ defined by an increasing and concave function when the agent is ambiguity averse.

As mentioned previously, we consider the problem in two steps. First, we focus on the impact of ambiguity aversion on the optimal production, $\hat{q}^*$ and second on the optimal capital investment, $\hat{K}^*$.

For a given stock of investment, the first order condition for production is given by:

$$\int_{\underline{\theta}}^{\overline{\theta}}\phi'(V(K,q;\psi,\theta))\frac{\partial V(K,q;\psi,\theta)}{\partial q}dF(\theta) = 0 \tag{5}$$

where

$$\frac{\partial V(K,q;\psi,\theta)}{\partial q} = \left(E_{\psi\theta}P - c_q\right). \quad (6)$$

Proposition 1. For a given initial stock of capital investment, ambiguity aversion tends to decrease the agent's optimal level of production, $\hat{q}^* < q^*$.

Proof. We use the following notations:

$$\Delta(q,\theta) = \phi'(V(K,q;\psi,\theta))$$
$$\Lambda(q,\theta) = E_{\psi\theta}P - c_q.$$

By definition the covariance is:

$$\mathrm{cov}(\Delta(q,\theta),\Lambda(q,\theta)) = E(\Delta(q,\theta)\Lambda(q,\theta)) - E(\Delta(q,\theta))E(\Lambda(q,\theta)).$$

Then, with condition (5), we have

$$E(\Delta(\hat{q}^*,\theta)\Lambda(\hat{q}^*,\theta)) = J(\hat{q}^*) = 0$$

Comparison to neutrality ambiguity case.

From condition (2), we know that $E(\Delta(q^*,\theta)) = 0$ and then $cov(\Delta(q^*,\theta), \Lambda(q^*,\theta)) = E(\Delta(q^*,\theta)\Lambda(q^*,\theta))$.

So if $cov(\Delta(q^*,\theta), \Lambda(q^*,\theta)) < 0$ that implies $E(\Delta(q^*,\theta)\Lambda(q^*,\theta)) < 0$. This is equivalent to $J(q^*) < 0 = J(\hat{q}^*)$. Since ϕ is increasing and concave, $J(.)$ is decreasing function and $q^* > \hat{q}^*$. The sign of covariance is given by differentiate $\Delta(q,\theta)$ and $\Lambda(q,\theta)$ with respect to θ where

$$\frac{\partial \Lambda(q,\theta)}{\partial \theta} = \frac{\partial E_{\psi\theta}}{\partial \theta} < 0$$

and

$$\frac{\partial \Delta(q,\theta)}{\partial \theta} = \phi''(V(K,q;\psi,\theta))\frac{\partial V(K,q;\psi,\theta)}{\partial \theta} > 0$$

with $\phi''(V(K,q;\psi,\theta)) < 0$ and $\partial V(K,q;\psi,\theta)/\partial\theta < 0$. Therefore, $cov(\Delta(q^*,\theta), \Lambda(q^*,\theta)) < 0$ and $q^* > \hat{q}^*$. □

Let us now turn to the analyze of the agent's optimal investment in capital. Eq. (5) implies that $\hat{q}^* \equiv \hat{q}^*(K)$ and the first order condition is:

$$\int_{\underline{\theta}}^{\bar{\theta}} \phi'\left(V(K,\hat{q}^*(K);\psi,\theta)\right)\frac{\partial V(K,\hat{q}^*(K);\psi,\theta)}{\partial K}dF(\theta) = 0 \quad (7)$$

where

$$\frac{\partial V(K,\hat{q}^*(K);\psi,\theta)}{\partial K} = -I'(K) + \beta\frac{d\hat{q}^*(K)}{dK}E_{\psi\theta}P - \beta\left(c_q\frac{d\hat{q}^*(K)}{dK} + c_K\right). \quad (8)$$

Proposition 2. If $\partial^2 c(q^*,K^*)/\partial q\partial K < 0$ then ambiguity aversion tends to decrease the agent's optimal investment level, $\hat{K}^* < K^*$.

Proof. Similar to the proof of Proposition 1 with conditions (3) and (7). □

Aversion to ambiguity concerning the competition effect leads the agent to reduce his investment in capital and his production. Actually, the agent has doubts about its own subjective beliefs on the competition effect. This adds a new uncertainty dimension for him and discourages him from investing and producing. Ambiguity aversion then restrains investment and production in the new process. This may have drastic consequences on the development of emerging processes.

4. Numerical analysis

The empirical analysis is based on the French biomass pretreatment industry. The case of France is a particularly interesting subject of study, because active research studies are being conducted on second generation biofuel technologies (ADEME, 2009). One of the pilot programmes in which five French partners and one German partner participate, has launched BioTfueL, a million Euro project that uses the Fischer-Tropsch process to convert torrefied wood biomass into drop-in renewable fuel. This group will launch pilot projects in France that will commence in 2012. The domestic biomass resources available are also large.[11] Prospects for the diffusion of torrefaction technology in such a dynamic and expanding market are also of particular interest if the economical profitability is to be enhanced.

To determine the profit flow the firm receives when the project is implemented, we suppose, as is frequently done, that sunk investment costs are linear: $I(K) = p_K K$, $p_K > 0$ and $I'(K) = p_K$ with $p_K \in [0, 1]$, the investment coefficient (Cairns, 2009). The quantity of pretreated biomass is a function of the amount of capital, K, that have to be paid for the installation of a production facility. Using (4), we can easily define different probability thresholds, θ and ψ by comparing different cases.

4.1. Determination of the cost function

Like Cairns (2009) and Tsatsaronis and Park (2002), we consider the avoidable cost of production $c(q, K)$ as a function of the amount of capital, K and the output production, q. The avoidable costs are commonly calculated by subtracting the unavoidable cost from the respective total cost excluding the sunk cost $I(K)$ such that:

$$c(q,K) = c^T(q,K) - c^{UN}(q,K)$$

where $c^T(q, K)$ is the total cost and $c^{UN}(q, K)$, the unavoidable costs.

The total cost function is a convex function composed of the capital costs and the production costs. We use a limited development at the order one of the translog function to represent the cost minimizing behaviour of the agent who uses the amount K of capital to produce a quantity q of output. For the torrefaction technology, the cost function is:

$$\ln\left(c^T(q,K)\right) = a_1 + a_2\ln(q) + a_3\ln(K) + a_4\ln(q)\ln(K)$$

where $a_1 > 0$, is a fixed cost, a_2 and a_3 are the cost elasticity of the production and the capital respectively, a_4, is the cross elasticity between production and capital. We assume that the unit costs of production are increasing in accumulated production so $a_2 > 0$ and the investment costs of invested capital K are decreasing in accumulated capital so $a_3 < 0$. The data on operating costs of a torrefaction plant were taken from the existing literature and consists of engineering estimates. The technology exists today but it is tested at pilot scale, so we estimate our coefficients on the basis of economic data for different possible capacities of units (c.f. Table (B.1) in appendix). We assume that unit runs at full capacity. The estimates are presented in Table B.2 in appendix.

We then determine the unavoidable cost rate related to the production and the investment as follows (Tsatsaronis and Park, 2002). Due to technical limitations imposed by the availability and/or costs of materials and manufacturing methods, a maximum value of the mass efficiency of the torrefaction process cannot be exceeded regardless of the amount invested. This efficiency is achieved at the point where the investment cost becomes infinite. This point

[11] The French potential of forest residues was estimated at over 30 Mt per year available for energetic use in 2015 (MEEDDAT, 2010).

determines the unavoidable destruction of raw biomass per unit of torrefied biomass . Thus, we could determine the cost rate associated with the unavoidable raw biomass destruction Z_q^{UN}. Similarly, the unavoidable investment costs per unit of torrefied biomass, Z_K^{UN}, are obtained by considering an extremely inefficient version of the technology, that is a version that would never be feasible in practice because of the very high biomass costs associated with it.[12] We assume that the percentage of the total costs that cannot theoretically be avoided, in view of today's technology and economic environment of the torrefaction, technology is between 20% and 50% (Tsatsaronis and Park, 2002). We take an average unavoidable cost Z^{UN} such as $Z^{UN}=Z_q^{UN}=Z_K^{UN}=35\%$. Then the avoidable costs are calculated by subtracting the unavoidable cost rates from the respective cost rates:

$$c(q,K)=\left(1-Z^{UN}\right)e^{a_1+a_4\ln(K)\ln(q)}K^{a_3}q^{a_2}.$$

Then we have to select an appropriate discount rate. It is an important topic in investment decision.[13] Various ways of calculating discount rates adjusted for risk, have been proposed by Trigeorgis (1996). Schmit et al. (2009) assume a discount rate of 8% to reflect a relatively high credit risk for the investment in ethanol plant, whereas Uslu et al. (2008) chooses a discount rate of 12.5% for an investment in torrefaction. The discount rate of the refinery unit is between 8 and 10% (Dangl, 1999; Felfli et al., 2005). In our analysis, we assume it is equal to 10% because torrefaction units will supply BtL and refinery units. We will vary this rate in the sensitive analysis.

We illustrate the results determined in Section 3 for an ambiguity neutral agent and an ambiguity averse agent.

4.2. Agent's preferences

4.2.1. Ambiguity-neutral agent

According to operating data for torrefaction plant, the marginal cost of production decreases in K and increases in q (Table (B.1)). Furthermore, the cost function does not vary with the number of uncertainty such that $c(q_C^*, K_C^*)=c(q^*, K^*)$ and $c(q_{DU}^*, K_{DU}^*)=c(q_{CU}^*, K_{CU}^*)$. To illustrate our results, we consider the following scenario: $p_K=0.5$,[14] $\theta=0.5$, $\psi=0.5$.[15] We take the prices of torrefied biomass collected during a survey conducted among potential buyers of torrefied biomass in France such as $P_{LW}=100$ Euros/t, $P_{HW}=200$ Euros/t, $P_{LS}=80$ Euros/t and $P_{HS}=148$ Euros/t.[16] From Eqs. (2) and (3), we determine the optimal level of production and investment for the situation in which there are both types of uncertainty, the situation in which there is certainty and the situation in which there is only one uncertainty. The results are summed up in Table (B.3) for the different cases $P_i=P_{jm}$ for $j\in\{L, H\}$ and $m\in\{W, S\}$.

Taking into account of the operating costs, the optimal investment in capital, K^* and the optimal levels of production, q^* are ranked to the uncertainty which the agent faces.

We observe the asymmetric effects of uncertainty on the optimal amount of investment and optimal production. We show that the effect of number of buyers related uncertainty is stronger than that of the competition related uncertainty as the investment and the production levels are higher. This is true when, in the case of certainty, the effect of competition is weak and the number of buyers is low, or high if and only if the agent's subjective probability on the weak competition is lower than a certain threshold . Furthermore, if in the situation of certainty the agent knows the competition effect is weak and the number of buyers is high, the combination of both types of uncertainty leads him to invest less. He behaves similarly if the number of buyers is low in the certainty case if and only if his subjective probability concerning number of buyers is lower than a certain threshold (cases $P_{LW}=100$ Euros/t and $P_{HW}=200$ Euros/t of Table (B.3)).

Secondly, the effect of the competition related uncertainty is stronger than the uncertainty concerning the demand uncertainty as the investment and production levels are higher. This is true when in the case of certainty the competition is strong and the number of buyers is high, or low if and only if the agent's prior belief concerning the weak competition is higher than a certain threshold. Besides, if in the certainty case the agent knows the competition is strong and the market size is low, the combination of both types of uncertainty leads him to invest more. If the market size is high in the certainty case, he has the same behaviour if and only if his prior belief on market size is higher than a certain threshold (cases $P_{HS}=148$ Euros/t and $P_{LS}=80$ Euros/t of Table (B.3)).

Finally, we study the effect of increasing and decreasing the investment coefficient. We sum up the results in Table (B.4) in appendix for different value of $p_K\in[0, 1]$. We notice that K^* decreases when p_K increases whether there is one or two types of uncertainty. As proved in the Lemma 1, a higher investment coefficient increases the cost of investment so the agent decreases his capital investment.

4.2.2. Ambiguity-averse agent

We now illustrate Propositions 1 and 2 to examine the difference ambiguity causes in the results. Following Judd (1999); Miranda and Fackler (2004), we use a Gaussian quadrature to produce the Legendre-Gauss weights and nodes for computing the integral of the continuous function W on interval $[\underline{\theta}, \overline{\theta}]$ with $\underline{\theta}=0$ and $\overline{\theta}=1$. We use a beta distribution $B(\theta; \eta, \mu)$ with the parameter $\eta=0.5$ and $\mu=0.5$ to specify the probability distribution over the set of plausible distribution of the competitive effect. Indeed, the beta distribution is often used to describe the distribution of an unknown probability value, typically, as the prior distribution over a probability parameter. It is defined on the interval [0, 1]. η and μ give the shape of the probability density function. If $\eta<1$ and $\mu<1$, the beta density function is U-shaped and symmetric about 1/2 if $\eta=\mu$. Following Engle-Warnick et al. (2008); Klibanoff et al. (2005), we consider a constant absolute ambiguity aversion (CAAA) utility function such as:

$$\phi(V(K,q;\psi,\theta))=\begin{cases}\dfrac{1-e^{-\tau V}}{1-e^{-\tau}} & \text{if } \tau>0\\ V & \text{if } \tau=0\end{cases}$$

where τ is the coefficient of ambiguity aversion. For the figure clarity, we take $\tau=15$ to compare the case of an agent who is highly averse to ambiguity with that of an ambiguity neutral agent.[17] Figs. (A.1) and (A.2) below show the marginal payoffs, $\partial W(q, K; 0.5, \theta)/\partial q$ in function to q to determine q^* and $\partial W(q(k), K; 0.5, \theta)/\partial K$ in function to K to determine K^* for both an ambiguity neutral and an ambiguity averse agents.

The marginal values are decreasing in q and K. Thus we find that an ambiguity averse agent produces less than an ambiguity-neutral agent and invests less as defined in the Proposition 1 and 2. The results are the same for different value of τ. Due to ambiguity, an agent who invest in biomass torrefaction facilities chooses a lower capacity for his units than he would if he were ambiguity neutral.

[12] In practical applications, this term is determined by arbitrarily selecting a set of parameters for this technology that lead to a very inefficient solution and by estimating the investment costs for this solution.

[13] See Kumbaroglu et al. (2008) for references.

[14] We study the effect of different values of this parameter in the sensitivity analysis.

[15] We take a average value between 0 and 1 for ψ and θ.

[16] These values were determined during a confidential survey conducted in 2010 among the French energy companies which are potential consumers of torrefied biomass. For more details, please contact the authors.

[17] The results are robust for any other lower value of τ. In the portfolio choice examples proposed by (Klibanoff et al., 2005), the coefficient of ambiguity aversion varies between 1 and 20. For sake of clarity, we then take $\tau=15$.

Ambiguity aversion leads the investor to evaluate probabilities distribution according to the least-favourable state, in this case the lowest pay-off. This behaviour could have consequences on the development of emerging BtL process. Indeed, as mentioned before, the pretreatment could enhance the deployment of BtL process because it can improve the economics of the overall production chain. If the producer invests less, the buyer takes the risk of not being supplied the right quantity. The buyer of the torrefied biomass perceives uncertainty about the availability of their inputs. They would be reluctant to invest in the new renewable energy process.

Finally, we study the effect of an increase and decrease in the investment coefficient p_K when the agent is ambiguity averse. Fig. (A.3) below shows the marginal payoffs $\partial W(q(K), K; 0.5, \theta)/\partial K$ in function to K for different values of $p_K \in [0, 1]$.

We notice that $\hat{K}^*$ decreases when p_K increases whatever the coefficient of ambiguity aversion level. A higher investment coefficient increases the cost of investment so the agent decreases his capital investment when the agent is ambiguity averse.

