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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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2

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.

4

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].

5

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

99 The above-mentioned societal concerns with biomass have pressed the need for a
100 certification of bioenergy chains, encompassing environmental, social and economic aspects
101 [10], with the challenge that many of the underlying processes and impacts are still debated in
102 the scientific community (eg, 11). Figure 1 attempts at summarizing the performance criteria
103 underlying these certification schemes, reflecting the expectations of both society at large and
104 economic stakeholders for bioenergy, with a focus on feedstock production and supply which
105 concentrates most of the sustainability-related challenges and is the actual scope of this paper.
106 The criteria are combined with the relevant scales (from field to global) on which they should
107 be addressed. Upscaling (from plot-scale to regional and possibly global scale) therefore
108 appears critical in the design and assessment of bioenergy projects.

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

117 local conditions of feedstock production. However, the latter actually contributes a major
118 share of the variability in the impacts of bio-energy chains [15].

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

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

139 Social implications of bio-based projects are important both in terms of public
140 perception of the risks and opportunities of these projects, and of the technical and
141 organisational innovations necessary for their successful implementation [22]. The spreading

7

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

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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

191 miscanthus and switchgrass were the most productive, particularly when harvested in autumn.
192 The conversion yields (CY) given in Table 1 for cellulosic ethanol production (in tons of oil
193 equivalent (toe) per ton of feedstock dry matter - DM) are generally smaller than those
194 recorded for first generation biofuels (0.09 to 0.18 toe t^{-1} DM vs. 0.22 to 0.40 toe t^{-1} DM).
195 Conversion yields vary according to the biochemical composition of biomass (Table S1),
196 being higher for triticale, short rotation coppices (SRC) and perennial rhizomatous crops, and
197 smaller for multiannual forage crops. In the French experimental network, biofuel yields per
198 ha were generally higher for perennial rhizomatous crops and triticale than for the other crops
199 (Table 1). In the Somme department, biofuel yields per ha were higher for perennial
200 rhizomatous crops, lower for pluriannual forage crops and intermediate for annual crops.

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

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

212

213 *Agricultural input requirements*

214 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

289 removal from arable cropping systems are also likely to decrease SOC stocks [15, 45]. In
290 contrast, the shift from annual crop to SRC or perennial grasses may increase SOC stocks
291 (Anderson-Teixeira *et al.* 2009), with large variations in C sequestration rates [3]. Climate and
292 soil conditions as well as crop management (e.g. fertilization, harvest time) are likely to
293 impact SOC sequestration [46]. Finally, the fate of this sequestered C after the end of the
294 plantation deserves further investigation.

295 Another major environmental issue with bioenergy feedstocks involves water bodies, from
296 either a quantitative or qualitative point of view. In agricultural landscapes, crop water
297 consumption is an important component of the hydrological cycle. For a given climate, there
298 are differences in water consumption among arable crops, mainly due to the duration and
299 position within the year of their growth cycle. In temperate climates like northern France,
300 spring crops like maize and sugar beet often have a higher water use than winter crops like
301 wheat and oilseed rape. This higher water consumption during crop growth reduces the
302 amount of water drained during the following winter and discharge to aquifers [47]. Lower
303 drainage under forage crops, with long growth cycle and deep root system like alfalfa, than
304 under annual crops has also been observed [48]. Perennial bioenergy crops may also have
305 higher water consumption than annual crops, because of their long growing season and deep
306 root system, and thus reduce drainage [49]. Field studies conducted in the Midwest US have
307 shown higher water use by miscanthus than maize but this was not necessary the case for
308 switchgrass [50, 51]. From a qualitative standpoint, crop type can also affect nitrate leaching.
309 For example, sugar-beet has a capacity to take up nitrate in autumn during a longer period
310 than other crops (eg, maize), and thus reduces nitrate leaching the following winter [47].
311 However, nitrate leaching is also dependent on crop management and on cropping systems
312 (crop rotation, catch crop, etc.), making it difficult to compare annual crops. Studies
313 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

387 natural ecosystems of the crop species itself as well as its associated weed community.

