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River Continuity Restoration and diadromous fishes: much more than an ecological issue

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Abstract

Ecosystem fragmentation is a serious threat to biodiversity and one of the main challenges in ecosystem restoration. River Continuity Restoration (RCR) has often targeted diadromous fishes, a group of species supporting strong cultural and economic values and especially sensitive to river fragmentation. Yet it has frequently produced mixed results and diadromous fishes remain at very low levels of abundance. Against this background, this paper presents the main challenges for defining, evaluating and achieving effective RCR. We first identify challenges specific to disciplines. In ecology, there is a need to develop quantitative and mechanistic models to support decision making, accounting for both direct and indirect impacts of river obstacles and working at the river catchment scale. In a context of dwindling abundances and reduced market value, cultural services provided by diadromous fishes are becoming increasingly prominent. Methods for carrying out economic quantification of non-market values of diadromous fishes become ever more urgent. Given current challenges for rivers to meet all needs sustainably, conflicts arise over the legitimate use of water resources for human purposes. Concepts and methods from political science and geography are needed to develop understandings on how the political work of public authorities and stakeholders can influence the legitimacy of restoration projects. Finally, the most exciting challenge is to combine disciplinary outcomes to achieve a multidisciplinary approach to RCR. Accordingly, the co-construction of intermediary objects and diagrams of flows of knowledge among disciplines can be first steps towards new frameworks supporting restoration design and planning.

Keywords: diadromous fishes; river fragmentation; ecosystem goods and services; territory; policy; multidisciplinary approach

1 Context: an intensification of efforts towards RCR and diadromous fishes' protection

1.1 Ecosystem restoration and the specific case of River Continuity Restoration in the light of river fragmentation

At the beginning of the 21st century, the Millennium Assessment pointed out that despite a global increase in human welfare, ecosystem modifications due to anthropogenic activities were threatening ecosystems' ability to sustainably provide important goods and services, especially for future generations (Millennium Ecosystem Assessment 2005). This alarming situation applied to both terrestrial and aquatic ecosystems. For example, rivers provide a multitude of goods and services to society (Postel and Richter 2003; Wolanski et al. 2011; Elliott and Whitfield 2011) that are potentially threatened due to many factors including: dam and dyke construction; pollution; water extraction for human consumption or irrigation; drying out of lateral wetlands; hydromorphological modifications; fishing; and land use in the floodplain (Elliott and Hemingway 2002; Postel and Richter 2003; Basset et al. 2013). In this article, using diadromous fishes and River Continuity Restoration (RCR, i.e. restoring free movement of fishes and/or physical and ecological components continuum) in France as an example, we will illustrate the need for an interdisciplinary approach to conceptualize, achieve and evaluate effective ecosystem restoration for diadromous fishes and identify key challenges raised by such an approach.

Indeed, ecological fragmentation disrupting ecological connectivity has been defined as one of the major challenges in ecosystem restoration and conservation (Tischendorf and Fahrig 2000a, b; Kondolf et al. 2006; Crook et al. 2009; Humphries and Winemiller 2009; Sutherland et al. 2013). The notion of "ecological connectivity/continuity" or more generally "landscape connectivity" comes from landscape ecology (Forman and Godron 1986). Ecological connectivity refers to the possibility of genes, individuals, energy or matter to move from an ecological patch (defined as a homogeneous unit of environment) to another because of the landscape structure (Ward and Stanford 1995; Ward et al. 1999). Ecosystem fragmentation can arise from natural or anthropogenic obstacles that impair animal movements. Dams or mill-weirs are among the most typical examples of obstacles in the case of river connectivity. Such obstacles can either be transversal (weirs, dams…), i.e. affecting movements upstream / downstream, or lateral (dykes), i.e. impacting movements between a river and its floodplain.

In aquatic ecosystems, river fragmentation has significant impacts on fish assemblages' composition, abundance and spatial distribution (Matthews and Robison 1998; Poulet 2007; Araújo et al. 2009; Nislow et al. 2011; Perkin and Gido 2012; Gardner et al. 2013), and on the resilience of populations because of genetic isolation (Jager et al. 1999, 2001; Fagan 2002; Horreo et al. 2011; Webb and Padgham 2013). However, river fragmentation has other kinds of impacts on ecosystem functioning such as habitat alteration or modification, variation of water table recharge, reduced denitrification, modification of flood regimes or changes in the interdependency between the river and its floodplain (Nilsson and Berggren 2000; Gergel et al. 2005). RCR aims at enhancing river ecological functioning by favouring a longitudinal biotic and physical continuum (Vannote et al. 1980), as well as a lateral continuity between rivers and their floodplains (Amoros and Roux 1988) and also a vertical continuity between the water column and river sediment.

In view of this, initiatives to restore river continuity have flourished at international, national and regional scales. In Europe for example, the Water Framework Directive (WFD - 2000/60/CE) established new requirements in order to achieve good ecological status of water bodies in each European Union (EU) Member State and specifically mentioned river continuity as a key component of good ecological status. In France, the WFD resulted, inter alia, in the implementation of a water and aquatic environments' law (Loi n° 2006-1772 30 December, 2006 sur l'eau et les milieux aquatiques: LEMA) which implements a new river classification system to prioritize rivers in which continuity must be restored or protected. Recently, the "Blue and Green Infrastructure" policies implemented in light of both the French environmental programme 2008 (Grenelle de l'Environnement), and the EU's "Green Infrastructure Strategy" (COM(2013) 249 final), detail specific projects on terrestrial and aquatic continuity preservation and restoration, based on a network of classified patches of biodiversity interconnected along ecological corridors (Forman and Godron 1986).