4.3. Parameter sensitive analysis

4.3.1. Sensitivity of the optimum strategy as regards the unavoidable cost rate Z^{UN}

In the reference example, the percentage of total costs that could be not avoided in view of today's technology and economic environment, is an average of maximum and minimum percentages that are possible today. The reference unit produced torrefied biomass relatively expensively compared with units for which the unavoidable cost rate is higher but the mass efficiency of the torrefaction is also better. Increasing the unavoidable cost rates should increase the competitive advantage of a high-output capacity due to the fact the avoidable cost is lower, but regardless the amount invested, the mass efficiency is lower. This can be verified in the Table (B.5) in which tests are made for minimum and maximum values in the range of possible unavoidable cost rates determined for this torrefaction process. A decrease in the proportion of the unavoidable cost reduces the profitability by increasing the avoidable cost price and therefore deters the entrepreneur for investing in high capacity. An increase in the unavoidable cost rate increases the optimal capital investment. However, whatever the unavoidable cost rate Z^{UN}, the ranking of optimal investment in capital is unchanged.

4.3.2. Variation in the discount rate

In our reference simulation, we considered a discount rate of 10% per year. In this section, we examine the effect of an increase in the discount rate from 10% to 12% and a decrease from 10% to 8%. A change in the discount rate modifies the optimum investment strategy. A higher discount rate penalizes the waiting time and therefore encourages the entrepreneur to invest earlier. Indeed, the sensitive analysis (c.f. Table (B.6)) shows the increase (decrease) in the discount rate leads to a high (low) investment in capital. Nevertheless, whatever the discount rate, the ranking of optimal investments in capital is unchanged.

5. Conclusion

In this paper, we assess the impact of two types of uncertainty and of the ambiguity aversion of the agent on his investment and production strategy. We develop a formal model for decision making in which agents are neutral to risk and averse to ambiguity about the true distribution of the competitive effect. We analyze the optimal capacity and production choices in this model. Using an analytical approach and numerical analysis, we first note that whatever the certainty or uncertainty context, the agent never invests or produces when he thinks that an increase in capital increases the cost of one more unit. Moreover, the agent's capital investment decision depends on the effects of the amount of capital invested, of the level of production on the cost and on the uncertainty to which the agent is confronted. Then, we observe asymmetric effects of demand uncertainty (in terms of number of buyers) and competitive effect uncertainty on the optimal amount of investment and optimal production. Finally, in the presence of ambiguity about the competition effect, agents will invest less in their units and their level of production is lower. The main feature of this model is that it helps to understand the behaviour of an agent who faces uncertainty about the market size and market competition if he is averse to ambiguity. This paper emphasizes the need to reduce the effects of ambiguity in the European policy framework that encourages the development of renewable energy production. The introduction of long-term contracts could contribute to reducing them. Actually, these contracts could be defined as agreements between a pretreated biomass producer (seller) and a renewable energy generator owner (buyer) for the purchase of torrefied biomass. By hedging against price volatility, these contracts would reduce the ambiguity impact of the competition effect. They could take the forms of competitive procurement process or bilateral contract negotiation (see Michaud (2010)).

An attractive feature of the model is to determine how the risk and ambiguity aversions of the buyer will affect the investment strategy of torrefied biomass producers. Finally, it will be important to check empirically, with potential agents (private forest owners, cooperatives…) the theoretical results obtained in our model and to evaluate the degree of their ambiguity aversion.

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Appendix A. Figures

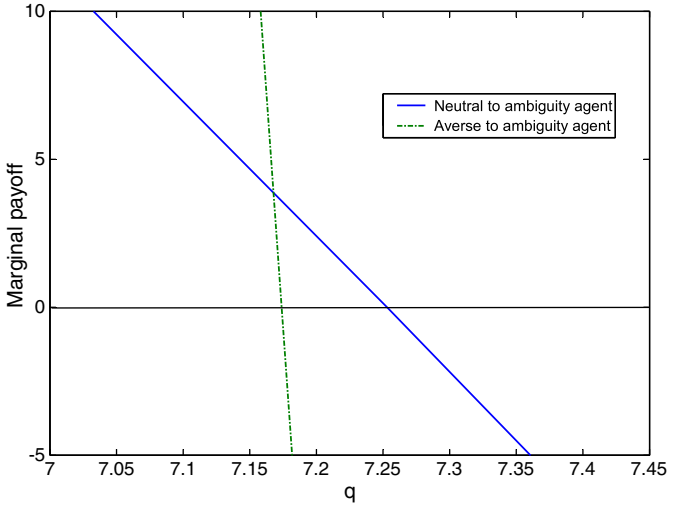

Fig. A.1. The marginal payoff $\partial W(6.34, q; 0.5, \theta)/\partial q$ in function to q. Calculated with $\beta = 0.1$, $\tau = 15$ and $p_K = 0.5$.

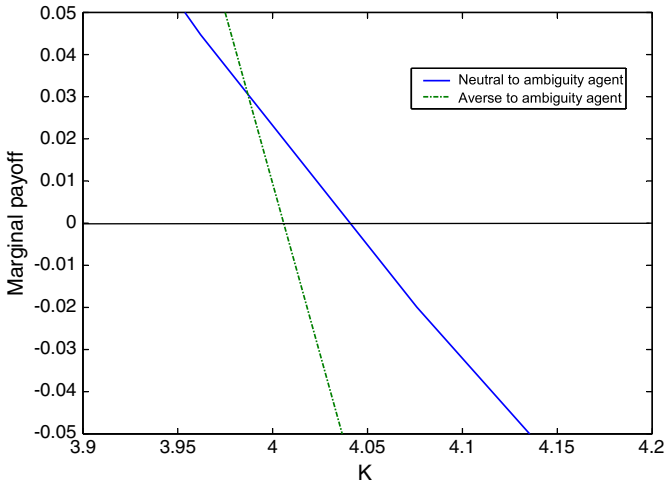

Fig. A.2. The marginal payoff $\partial W(K, q; 0.5, \theta)/\partial K$ in function to K for $\hat{q}^*(K) = 7.18$ and $q^*(K) = 7.26$. Calculated with $\beta = 0.1$, $\tau = 15$ and $p_K = 0.5$.

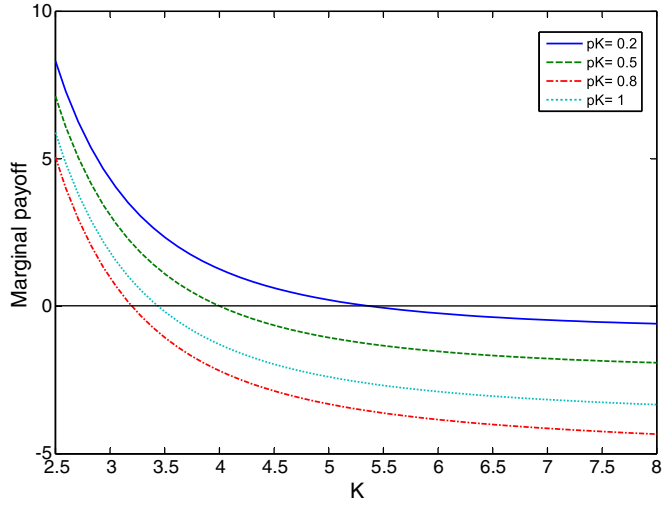

Fig. A.3. The marginal payoff $\partial W(K, q; 0.5, \theta)/\partial K$ in function to K for $\hat{q}^*(K) = 7.18$ for different values of p_K when the agent is ambiguity averse. Calculated with $\beta = 0.1$ and $\tau = 15$.

Appendix B. Tables

Table B.1
Operating expenses for the different scale of unit.

Parameters	Units	Capacity		
	t/an	80,000	200,000	400,000
K	MEuros	7.5	15.6	27.18
$\frac{\partial c(q,K)}{\partial K}$ (in absolute value)	Euros/t	35.6	29.6	25.8
$\frac{\partial c(q,K)}{\partial q}$	Euros/t	26	20.9	20.9
Biomass cost (1)	Euros/t	137	137	137
Total marginal cost	Euros/t	198.6	187.6	183.6

(1) We assume that biomass is sold at the same price regardless of unit capacity.

Table B.2
Estimation results for the cost function parameters.

Parameters	Values
a_1	1
a_2	2.33
a_3	−2.33
a_4	0.12

Table B.3
Optimal level of production and investment in function of the uncertainties for $P_{LW} = 100$ Euros/t, $P_{HW} = 200$ Euros/t, $P_{LS} = 80$ Euros/t and $P_{HS} = 148$ Euros/t.

Case	Number of uncertainties	ψ	θ	q^1	K^2	Ranking of optimal levels of q and K
	Two uncertainties	0.5	0.5	12.96	6.45	
$P_i = P_{LW}$	Certainty (C)	1	1	13.91	6.84	
	Competitive effect (CU)	1	0.5	11.83	5.98	$q^*_{DU} > q^*_C > q^* > q^*_{CU}$
	Demand (DU)	0.5	1	15.39	7.44	$K^*_{DU} > K^*_C > K^* > K^*_{CU}$
$P_i = P_{HW}$	Certainty(C)	0	1	16.79	8.00	
	Competitive effect (CU)	0	0.5	14.03	6.88	$q^*_C > q^*_{DU} > q^*_{CU} > q^*$
	Demand (DU)	0.5	1	15.39	7.44	$K^*_C > K^*_{DU} > K^*_{CU} > K^*$
$P_i = P_{LS}$	Certainty (C)	1	0	9.49	5.00	
	Competitive effect (CU)	1	0.5	11.83	5.98	$q^* > q^*_{CU} > q^*_{DU} > q^*_C$
	Demand (DU)	0.5	0	10.21	5.31	$K^* > K^*_{CU} > K^*_{DU} > K^*_C$
$P_i = P_{HS}$	Certainty (C)	0	0	10.90	5.59	
	Competitive effect (CU)	0	0.5	14.04	6.88	$q^*_{CU} > q^* > q^*_C > q^*_{DU}$
	Demand (DU)	0.5	0	10.21	5.31	$K^*_{CU} > K^* > K^*_C > K^*_{DU}$

(1) In ton per hour; (2) In MEuros.

Table B.4
Sensitive analysis as regards the investment coefficient, p_K for $\theta = 0.5$, $\psi = 0.5$ in case $P_i = P_{HS} = 148$ Euros/t.

Number of uncertainties	K^1	Values of p_K			
		0.2	0.5	0.8	1
Certainty (C)	K^*_C	8.73	6.45	5.52	5.13
Two Uncertainties	K^*	7.56	5.59	4.79	4.46
Competitive effect (CU)	K^*_{CU}	9.33	6.88	5.89	5.47
Demand(DU)	K^*_{DU}	7.16	5.31	4.55	4.23

(1) In MEuros.

Table B.5
Sensitive analysis as regards the unavoidable cost rate for $\theta = 0.5$, $\psi = 0.5$ in $P_i = P_{HS} = 148$ Euros/t.

Z^{UN}	Number of uncertainties	q^1	K^2	Ranking of optimal levels of q and K
20%	Two uncertainties	11.39	6.21	$q^*_{CU} > q^* > q^*_C > q^*_{DU}$
	Certainty (C)	9.58	5.39	
	Competitive effect (CU)	12.33	6.63	$K^*_{CU} > K^* > K^*_C > K^*_{DU}$
	Demand (DU)	8.97	5.12	
50%	Two uncertainties	15.26	6.77	$q^*_{CU} > q^* > q^*_C > q^*_{DU}$
	Certainty (C)	12.84	5.87	
	Competitive effect (CU)	16.52	7.23	$K^*_{CU} > K^* > K^*_C > K^*_{DU}$
	Demand (DU)	12.03	5.56	

(1) In ton per hour; (2) In MEuros.

Table B.6
Sensitive analysis as regards the discount rate for $\theta = 0.5$, $\psi = 0.5$ in $P_i = P_{HS} = 148$ Euros/t.

Discount rate	Number of uncertainties	q^1	K^2	Ranking of optimal levels of q and K
8%	Two uncertainties	12.96	5.99	$q^*_{CU} > q^* > q^*_C > q^*_{DU}$
	Certainty (C)	10.90	5.20	
	Competitive effect (CU)	14.04	6.39	$K^*_{CU} > K^* > K^*_C > K^*_{DU}$
	Demand (DU)	10.21	4.93	

Table B.6 (*continued*)

Discount rate	Number of uncertainties	q^1	K^2	Ranking of optimal levels of q and K
12%	Two uncertainties	12.96	6.85	$q^*_{CU} > q^* > q^*_C > q^*_{DU}$
	Certainty (C)	10.90	5.94	
	Competitive effect (CU)	14.04	7.32	$K^*_{CU} > K^* > K^*_C > K^*_{DU}$
	Demand (DU)	10.21	5.63	

(1) In ton per hour; (2) In MEuros.

Appendix C. Supplementary Data

Supplementary data to this article can be found online at doi:10.1016/j.eneco.2011.08.018.

References

ADEME (2009). *Grenelle Environnement : Fonds démonstrateur de recherche. Descriptif des projets validés par le Comité de pilotage*. Technical report, Agence de l'Environnement et de la Maitrise de l'Energie.

Bond, S., Moessner, R., Mumtaz, H., Syed, M., 2005. Microeconometric Evidence on Uncertainty and Investment. Mimeo. Institute for financial studies.

Cairns, R.D., 2009. *Sunk Cost and Cost Functions*. mimeo. Departement of Economics, McGill University.

Camerer, C., 1999. Ambiguity-aversion and non-additive probability: experimental evidence, models and applications. chapter Uncertain Decisions: Bridging Theory and Experiments. Kluwer Academic Publishers, pp. 53–80.

Carruth, A., Dickerson, A., Henley, A., 2000. What do we know about investment under uncertainty? Journal of Economic Surveys 14, 119–153.

Dangl, T., 1999. Investment and capacity choice under uncertain demand. European Journal of Operational Research 117, 415–428.

Dixit, Pindyck, 1994. Investment under uncertainty. Princeton University Press.

EEA, 2008. Energy and environment report 2008, European Environment Agency.

Elder, J., Serletis, A., 2009. Oil price uncertainty in Canada. Energy Economics 31 (6), 852–856 (Energy Sector Pricing and Macroeconomic Dynamics).

Elder, J., Serletis, A., 2010. Oil price uncertainty. Journal of Money, Credit, and Banking 42 (6), 1137–1159.

Ellsberg, D., 1961. Risk, ambiguity, and the savage axioms. Quarterly Journal of Economics 110 (3), 585–603.

Engle-Warnick, J., Escobal, J., Laszlo, S., 2008. Ambiguity aversion and portfolio choice in small-scale Peruvian farming. mimeo.

Etner, J., Jeleva, M., Tallon, J.-M., forthcoming. Decision theory under uncertainty. Journal of Economic Surveys.

European Commission, 2009. Directive 2009/28/CE du Parlement Européen et Conseil du 23 avril 2009 relative à la promotion de l'utilisation de l'énergie produite à partir de sources renouvelables et modifiant puis abrogeant les directives 2001/77/CE et 2003/30/CE.

Fan, Y., Zhu, L., 2010. A real options based model and its application to China's overseas oil investment decisions. Energy Economics 32 (3), 627–637.

Felfli, F.F., Luengo, C.A., Rocha, J.D., 2005. Torrefied briquettes: technical and economic feasibility and perspectives in the Brazilian market. Energy for Sustainable Development 9, 23–29.

Fellner, W., 1961. Two propositions in the theory of induced innovations. The Economic Journal 71 (282), 305–308.

Fellner, W., 1965. Probability and Profit. Yale University.

Gollier, C., 2006. Does ambiguity aversion reinforce risk aversion? Applications to portfolio choices and asset prices. *Séminaire d'Economie Théorique*: Université de Toulouse 1 Sciences Sociales.

Gollier, C., 2007. Comment intégrer le risque dans le calcul économique ? Revue d'économie politique 117 (2/2007), 209–223.

Heath, C., Tversky, A., 1991. Preference and belief: ambiguity and competence in choice under uncertainty. Journal of Risk and Uncertainty 4, 5–28.

Henry, C., 1974. Investment decisions under uncertainty: the "irreversibility effect". The American Economic Review 64 (6), 1006–1012.