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

398 To conclude, the biodiversity impact of biofuel crops will depend on the species and
399 the former land use. The reduction in biodiversity caused by increased perennial crops will be
400 likely lower than that for first-generation biofuel production [74]. But their consequences to
401 biodiversity remain largely unstudied. Perennial crops can be beneficial to biodiversity when
402 appropriate crops are grown and sustainably managed in suitable areas, especially degraded or
403 eroded lands; or when they are planted as buffers around conventional annual crops since they
404 can provide habitats to various animals, and be used to filter nutrients or pollutants [75].
405 Agricultural landscape heterogeneity may be a key, as at equal size, sites with high crop
406 diversity tend to have larger numbers of species than sites where only one type of crop is
407 grown [75, 76]. A landscape approach is thus required to consider the interacting factors at
408 play in the functioning of bioenergy agro-ecosystems, including the type and location of the
409 plant species to be grown, and farming and harvesting systems involved in their production.
410 Opportunities exist to develop systems that could provide net biodiversity benefits on the
411 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

559 studies assess the potential area that could be dedicated to energy crops at national or global
560 levels. We considered these studies as global biomass supply assessment based only on
561 potential resources (land availability, soil types, topography, climatic conditions, fixed food
562 demand, production costs, etc...). Within this group, three different approaches may be
563 distinguished:
564 Group 1a regroups non-spatialized, non-economic approaches. They either highlight conflicts
565 between agricultural and energy policies [99] by comparing technically achievable production
566 levels to targets set by policies, or simply quantify a country or a group of countries biomass
567 production levels [100]. Approaches from the group 1a can be used to help figuring out global
568 issues independently from actual driving forces of the land use process. They also provide a
569 base to assess GHG emissions at large scales.
570 Group 1b regroups spatialized, non-economic approaches. They differ from group 1a by the
571 fact that they introduce spatial differentiation to assess biomass potential production levels.
572 Spatial differentiation can be done on a coarse (e.g., at country level, [101]) or very fine scale
573 (e.g., with a 2 km² resolution, [102]) but ignores economic or sociological factors. Studies
574 from group 1b can be used for the same purposes as those of group 1a. They are however
575 more accurate regarding biophysical constraints as the spatialization is often a way to
576 discriminate regions based on their biophysical potentials to produce biomass.
577 Group 1c regroups spatialized economic approaches. In addition to the biophysicial
578 production potential, they map the potential production level under a given production cost
579 (i.e. providing cost-supply curves which are not based on opportunity costs).
580
581 One drawback of the Group 1 studies is that they make strong assumptions to assess biomass
582 supply. One of their most common tenets is the “Food – Feed – Nature first” paradigm [103]
583 which considers that biomass will not be grown on areas dedicated to food and feed

584 production, or natural reserves. It prevents the authors from addressing the issue of
585 competition between major land uses. Although excluding areas for energy feedstock
586 cultivation based on predefined rules could reflect future regulations, the reality shows that
587 competition between food and non-food crops does exist [104].
588
589 While Group 1 approaches may be used to anticipate the trends of bioenergy crops
590 development, assessing the actual location of these crops by taking into account economic
591 and/or sociological driving factors at a supply-area scale is also of great interest to address the
592 feasibility and sustainability of a local bioenergy project. In our classification, Group 2
593 approaches propose modeling frameworks to locate biomass crops and/or bioenergy
594 production plants as "driven" by economic or supply factors: a demand in quantity (either
595 tons of biomass or energy equivalent) or in price (either in €/ton or €/MJ). However, the
596 approach and the level of details vary greatly among the existing studies.
597
598 Group 2a studies assess biomass supply and farm-gate cost for given energy demand levels,
599 but without addressing the spatial location of the production. Approaches regrouped in Group
600 2b attempts to locate energy crops production so as to maximize their net energy supply, but
601 without accounting for the economic context and, thus, the feasibility of this production.
602 Conversely, Group 2c studies locate energy crops production based on more or less robust
603 economic criteria to meet a given demand. They can thus better assess the environmental
604 impacts of such a production due to land use change. Groups 2d to 2f approaches go one step
605 further by including a biorefinery or a power plant– either in a predetermined or open location
606 or – and by addressing transportation costs. Whereas Group 2d approaches sometimes rely on
607 strong hypotheses concerning the type of land available for bioenergy crops (e.g. marginal or
608 low-yielding land, food first paradigm), Group 2e studies allow for competition between food