1.2 Diadromous fishes: high value species impacted by river fragmentation

Diadromous fishes refer to approximatively 250 species that share their life cycles between freshwater and marine habitats (Myers 1949; McDowall 1997). Many of them are iconic food and sport fishes, and have been intensively studied (Bloom and Lovejoy 2014). As an illustration of the importance of diadromous fishes, in France their landings accounted for 75% of total income of the commercial inland fishery at the end of the 20th century (Champion 1999; Boisneau and Mennesson-Boisneau 2001). Historically, *Acipenser sturio* fishing and caviar production used to be an important industry at the beginning of the 20th century (Castelnaud 2011). Later, European eel (*Anguilla anguilla*) was the most important species landed in value in the Bay of Biscay (Castelnaud 2000) in the early 2000s, especially because of the high market value of glass eels (Ringuet et al. 2002; Briand et al. 2007). Other species have a more limited value when compared to marine species, however they may be of regional importance. Allis shad (*Alosa alosa*) and to a minor extent twait shads (*Alosa fallax*) are harvested in continental waters throughout their range though their market value has decreased because of abundance decline (Bagliniere et al. 2003). Lampreys (*Petromyzon marinus* and *Lampetra fluviatilis*) have a long history of commercial fishing because of their gastronomic delicacy (Kelly and King 2001). Atlantic salmon (*Salmo salar*) is targeted by a high profile recreational fishery, as all over its distribution area (Verspoor et al. 2007). This question of RCR is crucial for diadromous fish restoration. Most freshwater fishes carry out seasonal migrations (Brönmark et al. 2014), however, diadromous fishes must carry out migrations between fresh and marine waters to complete their life cycle (Myers 1949; McDowall 1988). There are three types of diadromous species (McDowall 1988). Anadromous species, such as many salmon, spend most of their growth phase at sea and reproduce in freshwater. On the other hand, catadromous species, such as the European eel, reproduce in marine waters and spend most of their growth phase in continental waters. Finally, amphidromous fishes reproduce in freshwater and share their growth phase between freshwater and marine waters (McDowall 1988). This remarkable life-history behaviour has evolved in many fish groups (Feutry et al. 2013) but many of these species, as more generally most migratory species from the animal kingdom (Sanderson et al. 2006; Berger et al. 2008; Wilcove and Wikelski 2008), are now in decline all over the world (McDowall 1999; Limburg and Waldman 2009). Many factors explain this decline, however river fragmentation due to dams, weirs, flood gates or other physical obstacles has been considered to be one of the main causes both of their decline (Limburg and Waldman 2009). By impairing free-movements from reproduction to growth habitats, obstacles can interrupt fishes life-cycle and have led to their extinction (*Salmo salar* in the Rhine River, in the Seine River or in the Garonne River for example), or indeed of their confinement in restricted areas of rivers basins (*Salmo salar* in Loire River, *Alosa alosa* in the Rhône River and the Garonne River) (Porcher and Travade 1992; Kondolf 1997; Coutant and Whitney 2000; Larinier 2001; Fukushima et al. 2007; Limburg and Waldman 2009; Lawrence et al. 2016). Because of their high economic and cultural values and other goods and services they support (Dams 1987; Citerne 1998, 2004; Limburg and Waldman 2009), RCR has often focused on diadromous fishes. For example, most WFD fish indicators include a metric based on diadromous species (Breine et al. 2007; Coates et al. 2007; Pont et al. 2009; Delpech et al. 2010; Scholle and Schuchardt 2012) aiming at assessing river continuity, one of the component of ecological quality defined in this directive. Similarly, in France, river classification and the French Blue Infrastructure were mostly based on species of interest including many diadromous fishes. Moreover, many types of fishways, the most common mitigation measure to river fragmentation, have been specifically designed for diadromous species, especially salmonids (Larinier 2001; Noonan et al. 2012). The predominance of diadromous fishes in RCR suggest that some diadromous fishes are good candidates to be considered as “cultural keystone species” as defined by Garibaldi and Turner (2004), i.e. “culturally salient species that shape in a major way the cultural identity of a people”. However, RCR for diadromous fishes implies modifications of barriers, or even obstacles removals, while many obstacles also carry strong cultural values and provide many services (Fox et al. 2016). The potential reshaping of ecosystems goods and services provided by diadromous fishes, from market to non-market values, because of their decline and the emerging conflicts with ecosystem goods and services provided by obstacles, are central questions for the future of RCR for diadromous fishes.

2 RCR for diadromous fishes: inconsistent results and upcoming challenges

2.1 Restoration of aquatic ecosystems and RCR for diadromous fishes: inconsistent results

Though aquatic ecosystem restoration has a long history in Europe and all over the world (Palmer et al. 2014; Morandi et al. 2014), its impacts are often considered mixed (Palmer et al. 2010; Suding 2011; Jähnig et al. 2011; Palmer et al. 2014). Several reasons have been proposed to explain these disappointing results. The first reason is the complexity of aquatic ecosystems functioning based on biological, physical and chemical processes and anthropogenic pressures that work at different temporal and spatial scales. This complexity impairs our ability to understand ecosystem functioning and challenges our ability to develop appropriate tools to predict and validate the effects of restoration actions (Arthington et al. 2010; Olden et al. 2014; Lamouroux et al. 2015). Additionally, it makes it difficult to implement restoration actions at appropriate temporal and spatial scales (Palmer et al. 2010; Hermoso et al. 2012; Perring et al. 2015). Over and above this complexity, the mixed results of aquatic ecosystem restoration may also be the result of a poor linkage between science and management. This results in gaps in scientific knowledge that would be crucial for managers, in scientific results that are of poor practical use for managers, and conversely, in the under-use of scientific results by managers (Cabin 2007; Palmer 2008; Suding 2011).

Another barrier to effective restoration is the lack of consideration of the societal context in which restoration programs take place (Hermoso et al. 2012; Wortley et al. 2013). In a review, Wortley *et al.* (2013) highlighted that socio-economic dimensions had been considered in only a few restoration programs even though Pahl-Wostl et al. (2013) had underlined that the main barriers to effective restoration often arise from the socio-economic context because of diverging and fluctuating objectives among stakeholders (Barthélémy and Souchon 2009; Jørgensen and Renöfält 2013; Perring et al. 2015) and unshared spatial and temporal scales at which they consider restoration (Hermoso et al. 2012).