Isik, M., Coble, K.H., Hudson, D., House, L.O., 2003. A model of entry-exit decisions and capacity choice under demand uncertainty. Agricultural Economics 28, 215–224.

Judd, K.L., 1999. Numerical methods in economics. MIT Press.

Klibanoff, P., Marinacci, M., Mukerji, S., 2005. A smooth model of decision making under ambiguity. Econometrica 73 (6), 1849–1892.

Kulatilaka, N., Perotti, E., 1998. Strategic growth options. Management Science 44, 1021–1031.

Kumbaroglu, G., Madlener, R., Demirel, M., 2008. A real options evaluation model for the diffusion prospects of new renewable power generation technologies. Energy Economics 30 (4), 1882–1908.

McDonald, R., Siegel, D., 1986. The value of waiting to invest. Quarterly Journal of Economics 101 (4), 707–728.

MEEDDAT (2010). *La fiscalité des biocarburants en France*. Technical report, Ministère de l'Ecologie, de l'Energie, du Développement Durable et de l'Amménagement du territoire, http://www.developpement-durable.gouv.fr/La-fiscalite-des-biocarburants-en.html.

Michaud, P.R. (2010). Long-term Renewable Energy Contracts, Net-Metering, and Ocean Wind Initiatives in New England. Technical report.

Miranda, M.J., Fackler, P.L., 2004. Applied computational economics and finance. The MIT Press.

Mohn, K., Misund, B., 2009. Investment and uncertainty in the international oil and gas industry. Energy Economics 31 (2), 240–248.

Murto, P., 2006. Timing of investment under technological and revenue-related uncertainties. Journal of Economic Dynamics and Control 31 (5), 1473–1497.

Murto, P., Näsäkkälä, E., Keppo, J., 2004. Timing of investments in oligopoly under uncertainty: a framework for numerical analysis. European Journal of Operational Research 157 (2), 486–500.

Sarkar, S., 2000. On the investment–uncertainty relationship in a real options model. Journal of Economic Dynamics and Control 24 (2), 219–225.

Schmit, T.M., Luo, J., Tauer, L.W., 2009. Ethanol plant investment using net present value and real options analyses. Biomass & Energy 33, 1442–1451.

Slovic, P., Tversky, A., 1974. Who accepts savage's axiom? Behavioral Science 19, 368–373.

Sutton, J., 1991. Sunk costs and Market structure. MIT Press.

Trigeorgis, L., 1996. Real Options. MIT Press.

Tsatsaronis, G., Park, M.-H., 2002. On avoidable and unavoidable exergy destructions and investment costs in thermal systems. Energy Conversion and Management 43 (9–12), 1259–1270.

Uslu, A., Faaij, A.P.C., Bergman, P., 2008. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy 33 (8), 1206–1223.

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Innovation and Information Acquisition under Time Inconsistency and Uncertainty

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When an agent invests in new industrial activities, he has a limited initial knowledge of his project's returns. Acquiring information allows him both to reduce the uncertainty on the dangerousness of this project and to limit potential damages that it might cause on people's health and on the environment. In this paper, we study whether there exist situations in which the agent does not acquire information. We find that an agent with time-consistent preferences, as well as an agent with hyperbolic ones, will acquire information unless its cost exceeds the direct benefit they could get with this information. Nevertheless, a hyperbolic agent may remain strategically ignorant and, when he does acquire information, he will acquire less information than a time-consistent type. Moreover, a hyperbolic-discounting type who behaves as a time-consistent agent in the future is more inclined to stay ignorant. We then emphasize that this strategic ignorance depends on the degree of precision of the information. Finally, we analyse the role that existing liability rules could play as an incentive to acquire information under uncertainty and with regard to the form of the agent's preferences.
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Keywords: information acquisition; uncertainty; self-control; time inconsistency; hyperbolic discounting preferences; liability rules

Introduction

Recent environmental policies favour the 'pollutant-payer' Principle. This Principle points out the pollutant financial liability for the eventual incidents induced by his activities. Investing in technological innovations generates uncertainty about the future returns, as well as about the damages that such innovations could involve and about the cost to pay in case of troubles. To reduce this uncertainty, the agent has the opportunity to acquire information, for example through research activities, on his project's potential consequences on human health and the environment. Does the agent systematically exert this option?

To address this question, we explore whether there exist situations in which a private agent chooses not to acquire information at the time he decides to develop new industrial activities. We define information acquisition as a costly agent's effort exercised in order to reduce the existing uncertainty on future payoffs. We associate a degree of information precision to this effort's level. A higher effort today will imply more precision tomorrow. Acquiring information also allows the agent to update his decisions, in particular he may decide to prematurely stop the project and then limit potential damages in case of accident. Using such an approach allows us to consider both the problem of emerging risk management and the trade-off between activities' development and precautionary measures.

Moreover, we consider that our agent may have hyperbolic discounting preferences. In other words, he may discount at a relatively higher rate the short-term events than the long-term events. Discount rate gathers all the psychological motives of the agent's investment choice, such as anxiety, confidence, or impatience. Our agent is also 'sophisticated', that is, he is perfectly aware that the decisions at period t may be different if we analyse them from the perspective of the agent at period $t+1$ than from the perspective of the agent at period t. In this regard, we consider the agent with hyperbolic discounting preferences as a collection of risk-neutral incarnations with conflicting goals.

Hyperbolic discounting preferences assumption still creates controversies (see Read, 2001 and Rubinstein, 2003). However, empirical evidences (Frederick *et al.*, 2002) persuade more and more economists on this type of preferences. In fact, Strotz (1956) is the first to suggest an alternative to exponential discounting. In addition, Phelps and Pollack (1968) introduce the hyperbolic discounted utility function as a functional form of these preferences. Elster (1979) applies this formalization to a decision problem in characterizing time inconsistency by a decreasing discount rate between the present and the future, and a constant discount rate between two future periods. Laibson (1997, 1998) uses this formulation to savings and consumption problems, while Brocas and Carrillo (2000, 2004, 2005) consider the problems of information value, irreversible consumption and irreversible investment. More recently, O'Donoghue and Rabin (2008) investigate procrastination on long-term projects by people who have a time-inconsistent preference for immediate gratification.

Our approach relies on two building blocks. First, it is related to the real options theory. Acquiring information is both costly and defined as a right, not as an obligation, for the agent. This real option allows him to stop his project and recover a part of his initial investment. This contrasts with the standard literature in which the investment is irreversible and the flow of information is exogenous (Arrow and Fisher, 1974; Henry, 1974; Brocas and Carrillo, 2000, 2004). This theoretical approach quantifies the value of management flexibility

in a world of uncertainty. It then contributes to add a new dimension with the introduction of endogenous information.

Furthermore, it also examines the literature relying on hyperbolic discounting preferences and information acquisition. Bénabou and Tirole (2002, 2004) show that a "comparative optimism", or a "self-confidence" is at the origin of time-inconsistent behaviour. Such behaviour inhibits all learning processes and uncertainty may strengthen this effect. In addition, Carrillo and Mariotti (2000) study intertemporal consumption decisions, involving a potential risk in the long run, and show that hyperbolic discounting preferences may favour *strategic ignorance*. In our paper, we view as a *dangerous ignorance* what Carrillo and Mariotti call a *strategic ignorance*. Indeed, when our agent refuses information, he does not get the possibility to prematurely stop his project and then to limit the potential cost of damages. Therefore, his behaviour might be dangerous for people's health and the environment.

Carrillo and Mariotti (2000) point out that a person with hyperbolic preferences might choose not to acquire free information in order to avoid over-consumption or engagement in activities that may require much more fundamental research on potential social costs or externalities than they could involve in the long term. Our model offers a new explanation. It shows that a hyperbolic agent does not refuse free information but free information with a certain degree of precision. By introducing a costly information linked to information precision, we find that a time-consistent agent as well as a hyperbolic type will acquire information unless the cost exceeds the direct benefit. Nevertheless, a hyperbolic agent may remain ignorant if the degree of information precision is not high enough to make information relevant for him. On the other hand, when a hyperbolic agent does acquire information, he acquires less information than a time-consistent type. Moreover, if we introduce the possibility that the hyperbolic agent behaves as a time-consistent agent on future actions, we show that the agent will be more inclined to remain ignorant. We then emphasize the relevance of information precision for hyperbolic types' information acquisition decision.

The asbestos case is a typical example of the suitability of information precision. Greeks and Romans were the first to remark that slaves were afflicted with a sickness of the lungs when they were in contact with asbestos. Then, in 1898, the annual reports of the Chief Inspector of Factories advised that asbestos creates health risks. However, asbestos industry evaluated that these reports lacked precision, and refused this available information on the asbestos risks. In the 1970s, after many facts revealed the link between cancer and asbestos, the first regulation appeared. The use of asbestos in new construction projects is now banned in many developed countries (Henry, 2003). The use of antibiotics as growth hormone is also a characteristic example. In 1943, the Luria–Delbruck experiment demonstrated antibiotic resistance

of bacterial populations.[1] However, the farming and Pharmaceutical industry considered that the information was not relevant, and preferred to ignore it (Henry and Henry, 2002). Currently, additional information leads the European Commission, the World Health Organisation, the Centers for Disease Control and the American Public Health Association to support the elimination of antibiotics growth.

We should also remark that the private agent considered in our approach can be viewed as a firm. If dramatic examples in the past could let us believe that firms' managers and/or shareholders may choose to neglect a potential danger in the long term, in order to get immediate gratification, there is no empirical study on such an assumption of time-inconsistent preferences of firms when facing uncertainty. Thus, it is not clear that a firm always behaves as a time-inconsistent private agent under uncertainty. One reason is that there are many interactions among people in a firm and particularly between its manager and shareholders, who are subject to conflicting goals and therefore do not consider time horizon in the same way, that is, manager might be more interested in the day-to-day performance of the firm, while shareholders might have a long-term view of the its development. Such conflicts should have an impact on the behaviour of the decisions makers, and time-inconsistent behaviour may, or may not, be a result of such conflicts.

In this regard, we allow, in the paper, the decision maker to be characterized by different types of preferences: time-consistent preferences, hyperbolic discounting preferences or hyperbolic discounting preferences with self-control. If we suppose that the decision maker is a firm, the firm's preferences will then be those of the decision maker, regardless of the possible interactions existing in the firm. Indeed, we suppose that the firm is represented by a board of shareholders in charge of all strategic decisions, which only maximizes the profit of the firm, and could be either time-consistent or time-inconsistent. Under such an assumption, the firm can be represented by a private arbitrary individual with time-consistent or hyperbolic discounting preferences.

Regarding environmental policies, it seems interesting that the agent acquires information. Indeed, this information allows him to give up his project and then to reduce harmful consequences on the environment in case of accident. In fact, exercising this option could be interpreted as an agent's voluntary application of the Precautionary Principle. From the Rio Conference, the Precautionary Principle states that: "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing

[1] See http://en.wikipedia.org/wiki/Luria-Delbr%C3%BCck_experiment.

cost-effective measures to prevent environmental degradation". The cost of protection is transferred from State to agents. We propose to study how State could lead the agent to acquire information when this agent misses to do it. We find that a strict liability rule, for example applying the "pollutant-payer" Principle, may not always be a useful tool to encourage the acquisition of information. On the other hand, to a certain extent, a negligence rule may offer an alternative solution to solve this uncertainty learning problem.

The remainder of paper is organized as follows. The next section presents the model. The subsequent section investigates the optimal decision making. The penultimate section proposes a sensitive analysis of the model's results to changes in the parameters. Finally, the last section analyses whether the existing liability frameworks, such as strict liability rule and negligence rule, encourage the agent to acquire information. All proofs are given in the Appendix.

The model

We consider a three-period model. At period 0, the agent invests a given amount of money $I>0$ in a project that may create damage to people's health and/or to the environment. There are two possible states of the world, H and L, associated with different probabilities of damage θ^H and θ^L, respectively. We assume that state H is more dangerous than state L, therefore

$$\theta^L < \theta^H.$$

At period 0, the prior beliefs of the agent are p_0 on state H, and $1-p_0$ on state L. Thus, the expected probability of the damage is given by:

$$E(\theta) = p_0\theta^H + (1-p_0)\theta^L.$$

At period 0, the agent pays $C \geqslant 0$ to obtain information at period 1 through a signal $\sigma \in \{h, l\}$ on the true state of the world. We define the precision of the signal as the probability the signal corresponds to the state. We represent it as an increasing and concave function $f(C)$ such that:

$$P(h|H, C) = P(l|L, C) = f(C)$$

and

$$P(h|L, C) = P(l|H, C) = 1 - f(C)$$

and

$$f(0) = \frac{1}{2}; f'(0) = +\infty \text{ and } f'(+\infty) = 0.$$

Hence, the information precision depends on the information cost C. If the agent does not pay, that is, $C=0$, then the signal is not informative.[2] On the other hand, a larger cost implies a higher precision.

According to Bayes' rule, the probability of being in state H given signal h and C, and the probability of being in state H given signal l and C are, respectively:

$$P(H|h,C) = \frac{p_0 f(C)}{p_0 f(C) + (1-p_0)(1-f(C))}$$

and

$$P(H|l,C) = \frac{p_0(1-f(C))}{p_0(1-f(C)) + (1-p_0)f(C)}.$$

At period 1, according to signal $\sigma \in \{h, l\}$, we define $x_\sigma \in \{0, 1\}$ as the agent's decision to stop the project ($x_\sigma = 0$), or to continue it ($x_\sigma = 1$). We assume that if the agent stops his project ($x_\sigma = 0$), then he recovers a part of his investment D, $0 < D < I$. In the standard literature, investment is irreversible. Under uncertainty on the payoffs, the agent has to choose the level of investment today and that of tomorrow. This creates flexibility for the investment. In our model, the agent invests and then starts the project regardless of the situation. Letting a possibility to recover a part of his investment allows recuperating management flexibility. In addition, under $D=0$, stopping the project would purely imply financial costs. This would seriously restrict decisions on precautionary measures.

At period 2, an accident may happen. If the project is carried out until period 2, the agent gets a payoff $R_2 > 0$. From this payoff must be subtracted the financial cost of the accident $K > 0$ that occurs with probability θ^H or θ^L depending on the state of the world. If the project has been stopped at period 1, this financial cost is lower $K' > 0$ and also occurs with probability θ^H or θ^L. According to the "pollutant-payer" Principle, the agent has to pay for his project's consequences on human health and the environment, even if as he has stopped his project the damages are less costly. We consider that K and K' represent the total cost relative to the negative external effect of the agent's decisions, that is, public and private costs.

[2] We do not consider exogenous information, such as public information. In this paper, our interest is an agent's own initiative in acquiring information and his willingness to pay for it.

In order to formalize the hyperbolic discounting preferences, we use Phelps and Pollack (1968)'s functional form. Let $D(k)$ represent a discount function such that:

$$\begin{cases} D(k) = 1 & \text{if } k = 0; \\ D(k) = \beta\delta^k & \text{if } k \neq 0. \end{cases}$$

Hyperbolic discounted utility function is then defined as follows:

$$U_t = \sum_{k=0}^{T-t} D(k)u_{k+t}, \qquad \text{with } t \in \{0,1,2\},\ T = 2,$$
$$\text{and } u_{k+t} \text{ the net instantaneous utility at period } k+t.$$

To simplify Phelps and Pollack's (1968) formalization, we assume that $\delta=1$.[3] Here and throughout the paper, as Frederick *et al.* (2002) suggest, the discount rate β gathers all the psychological motives of the agent's investment choice, such as anxiety, confidence, or impatience.[4] If $\beta=1$, the psychological motives have no influence on the agent's choice, and his preferences are time-consistent. On the other hand, if $\beta<1$, then the agent's preferences change over time, indicating that what the agent decides today might be discordant with what he decides tomorrow.

We consider an agent with hyperbolic discounting preferences as being made up of many different risk-neutral selves with conflicting goals.[5] Each self represents the agent at a different point in time. Hence, at each period *t,* there is only one self called "self-t". Each self-t depreciates the following period with a discount rate β.

