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Paving the way for sustainable bioenergy in Europe: technological options and research avenues for large-scale biomass feedstock supply

Running title: Sustainable biomass supply in Europe

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ABSTRACT

Biomass is expected to be a major player in the energy transition toward low-carbon economies, in response to the pressing challenges of climate change and dwindling fossil resources. Meeting the ambitious recently set for bioenergy development worldwide involve a several-fold increase in biomass production, and poses major challenges for feedstock supply chains in terms of competitiveness, reliability and sustainability.

This paper reviews current knowledge on the sustainability of agricultural feedstock supply chains and emphasize future research needs. It covers the range of feedstocks currently available in an European context, from arable crops to perennial lignocellulosic plants, and the various dimensions of sustainability: environmental and ecological, economic and social. Knowledge gaps and technological options to assess and meet sustainability criteria are reviewed from plot to landscape and global scales.

Bioenergy feedstocks present a wide range of dry matter yields, agricultural input requirements and environmental impacts, depending on crop type, management practices, and soil and climate conditions. Their integration into farmers' cropping systems poses specific challenges in terms of environmental impacts, but also opportunities for improvements via the use of grass-legume intercropping or residues from biomass conversion processes. Taking into account the spatial distribution of bioenergy crops is paramount to assessing their environmental impacts, in particular on biodiversity, or the food versus energy competition issue. However, few modelling frameworks convey the full complexity of the underlying processes and drivers, whether economic, social or biophysical. In particular, social impacts of bioenergy projects are seldom assessed and there is no methodological consensus.

The main research areas identified involve: multi-crop and multi-site experiments, along with modelling, to optimise management practices and cropping systems producing bioenergy, possibly on alternative lands and under future climate changes; the design of innovative

cropping systems using expert knowledge to ensure suitable integration into farmers' cropping systems; the collection of detailed data on the location of bioenergy crops to validate theoretical modelling frameworks and improve sustainability assessment; tackling direct and indirect effects of bioenergy development on land-use changes via coupled economic and agronomical models; investigating the effect of perennial stands on biodiversity in relation to previous land-use and landscape structure; and further developing currently-available methodologies to fully appraise the social implications of bioenergy projects.

Introduction

Biomass is expected to be a major player in the energy transition toward low-carbon economies, in response to the pressing challenges of climate change and dwindling fossil resources. According to the recent IPCC scenarios of energy transition, bioenergy may contribute up to half of total use of primary energy worldwide by 2050 [1]. Such high expectations are reflected in the ambitious bioenergy targets recently set in the EU, the US, Brazil or India, with bioenergy being attributed a 20% to 30% share of the overall energy mix within the next 20 years. This implies a several-fold increase compared to the present production of bioenergy, and poses major challenges for agriculture and forestry, since this expansion will for a large part rely on dedicated energy plants, including lignocellulosic crops and short rotation forestry [2]. In Europe for instance, bio-energy is the fastest growing renewable energy source with a production that almost doubled over the last 15 years, currently supplying 6% of the total primary energy [3]. Around 3.1 Mha in the European Union (EU) are currently used for bioenergy, mainly for biofuel production as biodiesel and ethanol, and biogas, all involving arable food and feed crops. A small proportion is derived from dedicated bioenergy crops. These crops are mostly perennials grown to generate electricity and heating, with the most frequent species being miscanthus, willow, reed canary grass and poplar. They were covering 50 000 to 60 000 ha in Europe in 2008, and about 100 000 ha in 2010 [4,3], underlining a rapid development. Such trend is likely to continue since it is estimated that 17-19 million hectares should be converted to bio-energy crops to meet the targets of the SET-plan in the EU, whether for heat, electricity of liquid biofuels production [3]. Meeting this demand raises considerable challenges for feedstock supply chains in terms of competitiveness, reliability and sustainability [5]. First, the availability of terrestrial land to grow the feedstock imposes major constraints on potential biomass supply, and secondly the conditions for a sustainable and reliable supply are yet to be defined [6].

The production of biomass from lignocellulosic crops interacts with a host of environmental, ecological, economic and social issues, together with human health [2]. Environmental impacts encompass water availability and quality, soil and air quality, biodiversity and climate through the emissions of greenhouse gases (GHG) and C sequestration in soils (*e.g.,* 7-8). Following the controversy on the GHG benefits of first generation biofuels [9], concerns have also been raised for lignocellulosic crops [6], mostly pointing at our limited knowledge of their environmental and economic performances.

The above-mentioned societal concerns with biomass have pressed the need for a certification of bioenergy chains, encompassing environmental, social and economic aspects [10], with the challenge that many of the underlying processes and impacts are still debated in the scientific community (eg, 11). Figure 1 attempts at summarizing the performance criteria underlying these certification schemes, reflecting the expectations of both society at large and economic stakeholders for bioenergy, with a focus on feedstock production and supply which concentrates most of the sustainability-related challenges and is the actual scope of this paper. The criteria are combined with the relevant scales (from field to global) on which they should be addressed. Upscaling (from plot-scale to regional and possibly global scale) therefore appears critical in the design and assessment of bioenergy projects.

Most sustainability assessments of bioenergy chains currently focus on the environmental impacts, and more specifically on GHG and energy balances [7,12]. Given the relevance of the socio-economic impacts of bio-energy, the latter are now present in most certification schemes [11]. However, economic and social criteria are seldom addressed, let alone combined with the environmental assessment [12]. Environmental impacts are usually quantified using life-cycle assessment (LCA) whose outcomes vary widely across studies for seemingly similar pathways [2, 13]. Other environmental impacts such as eutrophication or tropospheric ozone formation are sometimes included [14], but are rarely connected with the local conditions of feedstock production. However, the latter actually contributes a major share of the variability in the impacts of bio-energy chains [15].

The introduction of biofuel crops in agricultural landscapes will certainly lead to important but still poorly evaluated changes in processes maintaining biodiversity in both space and time, which should be addressed at the field and landscape scales [16-18]. Upscaling from plot to landscape level is also necessary to properly address the other categories of environmental impacts, which implies and upscaling of input data and/or upscaling modelled processes [19]. The 'cascade' of N flows and impacts in the landscapes provides a prime example of these challenges [20], and is a source of indirect emissions of N_2O (a potent greenhouse gas) for crops outside the cultivation field which came into sharp focus for biofuels lately [11].

Compared to food crops, the economics of lignocellulosic crops are particular in that they have higher dry matter yields and lower input levels, but higher establishment and land costs. These traits determine the outcome of the competition with food crops for land and the availability of biomass feedstock for bioenergy conversion units, but are seldom fully accounted for when assessing biomass potentials. This results in a large variation of estimates for biomass potentials [21], which should be addressed by accounting for land use competition and substitution, policy constraints, the spatial distribution of bioenergy crops and other feedstock types (including forest products), and logistics constraints [22]. Approaches that account for spatial and temporal variations of feedstock supply are also warranted to gain a better insight into the overall competitiveness of bioenergy based on lignocellulosic biomass, which is still debated [2].

Social implications of bio-based projects are important both in terms of public perception of the risks and opportunities of these projects, and of the technical and organisational innovations necessary for their successful implementation [22]. The spreading and uptake of new knowledge is necessary, regarding the farming of crops as well as the forms of organisation to be set up over the feedstock supply area and the biomass value-chain. However, there is a paucity of specific social sustainability assessment methodologies. Up to now, assessments have often been conducted through social impact assessment (SIA), extended to include other sustainability pillars, or by extending the framework of environmental impact assessment (EIA) to incorporate social issues.

The objective of this paper is to review current knowledge on the sustainability of agricultural feedstock supply chains and emphasize research needs for i/ a more reliable assessment of their impacts and ii/ establishing guidelines to improve their performance and ultimately provide guidance to stakeholders and policy-makers. The paper reviews all components of the feedstock supply chains, from feedstock production in agricultural fields to the supply-area scale including the drivers of biomass production. It points at the key issues and interlinkages between these components in terms of sustainability and practical feasibility (Figure 1).

Feedstock production and environmental impacts

Biomass and biofuel yields

Current and near-term conversion technologies lead to a wide range of candidate crops among which short rotation coppices [5], perennial rhizomatous grasses [23], pluriannual forage crops [24] and annual crops [25]. Crop residues such as corn stover or wheat straw are also an abundant source of biomass which could be used for bioenergy production [26]. Table 1 reviews the yields of the most investigated dedicated bioenergy crops in each category and compares them to the yields currently achieved by the main conventional crops used for bioenergy production and their residues. Yields are expressed in dry matter and in toe (tons of oil equivalent) in the case of biofuel production, using commercial conversion yields for first generation biofuels and expected conversion yields of cellulosic ethanol for dedicated crops and crop residues (Table S1).