Despite long-terms efforts to restore diadromous fishes (the first laws were adopted in the 1700s for salmon: (Brown et al. 2013)), these restoration programs have also had mixed success (Lichatowich and Lichatowich 2001; Lichatowich and Williams 2009). A famous example is the failure of the recovery program of Pacific salmon in the Columbia river, which has been called the world's largest attempt at ecosystem restoration, but resulted in a failure (Lichatowich and Williams 2009). Regulation on fishing activities, construction of fishways and restocking from hatcheries are among the main measures implemented to conserve and restore diadromous fishes. Regarding more specifically RCR for diadromous fishes, the construction of fishways to mitigate the impact of obstacles to migration is the most common mitigation measure. But, fishways can be considered as half-way measures (Brown et al. 2013), i.e. measures that do not prevent or solve the problem but only mitigate the symptoms, and often have limited efficiency (Noonan et al. 2012). Obstacles removal appears to be much more ecologically efficient (Garcia De Leaniz 2008; Hitt et al. 2012) and is more and more perceived as a critical tool in river restoration in general and migratory fishes in particular (Doyle et al. 2003; Magilligan et al. 2017). However, it raises many more socio-economic questions than half-way measures (Jørgensen and Renöfält 2013; Magilligan et al. 2017) because of the potential loss of recreational benefits or cultural, aesthetic and historical values provided by the obstacle (e.g. historical heritage of mills, artificial reservoirs creates by the dams used for fishing, sailing or canoeing).

In light of this, the next section will address the ecological challenges raised by the RCR for diadromous fishes. The following sections will then focus on why RCR for diadromous fishes should not just be treated as an ecological issue and why, on the contrary, we need integrated multidimensional approaches (Barthélémy and Souchon 2009) to achieve legitimate and comprehensive RCR.

2.2 Three upcoming ecological challenges: a need for tools to support decision making at the appropriate scale

Scientific tools to support decision making are crucial for managers (Palmer 2008; Suding 2011). Consequently, there is a need to develop tools to predict the ecological outcomes of management options. For RCR, this raises three different challenges: (i) the need to work at an appropriate spatial scale, (ii) the need for comprehensive quantification of the impact of obstacles on diadromous fishes, (iii) the need to take these quantifications into account in predictive models.

2.2.1 First challenge: shifting from ‘site’-based approaches to ‘population scale’-based approaches

The question of scale is a key one in ecology (Levin 1992; Chave 2013) and a key issue for our complete understanding of diadromous fish ecology and conservation (McDowall 2008). The impact of river fragmentation is generally studied at three biological scales: individual scale, the population/meta-population scale and the ichthyofaunistic assemblage scale. Though the catchment scale has sometimes been explored for anadromous species (Buchanan and Skalski 2007; Crane 2009; Susquehanna River Anadromous Fish Restoration Cooperative 2010), surprisingly, the impact of obstacles on diadromous fishes has generally been assessed either at the individual or at the population scale but focusing on a specific life stage (upstream or downstream migration) and at the obstacle or river section spatial scale. Since population dynamics processes operate at these scales, working at smaller scale can impair the ability to assess the effect of obstacles on diadromous population dynamics and on their viability. This is even more crucial as the dendritic nature of rivers implies that obstacles and restoration actions in specific sites of a catchment interact in complex ways (Fagan 2002; Labonne et al. 2008; Kemp and O'Hanley 2010), and consequently, the effect of several RCR actions is not necessarily equal to the sum of individual restoration effects (Kuby et al. 2005; O'Hanley and Tomberlin 2005; Palmer and Bernhardt 2006). In the light of these kinds of findings, there is clearly a need to upscale RCR for diadromous fishes from a local approach to a catchment scale thereby bringing this form of restoration in line with calls to upscale aquatic ecosystem restoration more generally (Friberg et al. 2017).

2.2.2 Second challenge: considering indirect impacts of obstacles on diadromous fishes

There is an abundant literature about the impact of obstacles on diadromous fishes. Two types of impacts have mainly been studied: direct mortality due to downstream passage through hydropower facilities, either at the obstacle scale (Travade et al. 1987; Čada et al. 2006; Dedual 2007; Svendsen et al. 2011) or at the river section scale (Blackwell et al. 1998a; McCleave 2001; Buchanan and Skalski 2007; Welch et al. 2008; Rechisky et al. 2009; Holbrook et al. 2011; Pedersen et al. 2012), and fish blockage at upstream migration that impairs or delays the completion of the migration. However, beyond turbine mortality or blockage at upstream migration, obstacles can have other more indirect impacts such as over-predation, (Agostinho et al. 2012; Drouineau et al. 2015), overfishing (Briand et al. 2003; Garcia De Leaniz 2008), stress, diseases, energetic costs (Budy et al. 2002) or selective pressure (Caudill et al. 2007; Podgorniak et al. 2015).

These indirect impacts can be significant. For example, energetic costs can impair reproduction success for eels, salmon or shads, which stop feeding during reproduction migration (Bracken and Kennedy 1967; Quignard and Douchement 1991; Kadri et al. 1995; Bruijs and Durif 2009). Recently, Mateo et al. (2017) showed that obstacles to eel upstream migration can indirectly severely impact spawning stock biomass even without direct mortality. Regarding eel downstream migration, Drouineau *et al.* (2017) pointed out that indirect impacts are potentially as important as direct impacts and, that they too, should be taken into account in the future when assessing the impact of obstacles. Restricting the impacts of mortality to direct mortality can lead to an inadequate quantification of those impacts and therefore to an inappropriate prioritization of management actions.

2.2.3 Third challenge: a need for tools to support decision-making

We have seen that RCR for diadromous fishes should be considered at the river basin scale and that indirect impacts of obstacles should not be neglected. At such a large spatial scale, managers need tools to support and prioritize decisions (Doyle et al. 2003; Kemp and O'Hanley 2010). Kemp and O'Hanley (2010) made a review of existing tools to prioritize management actions. They distinguished three main kinds of approaches. Criterion-based approaches used a set of indicators to evaluate the impact of each obstacle independently and, to some extent, to their cumulative impacts (Nunn and Cowx 2012). While these methods are generally easy to implement, they tend to neglect the complexity of river networks and population dynamics. A second family of approaches relies on GIS (Brevé et al. 2014) and more-recently graph theory (Segurado et al. 2013). While these approaches can be applied at a large scale and produce appealing maps to support decision-making, they generally suffer from an improper consideration of fish movements and population dynamics, and from a limited ability to describe the impact of obstacles on fishes. The optimisation method (Kuby et al. 2005; O'Hanley and Tomberlin 2005) is a third method which appears very relevant despite a higher computation cost. This is based on a model that quantifies the benefits of different restoration actions on one of several criteria such as available habitats (O'Hanley and Tomberlin 2005), but also economic criteria such as minimal loss of hydropower and storage capacity (Kuby et al. 2005). A numerical optimizer can then be used to objectively to find the sets of restorations actions that maximize outcomes (Zheng et al. 2009).