609 and energy crops on agricultural land, thus being more realistic. Group 2f studies make the
610 first step towards better accounting for farmers and stakeholders behaviours by integrating
611 decision processes in their models (e.g.: using a rule based model in ref 105 or an agent-
612 based model in ref 106).
613
614 Regarding sustainability assessment, studies from group 2 seem more interesting as they
615 simulate more realistic scenarios of bioenergy production. Their accuracy towards the
616 assessment of future development of bioenergy crops increases as they take into account the
617 complexity of the processes involved. However, very few studies attempt to address this
618 complexity (only Group 2f does), most of them relying on hypotheses to circumvent it.
619 Taking into account this complexity involves several dimensions:
620 - biomass managers' choices to grow and locate bioenergy crops: most of the models
621 taking into account stakeholders' decision to grow energy crops yield the "optimal"
622 spatial distribution of energy crops based on farmers' profit maximization and also
623 often on transport cost minimization. As a matter of fact, the spatial distribution of
624 agricultural crops is determined by several factors: biophysical and economic ones
625 (that determine crops' relative competitiveness), but also technical and sociological
626 ones [107, 108]. On the economic side, farmers are not mere profit maximizers.
627 Studies at a finer grain therefore have to take into account farmers' risk aversion as
628 well as the spatial configuration of farms, when it comes to the adoption of new crops
629 and especially perennials, which require a large upfront investment and provide
630 income only after a few years' time [109]. Moreover, these crops actually involve a
631 larger range of stakeholders since they can be grown by farmers but also by energy
632 producers or institutional stakeholders [110]. Modelling approaches should then be
633 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

658 and opportunities of these projects, and of the technical and organizational innovations
659 necessary for their successful implementation [27, 113].
660 One of the challenges associated to conducting a comprehensive social sustainability
661 assessment of bioenergy chains is the geographical dispersion and heterogeneity of the
662 population potentially affected. Given the number of countries involved in the bioenergy
663 value chain –both in the developed and developing world, there exist multiple types of socio-
664 economic impacts depending on the legal framework, institutional arrangements, social norms
665 as well as socio-economic characteristics of the affected population. As a result, the potential
666 effects associated to the production and consumption of bio-energy products may be
667 considerably different in terms of the type of impact, relevance and/or its magnitude
668 depending on the considered region and, of course, the specificities of each step of the value-
669 chain analyzed. This fact represents a methodological challenge but successful initiatives have
670 emerged over the last few years which represent a considerable step forward in the right
671 direction [114, 115].
672 In developed countries, where the focus is on reviving economic growth and mitigating
673 climate change, bioenergy can stimulate a green recovery –generating more jobs and
674 stimulating the economy, diversify energy supply and abate greenhouse gas emissions [114].
675 Nevertheless, given the economic crisis that is currently affecting Europe and most of the
676 word, the social acceptability of any bio-based project is very much related to its potential net
677 impact in terms of economic stimulus and job creation opportunities. In fact, the latter is one
678 of the reasons frequently cited for encouraging deployment of bioenergy systems, particularly
679 when projects take place in rural areas, with high levels of unemployment or depopulation
680 trends [116]. Compared to fossil fuels, the employment rate of biofuel production is much
681 higher [117]. To carefully assess these aspects, one must not only take into consideration the
682 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