The yields of arable crops were evaluated using available agricultural statistics since there is no or little difference between the cultivars and crop management practices used for food or bioenergy production. We focused on three different scales: EU-27, France, and an administrative department (6170 km^2 in area) called “Somme” in northern France, in a region of intensive arable crop production. The hierarchy between crops was identical across the 3 scales, with sugar-beet being the most productive crop and oilseed rape the less productive. This ranking also applied to biofuel production, with an output approximately 3 times higher for sugar-beet than for oilseed rape per ha, even though the latter has the highest grains to biofuel conversion yield.

The biomass production potential of dedicated lignocellulosic crops has mostly been investigated in experimental plots, mainly in Europe and North America, and involving only one crop type, which makes it difficult to compare crops. As a consequence, dry matter yields found in the literature (Table 1) should not be used to rank crops because of the differences in soil and climate conditions between studies. For instance, fiber sorghum was only investigated in southern Europe whereas willow data originate from northern Europe. The large variability in the literature data for a given crop type (Table 1) also arises from differences in crop management (eg, irrigation and fertilizer inputs) between studies. For the scale of France, Table 1 displays the results of an experimental network (called “Regix”) comparing 6 species in 10 sites located in northern, central and southern France [27]. The data evidence a large variability between sites, due to the interaction between crops and soil and climate conditions, with no consistent ranking of crops across the network of sites. At departmental scale in Somme, the data of Table 1 were obtained in a single experimental site with a soil representative of this area [28]. In this site, the perennial rhizomatous crops miscanthus and switchgrass were the most productive, particularly when harvested in autumn. The conversion yields (CY) given in Table 1 for cellulosic ethanol production (in tons of oil equivalent (toe) per ton of feedstock dry matter - DM) are generally smaller than those recorded for first generation biofuels (0.09 to 0.18 toe t^{-1} DM vs. 0.22 to 0.40 toe t^{-1} DM). Conversion yields vary according to the biochemical composition of biomass (Table S1), being higher for triticale, short rotation coppices (SRC) and perennial rhizomatous crops, and smaller for multiannual forage crops. In the French experimental network, biofuel yields per ha were generally higher for perennial rhizomatous crops and triticale than for the other crops (Table 1). In the Somme department, biofuel yields per ha were higher for perennial rhizomatous crops, lower for pluriannual forage crops and intermediate for annual crops.

Crop residue production from conventional crops is estimated in Table 1, using grain/straw ratios from [29]. Residue yields are in the same order of magnitude as grain yields, but biofuel yields per ha are approximately one third lower than grains because of lower conversion yields.

Biofuel yields for various feedstocks may be compared in the case of the Somme department, characterized by deep loamy soils, temperate climate and intensive agricultural practices. The highest yield is achieved by the perennial crop miscanthus harvested in autumn (4.3 toe ha^{-1} yr^{-1}) but sugar beet is the second more productive crop with 3.9 toe ha^{-1} yr^{-1} and whole-plant maize the third more productive with 3.3 toe ha^{-1} yr^{-1}. The other crops rank as follow: miscanthus harvested in winter and switchgrass > dedicated annual crops and other conventional crops (whole plant) > conventional grain crops > pluriannual forage crops.

Agricultural input requirements

Conventional crops are highly dependent on agricultural inputs, particularly chemical fertilizers and pesticides. Crop nutrient requirements are of prime importance because nitrogen fertilization has a huge impact of the overall GHG balance of bioenergy crops [11] and because P and K are non-renewable resources that cannot be synthesized. In France in 2006, the mean fertilization rates for winter wheat, maize, oilseed rape and sugar beet were respectively 162, 150, 162, 103 kg N ha^{-1}, 11, 25, 22, 30 kg P ha^{-1} and 20, 52, 41, 121 kg K ha^{-1} [30].

The nutrient requirements of lignocellulosic crops are still poorly known. The yield response of perennial crops to nitrogen fertilization varies between sites. For miscanthus, out of 11 studies reviewed by Cadoux *et al.* [31], 6 concluded to a positive but often limited response (an increase of 1 to 6 t DM ha^{-1} in autumn), while 5 showed an absence of a response. The same variability was shown for switchgrass by Monti *et al.* [32], who reviewed 6 studies with 10 locations in the USA. No response or an increase of less than 2 t DM ha^{-1} was observed in 4 sites while in 6 sites an increase of 2 to 11 t DM ha^{-1} was observed. Among pluriannual forage crops, alfalfa does not require N inputs because of its N-fixing capacity [33], while the N requirements of fescue are high [34]. For annual crops, the yield triticale was shown to increase with N fertilization in 4 locations in Southwest Germany, which is consistent with the relatively high N requirements of this crop [35]. Surprisingly, no effects of N inputs on the yield of fiber sorghum were evidenced in a field trial in northern Italy [36]. Finally, unlike nitrogen, the role of P and K as possible limiting factor of biomass yields has been little investigated for lignocellulosic crops [37].

An indirect way of assessing the nutrient requirements of crops is to compare nutrient concentrations at harvest. For a given crop type, the latter can vary because of differences in soil nutrient availability, crop management (harvest time, fertilization) and DM yield. Despite this variability, literature data show that nutrient concentrations are crop-specific and very variable between feedstocks (Table 2). Across the crops considered in this Table, N concentration varies between 3.3 and 31.8 g N kg^{-1} DM, P concentration between 0.4 and 6 g P kg^{-1} and K concentration between 2.1 and 21.4 g K kg^{-1}. This variability also exists between arable crops, with sugar-beet having much smaller N and P concentration than the other crops and especially oilseed rape. The differences in N, P and K concentrations between these crops are consistent with the observed mean fertilization rates expressed per ton of harvested biomass. Overall, the highest N concentrations are observed for arable crops except for sugar-beet and forage crops, and the lowest N concentrations are observed for SRC and perennial rhizomatous crops. The same trend applies to P concentrations, with crop residues having also very low P concentrations. For K, forage crops have the highest concentrations, followed by crop residues, while SRC willow and poplar have the lowest concentrations.

Conversion yields presented in Table 1 were used to calculate the amount of nutrient removed from the field per toe of biofuel produced (Table 2). It highlights the advantages of SRC, perennial rhizomatous crops, crop residues and also sugar beet, which export less N and P per toe of biofuel produced than the other feedstocks.

Pesticide requirements are another concern when choosing a type of feedstock. Agricultural surveys show a high level of pesticide use for arable crops with however a large variability between crops. For example, the mean number of pesticide applications was 4.0 for wheat, 1.9 for maize, 6.1 for oilseed rape and 4.2 for sugar-beet in France in 2006 [38]. Pesticide use is likely to be reduced with lignocellulosic crops, particularly with SRC, perennial and pluriannual crops which only require herbicide application during the establishment phase, and no pesticide applications afterwards.

Another advantage of perennial crops is that they require less cultural operations than annual crops. Thus, they reduce the use of fossil energy and the associated GHG emissions by a factor of 3 to 5 compared to annual food crops [39].

Environmental impacts

The choice of a given feedstock has implications on its environmental impacts at the field scale. Among them, biosphere-atmosphere exchanges of GHG in the field a crucial item for the overall GHG balance of bioenergy chains. The main fluxes include soil N_2O emissions and CO_2 balance, as controlled by changes in soil and biomass C pools [3]. Although there is a large body of work on these fluxes for arable crops, little data is available for lignocellulosic crops. In their review, Don *et al.* [3] presented the results of 5 European studies comparing N_2O emissions from arable and perennial lignocellulosic crops (willow SRC, poplar SRC and miscanthus), concluding the latter had significantly lower N_2O emissions than the former. This was not only an effect of lower N input rates with perennial crops but also of the reduction of the ratio of emissions to fertilizer rates (emission factor). However, in one of the 5 sites, the emission factor for miscanthus was more than 3 times higher than for winter rye [40]. A recent study comparing GHG emissions from miscanthus, willow and maize at two fertilization rates (0-240 kg N ha^{-1} for maize and 0-80 kg N ha^{-1} for miscanthus and willow) also lead to contrasted conclusions [41]. The emission factors were 0.95% for maize, 1.1% for miscanthus and only 0.04% for willow. Two other recent studies showed a large increase of N_2O emissions from perennial crops (miscanthus and switchgrass) with increasing fertilizer N input rates [42,43]. It seems that the latter are a key point for controlling N_2O emissions from perennial bioenergy crops and that a balance has to be found between increasing biomass yields and minimizing N_2O emissions per ton of feedstock produced.

Changes in soil organic carbon (SOC) content depends on crop type and management but also on the former land-use history. Conversion of forest or grassland to annual crops leads to very high SOC losses, creating a carbon debt equivalent to 17 to 420 times the annual GHG reduction resulting from the displacement of fossil fuel by first generation biofuels [44]. Increasing the cultivation of whole-plant annual lignocellulosic crops or the rates of residue removal from arable cropping systems are also likely to decrease SOC stocks [15, 45]. In contrast, the shift from annual crop to SRC or perennial grasses may increase SOC stocks (Anderson-Teixeira *et al.* 2009), with large variations in C sequestration rates [3]. Climate and soil conditions as well as crop management (e.g. fertilization, harvest time) are likely to impact SOC sequestration [46]. Finally, the fate of this sequestered C after the end of the plantation deserves further investigation.