Different models can be used in conjunction with the optimizers. A common approach is to use a statistical species distribution model (SDM) that assesses the impact of obstacles on the distribution of diadromous fishes in a river catchment (Segurado et al. 2014; Clavero and Hermoso 2015). This approach is suitable when historical data are available and can be used to prioritize management actions. However, similarly to the call for the development of predictive mechanistic SDM (Keith et al. 2008; Thuiller et al. 2008; Franklin 2010), the development of mechanistic models that combine river fragmentation and diadromous fishes population dynamics is a challenge to predict ecological effectiveness of management measures and support decision-making at the river basin scale. Such models are required to account for population dynamics and fish movement (Letcher et al. 2007). Similarly to SDMs, mechanistic models can provide complementary results to correlative approaches, and enhance predictive ability (Kearney et al. 2010; Rougier et al. 2015).

In view of this, there is an obvious need for mechanistic model that accounts for fish movements and population dynamics, dendritic structure of fragmented river networks, direct and indirect impact of obstacles to (i) assess the impact of obstacles at the obstacle scale and at the population scale and to (ii) predict the effect of restoration actions. These models can then be coupled with an optimization tool to support decision-making.

2.3 RCR and diadromous fishes much more than an ecological issue

2.3.1 RCR and diadromous fishes: interactions of regulations and regulators

In addition to the increasing numbers of regulation on ecological continuity that target diadromous fishes, many kinds of regulation, implemented at different spatial scales, also target diadromous fishes. For example, the Natural Habitats (Natura 2000) Directive (92/43/EEC), a directive that aims at protecting biodiversity, imposes on each MS of the EU to draw up a list of sites hosting natural habitats and wild fauna and flora of interests. Many diadromous fishes are part of the list of species of interest: for example, sturgeon (*Acipenser sturio*), shads (*Alosa alosa* and *Alosa fallax*) and lampreys (*Petromyzon marinus* and *Lampetra fluviatilis*). Diadromous fishes conservation is also targeted by international measures or recommendations: for example, the North Atlantic Salmon Conservation Organization recommendations, the Bern Convention on the conservation of European wildlife and natural habitats, the Bonn Convention on the Conservation of Migratory Species of Wild Animals) or Life projects (LIFE Project on shad 2007-2010 ; Life+ project on shad 2011-2014). Regarding eels, the European Eel Regulation (1100/2007 CE) imposes a new set of measures on MSs designed to reverse the decline of the European eel (*Anguilla anguilla*) population by decreasing all sources of anthropogenic mortality, including impacts of obstacles on migration. Regulations have also been implemented at lower scales. In France, six water agencies manage water in regional hydrographic districts. They coordinate the district master plan for water management (SDAGE, “schéma d’aménagement et de gestion des eaux”) - a planned and concerted water management tool at the basin scale- and river basin water management plans (SAGE, Schémas d’Aménagement et de Gestion des Eaux) at the river basin scale (Richard et al. 2010). At this scale, committees for the management of migratory fish (COGEPOMI COmité de GEstion des POissons MIgrateurs) are in charge of the management of diadromous fishes through the implementation of migratory fish management plans (PLAGEPOMI/ PLAn de GEstion des POissons MIgrateurs).

Dekker (2016) illustrates the difficulties of this piling up of overlapping regulations and organisations with the example of the European eel. He suggested that the lack of coordination and control between these different regulatory scales is potentially a key explanation for failure to achieve efficient restoration of this species. This type of hypothesis thus merits detailed analysis mobilising social science discipline research techniques and methods. This is particularly so because challenges emerging from interdependent regulations operating at different scales managing diadromous fishes are neither specific to France nor to Europe. For example, the American eel (*Anguilla rostrata*) is both managed at the state and the federal scales in Canada and in the United States of America and efforts are made to implement a bi-national management (Haro et al. 2000; MacGregor et al. 2008, 2009). Regarding Atlantic salmon (*Salmo salar*), management is based on shared stewardship between federal and states governments, First Nations and other Aboriginal organizations, volunteers, other stakeholders and other federal agencies, and Canada is also member of the North Atlantic Salmon Conservation Organization, an international organization aiming at restoring and protecting the Atlantic salmon.

All these conservation and restoration regulations potentially interact with one another and, depending on how they are interpreted by policy actors, can cause policy conflicts. For example, some wetlands or lakes created by the construction of a dam are classified by Natura 2000 because of interest for birds or other animals or plants, though they alter fish and sediment free-circulation. But this regulation may conflict with others, for example on water usage. For example, at the European scale, Directive 2009/28/CE promotes the use of renewable energy, including hydropower, though hydropower facilities are often an obstacle to fish free-movement and a source of mortality to migrant species (Blackwell et al. 1998b; Muir et al. 2006; Larinier 2008; Pedersen et al. 2012). RCR also potentially comes into conflict with regulations on the spreading of alien species and diseases (Rahel 2013; McLaughlin et al. 2013; Tullos et al. 2016). Rahel (2013) provides many interesting examples on how fragmentation was used by managers to prevent the spread of diseases in Norway, Czech Republic or United States. In Europe, this issue is especially important for fish farming aquaculture: the European Directive 2006/88/CE defines the condition that should be fulfilled for a zone to be considered as “disease-free”, granting specific facilities for aquaculture. Such a zone may either be one or several entire catchments, or a sub-part of the catchment delimited by “a natural or artificial barrier that prevents the upward migration of aquatic animals”. Consequently, restoring connectivity and migration may question the disease-free status granted to Finnish, Swedish, Irish, Danish or British areas (European Commission Decision of 15 April 2010). Finally, RCR may interfere with other water usage regulation, especially rules about minimum discharge and water extraction.