708 be covered in an assessment and the way this should be done should be case and context
709 specific. Thereferore, there is no general consensus on which indicators to use and how to
710 assess social impacts of bioenergy projects with SIA.
711
712 Similarly, environmental impact assessment methods (such as environmental life cycle
713 assessments) have also been “streched” to incorporate social issues. In 2006, life-cycle
714 experts acknowledged the necessity to offer a complementary tool to assess products´social
715 life cycle aspects [121]. As a result of this, the Social Life Cycle Assessment (S-LCA) concept
716 emerged aiming at complementing the Environmental Life Cycle Assessment (E-LCA) and
717 the Life Cycle Costing (LCC) in contributing to the full assessment of goods and services
718 within the context of sustainable development (UNEP, 2008). The ultimate goal of a S-LCA
719 is to promote improvement of social conditions throughtout the life cycle of a product. S-LCA
720 is intended to assess product and production related social and- to some extent- economic
721 impacts using a life cycle perspective.
722
723 Qualitative research, combining perspectives from institutional theory, social anthropology
724 [122] and knowledge/innovation studies [123] may be used to examine these effects though
725 they have not yet been applied to bio-energy or bio-materials sectors. These approaches rely
726 on empirical investigations such as stakeholder analysis [124] or the so-called CIPP (Context,
727 Input, Processes and Products) approach [125] to analyse a value chain. In addition to
728 employment and economic stimuli, innovative capacity is an important dimension to assess.
729 How the innovative capacity is affected by the context, input processes and products of the
730 studied systems and how specific barriers and potentials may be identified and addressed to
731 increase the sustainability of the proposed solutions. Moreover, there exist other impacts

732 related to quality of life (health, housing, education, safety), equity, diversity, social mixing
733 cohesion, participation and governance and maturity that need to be assessed.
734
735 Populations from developing countries may also be affected by the increasing use of modern
736 bioenergy. As an example, switching from traditional to modern bioenergy systems can reduce
737 death and disease from indoor air pollution, free women and children from collecting
738 fuelwood and reduce deforestation [126]. It can also cut dependence on imported fossil fuels,
739 improving countries´ foreign exchange balances and energy security. Furthermore, bioenergy
740 can expand access to modern energy services and bring infrastructure as roads,
741 telecommunications, schools and health centres to poor rural areas. In such areas, bioenergy
742 can increase the income of small-scale farmers, alleviating poverty and decreasing the gap
743 between rich and poor. In urban centres, using biofuels in transport can improve air quality
744 [114]. On the other hand, large-scale bioenergy projects may be dominated by large
745 international companies leading to negative socioeconomic impacts especially on land tenure
746 issues. Unclear land rights and poorly regulated land acquisition may lead to depriving small
747 farmers of their properties [117]. Bioenergy can also contribute to increased or reduced food
748 security depending on policies, agricultural systems, markets, prices and income levels. There
749 is now an increased concern about negative effects of bioenergy through increased food prices
750 that can negatively affect food importing countries [117].
751
752 To address the challenge to simulatenously promote sustainable production and use of
753 bioenergy worldwide, international cooperation is essential for building capacity to implement
754 successful solutions. As an attempt to promote the wider prodution and use of modern
755 bionergy, the Global Bioenergy Sustainability Partnership (GBEP) proposed 24 indicators of
756 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.

781 It is impossible in practice to isolate LUC effects of biofuels (in particular indirect ones)
782 based solely on historic observations because of the simultaneous influence of several factors
783 affecting market equilibrium. In order to isolate LUC effects of biofuels, it is thus necessary
784 to rely on models capable of comparing, ceteris paribus, *ie* simulations « with » and « without
785 » biofuel development. Available evaluations in the literature are based either on (partial or
786 general equilibrium) economic models, or more heuristic approaches (causal-descriptive,
787 consequential LCA). The latter have the advantage of relying on a fairly simple, transparent,
788 and normalized framework that can be easily connected to that of standard LCAs. However,
789 as they rely solely on a quantity-based framework, these approaches are not well adapted to
790 fully account for market adjustments and the related indirect LUC effects. By construction,
791 economic model are better equipped in this respect. Nevertheless, their structure does not
792 always permit a clear distinction between direct and indirect LUC effects. In addition, the
793 complexity of the required modeling often makes the communication of results based on these
794 models more difficult. LUC effects on GHG emissions may be synthetized by indicators that
795 reflect annualized LUC emissions per unit of energy produced by biofuels. dLUC, iLUC, and
796 d+iLUC factors measure the direct, indirect, and total component of these emissions,
797 respectively.
798 A recent meta-analysis [127], based on a systematic search of available bibliographic
799 references and a detailed analysis of the 71 most relevant and exploitable studies on LUC
800 issues, revealed a following conclusions. First, accounting for LUC due to the development of
801 biofuels is likely to increase GHG emissions that can be attributed to biofuels. Almost 90% of
802 the collected evaluations conclude that the development of biofuels leads to (direct or
803 indirect) LUC that cause GHG emissions (positive d+iLUC factor). Secondly, for more than a
804 quarter of the collected evaluations, the sole effect of LUC leads to emissions that are greater
805 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.