Another major environmental issue with bioenergy feedstocks involves water bodies, from either a quantitative or qualitative point of view. In agricultural landscapes, crop water consumption is an important component of the hydrological cycle. For a given climate, there are differences in water consumption among arable crops, mainly due to the duration and position within the year of their growth cycle. In temperate climates like northern France, spring crops like maize and sugar beet often have a higher water use than winter crops like wheat and oilseed rape. This higher water consumption during crop growth reduces the amount of water drained during the following winter and discharge to aquifers [47]. Lower drainage under forage crops, with long growth cycle and deep root system like alfalfa, than under annual crops has also been observed [48]. Perennial bioenergy crops may also have higher water consumption than annual crops, because of their long growing season and deep root system, and thus reduce drainage [49]. Field studies conducted in the Midwest US have shown higher water use by miscanthus than maize but this was not necessary the case for switchgrass [50, 51]. From a qualitative standpoint, crop type can also affect nitrate leaching. For example, sugar-beet has a capacity to take up nitrate in autumn during a longer period than other crops (eg, maize), and thus reduces nitrate leaching the following winter [47]. However, nitrate leaching is also dependent on crop management and on cropping systems (crop rotation, catch crop, etc.), making it difficult to compare annual crops. Studies investigating nitrate leaching under perennial bioenergy crops concluded to low amounts of nitrogen leached under established miscanthus, switchgrass or willow SRC, with nitrate concentration in drainage water usually bellow 25 mg NO3 l^{-1} [51, 52, 53, 54 55, 56]. Nitrate concentration was little affected by the N input rates, except in one study with miscanthus for the highest N rate [53]. However, high nitrate concentrations were observed during the establishment phase of miscanthus and SRC willow (one or two years after establishment), with nitrate concentrations in some cases higher than 100 mg l^{-1}. This was probably due to an imbalance between the soil mineralization rate and the low N uptake rates of these crops in this period. Another increase in nitrate concentration was also observed after the destruction and replanting of a SRC |54].

In conclusion, bioenergy crops present a wide range of biomass production per unit area and input requirements per ton of feedstock. Their environmental impacts are also variable depending on crop type, management practices and soil and climate conditions. There is thus a need to better quantify their productivity in relation to soil and climate conditions, and to determine optimized cultural practices combining high biomass production and low environmental impacts. The crop-management-site interactions emphasize the need for multi-crops, multi-practices and multi-local experiments (regarding both biomass production and environmental impacts) and for the development of soil-crop models adapted to these new crops to generalize plot-scale results to larger areas.

Impacts on biodiversity

While annual crops have been extensively studied with respect to their impact on biodiversity, fewer studies address the impacts of lignocellulosic plants. Yet, the introduction of perennial bioenergy crops in a European agricultural landscape dominated by annual crops will certainly lead to marked changes to agrosystems and arable landscapes, especially when perennial crops such as miscanthus or switchgrass, and/or short rotation coppices of woody species, such as poplars or willows, will be grown besides annual crops. It is likely that processes maintaining biodiversity in both space and time would subsequently change, but this remains largely under-evaluated.

First of all, direct or indirect land use change due to expansion of biofuel cultivation may cause deforestation and destroy semi-natural habitats such as grasslands [57, 58], which in turn may lead to the loss of biodiversity [59, 60]. This has been extensively documented in several tropical regions around the world, but remains exceptional in Europe [61]. The situation strongly differs when bioenergy crops are grown on arable lands. In our contemporary agricultural landscapes, arable weeds and their associated invertebrates have dramatically declined due to the heavy use of agrochemicals, especially pesticides. Since lignocellulosic crops have the great advantages of requiring a single initial planting and no major chemical inputs, they are thought to be beneficial to biodiversity.

Comparing miscanthus to reed canary-grass (*Phalaris arundinacea*), Semere & Slater [16, 17] found that ground beetles, butterflies, arboreal invertebrates were more abundant and diverse in miscanthus fields, because the latter were also more floristically diverse with respect of weeds. Birds followed the same trend while small mammals showed no preference [16]. However, for all investigated taxa the greatest number of species tended to concentrate in the uncultivated field margins and, to a lesser degree, in openings. In contrast, on the crop itself, the arthropod fauna was less diverse on the exotic miscanthus than on the native reed canary-grass. It should be noted however that the study fields were not mature at the time of their study (≤3 years) and thus miscanthus did not reach canopy closure yet, on the contrary to reed canary-grass. Whether the observed beneficial effect of miscanthus crops persist as the crop is aging remains an unanswered question, but is very unlikely. Regarding plant species diversity, very few data is available. Studies on plant diversity are complicated by the fact that only 1 to

20% of the local species pool do actually express annually in cultivated fields [62].

Several studies revealed that plant biodiversity was greater in SRC plantations compared to arable fields (see review by Rowe *et al.* [63]). This benefit persists over time, even after several rotations. Most of the species recorded were common, ruderal herbs. However, the direct introduction of shade-tolerant woodland species in the understories of SRC has been successfully applied to increase plant biodiversity.

Positive effects of SRC on vertebrate (birds, mammals, amphibians, reptiles) and invertebrate (coleoptera, butterflies, canopy insects) biodiversity compared to arable fields have also been reported by various studies in Europe [63]. These positive effects have been primarily attributed to the low chemical inputs compared to arable fields. For example, up to 19 more bird species were recorded in SRC compared to arable and grassland controls [64]. SRC benefits to woodland bird species, whilst species associated with open farmlands were rather negatively impacted.

In SRC, biodiversity has been shown to depend on a host of factors, including stand age, rotation length, crop type, stand size, and habitat connectivity [18]. For example, willow SRC was found to benefit more to vertebrates and invertebrates than poplar SRC [63].

Almost no study provides an integrative view of the relationship between plant biodiversity and the other trophic levels of the agro-ecosystem (with the exception of [16, 17]), especially phytophageous insects and their parasitoids/predators [65]. A notable exception is Huggett *et al.* [66], who showed that some Aphids species, *Rhopalosiphum padi* and *R. maidis*, were able to colonize miscanthus crops from other source crops, and inoculate a potentially harmful virus.

A scarcely considered aspect is the potential increase in the introduction of invasive alien species that bioenergy crops may cause [57, 67, 68]. This encompasses the potential to invade natural ecosystems of the crop species itself as well as its associated weed community.

Perennial grasses have many life history traits in common with invasive species, given they are selected to tolerate poor quality habitats, rapid growth, high seed production, resistance to pests, etc. [69, 70]. If non-invasiveness may be expected for the triploid, sterile *Miscanthus* x *giganteus* (but see 71) other species like e.g. *M. sinensis* has already escaped from where it was grown as an ornamental and became a harmful invader [71, 72]. Plant species that are to be cultivated outside their native range, like miscanthus and switchgrass in Europe are at potential risk of becoming invasive. However, even native plants if genetically modified would pose a similar risk, as recently demonstrated with switchgrass in North America, since physiologic and phenotypic changes led to alterations in plant-plant interactions and ecological functions [73].

To conclude, the biodiversity impact of biofuel crops will depend on the species and the former land use. The reduction in biodiversity caused by increased perennial crops will be likely lower than that for first-generation biofuel production [74]. But their consequences to biodiversity remain largely unstudied. Perennial crops can be beneficial to biodiversity when appropriate crops are grown and sustainably managed in suitable areas, especially degraded or eroded lands; or when they are planted as buffers around conventional annual crops since they can provide habitats to various animals, and be used to filter nutrients or pollutants [75]. Agricultural landscape heterogeneity may be a key, as at equal size, sites with high crop diversity tend to have larger numbers of species than sites where only one type of crop is grown [75, 76]. A landscape approach is thus required to consider the interacting factors at play in the functioning of bioenergy agro-ecosystems, including the type and location of the plant species to be grown, and farming and harvesting systems involved in their production. Opportunities exist to develop systems that could provide net biodiversity benefits on the short term (e.g. habitats for other species), but risks for long-term negative impacts (e.g.

biological invasions by the crops or their associated biota) still need to be evaluated. This should become easier as the number of these plantations in Europe increases.

Integration into cropping systems

Why considering bioenergy crops within a cropping system?

The cropping system is defined as "a set of management procedures applied to a given, uniformly treated area, which may be a field, part of a field or a group of fields" [77]. These procedures include the crop sequence and management for each crop within the sequence.