Grabosky (1995) mentioned 7 types of potential interactions amongst regulations ranging from synergy to neutralisation. Understanding interactions between conservation regulation and other public policy rules is therefore crucial for offering a comprehensive understanding of why RCR measures can be ineffective. This point has been recently recognised by the European Commission in its encouragement of the integration of ecosystem restoration agenda within the delivery of major policy objectives, especially regional development (rural or urban). For example, the 2020 Strategy for biodiversity and the “Green Infrastructure” both call for a better integration of environment preservation policy within other public policies on territorial development to achieve a better reconciliation of environmental and socio-economic targets. Yet, this question of interdependent regulation goes far beyond a simple ignorance of potential interactions: depending on territories, stakeholders might choose to favour a policy to the detriment of another one for political reasons. For these reasons too RCR should not be analysed in a vacuum but integrated within broader social science evaluations of tensions between public policies and local territorial projects (Carter et al. submitted; Friberg et al. 2017). This also explains why ‘one size fits all’ strategies do not work to achieve effective RCR for diadromous fishes.

2.3.2 RCR and diadromous fishes and territorial development: competitions of ecosystems goods and services

Though river connectivity is an ecological concept, RCR is not only an ecological issue but also a socio-economic issue (Pahl-Wostl et al. 2007; Hermoso et al. 2012; Pahl-Wostl et al. 2013; Wortley et al. 2013; Olden et al. 2014; Barthélémy and Armani 2015), especially because of the multitude of goods and services provided by rivers. In a context of climate change and increasing tensions about water use, obstacles have become a cornerstone of competitions between ecosystem goods and services (Figure 1).

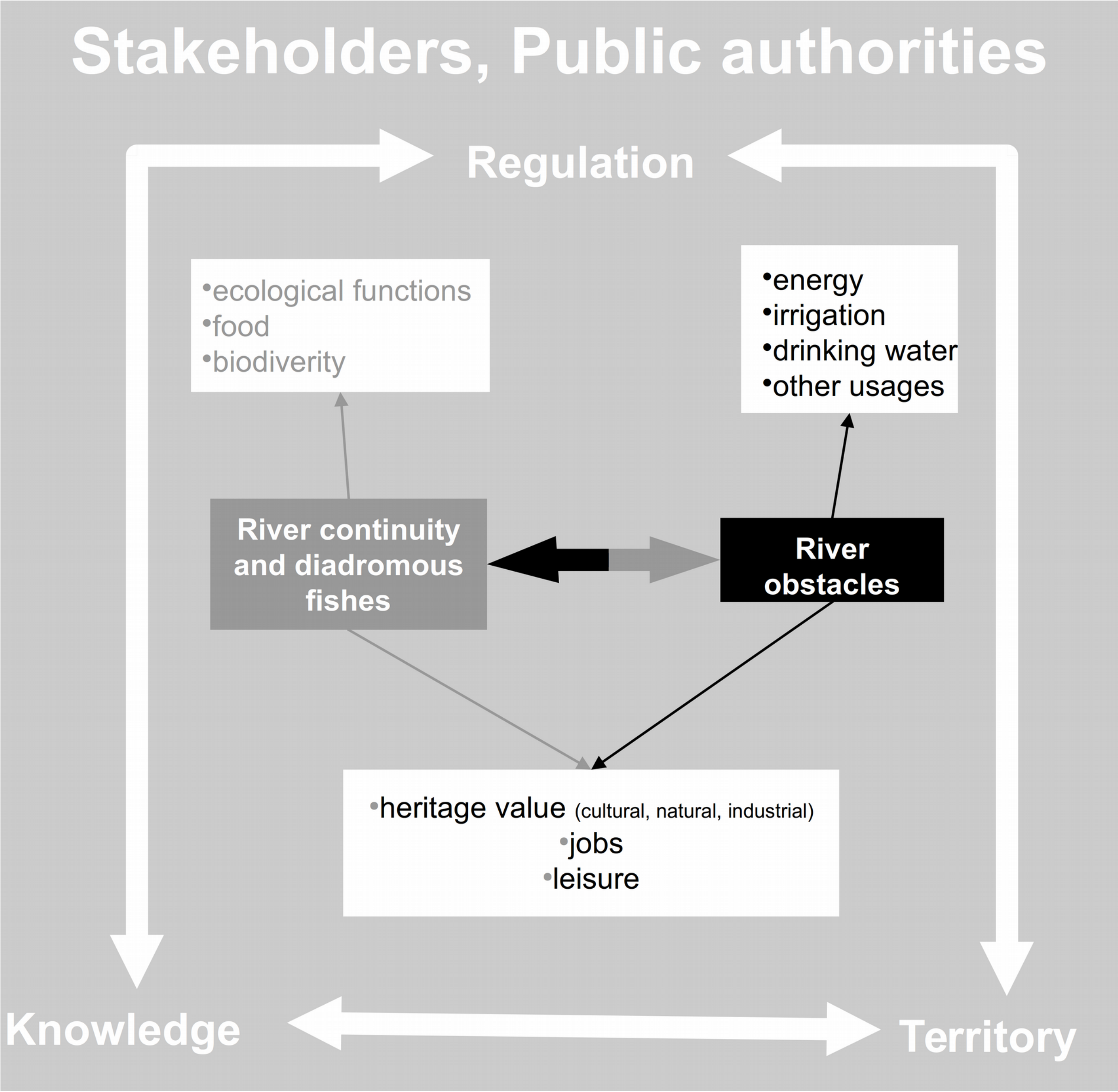

Figure 1. Context of river continuity restoration. Both diadromous fishes (dark grey box) and river obstacles (black box) potentially provide ecosystem goods and services (white boxes). The hierarchy given by actors to these competing ecosystem goods and services – and which may change over time - results from political work between stakeholders and public authorities over knowledge, territory and regulation interdependencies.

- Assessing ecosystems goods and services supported by diadromous fishes

About ten years after the Millennium Assessment, the EU biodiversity strategy for 2020 emphasised goods and services provided by healthy ecosystems (EU Commission 2011). For example, Target 2 of the EU strategy was aimed at maintaining and restoring ecosystems and their services. In meeting this target, MSs are required to develop a framework to map and assess ecosystem states and their services and to better integrate the value of ecosystem services into national and EU accounting and reporting systems (EU Commission 2011). Ecosystem goods and services tend to become the quantitative tool to integrate biodiversity into other sectoral policies that may be used to support decision-making (Turner et al. 2000; Daily et al. 2009; de Groot et al. 2010), to arbitrate trade-offs between services provided by services (Maes et al. 2012) but also with goods and services provided by other sectoral activities. As such, ecosystem goods and services can be used as a tool to arbitrate the trade-offs among interdependent activities impacted by the RCR (Figure 1).