Therefore, expected payoffs of self-2, self-1, and self-0 may be expressed recursively. If signal σ has been perceived, $V_2(x_\sigma,\sigma,C)$ is self-2's expected payoff:

$$V_2(x_\sigma,\sigma,C) = x_\sigma[P(H|\sigma,C)(R_2-\theta^H K)+(1-P(H|\sigma,C))(R_2-\theta^L K)]$$
$$-(1-x_\sigma)[P(H|\sigma,C)\theta^H K'+(1-P(H|\sigma,C))\theta^L K'].$$

[3] $\delta<1$ only implies a lower discount rate. Taking $\delta=1$ does not change any results.

[4] In fact, Akerlof (1991) defines β as the "salience of current payoffs relative to the future stream of returns". In the literature, it is also interpreted as a lack of willpower (Bénabou and Tirole, 2002), of foresight (O'Donoghue and Rabin, 1999; Masson, 2002) or as impulsiveness (Ainslie, 1992).

[5] Following Strotz (1956), this conflict captures the agent's time-inconsistency preferences.

Likewise, self-1's expected payoff is

$$V_1(x_\sigma, \sigma, C) = (1 - x_\sigma)D + \beta V_2(x_\sigma, \sigma, C),$$

where $(1-x_\sigma)D$ represents self-1's current payoffs and $\beta V_2(x_\sigma,\sigma,C)$ self-1's expected payoffs for period 2. Finally, self-0's expected payoff can be expressed as follows:

$$\begin{aligned} V_0(x_h, x_l, C) = -I - C + \beta[p_0 f(C) + (1 - p_0)(1 - f(C))]\,[(1 - x_h)D + V_2(x_h, h, C)] \\ + \beta[(1 - p_0) f(C) + p_0(1 - f(C))]\,[(1 - x_l)D + V_2(x_l, l, C)]. \end{aligned}$$

When self-1 knows with certainty the state $S \in \{L, H\}$, let us consider $B^S(\beta)$ as the difference between self-1's expected payoff when he decides to carry on the project, and self-1's expected payoff when he decides to stop it:

$$B^S(\beta) = \beta R_2 - D - \beta\theta^S(K - K').$$

We assume that it is always more profitable for self-1 to stop (continue) his project when he knows with certainty that the true state of the world is H (L). Therefore, we suppose that:

$$B^H(\beta) < 0 < B^L(\beta).$$

The agent has the possibility not to acquire information (C=0) and thus to remain uninformed (No Learning). Under no learning, define self-1's expected payoff when he decides to achieve the project as follows:

$$V_1^{NL}(1) = \beta[p_0(R_2 - \theta^H K) + (1 - p_0)(R_2 - \theta^L K)],$$

and self-1's expected payoff when he decides to stop the project by

$$V_1^{NL}(0) = D - \beta[p_0\theta^H K' + (1 - p_0)\theta^L K'].$$

We consider that the agent who starts a project without information always completes it. It is then more profitable for him to continue the project than stopping it at period 1. Formally, for $\beta \leqslant 1$:

$$V_1^{NL}(0) < V_1^{NL}(1) \text{ which is equivalent to } E(\theta) < \frac{\beta R_2 - D}{\beta(K - K')}.$$

For all $\beta \leqslant 1$, define $\hat{\theta}(\beta)$ as the probability of a damage that makes the agent indifferent between continuing the project and stopping it at period 1. That is:

$$\beta(R_2 - \hat{\theta}(\beta)K) = D - \beta\hat{\theta}(\beta)K' \text{ which is equivalent to}$$
$$\hat{\theta}(\beta) = \frac{\beta R_2 - D}{\beta(K - K')}.$$

Hence for $\beta \leqslant 1$, at period 1, it is more profitable for an uninformed agent to continue the project than to stop it if:

$$E(\theta) < \hat{\theta}(\beta). \tag{1}$$

Under such an assumption, we consider that the uninformed agent adopts a non-precautionary behaviour. Indeed, by ignoring information, he does not make any effort either to reduce the uncertainty linked to his project, or to protect human health and the environment.

To ensure that an uninformed agent always chooses to complete his project, we restrict our study to an agent with hyperbolic discounting preferences that satisfy condition (1). Since $\hat{\theta}(\beta)$ is increasing with β,[6] condition (1) is equivalent to $\tilde{\beta} < \beta$, with $\tilde{\beta}$ given by $E(\theta) = \hat{\theta}(\tilde{\beta})$.[7] Therefore, we analyse the hyperbolic agent's behaviour with a discount rate $\beta \in (\tilde{\beta}, 1)$.

The optimal decision making

In this section, we present the agent's optimal decision making. We propose to study three kinds of preferences. First, time-consistent preferences which suppose that the agent's optimal decision is sustained as circumstances change over time, and thus that his future selves act according to the preferences of his

[6] Proof in the Appendix section.

[7] According to self-1's expected payoffs, an uninformed agent with a discount rate $\beta = 0$ does not pay attention to the future, and then always prefers stopping his project in order to recover at least a part D of his initial investment. As the agent is indifferent between stopping and carrying on the project, we get $\beta = \tilde{\beta}$, then $\tilde{\beta}$ is different to zero.

current self. In other words, a time-consistent agent gives the same weight to the current period and the future one. Then, hyperbolic discounting preferences is one where the agent's future selves choose strategies that are optimal for them, even if these strategies are suboptimal from the current self's point of view. With this kind of preferences, the agent gives a larger weight to the present, and the same weight to future periods. Finally, we analyse hyperbolic discounting preferences with self-control in the future. A hyperbolic agent with self-control gives a larger weight to the first period, but at the following periods he behaves as a time-consistent agent, that is, he gives the same weight to what will be current and future periods.

Regardless of the preferences, at each period t, the agent is represented by his self-t. At period 0, self-0 chooses how much he is willing to pay to acquire information, knowing that at period 1, self-1 takes decision to stop or to continue the project. We use the backward induction method in order to characterize the agent's optimal decisions.

Stopping or continuing the project

We start by studying self-1's behaviour. Regardless of the preferences, for $\sigma \in \{h, l\}$ and for $C \geqslant 0$, self-1 continues the project if his expected payoff by continuing the project is higher than when he stops it. That is:

$$V_1(0, \sigma, C) < V_1(1, \sigma, C).$$

Since a time-consistent agent and a hyperbolic type with self-control give the same weight to period 1 and period 2, that is, $\beta=1$ between both periods, then for $\sigma \in \{h, l\}$ and for $C \geqslant 0$, their expected payoff is as follows:

$$V_1(x_\sigma, \sigma, C) = (1 - x_\sigma)D + V_2(x_\sigma, \sigma, C).$$

By contrast, a hyperbolic agent prefers the present, that is, $\beta < 1$ between period 1 and period 2. Therefore, for $\sigma \in \{h, l\}$, $C \geqslant 0$ and $\beta < 1$, his expected payoff is:

$$V_1(x_\sigma, \sigma, C) = (1 - x_\sigma)D + \beta V_2(x_\sigma, \sigma, C).$$

For $\sigma \in \{h, l\}$ and $C \geqslant 0$, denote both the equilibrium strategy by x_σ^* and the revised expected probability of damage by $E(\theta|\sigma,C)=P(H|\sigma,C)\theta^H + (1-P(H|\sigma,C))\theta^L$. Conditions under which self-1 stops or continues his project are given by the following proposition.

Proposition 1 For $\sigma \in \{h, l\}$, $C \geqslant 0$ and $\beta \in (\tilde{\beta}, 1]$: If $E(\theta|\sigma, C) < \hat{\theta}(\beta)$, then the agent continues the project, that is, $x_\sigma^* = 1$; if $\hat{\theta}(\beta) < E(\theta|\sigma, C)$, then the agent stops the project, that is, $x_\sigma^* = 0$; finally, if $\hat{\theta}(\beta) = E(\theta|\sigma, C)$, then the agent is indifferent between stopping and continuing the project, that is, $x_\sigma^* \in \{0, 1\}$.

Owing to condition (1), regardless of the preferences, self-1 is confronted with two strategies. In the first strategy, he always continues the project regardless of the signal, and in the second one, he stops his project when he receives signal *h* (being in the most dangerous state of the world), while when he gets signal *l* he continues it. From an environmental point of view, we may qualify the former strategy as a cautious one. Indeed, in this strategy, the agent prefers withdrawing the project when there exists a possibility for the most dangerous state to be revealed. He is then more willing to prevent potential damages.

Lemma 1 For all $C \geqslant 0$, we have $E(\theta|l, C) \leqslant E(\theta) \leqslant E(\theta|h, C)$, and $E(\theta|h, C)$ is increasing with C while $E(\theta|l, C)$ is decreasing with C.

Hence, regardless of the preferences, the self-0's decision on the cost to spend in order to acquire information affects the self-1's choices. Indeed, a higher cost increases information precision at period 1. This increase both improves the perception of self-1 on the true state of the world and emphasizes the decision of stopping the project when self-1 receives signal *h*, that is, being in the most dangerous state of the world.

Information acquisition

We now turn to self-0's optimal decision to acquire information regarding the form of his preferences.

Agent with time-consistent preferences

Self-0 of a time-consistent agent ($\beta = 1$) chooses optimally how much he is willing to pay in order to acquire information knowing that self-1 either always decides to continue the project regardless of the signal (case 1), or only chooses to continue it if he receives signal *l* (case 2).

Under time-consistent preferences, define by $C^*_{x_h x_l}(1)$, the optimal information cost from self-0's perspective, under the strategy $\{x_h, x_l\}$. $C^*_{x_h x_l}(1)$ maximizes expected payoff, that is, it solves the following problem:

$$\max_{C \geqslant 0} V_0(x_h, x_l, C).$$

Let us first study case 1 in which self-1 always continues the project, that is, $\{x_h=1, x_l=1\}$. Self-0's expected payoff under this strategy is:

$$V_0(1,1,C) = -I - C + p_0(R_2 - \theta^H K) + (1-p_0)(R_2 - \theta^L K).$$

Since $V_0(1,1,C)$ is decreasing with C, it is obvious that, from self-0's perspective, the optimal information cost is: $C_{11}^*(1) = 0$. In such a case, the signal does not have any influence on self-1's behaviour, it is then not reliable for him to acquire it.

Let us turn to case 2 in which self-1 only gives up the project if he receives signal h, that is, $\{x_h=0, x_l=1\}$. Self-0's expected payoff under this strategy is as follows:

$$\begin{aligned} V_0(0,1,C) = -I - C + \big[&p_0(1-f(C))(R_2 - \theta^H K) \\ &+(1-p_0)f(C)(R_2 - \theta^L K)\big] \\ &+ \big[p_0 f(C)(D - \theta^H K') \\ &+(1-p_0)(1-f(C))(D - \theta^L K')\big]. \end{aligned}$$

Lemma 2 (i) $C_{01}^*(1)$ is characterized by:

$$f'(C_{01}^*(1)) = \frac{1}{(1-p_0)B^L(1) - p_0 B^H(1)}. \tag{2}$$

(ii) $C_{01}^*(1)$ *is strictly positive.*

Self-0 anticipates that self-1 only continues the project if he receives signal l. The signal is trustworthy, and it is optimal to pay a positive amount to get it.

Finally, define $C^*(1)$ as the optimal information level over all the strategies. To determine $C^*(1)$, we compare self-0's expected payoffs of both strategies and select the level of expense that leads, from self-0's perspective, to the highest expected payoff.

Proposition 2 If

$$C_{01}^*(1) < -\left[p_0 f(C_{01}^*(1))B^H(1) + (1-p_0)(1-f(C_{01}^*(1)))B^L(1)\right] \tag{3}$$

then self-0 pays $C^*(1)=C^*_{0l}(1)$ to acquire information; otherwise, $C^*(1)=0$, that is, self-0 remains uninformed.

We remark that if self-0 could get the level of information precision $f(C^*_{01}(1))$ without paying, that is, free information, condition (3) would always be satisfied. Indeed, according to Proposition 1, the right-hand side of condition (3) is always positive.[8] Information cost may be a brake to information acquisition. Self-0 may then stay ignorant if information is too costly.

Agent with hyperbolic discounting preferences

Self-0 of a hyperbolic agent ($\beta\in(\tilde{\beta},1)$) selects the optimal level of information knowing that his future selves may deviate from this optimal choice. Our agent is sophisticated, he recognizes that there is a conflict between his early preferences and his later ones, contrary to a naive agent who does not foresee such a conflict and believes that in the future he will behave as a time-consistent agent.

As previously, two cases arise. First case, self-1 always completes his project whatever the signal, and second case he stops it if he receives signal h.

Under hyperbolic preferences, define by $C^*_{x_h x_l}(\beta)$ the optimal information cost from self-0's perspective, under strategy $\{x_h, x_l\}$. $C^*_{x_h x_l}(\beta)$ is characterized as follows: self-0 first anticipates that self-1 will implement the strategy $\{x_h, x_l\}$, and thus chooses the cost that maximizes his expected payoff under the anticipated strategy $\{x_h, x_l\}$. If this cost is rather precise (high) to ensure that self-1 actually chooses the anticipated strategy, then this cost is optimal. Otherwise, if it is not that precise, self-0 pays the lowest cost that leads self-1 to implement strategy $\{x_h, x_l\}$.

Therefore if self-1 always continues the project (case 1), self-0's expected payoff under strategy $\{x_h=1,\ x_l=1\}$ is given by:

$$V_0(1,1,C) = -I - C + \beta[p_0(R_2 - \theta^H K) + (1-p_0)(R_2 - \theta^L K)].$$

$C^*_{11}(\beta)$ solves the following problem:

$$\begin{cases} \max\limits_{C\geqslant 0} \ V_0(1,1,C) \\ E(\theta|l,C) < E(\theta|h,C) < \hat{\theta}(\beta). \end{cases}$$

[8] We note that $p_0 f(C^*_{01}(1))B^H(1) + (1-p_0)(1-f(C^*_{01}(1)))B^L(1)$ may be rewritten as $[p_0 f(C^*_{01}(1)) + (1-p_0)(1-f(C^*_{01}(1)))][K-K'][\hat{\theta}(1) - E(\theta|h, C^*_{01}(1))]$.

According to Proposition 1, the constraint $E(\theta|l,C)<E(\theta|h,C)<\hat{\theta}(\beta)$ allows to verify that the information cost chosen by self-0 always leads self-1 to continue the project regardless of the signal. As $V_0(1,1,C)$ is decreasing with C, it is not optimal to acquire information. Moreover, according to condition (1), when self-0 decides not to acquire information, self-1 always chooses to carry on the project. Then not acquiring information satisfies the constraint, and $C_{11}^*(\beta)=0$.

If self-1 only gives up the project if he receives signal h (case 2), self-0's expected payoff under strategy $\{x_h=0,\ x_l=1\}$ is given by:

$$\begin{aligned} V_0(0,1,C) = &-I-C+\beta\big[p_0(1-f(C))(R_2-\theta^H K)\\ &+(1-p_0)f(C)(R_2-\theta^L K)\big]+\beta\big[p_0 f(C)(D-\theta^H K')\\ &+(1-p_0)(1-f(C))(D-\theta^L K')\big] \end{aligned}$$

In this case, strategy $\{x_h=0, x_l=1\}$ is ex post optimal. Thus, $C_{01}^*(\beta)$ solves the following problem:

$$\begin{cases} \max\limits_{C\geqslant 0} V_0(0,1,C) \\ E(\theta|l,C)<\hat{\theta}(\beta)<E(\theta|h,C). \end{cases}$$

To determine $C_{01}^*(\beta)$, let us first consider $C_{01}^*(\beta)$, the optimal information cost when self-0 anticipates that self-1 will implement the strategy $\{x_h=0, x_l=1\}$. $C_{01}(\beta)$ solves the following problem:

$$\max_{C\geqslant 0} V_0(0,1,C).$$

Lemma 3 (i) For $\beta\in[\tilde{\beta},1)$, $C_{01}(\beta)$ is characterized by:

$$f'(C_{01}(\beta)) = \frac{1}{\beta[(1-p_0)B^L(1)-p_0 B^H(1)]}. \tag{4}$$

(ii) $C_{01}(\beta)$ is strictly positive.