The introduction of bioenergy crops could generate several effects at cropping system level [78, 79]. These effects may be assessed through relevant performance criteria, which include dry matter yield and quality (especially *vis-a-vis* the pre-treatment and conversion process), energy balance, environmental impacts (such as GHG emissions, soil C dynamics, N losses and water consumption), production costs and profitability. These criteria may be calculated for a particular bioenergy crop but are strongly dependent on the cropping system it is integrated into. For instance, the former land use (cropland, grassland or woodland) determines whether energy crops are a net source or sink of GHG [3, 80].

Moreover, the management of bioenergy crops impacts the performance of the other crops within the cropping system. For instance, the environment of the following crop may be affected through the development of soil-borne pathogens or the availability of soil mineral N, with consequences on crop growth and yield [81]. In addition, long-term (or cumulative) effects may also be observed on weed seed bank, soil structure [82] and SOC content, which is likely to be affected by the withdrawal of cereal straw for bioenergy production [45]. Repeated annual harvests of perennial crops in winter could damage soil structure and thus limit the establishment and yields of the following crops [83].

Introducing annual/pluriannual crops versus perennial crops into cropping systems

Energy crops provide an opportunity to farmers to increase their crop portfolios and access new markets, albeit with specific challenges. Introducing annual/pluriannual crops for bioenergy production implies that cropping systems are only partly dedicated to bioenergy, as other crops within the crop sequence may still be grown for food and feed production. Moreover, such energy crops may be more easily introduced by farmers in usual crop sequences, allowing (i) combined food and feed production on the same field (thus mitigating the competition between food and non-food purposes), (ii) higher flexibility for farmers compared to perennial crops, which are established for at least 15 years [25], and (iii) a diversification of arable crop sequences with positive impacts on weed pressure [84], pest and disease risks [85], soil fertility and structure, and yields [25 81]. However, annual lignocelllulosic crops often have a higher reliance on chemical inputs than perennial crops [3, 8, 86]. Reducing this reliance implies a move towards agronomical low-inputs principles, starting with a diversification of crops within the cropping system: (i) over the crop sequence, (ii) within a growing season through species mixtures (possibly with mixed uses of the different crops, i.e. food/feed and bioenergy; 67), and (iii) with the introduction of cover crops.

In particular, the introduction of legumes and their conversion to energy deserves further investigation [33]. Given their capacity to fix atmospheric N, legumes allow a significant reduction of N fertilisation at the cropping system scale (no N fertilisation on a sole legume, or reduced N fertilisation on a legume-other species intercropping, and reduced N fertilisation on a crop following a legume). This reduces upstream GHG emissions due to fertilizer manufacturing and field emissions of N_2O resulting from fertilizer N applications, along with the energy consumption of the cropping system [33, 88]. Other benefits were observed in terms of ecosystem services, such as soil structure improvement, increase in C sequestration (due to higher soil organic N content) or lower nitrate leaching under pluriannual legumes with deep root systems [33]. Given these advantages, legumes could play a role in the production of biomass for bioenergy [33]. Valorisations for second-generation bioethanol have already been investigated, based either on whole plants [87] or co-products (alfalfa stems; 89). However, the use of sole legumes as energy crops incurs potential drawbacks such as lower soil fertility in the case of whole-plant harvesting, lower yields compared to other energy crops, and biomass quality constraints with respect to the conversion processes [87, 90, 91]). Intercropping legumes with other energy crops could be a way of achieving higher yields and better quality, which remains to be investigated on a commercial scale. The choice of species and cultivars as well as crop management are important issues, as well as the impact of the introduction of such intercrops in cropping systems.

Other ways to reduce the use of chemical inputs while maintaining soil fertility may be investigated. The recycling of harvest or process residues is of primary importance to improve the overall sustainability of the bioenergy production from dedicated crops. For instance, part of the straw produced by the cropping systems should be returned to soils to maintain their SOC content. For that purpose, tools can be developed in order to determine the amount of straws that can be exported without jeopardizing the organic quality of the soils (e.g. 45). Moreover, the use of process residues from biomass pre-treatment and conversion processes offer a particularly interesting avenue to substitute chemical fertilizers. More generally, the use of urban wastes as fertilizers is probably easier on non-food crops than on food crops, since contamination risks are less critical.

Compared to (pluri-)annual crops, the advantages of perennial crops are the production of high amounts of biomass per hectare with low inputs, together with low environmental impacts compared to arable crops (e.g., [3, 27]). However, some concerns should be raised, for instance on the impacts after their cultivation (e.g. on GHG emissions, soil fertility and on the establishment of succeeding crops), or the location of these crops (current cropland vs. other types of lands). The competition between food and energy crops provides an incentive for establishing perennial lignocelllulosic crops on alternative lands (marginal lands, including contaminated soils, fields that are far from the farm headquarters or difficult to manage).

Future research needs

Various crop management systems have been compared for energy crops [3, 8, 89], but few options have been investigated on the crop sequence itself (in which annual, multiannual and perennial crops are included). Thus, further research is warranted to design and assess innovative cropping systems including the range of candidate bioenergy crops, possibly grown in alternative lands, and also in the face of future climate changes. As mentioned earlier, bioenergy crops both include well-known crops (already grown by farmers for food or feed purposes, such as cereals or legumes) and dedicated crops (usually newly introduced in a given area, such as miscanthus, switchgrass or SRC).

The design of innovative cropping systems using expert knowledge [92] is a methodology that could be appropriate to identify cropping systems including bioenergy crops due to the fragmentary information available on food, feed and bioenergy crops (distributed among experts), including their combined effects in a crop sequence. Experts could be local advisors of extension services (to benefit from their knowledge on the crops currently grown in the study area, either for food, feed or possibly bioenergy purposes) and scientists (more familiar with dedicated bioenergy crops). Synthetizing the available information on bioenergy crops – which have already been grown in experimental conditions in several locations – through meta-analysis (e.g., [93]) could help enhancing the expertise on bioenergy crops.

To implement an *ex ante* assessment of innovative cropping systems including bioenergy crops, future research is required on the rotational management of new annual/pluriannual bioenergy crops [25], but also on the long-term effects of perennial crops such as miscanthus on soil structure and SOC content and their subsequent effects of the following crops. In addition, it would be necessary to investigate a wider range of crop management systems, soil and weather contexts than currently documented in the literature. The references on bioenergy crops have been indeed mainly established on field experiments in which limiting factors are usually well controlled. On-farm assessment should be developed, and marginal lands for the production of perennial energy crops should be investigated. Regarding the soil and weather contexts, modelling (using dynamic crop-soil models) is a mean to explore new climatic conditions, and to help identifying cropping systems suited to climate change scenarios. Lastly, multi-criteria decision-aid methods such as MASC [94] could be useful to facilitate the assessment of cropping systems including bioenergy crops.

Upscaling from local to supply-area scale

Taking into account the spatial distribution of bioenergy crops is paramount to assessing their environmental impacts, to the biomass logistics and supply chains, or even the food versus energy competition issue [95]. For example, assessing biodiversity impacts implies a knowledge of both the spatial distribution pattern of these crops and the species' natural habitats [96]. The same assumption can be made regarding impacts on water quantity and quality [97].

The spatial allocation of bioenergy crops, as any other agricultural land-use change, is a complex process driven by biophysical, economic and social factors (e.g.: soil type, land use competition, social acceptability; [98]). The biophysical context (agro-pedo-climatic conditions) first determines if and where a given crop specie can be grown together with its corresponding potential yield. As many crop species may be grown on the same tract of land, resulting in a competition between crops, land-use allocation is theoretically determined by the relative profitability of these crops (income minus production cost), assuming that prices result from the balance between biomass supply and demand. However, as opposed to wheat grains, biomass feedstock is an emerging commodity for which there is currently no real market price. For lignocellulosic crops to be adopted by farmers, their farm-gate price should cover at least their production cost plus the foregone revenues due to land-use substitution – what is termed “opportunity costs”. Stakeholders' characteristics and behavior (e.g. risk aversion, social embeddedness), as well as technical and policy constraints at the plot, farm or landscape levels (e.g., plot size and distance to the farm headquarters) should also be taken into account to determine the availability of biomass. Lastly, on the demand side, the biorefinery-gate cost includes at least transportation costs. All these factors have to be accounted for, and determine the relative location of biomass crops and biorefineries, as well as the feedstock supply mix and price.

Several studies assess the sustainability of biomass feesdstock supply from a full-scale bioenergy plant to world-scale scenarios of bioenergy deployment. Based on a literature review, we propose a framework to classify such studies and characterize their accuracy and relevance to aid in designing sustainable biomass supply areas (Table 4). We mainly categorized the studies based on their approaches in terms of agronomic, economic and behaviour analyses, combined with the extent to which these approaches were spatially-explicit.