References

[1] Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadnert S al. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press. Cambridge United Kingdom and New York, NY, USA; 2011.

[2] Chum H, Faaij APC, Moreira J, Berndes G, Dhamija P, Dong H et al. Bioenergy. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadnert S et al., editors. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA; 2011.

[3] Don A, Osborne B, Hastings A, Skiba Ute, Carter MS, Drewer J et al. Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. Global Change Biology Bioenergy 2011;4,372-391.

[4] AEBIOM. Annual statistical report on the contribution of Biomass to the Energy System in the EU 27. European Biomass Association, Brussels ; 2011.

[5] Karp A, Shield I. Bioenergy from plants and the sustainable yield challenge. New Phytol 2008;179:15-32.

[6] Robertson GP, Dale VH, Doering OC, Hamburg, SP, Melillo JM, Wander, MM et al. Sustainable biofuels redux. Science 2008;322:49-50.

[7] von Blottnitz H, McCurran MA. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. J. Cleaner Prod. 2007;15:607-19.

[8] Boehmel C, Lewandowski I, Claupein W. Comparing annual and perennial energy cropping systems with different management intensities. Agricultural Systems 2008;96:224-236.

869 [9] Searchinger T, Heimlich R, Houghton R, Dong F, Elobeid A, Fabiosa J et al. Use of U.S
870 crop land for biofuel increases Greenhouses gases through emissions from land use change.
871 Science 2008;319:1238-40.

872 [10] van Dam J, Junginger M, Faaij A, Jurgens I, Best G, Fritsche U. Overview of recent
873 developments in sustainable biomass certification. Biomass Bioenergy 2008;32:749-80.

874 [11] Crutzen PJ, Mosier AR, Smith KA, Winiwarter W. N2O release from agro-biofuel
875 production negates global warming reduction by replacing fossil fuels. Atm Chem Physics
876 2008;8:389-95.

877 [12] Prieur A. Environmental and socio-technico-economic analysis of bio-based value
878 chains. Final report of project PNRB-ANABIO (0501C0083). IFP EN, Rueil-Malmaison,
879 France (in french); 2008.

880 [13] Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M, van Kammen DM. Ethanol can
881 contribute to energy and environmental goals. Science 2006;31:506-508.

882 [14] Reinhardt G. Bio-energy for Europe. Which ones fit best? Final report EC contract
883 CT98-3832, IFEU, Heidelberg; 2000.

884 [15] Gabrielle B, Gagnaire N. Life-cycle assessment of straw use in bio-ethanol production: A
885 case study based on biophysical modelling. Biomass Bioenergy 2008;32:431-41.

886 [16] Semere T, Slater FM. Invertebrate populations in Miscanthus (Miscanthus x giganteus)
887 and reed canary-grass (Phalaris arundinacea) fields. Biomass Bioenergy 2007;31:30-9.

888 [17] Semere T, Slater FM. Ground flora, small mammal and bird species diversity in
889 Miscanthus (Miscanthus x giganteus) and reed canary-grass (Phalaris arundinacea) fields.
890 Biomass Bioenergy 2007;31:20-29.

891 [18] Gosselin M. Impact de la production intensive de biomasse sur la biodiversité dans les

892 taillis à très courte rotation. In: Landmann G, Gosselin F, Bohême I (editors) Bio2, Biomasse
893 et biodiversité forestières; augmentation de l'utilisation de la biomasse forestière :
894 implications pour la biodiversité et les ressources naturelles. Paris, MEEDDM-Ecofor; 2009.