As for a time-consistent agent, if self-0 of a hyperbolic type anticipates that self-1 only continues the project if he receives signal l, then the signal is useful for him. Thus, self-0 is willing to pay a positive cost to acquire it.

In order to select $C_{01}^*(\beta)$, self-0 has to check that $C_{01}(\beta)$ is rather high to lead self-1 not to deviate to strategy $\{x_h=0, x_l=1\}$. In other words, according to

Proposition 1, we have to verify that $C_{01}(\beta)$ satisfies the constraint $E(\theta|l,C) < \hat{\theta}(\beta) < E(\theta|h,C)$. Otherwise, from self-0's perspective, the signal given by the $C_{01}(\beta)$ is not informative enough, and self-0 selects the smallest information level that leads self-1 to implement the strategy $\{x_h=0, x_l=1\}$. Let us define by $\hat{C}(\beta)$ the smallest information cost that ensures strategy $\{x_h=0, x_l=1\}$ is optimal for self-1. That is, $\hat{C}(\beta)$ is the smallest $C \geqslant 0$ that verifies that $E(\theta|l,C) \leqslant \hat{\theta}(\beta) \leqslant E(\theta|h,C)$.

Lemma 4 (i) For $\beta \in [\tilde{\beta},1)$, $\hat{C}(\beta)$ is characterized by:

$$f(\hat{C}(\beta)) = \frac{(1-p_0)B^L(\beta)}{(1-p_0)B^L(\beta) - p_0 B^H(\beta)}.$$

(ii) $f(\hat{C}(\tilde{\beta}))=f(0)=\frac{1}{2}$.

We then characterize the optimal level of information, $C_{01}^*(\beta)$ in the following lemma.

Lemma 5 For $\beta \in (\tilde{\beta},1)$, if

$$f(\hat{C}(\beta)) < f(C_{01}(\beta)) \tag{5}$$

then $C_{01}^*(\beta)=C_{01}(\beta)$. Otherwise, $C_{01}^*(\beta)=\hat{C}(\beta)$.

Hence, information precision needs to reach at least the information precision level $f(\hat{C}(\beta))$ in order to avoid a deviation of strategy at period 1.

Now, we determine the optimal level of information $C^*(\beta)$ by comparing self-0's expected payoff of the two studied strategies and selecting the level of information that leads to self-0's highest expected payoff.

Proposition 3 For $\beta \in (\tilde{\beta},1)$ if

$$C_{01}(\beta) < -\beta[p_0 f(C_{01}(\beta))B^H(1) + (1-p_0)(1-f(C_{01}(\beta)))B^L(1)] \tag{6}$$

and (5) hold then self-0 pays $C^*(\beta)=C_{01}(\beta)$ to acquire information; otherwise, if one of these two conditions is not satisfied, then self-0 does not pay $C^*(\beta)=0$, and stays uninformed.

Conditions (5) and (6) both define conditions under which self-0 of a hyperbolic agent acquires information. Condition (5) emphasizes the role of

information precision; self-0 refuses information with a certain degree of precision, lower than $f(\hat{C}(\beta))$.

According to Proposition 1, and since $\hat{\theta}(\beta)$ is increasing with β, the right-hand side of condition (6) may be negative.

If the right-hand side of condition (6) is positive, condition (6) may also not hold. The discount factor may be so low that information cost exceeds expected benefit. Self-0 prefers ignoring information in order to get higher payoff.

On the other hand, if the right-hand side of condition (6) is negative, then condition (6) never holds. Expected payoff without information is higher than the one with information. It is then not optimal for self-0 to acquire information.

Let us introduce the possibility that information precision $f(C_{01}(\beta))$ is free. If the right-hand side of condition (6) is positive, then the information acquisition decision depends only on condition (5), that is, on the degree of information precision. In this case, if $f(C_{01}(\beta))$ is high enough, that is, higher than $f(\hat{C}(\beta))$, self-0 acquires free information. By contrast, if the right-hand side of condition (6) is negative, then self-0 never acquires information. In fact, the possibility that self-1 gives up the project is so high that self-0 may choose not to acquire information, even if it is free, in order to avoid such a risk of withdrawing.

Agent with hyperbolic discounting preferences and self-control

Self-0 of a hyperbolic agent with self-control's expected payoff is similar to the that of self-0 of a hyperbolic agent. However, hyperbolic agent with self-control behaves in the future as a time-consistent agent, implying that conditions under which his self-1 continues and stops the project are similar to the ones of self-1 of a time-consistent agent.

Hence, self-0 of a hyperbolic agent with a self-control problem under strategy $\{x_h=1, x_l=1\}$ is

$$\begin{cases} \max\limits_{C\geqslant 0} V_0(1,1,C) \\ E(\theta|l,C) < E(\theta|h,C) < \hat{\theta}(1). \end{cases}$$

and under strategy $\{x_h=0, x_l=1\}$:

$$\begin{cases} \max\limits_{C\geqslant 0} V_0(0,1,C) \\ E(\theta|l,C) < \hat{\theta}(1) < E(\theta|h,C). \end{cases}$$

Under such preferences, let us define $C^{**}(\beta)$ as the optimal level of information. With similar resolution then for hyperbolic agent, we obtain the following proposition.

Proposition 4 For $\beta \in (\tilde{\beta},1)$ if condition (6) and

$$f(\hat{C}(1)) < f(C_{01}(\beta)) \tag{7}$$

hold then self-0 pays $C^{**}(\beta)=C_{01}(\beta)$ to acquire information; otherwise, if one of these two conditions is not satisfied, then he does not pay $C^{**}(\beta)=0$, and stays uninformed.

Conditions (6) and (7) both define the decision of a hyperbolic agent with self-control to acquire information.

According to Proposition 1, the right-hand side of condition (6) is always positive. However, condition (6) may not hold if the discount factor is such that the cost of acquiring information is higher than the expected benefit. In this case, a hyperbolic agent with self-control does not acquire information.

Let us turn to condition (7). This condition implies that self-0 will never acquire information if the degree of precision of this information does not reach a certain threshold $f(\hat{C}(1))$. Below this threshold, self-1 does not stop the project when he receives signal h, being in the most dangerous state of the world. He always carries on the project: the information is then not relevant for him.

With the possibility of getting $f(C_{01}(\beta))$ for free, then condition (6) always holds. The decision to get information is only restricted by condition (7). In other words, self-0 of a hyperbolic agent with self-control will refuse free information with a degree of precision lower than $f(\hat{C}(1))$.

Differences in behaviour according to preferences

Using decisions made by a time-consistent agent as a benchmark on information acquisition, we propose in this part to compare these decisions to those of a hyperbolic agent and to those of a hyperbolic type with self-control.

According to Proposition 1, we note that since $\hat{\theta}(\beta)$ is increasing with β, for a given information precision, hyperbolic discounting preferences favour the decision to give up the project. Indeed, compared to self-1 of hyperbolic agent, a higher information precision is necessary to prompt self-1 of a time-consistent agent and self-1 of a hyperbolic agent with self-control to stop the project. In fact, hyperbolic discounting emphasizes a taste for immediate benefits rather than for long-term ones.

Moreover, we observe that Eq. (2) is equivalent to Eq. (4) with $\beta=1$. This implies that $C_{01}(\beta)$ with $\beta=1$ has a similar characterization than $C_{01}^{*}(1)$. Therefore, $C_{01}(\beta)$ with $\beta=1$ may be interpreted as the cost that both the hyperbolic agent and the hyperbolic agent with self-control are willing to pay to get information when they behave as a time-consistent agent, that is, their future selves act according to the preferences of their current self.[9]

We also note that $C_{01}(\beta)$ is increasing with β.[10] When both types of hyperbolic agents choose to be informed, they acquire less information than a time-consistent agent. In fact, this is because a time-consistent agent puts more weight on the future[11] and is more interested in the future benefits and costs than hyperbolic agents.

Let us deeply consider the conditions related to information acquisition, that is, condition (3) for a time-consistent agent; conditions (5) and (6) for a hyperbolic agent; and conditions (6) and (7) for a hyperbolic agent with self-control.

Regarding condition (6), its fulfilment can be characterized as follows:

Lemma 6 If condition (3) holds, then there exists $\bar{\beta}\in(\tilde{\beta},1]$ such that for all $\beta\in(\tilde{\beta},\bar{\beta}]$ condition (6) does not hold and for all $\beta\in(\bar{\beta},1]$ condition (6) holds. Otherwise, for all $\beta\in(\tilde{\beta},1]$, condition (6) does not hold.

Self-0 of a time-consistent agent may acquire information, while self-0 of hyperbolic agent and self-0 of hyperbolic agent with self-control do not. Since self-0 of hyperbolic agent and self-0 of hyperbolic agent with self-control use a lower discount factor, they have a higher preferences for the present than self-0 of a time-consistent agent. Therefore, the cost of information may then be more valuable than future payoffs, implying an information refusal. Moreover, for hyperbolic agent, condition (6) also may not hold because the effect of the discount factor between period 1 and 2 creates a higher taste for the immediate gratification at period 1. As self-1 may prefer giving up the project, self-0 prefers staying uniformed.

This result on hyperbolic type is also emphasized by the existing literature. As underlined by Carrillo and Mariotti (2000), there is a direct impact of hyperbolic preferences, which may lead the agent to ignore information. Indeed, an agent with strong preferences for the present is more willing to earn money now and then to withdraw his project, than to wait for future payoffs and potentially suffer a financial cost. Moreover, according to Akerlof (1991),

[9] In the literature, this agent is called a myopic agent.
[10] Proof in the Appendix section.
[11] The result also holds if the agent puts more relative weight on the future.

a hyperbolic agent, also, always postpones a costly activity. It is thus not surprising that a hyperbolic agent may choose to postpone his acquisition of information, which is here equivalent to not doing it.

Let us now characterize condition (5). It imposes a minimum information precision to ensure that a hyperbolic agent's future self takes into account the signal he receives. However, the specifications under which this condition is satisfied are not straightforward. According to Part (ii) of Lemma 4, $f(\hat{C}(\tilde{\beta})) = \frac{1}{2} < f(C_{01}(\tilde{\beta}))$. However, due to the general form of our precision function, we are not able to define when $f(\hat{C}(\beta))$ is higher than, equal to, or lower than $f(C_{01}(\beta))$. Therefore, three possibilities arise:

- $(P1)$: There is no intersection between $f(\hat{C}(\beta))$ and $f(C_{01}(\beta))$. That is for all $\beta \in (\tilde{\beta},1)$, $f(\hat{C}(\beta)) < f(C_{01}(\beta))$;
- $(P2)$: There exists one intersection between $f(\hat{C}(\beta))$ and $f(C_{01}(\beta))$. Define $\beta_1 \in (\tilde{\beta},1)$ such that $f(\hat{C}(\beta_1)) = f(C_{01}(\beta_1))$. Then, for all $\beta \in (\tilde{\beta}, \beta_1)$, $f(\hat{C}(\beta)) < f(C_{01}(\beta))$ while for all $\beta \in (\beta_1,1)$, $f(C_{01}(\beta)) \leqslant f(\hat{C}(\beta))$;
- $(P3)$: There exist several intersections between $f(\hat{C}(\beta))$ and $f(C_{01}(\beta))$. Therefore, for some $\beta \in (\tilde{\beta}, 1)$, $f(\hat{C}(\beta)) < f(C_{01}(\beta))$, and for the others $f(C_{01}(\beta)) \leqslant f(\hat{C}(\beta))$.

Let us now characterize condition (7). As for condition (5), three possibilities arise when considering the optimal level of information:

- $(\tilde{P}1)$: There is no intersection between $f(\hat{C}(1))$ and $f(C_{01}(\beta))$. That is, for all $\beta \in (\tilde{\beta}, 1)$, $f(\hat{C}(1)) < f(C_{01}(\beta))$;
- $(\tilde{P}2)$: There exists one intersection between $f(\hat{C}(1))$ and $f(C_{01}(\beta))$;
- $(\tilde{P}3)$: There is no intersection between $f(\hat{C}(1))$ and $f(C_{01}(\beta))$. That is, for all $\beta \in (\tilde{\beta}, 1)$, $f(\hat{C}(1)) \geqslant f(C_{01}(\beta))$.

Time-consistent preferences vs. hyperbolic preferences With regard to these conditions, let us consider possibility $(P1)$. Condition (5) is always satisfied, which means that the minimum precision imposed on the signal to be powerful is lower than the information precision provided by $C_{01}(\beta)$. In such a case, the decision to get information for a hyperbolic agent only depends on condition (6).

According to Lemma 6, if a time-consistent agent does not acquire information, a hyperbolic one does not either. In fact, information is too costly for both types of agent. On the other hand, even if a time-consistent agent acquires information, a hyperbolic one may remain ignorant.

As depicted in Figure 1, below $\bar{\beta}$ a hyperbolic agent has such strong preferences for the present that he prefers ignoring the information in order to avoid a premature stop of his project. Carrillo and Mariotti (2000) view such a strategic ignorance as a way to prevent the consumption of a potentially

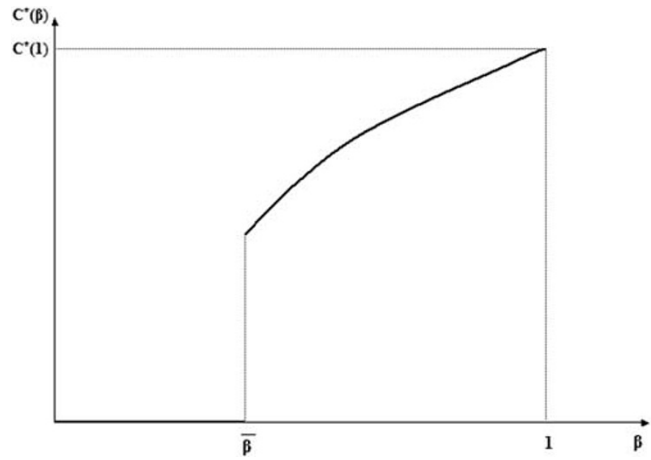

Figure 1. (P1) – Optimal expense to acquire information when condition (5) is always satisfied.

dangerous product. In our case, it describes a dangerous behaviour, which favours innovation to the detriment of any precautionary efforts. We consider this ignorance to be dangerous.

On the other hand, above $\bar{\beta}$ the agent is willing to pay to be informed and follows the strategy $\{x_h=0, x_l=1\}$. By acquiring information in order to reduce the uncertainty on the potential risks, the hyperbolic agent chooses to adopt a precautionary behaviour. We note that the optimal level of information increases with β. Therefore, a time-consistent agent is willing to pay a higher information cost than a hyperbolic agent. Indeed, as previously underlined, a time-inconsistent agent is more concerned by current reward and cares less about a potential delayed financial cost.

Tables 1 and 2 briefly consider possibility ($P2$). It is a more sophisticated case insofar as conditions (3), (5) and (6) interact with the agent's decision to get information.