First, some studies focus on the production potential of biomass without taking into account an overall demand for feedstock (whether in quantity or price) or the economic context, nor providing information on how to actually achieve this potential (Group 1). Most of these studies assess the potential area that could be dedicated to energy crops at national or global levels. We considered these studies as global biomass supply assessment based only on potential resources (land availability, soil types, topography, climatic conditions, fixed food demand, production costs, etc...). Within this group, three different approaches may be distinguished:

Group 1a regroups non-spatialized, non-economic approaches. They either highlight conflicts between agricultural and energy policies [99] by comparing technically achievable production levels to targets set by policies, or simply quantify a country or a group of countries biomass production levels [100]. Approaches from the group 1a can be used to help figuring out global issues independently from actual driving forces of the land use process. They also provide a base to assess GHG emissions at large scales.

Group 1b regroups spatialized, non-economic approaches. They differ from group 1a by the fact that they introduce spatial differentiation to assess biomass potential production levels. Spatial differentiation can be done on a coarse (e.g., at country level, [101]) or very fine scale (e.g., with a 2 km² resolution, [102]) but ignores economic or sociological factors. Studies from group 1b can be used for the same purposes as those of group 1a. They are however more accurate regarding biophysical constraints as the spatialization is often a way to discriminate regions based on their biophysical potentials to produce biomass.

Group 1c regroups spatialized economic approaches. In addition to the biophysicial production potential, they map the potential production level under a given production cost (i.e. providing cost-supply curves which are not based on opportunity costs).

One drawback of the Group 1 studies is that they make strong assumptions to assess biomass supply. One of their most common tenets is the “Food – Feed – Nature first” paradigm [103] which considers that biomass will not be grown on areas dedicated to food and feed production, or natural reserves. It prevents the authors from addressing the issue of competition between major land uses. Although excluding areas for energy feedstock cultivation based on predefined rules could reflect future regulations, the reality shows that competition between food and non-food crops does exist [104].

While Group 1 approaches may be used to anticipate the trends of bioenergy crops development, assessing the actual location of these crops by taking into account economic and/or sociological driving factors at a supply-area scale is also of great interest to address the feasibility and sustainability of a local bioenergy project. In our classification, Group 2 approaches propose modeling frameworks to locate biomass crops and/or bioenergy production plants as “driven” by economic or supply factors: a demand in quantity (either tons of biomass or energy equivalent) or in price (either in €/ton or €/MJ). However, the approach and the level of details vary greatly among the existing studies.

Group 2a studies assess biomass supply and farm-gate cost for given energy demand levels, but without addressing the spatial location of the production. Approaches regrouped in Group 2b attempts to locate energy crops production so as to maximize their net energy supply, but without accounting for the economic context and, thus, the feasibility of this production. Conversely, Group 2c studies locate energy crops production based on more or less robust economic criteria to meet a given demand. They can thus better assess the environmental impacts of such a production due to land use change. Groups 2d to 2f approaches go one step further by including a biorefinery or a power plant– either in a predetermined or open location or – and by addressing transportation costs. Whereas Group 2d approaches sometimes rely on strong hypotheses concerning the type of land available for bioenergy crops (e.g. marginal or low-yielding land, food first paradigm), Group 2e studies allow for competition between food and energy crops on agricultural land, thus being more realistic. Group 2f studies make the first step towards better accounting for farmers and stakeholders behaviours by integrating decision processes in their models (e.g.: using a rule based model in ref 105 or an agent-based model in ref 106).

Regarding sustainability assessment, studies from group 2 seem more interesting as they simulate more realistic scenarios of bioenergy production. Their accuracy towards the assessment of future development of bioenergy crops increases as they take into account the complexity of the processes involved. However, very few studies attempt to address this complexity (only Group 2f does), most of them relying on hypotheses to circumvent it. Taking into account this complexity involves several dimensions:

- biomass managers' choices to grow and locate bioenergy crops: most of the models taking into account stakeholders' decision to grow energy crops yield the "optimal" spatial distribution of energy crops based on farmers' profit maximization and also often on transport cost minimization. As a matter of fact, the spatial distribution of agricultural crops is determined by several factors: biophysical and economic ones (that determine crops' relative competitiveness), but also technical and sociological ones [107, 108]. On the economic side, farmers are not mere profit maximizers. Studies at a finer grain therefore have to take into account farmers' risk aversion as well as the spatial configuration of farms, when it comes to the adoption of new crops and especially perennials, which require a large upfront investment and provide income only after a few years' time [109]. Moreover, these crops actually involve a larger range of stakeholders since they can be grown by farmers but also by energy producers or institutional stakeholders [110]. Modelling approaches should then be refined regarding the decision processes of these stakeholders.

- taking into account the diversity of production systems within the feedstock supply area: biomass production systems are more diversified than with arable crops (e.g.: farm based, industry based, collective management). To our knowledge, there is currently no modeling framework dealing with this question. Thus, researchers should seek to account for this diversity to develop sustainable biomass supply areas.
- taking into account the interlinkages between these systems to understand and predict the development of feedstock supply areas: the diversity of crop production systems induces a diversity of management scales (e.g. field, farm, industry supply area, municipality; Figure 1), thus increasing the complexity of the biomass development process [111, 112].

As appears in Table 3, existing modelling frameworks to assess energy crops spatial development only partly address this complexity. Also, our knowledge of energy crops is currently limited, whether in terms of empirical data or theoretical frameworks. In conclusion, the availability of data related to bioenergy crops location, development and impacts should be improved to validate theoretical modelling frameworks and to improve the sustainability assessment of biomass supply.

Social sustainability of bioenergy chains

When compared to the other two pillars of sustainable development –environmental and economic, the social assessment of bio-energy projects has been lagging behind initially. However, over the last few years, the social dimension of bioenergy projects has received increasing attention both from the general public and the scientific community. The social implications of bio-based projects are important both in terms of public perception of the risks and opportunities of these projects, and of the technical and organizational innovations necessary for their successful implementation [27, 113].

One of the challenges associated to conducting a comprehensive social sustainability assessment of bioenergy chains is the geographical dispersion and heterogeneity of the population potentially affected. Given the number of countries involved in the bioenergy value chain –both in the developed and developing world, there exist multiple types of socio-economic impacts depending on the legal framework, institutional arrangements, social norms as well as socio-economic characteristics of the affected population. As a result, the potential effects associated to the production and consumption of bio-energy products may be considerably different in terms of the type of impact, relevance and/or its magnitude depending on the considered region and, of course, the specificities of each step of the value-chain analyzed. This fact represents a methodological challenge but successful initiatives have emerged over the last few years which represent a considerable step forward in the right direction [114, 115].

In developed countries, where the focus is on reviving economic growth and mitigating climate change, bioenergy can stimulate a green recovery –generating more jobs and stimulating the economy, diversify energy supply and abate greenhouse gas emissions [114]. Nevertheless, given the economic crisis that is currently affecting Europe and most of the word, the social acceptability of any bio-based project is very much related to its potential net impact in terms of economic stimulus and job creation opportunities. In fact, the latter is one of the reasons frequently cited for encouraging deployment of bioenergy systems, particularly when projects take place in rural areas, with high levels of unemployment or depopulation trends [116]. Compared to fossil fuels, the employment rate of biofuel production is much higher [117]. To carefully assess these aspects, one must not only take into consideration the direct impact on the local or global economy –that is the effects on those sectors directly affected by the bioenergy value chain–, but also the indirect effects –that is the impact on those other sectors that supply goods and services to the other sector that are directly affected.

One of the most widely used methodologies to quantify the direct and indirect effects of projects is the Input-Output methodology [118, 119]. The I-O methodology is considered asNeuwahl F, Löschel A, Mongelli I, Delgado L (2008) Employment impacts of EU biofuels policy: combining bottom-up technology information and sectoral market simulations in an input-output framework. *Ecological Economics,* **68,** 447-460. a tool to gather information in a systematic way about the productive relations between the different sectors in any given country or regional economy. Besides estimating the associated direct and indirect effects on the economy and job creation, the I-O models are used to estimate the multiplying effect that a certain investment generates in the economy. In order to apply this methodology, data requirements include: direct costs associated to the studied new activity as well as the National Input-Output table (or, if available, the regional Input-Output table) which reflects the flows between the different sectors comprised in a certain economy and that are regularly published by the National Statistics Institutes.

However, one must go beyond the pure quantitative figures and also consider, for example, the qualitative attributes of such employment (for example: what is their qualification, duration, gender, etc). Social Impact Assessments (SIA) have been often used to complement the more quantitative results derived from an input-output model. Burdge [120] defines SIA as the systematic appraisal of “impacts on the day-to-day quality of life or persons and communities whose environment is affected by a proposed policy, plan, programme or project”. Guidelines for SIA have been developed, among others, by the World Bank and the International Association for Impact Assessment. The social (and socio-economic) impacts to be covered in an assessment and the way this should be done should be case and context specific. Thereferore, there is no general consensus on which indicators to use and how to assess social impacts of bioenergy projects with SIA.