895 [19] Stein A, Riley J, Halberg N. Issues of scale for environmental indicators. Agric Ecosyst
896 Environ 2001;87:215-232.

897 [20] Galloway JN, Aber JD, Erisman JW, Seitzinger SP, Howarth RW, Cowling EB et al. The
898 Nitrogen Cascade. BioScience 2003;53:341-56.

899 [21] Batidzirai B, Smeets E, Faaij A. Harmonising bioenergy resource potentials.
900 Methodological lessons from review of state of the art bioenergy potential assessments.
901 Renew Sustain Energy Rev 2012;16:6598-630.

902 [22] Mayfield CA, Foster CD, Smith CT, Gan J, Fox S. Opportunities, barriers, and strategies
903 for forest bioenergy and bio-based product development in the Southern United States.
904 Biomass Bioenergy 2007;31:631-7.

905 [23] Lewandowski I, Scurlock JMO, Lindvall E, Christou M. The development and current
906 status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass
907 Bioenergy 2003;25:335-61.

908 [24] Sanderson MA, Adler PR. Perennial forages as second generation bioenergy crops. Int J
909 Molecular Sci 2008;9:768-88.

910 [25] Zegada-Lizarazu W, Monti A. Energy crops in rotation. A review. Biomass Bioenergy
911 2011;35:12-25.

912 [26] Lal R. Crop residues as soil amendments and feedstock for bioethanol production. Waste
913 Management 2008;28:747-58.

914 [27] Cadoux S, Briand S, Chabbert B, Besnard A, Félix I, Savouré ML et al. Biomass

915 productivity of different energy crops under French conditions. Results of the « REGIX »
916 experimental network. In: Proceedings 18th European Biomass Conference & Exhibition,
917 Lyon, France; 2010, p. 269-272.

918 [28] Cadoux S, Ferchaud F, Demay C, Boizard H, Machet J-M, Fourdinier E et al.
919 Implications of productivity and nutrient requirements of greenhouse gas balance of annual
920 and perennial bioenergy crops. GCB Bioenergy; in press.

921 [29] Scarlat N, Martinov M, Dallemand JF. Assessment of the availability of agricultural crop
922 residues in the European Union: Potential and limitations for bioenergy use. Waste Manag
923 2010;30:1889-97.

924 [30] Agreste. Enquête pratiques culturales 2006. Web-based data base :
925 http://agreste.maapar.lbn.fr/ReportFolders/ReportFolders.aspxCS_referer=&CS_ChosenLang
926 =fr (last visited 2 April 2013), Ministère de l'agriculture, de l'agroalimentaire et de la forêt,
927 Paris.

928 [31] Cadoux S, Riche AB, Yates NE, Machet JM. Nutrient requirements of Miscanthus x
929 giganteus: Conclusions from a review of published studies. Biomass Bioenergy 2012;38:14-
930 22.

931 [32] Monti A, Barbanti L, Zatta A, Zegada-Lizarazu W. The contribution of switchgrass in
932 reducing GHG emissions. GCB Bioenergy 2012;4:420-34.

933 [33] Jensen E, Peoples M, Boddey R, Gresshoff P, Hauggaard-Nielsen H, Alves B et al.
934 Legumes for mitigation of climate change and the provision of feedstock for biofuels and
935 biorefineries. A review. Agron Sustain Dev 2012;32:329-64.

936 [34] Cheney JH, Johnson KD, Volenec J, Greene DK. Biomass potential of selected grass and
937 legume crops. Energy Sources 1991;13:283-92.

938 [35] Lewandowski I, Kauter D. The influence of nitrogen fertilizer on the yield and

939 combustion quality of whole grain crops for solid fuel use. Industrial Crops and Products
940 2003;17:103-17.

941 [36] Barbanti L, Grandi S, Vecchi A, Venturi G. Sweet and fibre sorghum (Sorghum bicolor
942 (L.) Moench), energy crops in the frame of environmental protection from excessive nitrogen
943 loads. Eur J Agron 2006;25:30-9.