Let us consider the two cases (Table 1) in which a time-consistent agent always acquires information (i.e., condition (3) holds and thus $\bar{\beta}$ exists). First, regarding the case where $\bar{\beta} \leqslant \beta_1$, one should notice the possibility that the agent prefers staying uninformed even if the discount rate is close to one and chooses to get information for lower values of β. Such a result is explained by the fact that the minimum precision imposed by the hyperbolic agent through condition (5) is very high. It is thus not possible in this case to define an information cost that allows reaching this minimum precision, even if this cost provides enough precise information to fulfil condition (6). Secondly, it is possible that, when $\bar{\beta} > \beta_1$, getting enough precision is always too costly for a

Table 1 Optimal expense to acquire information when condition (3) is fulfilled

$\bar{\beta}$ *exists: a time-consistent agent always gets information*			
$\bar{\beta} \leqslant \beta_1$	$\beta \in (\tilde{\beta}, \bar{\beta}]$	$\beta \in (\bar{\beta}, \beta_1)$	$\beta \in (\beta_1, 1)$
Conditions fulfilled	(5)	(5) and (6)	(6)
Optimal amount paid	0	$C_{01}^{*}(\beta)$	0
Interpretation	Ignorance	Precaution	Ignorance
$\bar{\beta} > \beta_1$	$\beta \in (\tilde{\beta}, \beta_1]$	$\beta \in (\beta_1, \bar{\beta})$	$\beta \in (\bar{\beta}, 1)$
Conditions fulfilled	(5)	none	(6)
Optimal amount paid	0	0	0
Interpretation	Ignorance	Ignorance	Ignorance

Table 2 Optimal expense to acquire information when condition (3) is never fulfilled

$\bar{\beta}$ *does not exist: a time-consistent agent never gets information*		
	$\beta \in (\tilde{\beta}, \beta_1]$	$\beta \in (\beta_1, 1)$
Conditions fulfilled	(5)	none
Optimal amount paid	0	0
Interpretation	Ignorance	Ignorance

hyperbolic agent. In fact, when $\bar{\beta} > \beta_1$, there is no cost that would provide useful information, such that condition (5) holds, and condition (6) is satisfied. In this case, for any value of $\beta < 1$, hyperbolic agent never acquires information while a time-consistent agent is always willing to do so.

By considering the results in Table 2, it is also not optimal to acquire information regardless of the form of the preferences. Indeed, if the cost of the information that would provide enough precision to a time-consistent agent is too high, condition (3) is not satisfied. In such a case, it is not possible to define $\bar{\beta}$ and thus to fulfil condition (6). In others words, as for a time-consistent agent, the level of information that would provide a hyperbolic agent with enough precision on the dangerous state H is too costly with regard to the expected payoff that he could get with such information.

Finally, since possibility ($P3$) is a mix of possibilities ($P1$) and ($P2$), it does not raise new results. We do not detail it.

Time-consistent preferences vs. hyperbolic preferences with self-control Let us then consider possibility ($\tilde{P}1$). Condition (7) is always satisfied and thus we get the same results as for possibility ($P1$) described in the previous section.

Regarding possibility ($\tilde{P}2$), conditions (3), (6) and (7) have to be characterized to determine the optimal cost of information that the hyperbolic agent with self-control is willing to pay. Let us first consider condition (7). The level of information precision from which self-1 of a hyperbolic agent with self-control decides to implement strategy $\{x_h=0, x_l=1\}$ is independent of β because its self-1 and self-2 behave as time-consistent selves. Define $\beta_2 \in (\beta, 1)$ such that $f(\hat{C}(1))=f(C_{01}(\beta_2))$. Since a higher β implies a higher $C_{01}(\beta)$ and since f is increasing, then below β_2 condition (7) is not satisfied while it is above β_2. When taking conditions (3) and (6) into account, two cases arise: If the agent's preferences are such that the cost of information that provides a precise enough signal to implement the strategy $\{x_h=0, x_l=1\}$, and if $\beta \in (\max\{\bar{\beta},\beta_2\},1]$, then the agent always chooses to pay this cost and thus to acquire information. On the other hand, if either the cost of information that needs to be paid to get a useful signal does not satisfy conditions (3) and (6), or if the agent's preferences for the present are too strong, the hyperbolic agent prefers staying ignorant. Moreover, according to Lemma 6, if a time-consistent agent does not satisfy condition (3), a hyperbolic one with self-control does not satisfy condition (6) either. Then, both types of agents do not acquire information.

Finally, let us turn to possibility ($\tilde{P}3$). In this case, condition (7) is never satisfied, and thus a hyperbolic agent with self-control, even if he behaves as a time-consistent agent in the future, never gets information. Indeed, he prefers staying ignorant in order to avoid a lower expected payoff.

Hyperbolic preferences vs. hyperbolic preferences with self-control Condition (6) is common to both types of hyperbolic agents, that is, with and without self-control. Therefore, the difference between their decisions to acquire information comes from the fulfilment of conditions (5) and (7).

According to Propositions 3 and 4, since f and $\hat{C}$ are increasing, when condition (7) holds, then condition (5) is also satisfied. However, the reverse is not always true. When a signal h is produced, a hyperbolic agent without self-control requires less precise information to stop the project than if he had a self-control capacity. Indeed, such an agent is more concerned by current rewards and is more willing to give up in order to recover a part of his investment. Behaving as a time-consistent agent in the future increases the threshold of the minimum degree of information precision that conditions the relevance of the information. Thus, while a hyperbolic agent acquires information, a hyperbolic agent with self-control may remain ignorant because the signal produced does not lead him to withdraw the project when it is dangerous.

Overall, we sum up our results. We find that all types of agents, regardless of their preferences, always acquire information unless the cost exceeds direct benefits. Nevertheless, a hyperbolic agent may remain strategically ignorant

and, when he does acquire information, he acquires less information than a time-consistent agent. Likewise, such a hyperbolic agent who behaves as a time-consistent agent with regard to future actions is more inclined to remain ignorant. In fact, with self-control, the agent needs a higher information precision to give up his project. Moreover, the information refusal depends not only on the cost of this information but also on the degree of the precision that this information is able to provide. Information precision plays a vital role in the information acquisition decision of hyperbolic agents.

Sensitivity analysis

In order to get a better understanding of the agent's behaviour in the context of uncertainty, we propose to study, for each kind of preferences, the effects of changes in the parameters. In particular, we wonder how the agent's prior beliefs may affect the agent's strategy; whether the probability level that a damage occurs has an impact on the agent's decision making; and what are the influences of a project's returns and costs on the agent's behaviour.[12]

We find that prior beliefs have a clear effect on the time-consistent agent's decisions. When the agent has a strong prior belief on realization of the worse state of the world (state H), his ability to both acquire information and to stop the project increases, while his information level is decreases. Since the agent believes that an accident has a higher risk to occur, information on the project consequences is more reliable because it gives him the possibility to give up his investment. In addition, this withdrawal opportunity is more often chosen because the agent's beliefs of getting a negative payoff increased if he continues the project. However, such an increase leads to a lower expected payoff and therefore to a lower expense to get information.

By contrast, since the decision to acquire information also depends on the level of its precision, the impact of prior belief on the two types of hyperbolic agent is unclear. First of all, we have an unambiguous effect on the chosen level of information and on the decision to give up the project. As the agent reduces the level of information acquired, the precision of this information also decreases. On the other hand, as it increases the agent's willingness to stop the project, the necessary minimum level of information precision induced also decreases. In other words, the agent's prior belief creates a trade-off between information precision and the project's development, and then has an ambiguous effect on his choice to be informed.

In addition, we observe that a change of the probability that a damage occurs differently affects the chosen level of information according to the state

[12] Proofs are in the Appendix section.

in which the change occurs. For all kinds of preferences, a higher probability in state L has a similar effect on the agent's decision than a higher prior belief on the realization of state H. A higher probability in state H also produces the same impact on the decision of stopping the project and acquiring information, but it leads to a higher level of information to acquire for all kinds of preferences. Since by assumption, for all $\beta \in (\tilde{\beta}, 1]$ $B^H(\beta) < 0 < B^L(\beta)$ then a lower probability in state H, and/or a higher probability in state L leads to a reduction of the expected payoff. In order to compensate for this waste of money, the agent prefers paying less to be informed.

Now, we analyse the effects of the project's returns and costs on the agent's decisions. In fact, these parameters have a direct impact on the expected payoff. We observe that, regardless of the preferences, a higher R_2, a lower D, a lower K and/or a higher K' imply a higher expected payoff by continuing the project than the one by stopping it. Hence, these changes decrease the agent's ability to withdraw the project regardless of the design of his preferences.

Furthermore, for all kinds of preferences, we note that the effect of R_2 and D on the expected payoff also depends on the prior belief. Indeed, if $p_0 > \frac{1}{2}$ ($p_0 < \frac{1}{2}$), that is, if the agent thinks that realization of the worse state of the world has a higher probability to occur than the one of the less dangerous, a higher (lower) R_2 and/or a lower (higher) D decreases the expected payoff. In this context, the agent chooses to get less information in order to compensate for the loss of money. However, the costs' effect on the acquired level of information is ambiguous; it depends on both the agent's beliefs and the probability that a damage occurs.

Finally, as previously explained, since the two types of hyperbolic agents face a constraint on the precision of the information, the impact of both returns and costs on the agent's choice to be informed is ambiguous. There is a trade-off between the variations of the minimum level of information precision, and the level of precision effectively chosen. On the other hand, for a time-consistent agent, returns and costs have a clear impact. If the expected payoff, when the agent continues the project, increases, that is, R_2 increases and/or K decreases, then the agent is less willing to acquire the information in order to avoid stopping the project. If the expected payoff induced by the withdrawal of the project increases, that is, D increases and/or K' decreases, then the agent will acquire more often information. In fact, he favours the possibility to stop the project by acquiring information. Table 3 summarizes all these results.

Liability rules' influence on the information acquisition

All firms are constrained by a legal framework in which liability rules specify how to allocate financial damages from an accident. Regarding technological

Table 3 Static comparative analysis: main results

	Willingness to stop project	*Ability to acquire info.*	*Level of info.*
Time-consistent preferences			
p_0	+	+	−
θ^L	+	+	−
θ^H	+	+	+
R_2	−	−	−if $p_0 > 1/2$ + otherwise
D	+	+	+ if $p_0 > 1/2$ − otherwise
K	+	+	?
K'	−	−	?
Hyperbolic preferences: hyperbolic preferences with self-control			
p_0	+	?	−
θ^L	+	?	−
θ^H	+	?	+
R_2	−	−if $p_0 > 1/2$ + otherwise	−if $p_0 > 1/2$ + otherwise
D	+	+ if $p_0 > 1/2$ − otherwise	+ if $p_0 > 1/2$ − otherwise
K	+	?	?
K'	−	?	?

Note: When the effect of the parameter is not straightforward, we use the notation "?".

innovations as well as other risky activities, it is important that firms receive the right incentives in order not to neglect risk and uncertainty in learning. In this regard, this section proposes to analyse whether, at the agent level, existing regulatory frameworks of risk, such as strict liability rule and negligence rule, may have an impact on the agent's willingness to acquire information.

The strict liability rule

Under a strict liability rule, it is said that "if the victims can demonstrate a causality link between the damages and the agent's activity or the product sold, the agent is fully liable and thus he must pay for the damages caused by his activities".[13] Shavell (1980) and Miceli (1997) show that, under time-consistency, such a rule is an incentive for agents to consider the effect of both their level of care and their level of activity on accident losses. Hence, this rule allows both to prevent risks and to reduce the potential damages by leading the agent to exercise an optimal level of prevention.

In the model, we assume that if an accident occurs, the agent is liable for damages and must pay for them. Therefore, in defining the level of care, as the amount paid by the agent to acquire information, we implicitly suppose that a

[13] See Shavell (1980) and Miceli (1997).

strict liability rule is enforced.[14] Acquiring information reflects the agent's level of interest for the potential activity's losses. Indeed, if the agent is informed, he may stop his activity and then limit the cost of damages to K'. On the other hand, if he does not acquire information, he never stops his project and therefore exposes people and the environment to a more severe risk.

As previous sections emphasize, regardless of the agent's preferences (time-consistent or hyperbolic), if the optimal amount paid related to the strategy $\{x_h=0, x_l=1\}$ does not satisfy conditions (3) and (6), the agent never chooses to implement this strategy and always prefers staying uninformed. In others words, even if the agent is fully liable, if developing research activities or resorting to experts is too costly with regard to the expected returns of his project, the agent has to choose staying ignorant about the level of danger of this project in order to be able to realize it. When considering the efficiency of such behaviour, we remark that, in this case, it is Pareto efficient for both agents not to acquire information. Using long-run preferences to measure the welfare, as suggested by O'Donoghue and Rabin (1999), it is efficient not to acquire information. Indeed, such a criterion supposes that we compare the decisions of a time-consistent agent to those of a hyperbolic one.[15] It seems that the source of problem is not the liability rule enforced, but the cost of information acquisition when facing the development of new technologies. This raises arguments to limit innovation when uncertainty is too strong in that it could encourage all kinds of decision makers to neglect a potential danger.

However, even if the optimal amount paid related to the strategy $\{x_h=0, x_l=1\}$ satisfies conditions (3) and (6) when an agent has strong preferences for the present, it does not mean that he always chooses to acquire information, even if he is fully liable. Moreover, even if he has weaker preferences for the present, such behaviour may still occur. Indeed, if the signal provided is not viewed as reliable, the agent always prefers staying ignorant (conditions (5) and (7)). In such a case, ignorance is Pareto efficient behaviour, while using long-run preferences as a welfare measure, it is not an efficient decision. Thus, according to the welfare criteria chosen, the strict liability rule allows either efficient, but potentially dangerous, behaviour, or inefficient behaviour. Both cases inhibit any precautionary efforts, and thus might expose people and the environment to severe risks in the future.

Overall, a strict liability rule does not seem to be a useful tool to encourage agent to acquire information. This raises the question: how to design correct

[14] However, we do not take into account the way in which victims have to demonstrate a causality link between damages and the activity or the product sold.

[15] O'Donoghue and Rabin (1999) define long-run preferences by: $U^0(u_t, \ldots, u_T) = \Sigma_{\tau=t}^{T} \delta^{\tau=t} u_\tau$. In the paper, we assume that $\delta=1$ and thus $U^0=V_0$ when $\beta=1$.

incentives which would lead people to take the best decision for their own long run interest?

The negligence rule

Under a negligence rule, it is said that "the injurer is liable for the victims' damages only if he fails to take a minimum level of care".[16] In other words, after an accident, the Court of Law does not consider that an agent is liable and has to pay a financial cost for the damages if he has exercised the minimum level of care specified by the legal framework. In such a case, victims or States have to assume financial costs.

However, how is one to define the minimum level of care? According to Shavell (1980, 1992) and Miceli (1997), under a negligence rule, the minimum level of care is defined as the optimal level of care that an injurer chooses if he has to pay for the damages. In our model, the minimum level of care is then the optimal amount paid to acquire information. Propositions 2–4 imply that when condition (3) does not hold for the agent with time-consistent preferences, when conditions (5) and (6) do not hold for hyperbolic agent, and when conditions (7) and (6) do not hold for hyperbolic agent with self-control, then it is not optimal for him to acquire information, that is, $C^*(\beta)=C^{**}(\beta)=0$. On the other hand, when these conditions are satisfied, acquiring information is optimal ($C^*(\beta)>0, C^{**}(\beta)>0$) for the agent, regardless of his preferences. Hence, this definition of the minimum level of care may lead the agent to neglect information without being liable for the damages. This does not encourage the agent to acquire information and then to decide whether he continues or stops the project in order to limit the cost of damages.

Therefore, how do incentive agents get information? We propose to define the minimum level of care as the minimum amount, $C^{min}(\beta)$, that an agent has to pay not to be liable if an accident occurs, and which leads him to acquire information, regardless of his preferences. In this respect, the agent has an incentive to be informed.

Self-0's intertemporal expected payoff when the agent is not responsible for the financial damages in case of an accident occurs is thus given by:

$$V_0^{NR}(x_h, x_l, C) = -I - C + \beta[p_0 f(C) + (1-p_0)(1-f(C))](x_h R_2 + (1-x_h)D) + \beta[(1-p_0)f(C) + p_0(1-f(C))](x_l R_2 + (1-x_l)D).$$

[16] See Shavell (1980) and Miceli (1997).

In fact, $V_0^{NR}(x_h, x_l, C)$ equals self-0's intertemporal expected payoff $V_0(x_h, x_l, C)$ with $K=K'=0$.