However, this raises specific challenge for diadromous fishes. Diadromous fishes provide four types of ecosystem goods and services (Limburg and Waldman 2009): (i) provisioning of proteins and other products because of their historic abundance and high catchability during migration, (ii) a transfer of proteins between marine and continental ecosystems as illustrated by the decomposition of salmon carcasses that contribute to the development of riparian vegetation, (iii) supporting the marine food-web and (iv) an important contribution to both indigenous and non-indigenous culture. These species used to have high market value (McDowall 1988, 1999), but the total income of the commercial inland fishery has strongly declined because of the collapse of populations (Champion 1999; Boisneau and Mennesson-Boisneau 2001). Meanwhile, other goods and services provided by diadromous fishes, such as cultural services, are potentially becoming more prominent and the value of diadromous fishes should not be restricted to their commercial value. Therefore, there is a need to quantify and qualify new emerging non-market values such as cultural, recreational and/or territorial values. For example, McClenachan et al. (2015) pointed out that the economic benefit in a case of alewives restoration was only a small portion of the overall social benefits for stakeholders. While the turnover generated by the fishery used to be more or less proportional to catches, and therefore to fish abundance, the relationship between fish abundance and the quantity of cultural or recreational value they provide is less obvious. The dramatic decline in the market values of diadromous fishes urges (i) updating the ecosystem goods and services directly associated with diadromous fishes and obstacles (ii) based on traditional methods used to quantify non-market ecosystem goods and services, developing a method to assess ecosystem goods and services provided by diadromous fishes and RCR. This framework could be developed around well-honed methods to elicit non-market values, such as choice experiment analysis (Adamowicz et al. 1998; Cameron et al. 2002; List et al. 2006) and could take into account both their uses evolution including economic/productive and environmental, and stakeholders' needs and expectations. Then, indirect goods and services impacted by RCR could be listed and quantified and the relationship between fish abundance and quantity of services elicited.

This challenge is crucial to carry out costs-benefit analysis of RCR for diadromous fishes, and consequently to support decision-making.

- Understanding the social construction of RCR to identify political opportunities and points of tension

Whereas, as we have argued, public policies and regulation play a critical role in structuring RCR actions, in fact knowledge gaps exist concerning political processes leading to their implementation which are often invisible in practice and little studied in the literature. Indeed, few studies have focused expressly on the link between ecosystem restoration and the politics of implementation of public policy (Baker and Eckerberg 2013). Even less have focused on ecosystem restoration as a territorial project (Germaine and Barraud 2014; Germaine and Lespez 2014). A critical challenge is grasping RCR analytically as a social construction. On the one hand, scholarship has shown the limits of functionalist accounts linking actors' incentives to policy contents: it is not possible to explain the origins and contents of policies based purely on their functions (Bartley 2007).

To illustrate this point, we can argue that from a functionalist perspective, the EU WFD and Blue and Green infrastructure are the results of the functional imperatives of European and French authorities to restore ecological continuity, therefore the efficiency of this measure will be directly assessed regarding economical or ecological outcomes, as in a DPSIR framework (OECD 1993; Gari et al. 2015). By comparison, from a constructivist approach, both the formulation and the local implementation of the WFD and the Green and Blue Infrastructure result from complex political action of many actors (European and French public authorities, local stakeholders, scientists...), and their contents must be explained as contingent 'settlements of conflicts' (Bartley 2007) over both ecological continuity and potentially also other regulations. This is because actors' interests are neither fixed nor can they be assumed: rather they are built in interaction with others' and are *socially constructed* (Eckersley 2004). In the case of RCR, through their collective interaction over policy implementation, actors' interests and understandings of fish, obstacles and rivers can transform and change.

On the other hand, RCR is not disconnected from other political projects but takes place in relation to other territorial projects and river management plans. Conflicts and tensions can emerge between industrial actors and public policies (e.g. when RCR causes tensions with sectoral policy objectives) and over the relative importance of RCR for a community (e.g. in some places RCR has been viewed favourably, McClenachan et al 2015; in others not, Fox et al, 2010). For example, the opposition of fish farmers to RCR does not necessarily relate to the direct issue of ecological continuity but to a connected issue of disease dispersal in river networks. Therefore, constructivist approaches postulate that the link between a public authority, an official objective and a regulation is not a linear one, and must be analysed in a more comprehensive way, and may change through time. This understanding is necessary to identify tensions and and incentives to achieve efficient reviews.

To provide critical understandings about the social construction of interests towards RCR and their outcomes, including how actors mange potentially conflicting policy processes, research can usefully draw upon the well-honed concept of 'political work' (Jullien and Smith 2014) used in public policy analysis. Political work is defined as action by public and collective private actors to translate their immediate local concerns into public problems and which demand public regulatory responses (e.g. public policies). Political work involves a number of activities including the making of arguments to put issues on the political agenda ; the forging of alliances with other actors ; the establishment of new decisional structures ; strategies of mediatisation and public speeches advancing and justifying actor positions held. Actors' political work can be aimed at putting in place new public policies, implementing public policies already in place, changing public policies, countering public policies. As an illustration, in the context of the RCR, the political work of some NGOs over RCR can consist in strategies to promote the restoration of continuity in opposition to other stakeholders, while at the same time promoting the development of renewable sources of energy in the context of energy transition. These links are crucial, especially in the current period of increasing involvement of local stakeholders in river management after decades of distant relationships (Zylberblat et al. 1996; Blackstock and Richards 2007; Pahl-Wostl et al. 2007; Germaine and Barraud 2014). Studying political work can therefore enable research to generate understandings about how successful RCR projects came to be successful (i.e. going beyond the question of social benefits of projects once implemented) and/or about lines of conflict and tension which require to be addressed to bring about future change.