944 [37] Jorgensen JR, Deleuran LC, Wollenweber B. Prospects of whole grain crops of wheat,
945 rye and triticale under different fertilizer regimes for energy production. Biomass Bioenergy
946 2007;31:308-17.

947 [38] Brunet N, Debaeke P, Delos M, Guérin O, Guindé L, Mischler P et al. Ecophyto R&E :
948 vers des systèmes de culture économes en intrants et en produits phytosanitaires. 2009; INRA,
949 Paris.

950 [39] Adler PR, Del Grosso SJ, Parton WJ. Life-cycle assessment of net greenhouse-gas flux
951 for bioenergy cropping systems. Ecolog Applications 2007;17:675-91.

952 [40] Jorgensen RN, Jorgensen BJ, Nielsen NE, Maag M, Lind AM. N2O emission from
953 energy crop fields of Miscanthus "Giganteus" and winter rye. Atmos Environ 1997;31:2899-
954 904.

955 [41] Gauder M, Butterbach-Bahl K, Graeff-Hönninger S, Claupein W, Wiegel R. Soil-derived
956 trace gas fluxes from different energy crops – results from a field experiment in Southwest
957 Germany. GCB Bioenergy 2012;4:289-301.

958 [42] Behnke G, David M, Voigt T. Greenhouse Gas Emissions, Nitrate Leaching, and Biomass
959 Yields from Production of Miscanthus × giganteus in Illinois, USA. BioEnergy Research
960 2012;4:801-13.

961 [43] Schmer MR, Liebig MA, Hendrickson JR, Tanaka DL, Phillips RL. Growing season
962 greenhouse gas flux from switchgrass in the northern great plains. Biomass Bioenergy

963 2012;45:315-19.

964 [44] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land Clearing and the Biofuel
965 Carbon Debt. Science 2008;319:1235-7.

966 [45] Saffih-Hdadi K, Mary B. Modeling consequences of straw residues export on soil
967 organic carbon. Soil Biol Biochem 2008;40:594-607.

968 [46] Bessou C, Ferchaud F, Gabrielle B, Mary B. Biofuels, greenhouse gases and climate
969 change. A review. Agron Sustain Dev 2011;31:1-79.

970 [47] Beaudoin N, Saad JK, Van Laethem C, Machet JM, Maucorps J, Mary B. Nitrate
971 leaching in intensive agriculture in Northern France: Effect of farming practices, soils and
972 crop rotations. Agric Ecosyst Environ 2005;111:292-310.

973 [48] Beaudoin N, Denys D, Muller JC, Monbrun MD, Ledain C. Influence d'une culture de
974 luzerne sur le lessivage du nitrate dans les sols de Champagne crayeuse. Fourrages
975 1992;129:45-57.

976 [49] Vanloocke A, Bernacchi CJ, Twine TE. The impacts of Miscanthus x giganteus
977 production on the Midwest US hydrologic cycle. GCB Bioenergy 2010;2:180-91.

978 [50] Hickman GC, Vanloocke A, Dohleman FG, Bernacchi CJ. A comparison of canopy
979 evapotranspiration for maize and two perennial grasses identified as potential bioenergy
980 crops. GCB Bioenergy 2010;2:157-68.

981 [51] McIsaac GF, David MB, Mitchell CA. Miscanthus and switchgrass production in Central
982 Illinois: impacts on hydrology and inorganic nitrogen leaching. J Environ Qual 2010;39:1790-
983 9.

984 [52] Aronsson PG, Bergstrom LF. Nitrate leaching from lysimeter-grown short-rotation
985 willow coppice in relation to N-application, irrigation and soil type. Biomass Bioenergy

986 2001;21:155-64.

987 [53] Christian DG, Riche AB. Nitrate leaching losses under Miscanthus grass planted on a
988 silty clay loam soil. Soil Use Manag 1998;14:131-35.

989 [54] Goodlass G, Green M, Hilton B, McDonough S. Nitrate leaching from short-rotation
990 coppice. Soil Use Manag 2007;23:178-84.