Propositions 2–4 show that regardless of his preferences, the agent may optimally prefer not to acquire information and be liable for the damages in case of an accident. To avoid such an effect, the legal framework should impose that the minimum level of care $C^{min}(\beta)$ verifies that regarding the strategy $\{x_h=0, x_l=1\}$, self-0's intertemporal expected payoff when self-0 pays $C^{min}(\beta)$ and is not liable for the damages, that is, $V_0^{NR}(0, 1, C^{min}(\beta))$, is at least equal to self-0's intertemporal expected payoff when self-0 does not pay and is then liable for the damages. According to condition (1), we know that when an agent decides to be uninformed, he always continues his project. Then, self-0's intertemporal expected payoff when self-0 decides not to pay and is liable for the damages is $V_0(1, 1, 0)$. The minimum level of care $C^{min}(\beta)$ is then characterized by:

$$V_0^{NR}(0, 1, C^{min}(\beta)) = V_0(1, 1, 0),$$

which is equivalent to

$$C^{min}(\beta) + \beta[p_0 f(C^{min}(\beta)) + (1 - p_0)(1 - f(C^{min}(\beta)))](R_2 - D) = \beta E(\theta)K.$$

We can easily check that $C^{min}(\beta)$ exists and is strictly positive. Therefore, regardless of his preferences, an agent has an incentive to pay at least $C^{min}(\beta)$. Indeed, for a time-consistent agent, who can commit in the long run, it is more interesting to invest $C^{min}(\beta)$ and implement the strategy $\{x_h=0, x_l=1\}$ than not getting any information. However, since a hyperbolic discounting agent does not have consistent preferences in the future, even if from self-0's perspective, $C^{min}(\beta)$ is more relevant, such a cost cannot ensure that self-1 chooses the strategy $\{x_h=0, x_l=1\}$. In fact, the agent is never liable when paying for such a cost regardless of the strategy chosen at period 1, thus self-1 always deviates from the anticipated strategy $\{x_h=0, x_l=1\}$. In other words, such a level of care supposes that the agent behaves as a naive agent who does not foresee any problem of self-control. Such a design of incentives does not influence him to behave in a precautionary way and does not limit the exposure of people or the environment to a potential danger.

Alternatively, a sophisticated agent is aware of his self-control problem and aims at overcoming it. In this regard, the minimum level of care should ensure that $V_0^{NR}(0, 1, C^{min}(\beta))=V_0(1, 1, 0)$, but also prevent any possible deviation from the strategy $\{x_h=0, x_l=1\}$. Thus, $C^{min}(\beta)$ should also verify that the intertemporal expected payoff, under the strategy $\{x_h=0, x_l=1\}$ when the agent is not liable, is at least equal to the intertemporal expected payoff under

the strategy $\{x_h=1, x_l=1\}$ when the agent is not liable. Finally, $C^{min}(\beta)$ is defined by:

$$V_0^{NR}(0,1,C^{min}(\beta)) = V_0(1,1,0) \text{ and } V_0^{NR}(1,1,C^{min}(\beta)) = V_0^{NR}(0,1,C^{min}(\beta)),$$

which is equivalent to $C^{min}(\beta) = \beta E(\theta)K$.

Such a design of incentives might influence the hyperbolic agent to behave in a precautionary way.

To go further …

Another point has to be mentioned concerning the level of the penalty if an accident occurs. What would happen if the returns of the agent were lower than or equal to the potential cost of damages, that is, $R_2 \leqslant K$ and $D \leqslant K'$? The results of the model apply. Indeed, the model's assumptions do not allow to consider cases where the agent would not invest in the project, and do not consider that the agent may not be able to financially assume the damages he may cause.

Intuitively, if we introduce this possibility, the agent should subscribe an insurance contract to cover potential damages linked to his activity. Moreover, if a limited liability rule is enforced, that is, *a catastrophic accident, whose damages are higher than the financial capacities of the firm, is considered as a bankruptcy, and the total cost of accident is limited to the return of the firms*, the agent will only be partly liable for these damages. Under uncertainty, such a protective measure may have perverse effects. Even if the cost of potential damages as well as its probability is not completely known, the agent may not care about reducing this uncertainty because he will only lose his benefits if an accident occurs, regardless of the size of this accident. Hence, limited liability application is not a relevant rule in the context of uncertainty. In addition, under such a liability rule, insurance might also have an important impact on firms' behaviour. An interesting further work would be to study the effect of the insurance premium on the information acquisition. Does it increase the information acquisition? Insurance could cover a part of the damage costs, however taking an insurance is costly. What would be the trade-off between this cost and benefit? What about the discounting effect?

Conclusion

In this paper, we consider an agent who invests in new industrial activities, and then has an uncertainty on activities' consequences. Getting information allows

him to reduce this uncertainty. To a certain extent, information acquisition could be viewed as precautionary efforts insofar as it allows the one under uncertainty to limit the potential damages that the project could entail, and to improve the protection of people's health and that of the environment. Possible examples of applications include innovations in new technologies (e.g., nanotechnologies, mobile phones), pharmaceutical firms (e.g., development and production of new drugs), or chemical firms (e.g., production of new fertilizers).

In our model, we analyse individual behaviour with different types of preferences: time-consistent, hyperbolic discounting and hyperbolic discounting with self-control in the future. However, we wonder if an institution as a firm still conserves hyperbolic behaviour. When one person owns a business, the preferences of the owner would define the preferences of the firm. When a firm comprises of more than one partner, then they would have strategic interaction among them. However, all of them should operate for the common goal of making profit. In the decision to acquire information, there should be no competition between individuals, they should all make a decision in order to favour their firm. Hence, the board of shareholders in charge of the strategic decisions may be represented by an arbitrary individual with time-consistent or hyperbolic discounting preferences.

We find that the hyperbolic agent does not refuse free information but free information with a certain degree of precision. By introducing a costly information linked to information precision, we find that a time-consistent agent as well as a hyperbolic type will acquire information unless the cost exceeds the direct benefit. Nevertheless, a hyperbolic agent may remain ignorant if the degree of information precision is not high enough to make information relevant for him. On the other hand, when a hyperbolic agent does acquire information, he acquires less information than a time-consistent type. Moreover, if we introduce the possibility that the hyperbolic agent behaves as a time-consistent agent on future actions, we show that the agent will be more inclined to remain ignorant. We then emphasize the relevance of information precision for hyperbolic types' information acquisition decision.

With a sensitive analysis, we show that prior beliefs, probabilities that damage occurs and returns and costs of the project do not influence the agent's decisions in the same way according to the preferences.

Finally, we analyse the way in which liability rules influence the agent's decision to acquire information. We find that a strict liability rule does not appear to be a useful tool in order to incentivize an agent, regardless of his preferences, to acquire information. However, we propose an alternative solution, the negligence rule, which might lead the agent to behave in a precautionary way, regardless of his preferences.

In addition, if the information acquisition is not spontaneous, other responsibility forms or rules might be considered. Strotz (1956) emphasizes the necessity to define pre-commitment strategies in a context of hyperbolic preferences in order to reduce the impact of the hyperbolic discounting preferences on the agents' decision. In an innovation context, pre-commitment could be realized with contracts establishing the innovation's agenda in the long run. From this perspective, the negligence rule could be an interesting alternative solution. Agents who are familiar with risk and uncertainty, such as the insurers, could also define such a pre-commitment strategy. One could then imagine insurance contracts with a deductible to allow better control of the precautionary efforts undertaken by agents and reduce the financial risk they are exposed. However, to go further, such a contract could only be defined if the probability of damages is known, which may not be the case under uncertainty (i.e., when facing scientific uncertainty). Indeed, insurance companies would have to charge an ambiguity premium in addition to the traditional premium, which could lead to an unaffordable contract, or would refuse to insure the project of the firm. Overall, insuring emerging risks is still under debate, mostly depending on the definition of a financial liability of firms for the damages that their activities might cause in the future, even if it is still not possible to precisely quantify such damages.

Moreover, regarding the current application of a strict liability rule, experience also underlines the persuasive role that such a rule can play on the producers' behaviour. Weill (2005) notes that when the "burden of the proof" is on the potential injurer, and not on the victims, as is the case under a negligence rule, producers are more likely to withdraw potentially dangerous products from the market. The recent European legislation on chemicals (REACH directive)[17] tackles the challenging issue related to the application of the precautionary principle to enhance innovation as well as protect people and the environment. It is based on a strict liability rule, under which the "burden of the proof" is on the industry, but it also requires manufacturers and importers to take the responsibility "to gather information on the properties and risks of all substances produced or imported".[18] This legislation proposes an interesting way to implement the precautionary principle to deal with chemicals, by combining the positive effects of a strict liability rule with a research obligation for firms that should avoid the negative ones. This approach should provide relevant elements in the current debate on the regulation of other kinds of scientific and/or technological innovation.

[17] REACH stands for Registration, Evaluation, Authorization and Restriction of Chemicals.
[18] For more details on REACH, see European Commission (http://ec.europa.eu/enterprise/reach).

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References

Ainslie, G. (1992) *Picoeconomics: The Strategic Interaction of Successive Motivational States within the Person*, New York: Cambridge University Press.

Akerlof, G.A. (1991) 'Procrastination and obedience', *American Economic Review* **81**(2): 1–19.

Arrow, K.J. and Fisher, A.C. (1974) 'Environmental preservation, uncertainty, and irreversibility', *Quarterly Journal of Economics* **88**(2): 312–319.

Bénabou, R. and Tirole, J. (2002) 'Self confidence and personal motivation', *Quarterly Journal of Economics* **117**: 871–913.

Bénabou, R. and Tirole, J. (2004) 'Willpower and personal rules', *Journal of Political Economy* **112**(4): 848–886.

Brocas, I. and Carrillo, J.D. (2000) 'The value of information when preferences are dynamically inconsistent', *European Economics Review* **44**: 1104–1115.

Brocas, I. and Carrillo, J.D. (2004) 'Entrepreneurial boldness and excessive investment', *Journal of Economics and Management Strategy* **13**(2): 321–350.

Brocas, I. and Carrillo, J.D. (2005) 'A theory of haste', *Journal of Economic Behavior and Organization* **56**: 1–23.

Carrillo, J.D. and Mariotti, T. (2000) 'Strategic ignorance as a self disciplining device', *Review of Economic Studies* **67**: 529–544.

Elster, J. (1979) *Ulysses and the Sirens: Studies in Rationality and Irrationality*, New York: Cambridge University Press.

Frederick, S., Loewenstein, G. and O'Donoghue, T. (2002) 'Time discounting and time preference: A critical review', *Journal of Economic Literature* **40**: 350–401.

Henry, C. (1974) 'Investment decisions under uncertainty: The irreversibility effect', *American Economic Review* **64**(6): 1006–1012.

Henry, C. (2003) 'Seminar on "Principe de Précaution et Risque Environnemental', Chaire de développement durable EDF-Polytechnique, 16 June 2003.

Henry, C. and Henry, M. (2002) 'L'essence du principe de précaution: la science incertaine mais néanmoins fiable', Séminaire développement durable et économie de l'environnement, Iddri, EDF-Ecole Polytechnique, n11.

Laibson, D. (1997) 'Golden eggs and hyperbolic discounting', *Quarterly Journal of Economics* **112**(2): 443–477.

Laibson, D. (1998) 'Life cycle consumption and hyperbolic discount functions', *European Economic Review* **42**: 861–871.

Masson, A. (2002) 'Risque et horizon temporel: quelle typologie des consommateurs - épargnants?', *Risques* (49).

Miceli, T. (1997) *Economics of the Law*, New York: Oxford university Press.

O'Donoghue, T. and Rabin, M. (1999) 'Doing it now or later', *American Economic Review* **89**(1): 103–124.

O'Donoghue, T. and Rabin, M. (2008) 'Procrastination on long-term projects', *Journal of Economic Behavior and Organization* **66**(2): 161–175.

Phelps, E.S. and Pollack, R.A. (1968) 'On second-best national saving and game-equilibrium growth', *Review of Economic Studies* **35**(2): 185–199.

Read, D. (2001) 'Is time-discounting hyperbolic or subadditive?' *Journal of Risk and Uncertainty* **23**: 5–32.

Rubinstein, A. (2003) 'Is it economics and psychology?: The case of hyperbolic discounting', *International Economic Review* **44**: 1207–1216.

Shavell, S. (1980) 'Strict liability versus negligence', *Journal of Legal Studies* **9**(1): 1–25.

Shavell, S. (1992) 'Liability and the incentive to obtain information about risk', *Journal of Legal Studies* **21**(2): 259–270.

Strotz, R.H. (1956) 'Myopia and inconsistency in discounting utility maximization', *Review of Economic Studies* **23**(3): 165–180.

Weill (2005) 'European proposal for chemicals regulation: REACH and beyond proposition de règlement européen des produits chimiques: REACH, enjeux et perspective', Les actes de l'Iddri, n 2.

http://ec.europa.eu/enterprise/reach.

http://en.wikipedia.org/wiki/Luria-Delbr%C3%BCck_experiment.

Appendix

Proof of $\hat{\theta}(\beta)$ is increasing with β

We differentiate $\hat{\theta}(\beta)$ with respect to β, we obtain:

$$\hat{\theta}'(\beta) = \frac{D}{\beta^2(K - K')}$$

which is positive. Therefore, $\hat{\theta}(\beta)$ is increasing with β. □

Proof of Proposition 1 At period 1, the agent receives signal $\sigma \in \{h, l\}$. For all $C \geqslant 0$ and for all $\beta \in (\tilde{\beta}, 1]$: He chooses to continue, that is, $x_\sigma = 1$ if:

$$V_1(0, \sigma, C) < V_1(1, \sigma, C), \quad \text{which is equivalent to}$$
$$E(\theta|\sigma, C) < \hat{\theta}(\beta) \equiv \frac{\beta R_2 - D}{\beta(K - K')};$$

He chooses to stop, that is, $x_\sigma = 0$ if:

$$V_1(1, \sigma, C) < V_1(0, \sigma, C), \quad \text{which is equivalent to}$$
$$\hat{\theta}(\beta) \equiv \frac{\beta R_2 - D}{\beta(K - K')} < E(\theta|\sigma, C);$$

He is indifferent between stopping and continuing the project, that is, $x_\sigma \in \{0, 1\}$ if:

$$V_1(1, \sigma, C) = V_1(0, \sigma, C), \quad \text{which is equivalent to}$$
$$\hat{\theta}(\beta) \equiv \frac{\beta R_2 - D}{\beta(K - K')} = E(\theta|\sigma, C); \quad \square$$

Proof of Lemma 1 We first have:

$$E(\theta|l, C) - E(\theta) = \frac{(1 - p_0)p_0(\theta^H - \theta^L)(1 - 2f(C))}{(1 - p_0)f(C) + p_0(1 - f(C))}$$

and

$$E(\theta) - E(\theta|h, C) = \frac{(1 - p_0)p_0(\theta^L - \theta^H)(2f(C) - 1)}{p_0 f(C) + (1 - p_0)(1 - f(C))}$$

which are negative or equal to zero because $\theta^H > \theta^L$, and for all $C \geqslant 0$ we have $f(C) \geqslant 1/2$. Therefore for all $C \geqslant 0$, we get $E(\theta|l,C) \leqslant E(\theta) \leqslant E(\theta|h,C)$.

We then differentiate $E(\theta|h,C)$ with respect to C, we obtain:

$$\frac{\partial E(\theta|h,C)}{\partial C} = \frac{(1-p_0)p_0 f'(C)(\theta^H - \theta^L)}{[(1-p_0)(1-f(C)) + p_0 f(C)]^2}$$

which is positive because f is increasing and $\theta^H > \theta^L$. Thus, $E(\theta|h,C)$ is increasing with C.

We now differentiate $E(\theta|l,C)$ with respect to C, we obtain:

$$\frac{\partial E(\theta|l,C)}{\partial C} = \frac{(1-p_0)p_0 f'(C)((\theta^L - \theta^H)}{[p_0(1-f(C)) + (1-p_0)f(C)]^2}$$

which is negative because f is increasing and $\theta^H > \theta^L$. Thus, $E(\theta|l,C)$ is decreasing with C. □

Proof of Lemma 2

Part (i) of Lemma 2

For $\beta=1$, we study the concavity of $V_0(0,1,C)$: we differentiate twice times $V_0(0,1,C)$ with respect to C, we obtain:

$$\frac{\partial^2 V_0(0,1,C)}{\partial C^2} = \left[(1-p_0)B^L(1) - p_0 B^H(1)\right] f''(C)$$

which is negative because f is concave, $B^L(1)$ is positive and $B^H(1)$ is negative. Thus, for $\beta=1$, $V_0(0,1,C)$ is concave.