In a regulatory context, when the EU biodiversity strategy for 2020 (EU Commission 2011) calls for a better integration of biodiversity protection into major public policies, social science can and should provide valuable insights on how RCR impacts on-going territorial construction processes led by different or competing actors at different scales and whether RCR is altering peoples' relations to rivers and diadromous fish. This is a critical point, especially responding to climate change and increasing tensions around water use that may modify choices and priorities. For example, the decline of the abundance of diadromous species may either lead to a reinforcement of

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management actions (McClenachan et al. 2015) or to a loss of societal interest for these fish leading to loss of oversight of their decline. This last threat was defined as “ecosocial anomie” by Limburg and Waldman (2009). But, we contend, to assess whether migratory fish hold any cultural value will require social science analysis of political work of actors on RCR in different places compared. The example of the Scottish fishery (Carter 2014) is a very instructive example of a largely unpredictable mobilization of actors through political work that lead to deep modification of management and sustainable fisheries. Also within the example of Scottish-EU fisheries, Carter (2013) demonstrated how insights from constructivist approaches can identify lines of tension blocking implementation as well as opportunities for major change. Building on such approaches, a challenge to achieve effective RCR is to map political work socially constructing RCR for diadromous fishes, by describing actors networks, arguments, expectations and preferences over time. This task is required to elicit formal and informal links between stakeholders and how they manage interdependencies between possible divergent policy objectives, between territories and between knowledge forms (Carter et al. submitted). By doing this, research can identify the ‘type’ of political work around RCR and diadromous fishes; ‘how’ and ‘why’ incentives and conceptions of restoration and ecosystem services’ values may vary and the consequences for effective integration in particular territories. In so doing, it can point out the for legitimate RCR, conflicts blocking effective implementation, and potentially new types of incentives to achieve effective RCR.

2.4 Proposing tools to move beyond traditional disciplinary frontiers and achieve a multidimensional approach to RCR

2.4.1 Organising knowledge flows between disciplines

We have listed three types of challenges in three different fields and which more or less correspond to three groups of disciplines: ecology, environmental economics and geography/political science

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around the question of RCR and diadromous fishes (Figure 2). Each discipline provides unique insights on RCR. However, a comprehensive analysis requires that these insights are collectively organised in a coherent way. This is especially true since each discipline needs the results provided by the others for effective RCR evaluation. Consequently, it is important to acknowledge that disciplines are interdependent.

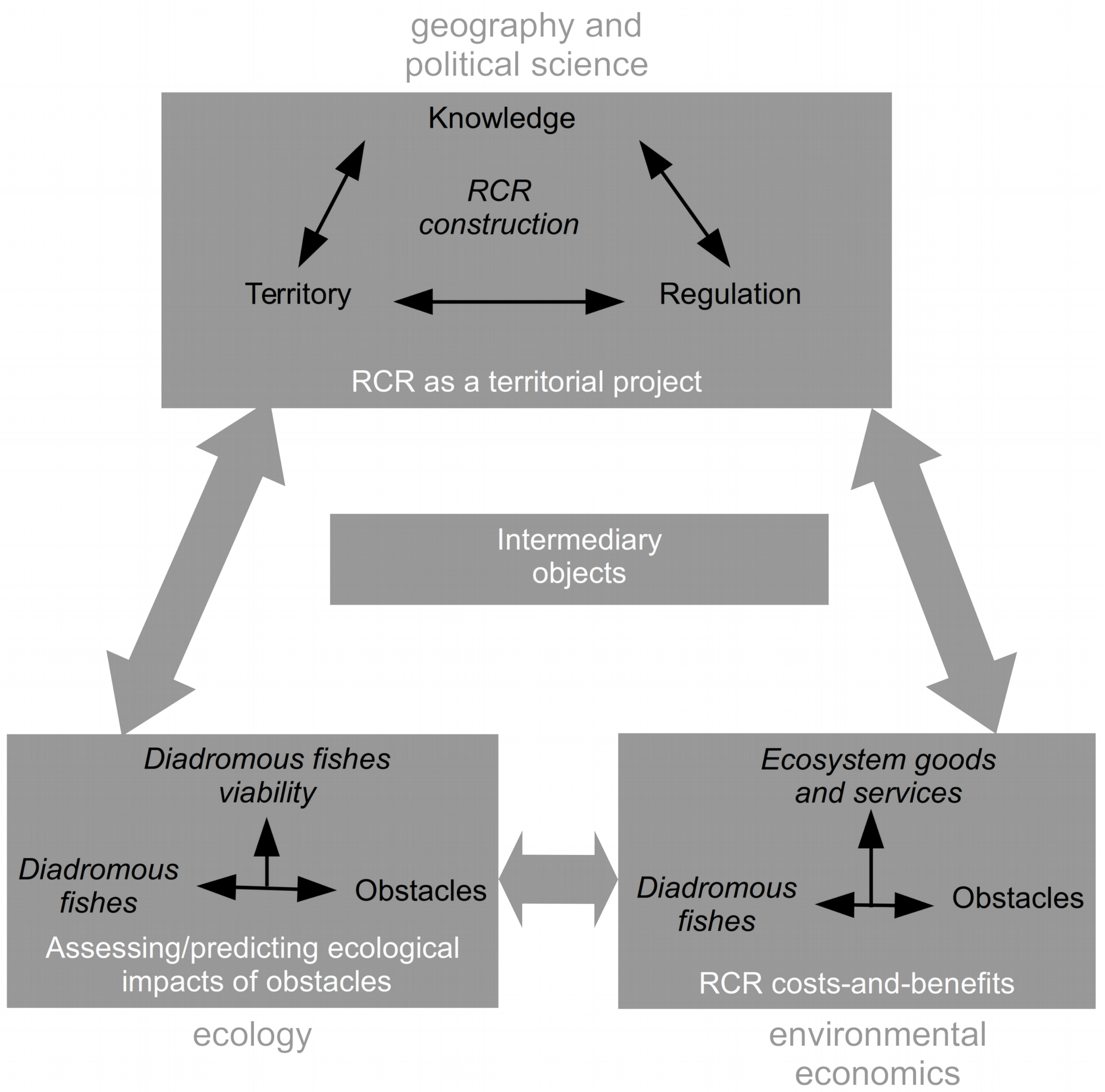

Figure 2. Conceptualising, evaluating and achieving RCR for diadromous fishes require interdisciplinary exchanges. Each discipline can provide different results (ecology: quantification of the ecological outcome of restoration, environmental economics: valuation in terms of ecosystem

goods and services, geography and political science: regulation, territories, actors and political work, specifying actors and arguments either ‘in favour’, ‘against’ or ‘indifferent’ to RCR).