Similarly, environmental impact assessment methods (such as environmental life cycle assessments) have also been “streched” to incorporate social issues. In 2006, life-cycle experts acknowledged the necessity to offer a complementary tool to assess products´social life cycle aspects [121]. As a result of this, the Social Life Cycle Assessment (S-LCA) concept emerged aiming at complementing the Environmental Life Cycle Assessment (E-LCA) and the Life Cycle Costing (LCC) in contributing to the full assessment of goods and services within the context of sustainable development (UNEP, 2008). The ultimate goal of a S-LCA is to promote improvement of social conditions throughtout the life cycle of a product. S-LCA is intended to assess product and production related social and- to some extent- economic impacts using a life cycle perspective.

Qualitative research, combining perspectives from institutional theory, social anthropology [122] and knowledge/innovation studies [123] may be used to examine these effects though they have not yet been applied to bio-energy or bio-materials sectors. These approaches rely on empirical investigations such as stakeholder analysis [124] or the so-called CIPP (Context, Input, Processes and Products) approach [125] to analyse a value chain. In addition to employment and economic stimuli, innovative capacity is an important dimension to assess. How the innovative capacity is affected by the context, input processes and products of the studied systems and how specific barriers and potentials may be identified and addressed to increase the sustainability of the proposed solutions. Moreover, there exist other impacts related to quality of life (health, housing, education, safety), equity, diversity, social mixing cohesion, participation and governance and maturity that need to be assessed.

Populations from developing countries may also be affected by the increasing use of modern bioenergy. As an example, switching from traditional to modern bioenergy systems can reduce death and disease from indoor air pollution, free women and children from collecting fuelwood and reduce deforestation [126]. It can also cut dependence on imported fossil fuels, improving countries´ foreign exchange balances and energy security. Furthermore, bioenergy can expand access to modern energy services and bring infrastructure as roads, telecommunications, schools and health centres to poor rural areas. In such areas, bioenergy can increase the income of small-scale farmers, alleviating poverty and decreasing the gap between rich and poor. In urban centres, using biofuels in transport can improve air quality [114]. On the other hand, large-scale bioenergy projects may be dominated by large international companies leading to negative socioeconomic impacts especially on land tenure issues. Unclear land rights and poorly regulated land acquisition may lead to depriving small farmers of their properties [117]. Bioenergy can also contribute to increased or reduced food security depending on policies, agricultural systems, markets, prices and income levels. There is now an increased concern about negative effects of bioenergy through increased food prices that can negatively affect food importing countries [117].

To address the challenge to simulatenously promote sustainable production and use of bioenergy worldwide, international cooperation is essential for building capacity to implement successful solutions. As an attempt to promote the wider prodution and use of modern bionergy, the Global Bioenergy Sustainability Partnership (GBEP) proposed 24 indicators of sustainability intended to inform policy-making and facilitate the sustainable development of bioenergy [114]. These indicators do not provide answers or correct values of sustainability but rather present the right questions to ask in assessing the effect of modern bioenergy production and use in meeting nationally defined goals of sustainable development (Figure 2). With regards to the social pillar, GBEP considers that the themes that are most relevant are: (i) price and supply of a national food basket, (ii) access to land, water and other natural resources, (iii) labour conditions, (iv) rural and social development, (v) access to energy, (vi) human health and (vii) safety (Figure 2).

In summary, the social implications of bioenergy projects are recognized as key aspects to assure the sustainability of biomass based energy generation. However, the complexity of the assessment of these social implications is high, and the proposed methodologies are still on their development stage with applications still scarce.

Consequences at global scales: direct and indirect land-use changes

At a global scale, displacing food crops with energy crops in Europe may result in net emissions of GHG through changes in land-use worldwide. A higher demand for agricultural commodities such as bioenergy feedstock leads to higher prices and larger incentives for farmers to increase their output, possibly through the conversion of non-agricultural land. The resulting land-use changes (LUC) may cause the release of the below- and above-ground carbon into the atmosphere. LUC emissions are direct if they result from for conversions of land for the production of biomass for bioenergy, and indirect if they are due to conversions to other land uses that would not have occurred without the development of biofuels. These emissions may negate the GHG benefits of substituting fossile energy sources with biomass [44], and are currently widely debated.

It is impossible in practice to isolate LUC effects of biofuels (in particular indirect ones) based solely on historic observations because of the simultaneous influence of several factors affecting market equilibrium. In order to isolate LUC effects of biofuels, it is thus necessary to rely on models capable of comparing, ceteris paribus, *ie* simulations « with » and « without » biofuel development. Available evaluations in the literature are based either on (partial or general equilibrium) economic models, or more heuristic approaches (causal-descriptive, consequential LCA). The latter have the advantage of relying on a fairly simple, transparent, and normalized framework that can be easily connected to that of standard LCAs. However, as they rely solely on a quantity-based framework, these approaches are not well adapted to fully account for market adjustments and the related indirect LUC effects. By construction, economic model are better equipped in this respect. Nevertheless, their structure does not always permit a clear distinction between direct and indirect LUC effects. In addition, the complexity of the required modeling often makes the communication of results based on these models more difficult. LUC effects on GHG emissions may be synthetized by indicators that reflect annualized LUC emissions per unit of energy produced by biofuels. dLUC, iLUC, and d+iLUC factors measure the direct, indirect, and total component of these emissions, respectively.

A recent meta-analysis [127], based on a systematic search of available bibliographic references and a detailed analysis of the 71 most relevant and exploitable studies on LUC issues, revealed a following conclusions. First, accounting for LUC due to the development of biofuels is likely to increase GHG emissions that can be attributed to biofuels. Almost 90% of the collected evaluations conclude that the development of biofuels leads to (direct or indirect) LUC that cause GHG emissions (positive d+iLUC factor). Secondly, for more than a quarter of the collected evaluations, the sole effect of LUC leads to emissions that are greater than that of the reference fossil fuel (83.8 CO_2eq. MJ^{-1}). When including life-cycle GHG emissions due to feedstock production, transformation and distribution of biofuels, the total emissions are greater than that of the reference fossil fuel for more than half of the collected evaluations. Thirdly, the collected evaluations are characterized by a large variability of the d+iLUC factor both between and within studies. This large variability actually reflects the diversity of approaches, definitions, and assumptions (relative to land-use changes, representation of underlying market mechanisms, biofuel chains, etc.) adopted in the studies. Significant differences occurred among feedstock types, biofuel types, supply regions and the regions of origin for biofuel demand. For example, the gap between biodiesel and bioethanol ranged from 22 to 27 g CO_2eq. MJ^{-1} depending on the methodology used to approach LUC effects.

Even there are far fewer references for first generation biofuels than for lignocellulosic feedstocks, the emissions related to LUC are lower by a factor of 2 to 10 with the latter type of feedstock [127]. As discussed in the 'Feedstock production' section of this paper, the conversion of arable food crops to lignocellulosics results in lower N_2O emissions and a temporary sequestration of C in the soil, ie negative dLUC emissions. Indirect LUC effects deserve further investigation with lignocellulosic feedstocks, but their burden is unlikely to significantly offset the GHG benefits from substituting fossile energy with bioenergy, especially if the feedstockis grown on marginal land [128].

Conclusion and outlook

Ensuring a reliable and sustainable supply of biomass to meet policy targets in Europe raises considerable challenges both in terms of research and practical implementation. While the limits of bioenergy chains based on food crops are clearly appearing [9], lignocelllulosic crops will be a key component of future feedstock supply chains, complementing other sources of biomass such as residues and waste streams. There is a potential for large-scale development of such species but there are still many unknowns in terms of yield potentials in a wide range of soil and climate conditions, on marginal lands or in the face of climate change. Based on current evidence, the performance of these crops appear promising but is still uncertain. Further research on yield drivers, optimal management at crop or cropping system level, spatial distribution and environmental impacts is therefore warranted to guide the design of feedstock supply chains.

Non-technical issues on production costs, learning curve and adoption, and farmers' risk aversion should also be taken on board in this process. The cooperation of scientists with stakeholders (farms, chain operators, value-chain), local authorities and policy-makers should be fostered to develop suitable tools (data bases, models, decision support systems) for the design, assessment and management of bioenergy chains that are efficient at abating GHG emissions, minimizing adverse environmental and social impacts and generating benefits for local communitities.

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Figure captions

Figure 1: Drivers and performance criteria for bioenergy value chains, from plot to global scales. Blue boxes = drivers; orange boxes = performance criteria.

Figure 2: Proposed indicators under the Social Pillar of the Global Bioenergy Sustainability Partnership (GBEP). Source: ref 114.

Figure 1. Drivers and performance criteria for bioenergy value chains, from plot to global scales. Blue boxes = drivers; orange boxes = performance criteria.