$C_{01}^*(1)$ is then characterized by the first-order condition:

$$\frac{\partial V_0(0,1,C)}{\partial C} = 0 \Leftrightarrow f'(C_{01}^*(1)) = \frac{1}{(1-p_0)B^L(1) - p_0 B^H(1)}.$$

Remark: Since $B^L(1)$ is positive and $B^H(1)$ is negative, we get $f'(C_{01}^*(1)) > 0$.

Part (ii) of Lemma 2

We suppose that $C_{01}^*(1)=0$. We then get $f'(C_{01}^*(1)) = +\infty$. However, since $0 < (1-p_0)B^L(1) - p_0 B^H(1)$ we cannot have $f'(C_{01}^*(1)) = +\infty$. There is a contradiction. Therefore, $C_{01}^*(1) > 0$. □

Proof of Proposition 2 In this part $\beta=1$. The optimal information level $C^*(1)$ is such that:

- if $V_0(1,1,0) < V_0(0,1,C^*_{01}(1))$ then $C^*(1)=C^*_{01}(1)$;
- otherwise $C^*(1)=0$.

We then compare $V_0(0,1,C^*_{01}(1))$ and $V_0(1,1,0)$. We obtain:

$$\begin{aligned} &V_0(1,1,0) < V_0(0,1,C^*_{01}(1)), \text{which is equivalent to} \\ &C^*_{01}(1) < -\left[p_0 f(C^*_{01}(1))B^H(1) + (1-p_0)(1-f(C^*_{01}(1)))B^L(1)\right]. \end{aligned} \tag{A.1}$$

Overall, we obtain if condition (8) holds then $C^*(1)=C^*_{01}(1)$, otherwise $C^*(1)=0$. □

Proof of Lemma 3

Part (i) of Lemma 3
Similar to the proof of part (i) of Lemma 2, thus omitted.

Part (ii) of Lemma 3
We suppose that there exists a $\beta_0 \in (\tilde{\beta}, 1]$ such that $C_{01}(\beta_0)=0$. We then get $f'(C_{01}(\beta_0))=+\infty$. Since $0<(1-p_0)B^L(1)-p_0B^H(1)$ then we get:

$$f'(C_{01}(\beta_0)) = +\infty \text{ if and only if } \beta_0 = 0.$$

However, $\beta_0 \neq 0$ because $\tilde{\beta} > 0$. There is a contradiction. Therefore for all $\beta \in (\tilde{\beta}, 1)$ we obtain $C_{01}(\beta) > 0$. □

Proof of Lemma 4

Part (i) of Lemma 4
For $\beta \in [\tilde{\beta}, 1)$, we define:

- $\hat{C}_1(\beta)$ the smallest $C \geqslant 0$, which satisfies $E(\theta|l,C) \leqslant \hat{\theta}(\beta)$;
- $\hat{C}_2(\beta)$ the smallest $C \geqslant 0$, which satisfies $\hat{\theta}(\beta) \leqslant E(\theta|h,C)$;
- $\hat{C}(\beta)$ the smallest $C \geqslant 0$, which satisfies $E(\theta|l,C) \leqslant \hat{\theta}(\beta) \leqslant E(\theta|h,C)$.

Since $E(\theta|h,C)$ is increasing with C and $E(\theta|l,C)$ is decreasing with C then $\hat{C}(\beta)=\max\{\hat{C}_1(\beta), \hat{C}_2(\beta)\}$.

We first study $\hat{C}_1(\beta)$: According to condition (1) and Lemma 1, for all $C \geqslant 0$ we have $E(\theta|l,C) \leqslant \hat{\theta}(\beta)$. We then get $\hat{C}_1(\beta)=0$.

Now, we turn to $\hat{C}_2(\beta)$: since $E(\theta|h, C)$ is increasing with C then $\hat{C}_2(\beta)$ is such that:

$$\hat{\theta}(\beta) = E(\theta|h, \hat{C}_2(\beta)), \text{which is equivalent to} f(\hat{C}_2(\beta)) = \frac{(1-p_0)B^L(\beta)}{(1-p_0)B^L(\beta) - p_0 B^H(\beta)}.$$

According to condition (1) and $B^H(\beta)<0$, we easily verify that $(1/2)\leqslant f(\hat{C}_2(\beta))\leqslant 1$. Moreover, since $1/2=f(\hat{C}_1(\beta))=f(0)\leqslant f(\hat{C}_2(\beta))$ and f is increasing with C, we get:

$$\hat{C}(\beta) = \max\{\hat{C}_1(\beta), \hat{C}_2(\beta)\} = \hat{C}_2(\beta).$$

Hence,

$$f(\hat{C}(\beta)) = \frac{(1-p_0)B^L(\beta)}{(1-p_0)B^L(\beta) - p_0 B^H(\beta)}.$$

Part (ii) of Lemma 4
By definition of $\tilde{\beta}$ and $\hat{C}(\beta)$, we get:

$$E(\theta) = \hat{\theta}(\tilde{\beta}) = E(\theta|h, \hat{C}(\tilde{\beta})).$$

Since $E(\theta)=E(\theta|h,0)=E(\theta|l,0)$, $\hat{C}(\beta)$ is increasing with β and $E(\theta|h, C)$ is increasing with C then $\hat{C}(\tilde{\beta})=0$. Therefore as f is increasing, we obtain that $f(\hat{C}(\tilde{\beta})=f(0)=1/2$. □

Proof of Lemma 5 For $\beta\in(\tilde{\beta}, 1)$, by definition of $\hat{C}(\beta)$, $C_{01}(\beta)$ and $C^*_{01}(\beta)$ we get that if

$$\hat{C}(\beta) < C_{01}(\beta) \tag{A.2}$$

then $C^*_{01}(\beta)=C_{01}(\beta)$, otherwise $C^*_{01}(\beta)=\hat{C}(\beta)$.

Since f is increasing, Eq. (A.2) is equivalent to $f(\hat{C}(\beta))<f(C_{01}(\beta))$. □

Proof of Proposition 3 For $\beta\in(\tilde{\beta}, 1)$, the optimal level of information $C^*(\beta)$ is such that:

- if $V_0(1,1,0) < V_0(0,1,C^*_{01}(\beta))$ then $C^*(\beta)=C^*_{01}(\beta)$;
- otherwise $C^*(\beta)=0$.

According to Lemma 5, for $\beta \in (\tilde{\beta}, 1)$ if condition (5) holds then $C_{01}^{*}(\beta)=C_{01}(\beta)$, otherwise $C_{01}^{*}(\beta)=\hat{C}(\beta)$.

We first compare $V_0(0,1,C_{01}(\beta))$ and $V_0(1,1,0)$. We obtain:

$$\begin{aligned} &V_0(1,1,0) < V_0(0,1,C_{01}^{*}(\beta)), \text{which is equivalent to} \\ &C_{01}(\beta) < -\beta\left[p_0 f(C_{01}(\beta))B^H(1) + (1-p_0)(1-f(C_{01}(\beta)))B^L(1)\right]. \end{aligned} \tag{A.3}$$

Therefore if condition (10) holds then $C^{*}(\beta)=C_{01}(\beta)$, otherwise $C^{*}(\beta)=0$.

Now, we compare $V_0(0,1,\hat{C}(\beta))$ and $V_0(1,1,0)$. We obtain:

$$V_0(0,1,\hat{C}(\beta)) - V_0(1,1,0) = -\hat{C}(\beta) - \beta[p_0 f(\hat{C}(\beta))B^H(1) + (1-p_0)(1-f(\hat{C}(\beta)))B^L(1)].$$

With

$$f(\hat{C}(\beta)) = \frac{(1-p_0)B^L(\beta)}{-p_0 B^H(\beta) + (1-p_0)B^L(\beta)}$$

we get:

$$V_0(0,1,\hat{C}(\beta)) - V_0(1,1,0) = -\hat{C}(\beta) - \beta p_0(1-p_0)\left[\frac{(1-\beta)(\theta^H-\theta^L)D(K-K')}{-p_0 B^H(\beta) + (1-p_0)B^L(\beta)}\right]$$

which is negative. Therefore, $V_0(0,1,\hat{C}((\beta))$ is always lower than $V_0(1,1,0)$. Hence, $C^{*}(\beta)=0$.

Overall, if conditions (5) and (10) hold then $C^{*}(\beta)=C_{01}(\beta)$, otherwise $C^{*}(\beta)=0$. □

Proof of Proposition 4 Similar to the proof of Proposition 3, thus omitted. □

Proof of $C_{01}(\beta)$ is increasing with β
We differentiate Eq. (4) with respect to β. We obtain:

$$f''(C_{01}(\beta))C_{01}(\beta) = \frac{-1}{\beta^2[(1-p_0)B^L(1) - p_0 B^H(1)]}$$

which is negative because $B^L(1) > 0$ and $B^H(1) < 0$. Therefore, since f is concave then $C_{01}(\beta)$ is increasing with β. $\square$

Proof of Lemma 6 For $\beta \in (\tilde{\beta}, 1)$, we define:

$$g(\beta) = -C_{01}(\beta) - \beta[p_0 f(C_{01}(\beta))B^H(1) + (1-p_0)(1-f(C_{01}(\beta)))B^L(1)].$$

We differentiate $g(\beta)$ with respect to β, we obtain:

$$\begin{aligned} g'(\beta) = &-C'_{01}(\beta) - \left[p_0 f(C_{01}(\beta))B^H(1) + (1-p_0)(1-f(C_{01}(\beta)))B^L(1)\right] \\ &- \beta\left[p_0 f'(C'_{01}(\beta))C'_{01}(\beta)B^H(1) - (1-p_0)f'(C_{01}(\beta))C'_{01}(\beta)B^L(1)\right]. \end{aligned} \tag{A.4}$$

According to Part (i) of Lemma 3:

$$f'(C_{01}(\beta)) = \frac{1}{\beta[(1-p_0)B^L(1) - p_0 B^H(1)]}.$$

In Eq. (A.4), we replace ($C_{01}(\beta)$) and get:

$$g'(\beta) = -[p_0 f(C_{01}(\beta))B^H(1) + (1-p_0)(1-f(C_{01}(\beta)))B^L(1)].$$

We now differentiate $g'(\beta)$ with respect to β, we obtain:

$$g''(\beta) = f'(C_{01}(\beta))C'_{01}(\beta)[(1-p_0)B^L(1) - p_0 B^H(1)]. \tag{A.5}$$

In Eq. (A.5), we then replace $f'(C_{01}(\beta))$ and get:

$$g''(\beta) = \frac{C'_{01}(\beta)}{\beta}$$

which is positive because $C_{01}(\beta)$ is increasing with β. Therefore, g is convex.

We note that $g'(\beta)$ may be positive, negative, or equal to zero. We first assume that $g'(\beta)$ is positive.

If condition (3) holds, then there exists a $\bar{\beta} \in (\tilde{\beta}, 1]$ such that for all $\beta \in (\tilde{\beta}, \bar{\beta}]$ condition (6) does not hold and for all $\beta \in (\bar{\beta}, 1]$ condition (6) holds.

However, if condition (3) does not hold, then for all $\beta \in (\tilde{\beta}, 1)$, condition (6) does not hold either.

We now assume that if $g'(\beta)$ is negative or equal to zero then for $\beta \in (\tilde{\beta}, 1]$, $g(\beta) < 0$. This implies that for all $\beta \in (\tilde{\beta}, 1)$ conditions (3) and (6) do not hold. □

Proofs of Section Sensibility analysis
1-Effect on decision of stopping the project:

Whatever the kind of preferences and with $\beta \in (\tilde{\beta}, 1]$:

For p_0:
We differentiate $E(\theta|h, C) - \hat{\theta}(\beta)$ with respect to p_0, we get:

$$\frac{(1 - f(C))f(C)(\theta^H - \theta^L)}{[p_0 f(C) + (1 - p_0)(1 - f(C))]^2}$$

which is positive. Then we differentiate $E(\theta|l,C) - \hat{\theta}(\beta)$ with respect to p_0, we get:

$$\frac{(1 - f(C))f(C)(\theta^H - \theta^L)}{[p_0(1 - f(C)) + (1 - p_0)f(C)]^2}$$

which is also positive. Therefore, according to Proposition 1, a higher prior belief on the worse state of the world increases the possibility for the agent to take decision of stopping the project.

For θ^H, θ^L, R_2, D, K and K', similar to the proof of p_0, thus omitted.

2-Effect on the level of information:
Whatever the kind of preferences and with $\beta \in (\beta, 1]$:

For p_0:
We differentiate Eq. (4) with respect to p_0, we get:

$$f''(C_{01}(\beta)) \frac{\partial C_{01}(\beta)}{\partial p_0} = \frac{B^L(1) + B^H(1)}{\beta[(1 - p_0)B^L(1) - p_0 B^H(1)]^2} \tag{A.6}$$

which is positive because $B^L(1) > -B^H(1)$. Then, since f is concave, $C_{01}(\beta)$ decreases with p_0. Therefore, according to Propositions 2–4, $C^*(\beta)$ decreases with p_0.

For θ^H, θ^L, R_2, D, K and K', similar to the proof of p_0, thus omitted.

3-Effect on decision of information acquisition:
For a time-consistent agent:

From condition (3), we write:

$$C_{01}^{*}(1) + p_0 f(C_{01}^{*}(1))B^{H}(1) + (1-p_0)(1-f(C_{01}^{*}(1)))B^{L}(1). \tag{A.7}$$

For p_0:
We differentiate Eq. (A.7) with respect to p_0, we obtain:

$$\frac{\partial C_{01}^{*}(1)}{\partial p_0} + \left[f(C_{01}^{*}(1))B^{H}(1) - (1-f(C_{01}^{*}(1)))B^{L}(1)\right] + \left[p_0 f'(C_{01}^{*}(1))\frac{\partial C_{01}^{*}(1)}{\partial p_0}B^{H}(1) - (1-p_0)f'(C_{01}^{*}(1))\frac{\partial C_{01}^{*}(1)}{\partial p_0}B^{L}(1)\right]. \tag{A.8}$$

According to Part (*i*) of Lemma 2:

$$f'(C_{01}^{*}(1)) = \frac{1}{[(1-p_0)B^{L}(1) - p_0 B^{H}(1)]}.$$

In Eq. (A.8), we replace $f'(C_{01}{}^{*}(1))$ and get:

$$f(C_{01}^{*}(1))B^{H}(1) - (1-f(C_{01}^{*}(1)))B^{L}(1)$$

which is negative. Therefore according to Proposition 2, a higher prior belief on the worse state of the world increases the information acquisition for an agent with time-consistent preferences.

For θ^{H}, θ^{L}, R_2, D, K and K', similar to the proof of p_0, thus omitted.

For a hyperbolic agent:
From condition (5), we write:

$$\frac{(1-p_0)B^{L}(\beta)}{(1-p_0)B^{L}(\beta) - p_0 B^{H}(\beta)} - f(C_{01}(\beta)). \tag{A.9}$$

For p_0:
We differentiate Eq. (A.9) with respect to p_0, we obtain:

$$\frac{B^{L}(\beta)B^{H}(\beta)}{[(1-p_0)B^{L}(\beta) - p_0 B^{H}(\beta)]^{2}} - f'(C_{01}(\beta))\frac{\partial C_{01}(\beta)}{\partial p_0}.$$

Since $B^H(\beta) < 0$ and $B^L(\beta) > 0$ the first part of the above equation is negative. By contrast, according to Eq. (A.6), $\partial C_{01}(\beta)/\partial p_0$ is negative then the second part is positive. Therefore according to Proposition 3, we cannot define the effect of p_0 on information acquisition decision.

For θ^H, θ^L, R_2, D, K and K', similar to the proof of p_0, thus omitted.

For a hyperbolic agent with self-control:

Similar to the proof of a hyperbolic agent, thus omitted. □

About the Author

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