Ecology is required to quantify and predict the effect of RCR on the abundance of diadromous fishes. Through the economical quantification of market and non-market values of diadromous fishes, their abundance can then be converted into goods and ecosystem services that can be used to manage trade-off between conflicting services. To elicit and understand these trade-offs and their shifts through time, geographers and political scientists can provide insights on the social construction of the restoration program and more specifically of the objectives of the different stakeholders and the temporal and spatial scales of political activity in territories. In turn, this analysis of the social construction of RCR requires spatial information on ecological factors (such as the spatial zones of ecological importance, the ecological importance of species or their interactions with other species) and economical ones (for example, economic valuation of services of services).

To organise the necessary exchange of knowledge and moreover, the sharing of assumptions among disciplines, we propose using cross-disciplinary knowledge flows (Figure 2). These are flows of questions and results and visions of the problems encountered by each discipline and which are communicated to the others. This does not necessarily happen spontaneously. To facilitate the process, we propose working with “intermediary objects” (Vinck 1999). In collaborative networks, intermediary objects refer to objects that are meaningful for all actors of the network, though their meaning can vary among actors (Vinck and Jeantet 1995; Vinck 1999; Boujut and Blanco 2003; Eckert and Boujut 2003; Vinck 2003; El-Kechai and Choquet 2006). They have proved to be valuable mediation tools among disciplines or domains, enhancing communication among them by facilitating translation and a support to share a representation of problems (Boujut and Blanco 2003; Buller 2009). Typically, in the case of the RCR, since spatial and temporal scales are especially important, maps and timelines are among the most relevant intermediary objects. The co-

construction of maps is a way to share visions of territories: each discipline can show on a same tool where and why specific zones are of interest (spawning grounds, administrative delimitation, implantation of an enterprise, conflicts…). Regarding a map of obstacles, while the geographical position is common to any discipline, the attributes of interest for the different disciplines are different (for example, passability in ecology, turnover in economy, cultural value in geography). Maps of actors are also useful tool for identifying the role and importance of different stakeholders and public authorities form a multidimensional perspective. Building a multidimensional timeline is a way to establish relationship between events from different fields. Listing and co-constructing intermediary objects can therefore be useful to achieve a comprehensive view of RCR in territories.

2.4.2 Addressing the complexity of spatial and temporal scalar interactions

We outlined earlier the major importance of time and space for restoration programs. Consequently scale integration is a major challenge in a multidisciplinary approach of RCR. Regarding diadromous fishes and RCR, the river basin scale seems to be a central integrative scale. This is both an ecological (population or sub-population scale) and physical/hydrological scale. The river catchment scale also corresponds to water administrative units. Hydrographic districts were introduced in the context of the Water Framework Directive, and correspond to one or several adjacent river basins in which MSs were required to implement River Basin Management Plans (presently, the plans cover the period 2009-2015). Finally, river basins tend also to be a political unit. Water and its governance is a cornerstone issue in the territorialisation process (Ghiotti 2006) and the notion of basin common principle is a key argument in many political constructions. For example, each Water Agency in France has articulated a specific understanding of the river basin common interest (Meublat and Lourd 2001; Bouleau 2014). In this context, the basin scale appears to be the landscape scale advocated by Perring *et al.* (2015) when calling for a scaling-up of restoration activities. It appears to be a unit scale common to the multiple dimensions involved in RCR. However, it will be necessary to understand how this central scale interacts with other spatiotemporal scales to achieve effective RCR for diadromous fishes. For example, while a river catchment is a water administrative unit, it does not match the geographical scale of administrative regions, nor other issues which are relevant for territorial development such as the governing of agriculture or fish farming. Moreover, the definition of basin might vary depending on questions and mobilizations (Fernandez et al. 2014; Bréthaut and Pflieger 2015). In this context of interacting scales in multiple dimensions, scale should not be seen only as an "euclidean distance" or "temporal-distance", but also as a relational concept which sees space as the result of sociological, ecological or biospherical relationships (Healey 2004). Places, sites and territories are not seen as geographical units but as a social-construct with meanings specific to the social context. The co-construction of intermediary objects such as maps, networks of actors and timelines should favour the understanding of scalar interactions around the river catchment scale. This is particularly important as the challenges of scalar interactions are not, as is sometimes implied, merely a matter of coordination, and being legitimate at one scale does not necessarily mean being legitimate at another (Carter et al. submitted).

2.4.3 Reconciling constructivism and functionalism to achieve efficient restoration

A specific challenge emerges bringing about knowledge flows in the case of RCR. This is because whereas ecological and economic valuations are frequently based on functionalist approaches, this is not necessarily the case for political science and geography. As we have argued, it has been well documented that river restoration is a social construction. Recognising this is especially important for building multidisciplinary evaluations of effectiveness. Since RCR is a social construction, an example of success or failure in one territory does not mean that the same approach would necessarily have had the same results in an other context: "one size does not fit all". For example, Blackstock *et al.* (2012) have shown that the process of implementing a program can be just as important for stakeholders as its outputs and, moreover, that effectiveness of outputs is directly associated by stakeholders with effectiveness of inputs.

Although all disciplines recognize the need for multiscalar and multidimensional approaches, the integration between functionalist and constructivist approaches is not straightforward because of ontological and methodological differences. Traditional frameworks support restoration planning, such as DPSIR and related frameworks (OECD 1993; Gari et al. 2015) or PCDA (Plan-Do-Check-Act) are generally based on linear causal relationships from an anthropogenic pressure to the implementation of a restoration measure. These functionalist approaches, consistent with some ecological and economical ontologies, have proved to be useful and efficient to describe systems and provide tools to support restoration planning. However, they loose their usefulness as soon as they confuse their simplified and static version of the world with an accurate description of reality. This is even more critical when evaluating the effectiveness of RCR since initial objectives and causal links may have changed through time.

Consequently, there is a need for new frameworks that aim to conciliate the constructivist point of view as upheld in some strands of political science and geography with the more functionalist approach of natural and economic science. It is not only a methodological challenge that would consist in lining up deliverables of a different nature (especially quantitative and qualitative results) but the development of a new framework based on two antagonistic ontologies, to achieve effective RCR for diadromous fishes. Once again, the co-construction of cross-disciplinary knowledge flows and intermediary objects can be critical elements of such frameworks to elicit, and hence make visible, complementarities between different ontologies.

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