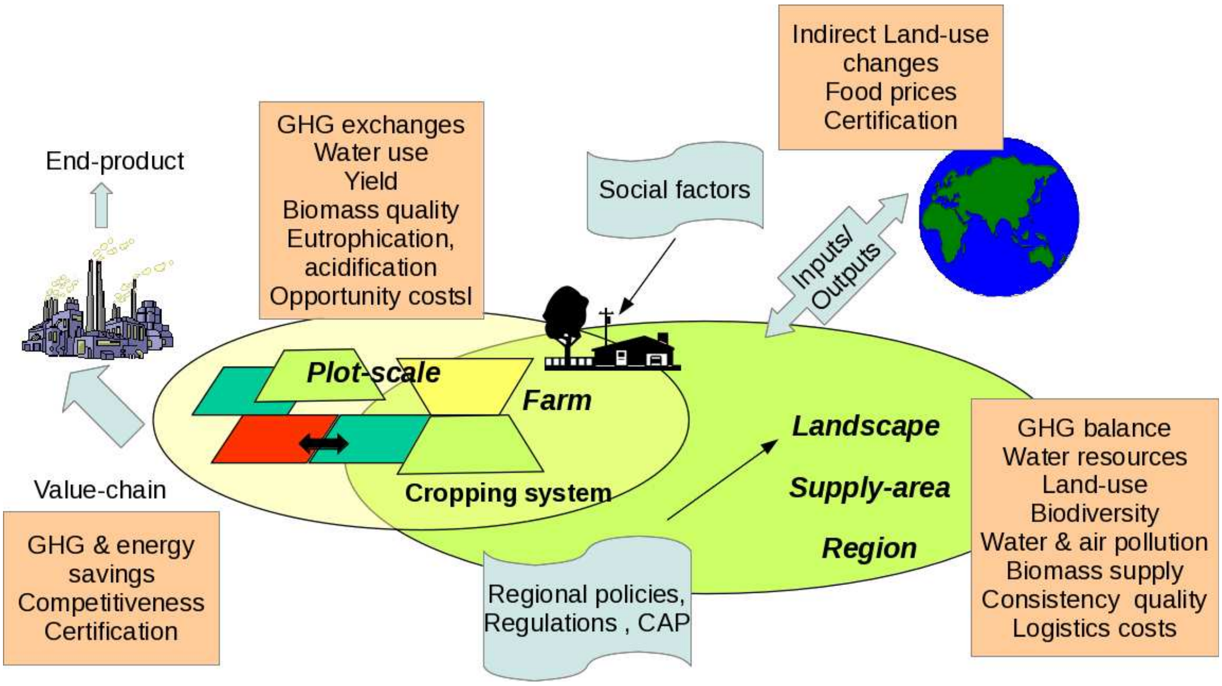
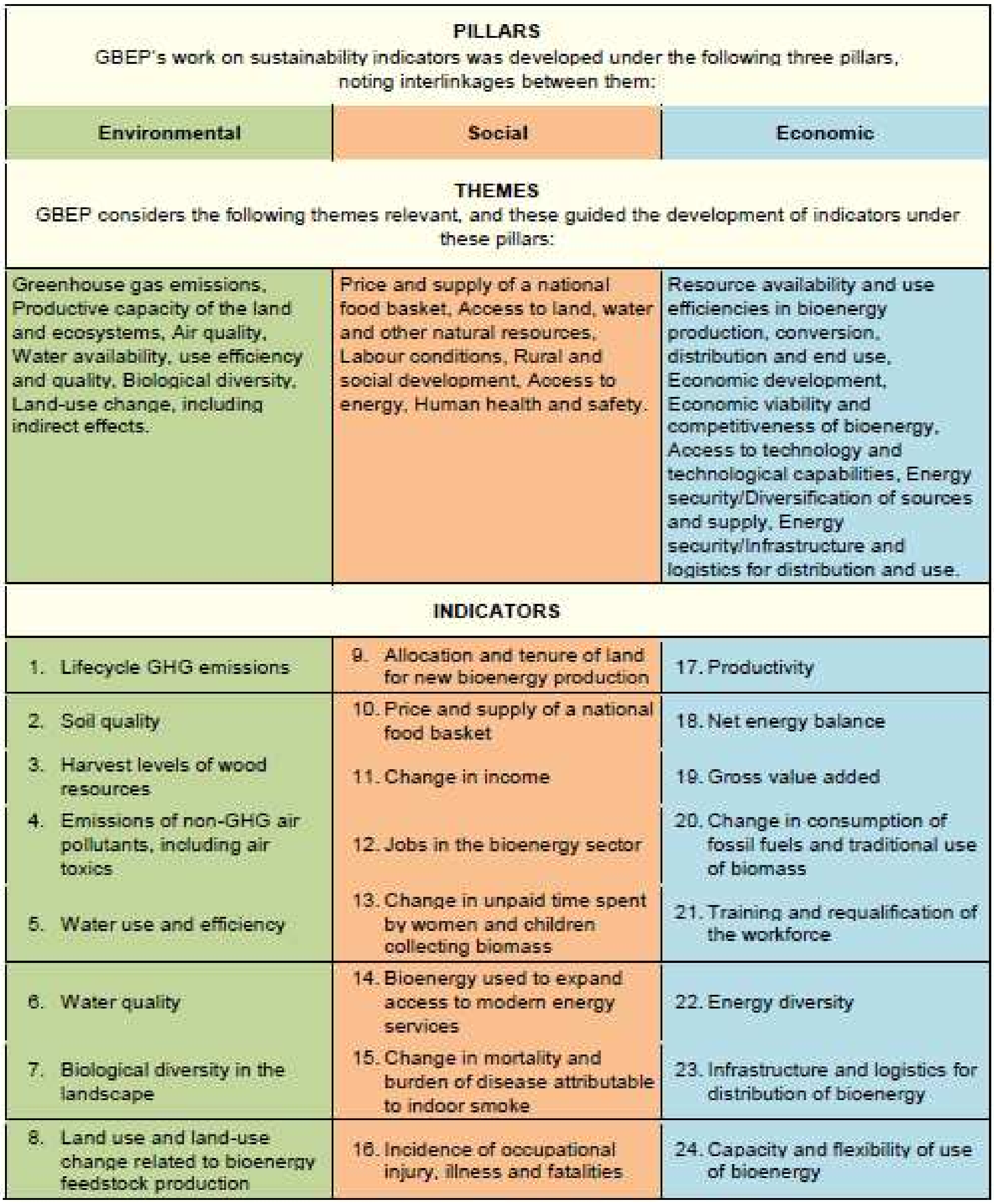


Figure 2. Proposed indicators under the Social Pillar of the Global Bioenergy Sustainability Partnership (GBEP). Source: ref 114.



PILLARS GBEP's work on sustainability indicators was developed under the following three pillars, noting interlinkages between them:		
Environmental	**Social**	**Economic**
THEMES GBEP considers the following themes relevant, and these guided the development of indicators under these pillars:		
Greenhouse gas emissions, Productive capacity of the land and ecosystems, Air quality, Water availability, use efficiency and quality, Biological diversity, Land-use change, including indirect effects.	Price and supply of a national food basket, Access to land, water and other natural resources, Labour conditions, Rural and social development, Access to energy, Human health and safety.	Resource availability and use efficiencies in bioenergy production, conversion, distribution and end use, Economic development, Economic viability and competitiveness of bioenergy, Access to technology and technological capabilities, Energy security/Diversification of sources and supply, Energy security/Infrastructure and logistics for distribution and use.
INDICATORS		
1. Lifecycle GHG emissions	9. Allocation and tenure of land for new bioenergy production	17. Productivity
2. Soil quality	10. Price and supply of a national food basket	18. Net energy balance
3. Harvest levels of wood resources	11. Change in income	19. Gross value added
4. Emissions of non-GHG air pollutants, including air toxics	12. Jobs in the bioenergy sector	20. Change in consumption of fossil fuels and traditional use of biomass
5. Water use and efficiency	13. Change in unpaid time spent by women and children collecting biomass	21. Training and requalification of the workforce
6. Water quality	14. Bioenergy used to expand access to modern energy services	22. Energy diversity
7. Biological diversity in the landscape	15. Change in mortality and burden of disease attributable to indoor smoke	23. Infrastructure and logistics for distribution of bioenergy
8. Land use and land-use change related to bioenergy feedstock production	16. Incidence of occupational injury, illness and fatalities	24. Capacity and flexibility of use of bioenergy

Table 1. Biomass and biofuel yields of arable crops, crop residues and dedicated lignocelllulosic crops

	Biomass yields (t DM ha^{-1} yr^{-1})			CY^{a}	Biofuel yields (toe ha^{-1} yr^{-1})		
Arable crops**:** *Current mean yields*							
	EU-27	France	Somme	toe t^{-1}DM	EU-27	France	Somme
Winter wheat	4.2	6.1	7.3	0.22	0.9	1.3	1.6
Maize	5.7	7.4	7.9	0.23	1.3	1.7	1.8
Oilseed rape	2.7	2.9	3.3	0.36	1	1	1.2
Sugar beet	12.3	15.9	16	0.24	2.9	3.7	3.8
Crop residues: *Estimated current mean yields*							
	EU-27	France	Somme	toe t^{-1}DM	EU-27	France	Somme
Winter wheat	4.6	5.8	6.5	0.16	0.7	0.9	1
Maize	5.9	7.2	7.6	0.15	0.9	1.1	1.1
Oilseed rape	4.4	4.6	4.9	0.15	0.6	0.7	0.7
Conventional crops (whole plant): *Total of conventional crops + crops residues*							
	EU-27	France	Somme		EU-27	France	Somme
Winter wheat	8.8	11.8	13.8		1.6	2.2	2.6
Maize	11.6	14.7	15.5		2.2	2.8	2.9
Oilseed rape	7.1	7.5	8.2		1.6	1.7	1.9
Dedicated lignocelllulosic crops : *Experi-mental yields*							
		France	Somme			France	Somme
	Literature*	Regix*	B&E	toe t^{-1}DM	Literature*	Regix*	B&E
Willow SRC	9 (5-11)	-	-	0.16	1.5 (0.7-1.8)	-	-
Poplar SRC	6 (2-10)	-	-	0.15	0.9 (0.4-1.5)	-	-
Miscanthus E	29 (14-60)	-	27	0.16	4.7 (2.3-9.7)	-	4.3
Miscanthus L	15 (5-43)	15 (3-23)	19	0.16	2.4 (0.8-6.9)	2.4 (0.4-3.7)	3.1
Switchgrass E	12 (1-22)	-	19	0.15	1.8 (0.2-3.3)	-	2.9
Switchrass L		14 (5-19)	16	0.15		2.2 (0.7-3.0)	2.5
Fescue	9 (4-14)	11 (3-23)	10	0.12	1.1 (0.5-1.7)	1.3 (0.3-2.8)	1.2
Alfalfa	11 (1-17)	14 (3-	12	0.09	1.0 (0.1-	1.2 (0.2-	1.0

		16)			1.5)	1.4)	
Triticale	13 (5-16)	13 (3-19)	12	0.18	2.3 (0.9-2.9)	2.3 (0.6-3.3)	2.2
Fiber sorghum	26 (16-43)	14 (5-23)	13	0.13	3.5 (2.1-5.7)	1.9 (0.7-3.1)	1.8

*median (min-max)

a CY = conversion yield

b Miscanthus and switchgrass: E = early harvest (September to November) and L = late harvest (January to April).

Biomass yields for conventional crops (grain yields) are from Eurostat mean yields (for the period 2000-2009) for EU-27 and Agreste mean yields (for the period 2000-2009) for France and Somme (sugar beet yields are calculated from fresh yields at 16% sugar content with an hypothesis of 20% dry matter content). Biomass yields for crop residues are calculated from grain yields and straw/grain ratios from ref. [29]. Biomass yields for dedicated lignocelllulosic crops are taken from:

- Literature data: literature reviews and compilations of individual studies (ref 129 for willow; refs 129 and 130 for poplar; ref 31 for miscanthus; ref 131 for switchgrass; refs 34 and 132 for fescue; ref 34 for alfalfa; refs 35, 37, and 35 and 133 for triticale; refs 36, 134 and 135 for fiber sorghum.
- Regix: experimental network of the French research project Regix (10 sites located in northern, central and southern France, years 2007-2008; ref 27)
- B&E: INRA experimental site “Biomass & Environment” located in the Somme department, years 2007-2010 [28]

Biofuel yields were obtained by multiplying biomass yield by an actual (conventional crops) or a theoretical (other feedstocks) conversion yield (CY, see supplementary material).

Table 2: Mean N, P, K concentration and N/C, P/C, K/C removal per toe of biofuel produced for conventional crops, crop residues and dedicated lignocellulosic crops.

	Nutrient concentration (g kg^{-1} DM)			Nutrient removal per toe of biofuel produced (kg toe^{-1})		
	N	P	K	N	P	K
Arable crops						
Winter wheat	20.3 ± 2.6	2.7	4.6 ± 0.4	91	12	21
Maize	12.9 ± 1.0	2.9 ± 0.8	5.9 ± 3.4	47	11	22
Oilseed rape	31.8 ± 1.6	6.0	7.8	79	15	19
Sugar beet	7.9 ± 2.0	1.2	7.9	32	5	32
Crop residues						
Winter wheat	6.0 ± 0.9	0.7 ± 0.3	13.5 ± 3.0	37	4	83
Maize	6.2 ± 1.2	1.0 ± 0.4	13.9 ± 5.3	42	7	96
Oilseed rape	6.3 ± 1.1	0.8	13.7	42	6	93
Dedicated lignocellllulosic crops						
Willow SRC	4.8 ± 0.9	0.8 ± 0.3	2.1 ± 0.7	30	5	13
Poplar SRC	5.2 ± 1.4	0.8 ± 0.4	3.3 ± 0.7	34	5	22
Miscanthus E	5.3 ± 0.5	0.6 ± 0.2	7.3 ± 1.8	33	4	45
Miscanthus L	3.3 ± 0.9	0.4 ± 0.0	5.0 ± 1.2	21	2	31
Switchgrass E	6.9 ± 2.1	1.0 ± 0.1	7.5 ± 1.9	45	7	49
Switchgrass L	4.4 ± 1.4	0.7 ± 0.2	3.2 ± 1.6	29	4	21
Fescue	15.5 ± 3.7	2.4 ± 0.3	19.9 ± 3.4	129	20	165
Alfalfa	27.2 ± 2.5	2.6 ± 0.2	21.4 ± 3.6	311	29	245
Triticale	10.3 ± 1.2	2.0	8.8 ± 1.2	58	11	50
Fiber sorghum	9.2 ± 0.1	1.8	12.3	70	14	93

Values (mean ± standard error) for nutrient concentration are from refs 5, 27, 28, 35, 36, 37, 133, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, and Machet, JM (INRA Laon), pers. Comm., 2012,. Standard errors are calculated when three or more references are available for a given feedstock.

Table 3. Classification framework for biomass supply models. Key to land-use (LU) hypotheses: 1: a few studies make soft hypotheses; 2: most studies make soft hypotheses; 3: studies make strong hypotheses (eg, food – feed – nature paradigm).

	Group	SPATIAL	ECONOMICS	PLANT	LU Hypotheses	Stakeholders/ farmers Behaviour	References
Group 1 « Undriven »	Group 1a				3		[99, 100, 162, 163, 164]
	Group 1b	X			3		[101, 102, 103, 165, 166, 167, 168]
	Group 1c	X	X				[169]
Group 2 « Driven »	Group 2a		X		1		[170, 171, 172]
	Group 2b	X					[173]
	Group 2c	X	X		(except one) ?		[174, 175, 176, 177]
	Group 2d	X	X	X	2		[61, 95, 178,] 179, 180, 181]
	Group 2e	X	X	X			[182, 183]
	Group 2f	X	X	X	2	X	[105, 106, 184]

Supplementary material

Table S1. Mean biomass composition and calculated conversion yield into ethanol of crop residues and dedicated bioenergy crops. For conventional crops, conversion yields were obtained from ref 185. For crop residues and dedicated bioenergy crops, conversion yields were calculated from averaged biomass composition of each feedstock and expected process efficiency for biological conversion of lignocellulose into ethanol [28]. For the energy content of biofuels, we used the following values: 0.89 toe t^{-1} biodiesel and 0.64 toe t^{-1} ethanol [4].

	Biomass composition (g kg^{-1} DM)*			Conversion yield	
	Cellulose	Hemi-cellulose	Starch	Ethanol (kg t^{-1} DM)	toe t^{-1} DM
Crop residues					
Winter wheat	391 ± 23	286 ± 9		245	0.16
Maize	364 ± 12	248 ± 14		228	0.15
Oilseed rape	398	221		230	0.15
Dedicated crops					
Willow	437	245		253	0.16
Poplar	439 ± 8	199 ± 49		238	0.15
Miscanthus E	446 ± 28	232 ± 10		256	0.16
Miscanthus L	446 ± 28	232 ± 10		256	0.16
Switchgrass E	363 ± 18	276 ± 24		239	0.15
Switchgrass L	363 ± 18	276 ± 24		239	0.15
Fescue	273 ± 26	231 ± 39		175	0.11
Alfalfa	266 ± 26	101 ± 29		143	0.09
Triticale	223	145	290	276	0.18
Fiber sorghum	326 ± 19	227 ± 45		255	0.16

* Values (mean ± standard error) are from refs 140, 141, 143, 148, 159, 186, 187, 188 and 189. Standard errors are calculated when three or more references are available for a given feedstock.