991 [55] Mortensen J, Nielsen KH, Jorgensen U. Nitrate leaching during establishment of willow
992 (Salix viminalis) on two soil types and at two fertilization levels. Biomass Bioenergy
993 1998;15,457-66.

994 [56] Schmidt-Walter P, Lamersdorf N. Biomass Production with Willow and Poplar Short
995 Rotation Coppices on Sensitive Areas—the Impact on Nitrate Leaching and Groundwater
996 Recharge in a Drinking Water Catchment near Hanover, Germany. BioEnergy Res
997 2012;5:546-62.

998 [57] Lewandowski I, Faaij A. Steps towards the development of a certification system for
999 sustainable biomass trade - analysis of existing approaches. Utrecht University. Utrecht, the
1000 Netherlands; 2004.

1001 [58] Koh LP, Ghazoul J. Biofuels, biodiversity, and people: understanding the conflicts and
1002 finding opportunities. Conservation Biol 2008;141:2450-60.

1003 [59] Danielsen F, Beukema H, Burgess ND, Parish F, Brühl CA, Donald PF et al. Biofuel
1004 plantations on forested lands: Double jeopardy for biodiversity and climate. Conservation
1005 Biol 2009;23:348-58.

1006 [60] Phalan B, Fitzherbert EB, Rafflegeau S, Struebig MJ, Verwilghen A. Conservation in Oil-
1007 Palm Landscapes. Conservation Biol 2009;23,244-5.

1008 [61] Hellmann F, Verburg PH. Impact assessment of the European biofuel directive on land

use and biodiversity. J Environ Manag 2010;91:1389-96.

[62] Debaeke P. Dynamique de quelques dicotylédones adventices en culture de céréales. I. Relation flore levée-stock semencier. Weed Res 1998;28:251-63.

[63] Rowe RL, Street NR, Taylor G. Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. Renew Sustain Energy Rev 2007;13:271-90.

[64] Sage RB, Cunningham M, Boatman N. Birds in willow short-rotation coppice compared to other arable crops in central England and a review of bird census data from energy crops in the UK. Ibis 2006;148:184-97.

[65] Spencer JL, Raghu S. Refuge or Reservoir? The potential impacts of the biofuel crop Miscanthus x giganteus on a major pest of maize. PLoS ONE 2009;4:e8336.

[66] Huggett DAJ, Leather SR, Walters KFA. Suitability of the biomass crop Miscanthus sinensis as a host for the aphids Rhopalosiphum padi (L.) and Rhopalosiphum maidis (F.), and its susceptibility to the plant luteovirus Barley Yellow Dwarf Virus. Agric Forest Entomol 1999;1:143-9.

[67] Chimera CG, Buddenhagen CE, Clifford PM. Biofuels: the risks and dangers of introducing invasive species. Biofuels 2010;1,785-96.

[68] Genovesi P. European biofuel policies may increase biological invasions: the risk of inertia. Current Opinion Environ Sustain 2011;3:66–70.

[69] Raghu S, Anderson RC, Daehler CC, Davis AS, Wiedenmann RN, Simberloff D et al. Adding Biofuels to the Invasive Species Fire? Science 2006;313:1742.

[70] Barney JN, DiTomaso JM. Non-native species and bioenergy: are we cultivating the next invaders? BioScience 2008;58:64-70.

1032 [71] Schnitzler A. Miscanthus: l'homme cultive-t-il un nouvel envahisseur? Agence de l'Eau
1033 Rhin-Meuse, Université de Metz Paul Verlaine, 41p.;2011.

1034 [72] Jörgensen U. Benefits versus risks of growing biofuel crops: the case of Miscanthus.
1035 Current Opinion Environ Sustain 2011;3:24-30.

1036 [73] DiTomaso JM, Barney JN, Fox AM. Biofuel Feedstocks: The Risk of Future Invasions.
1037 All U.S. Government Documents (Utah Regional Depository). Paper 79;2007.
1038 http://digitalcommons.usu.edu/govdocs/79

1039 [74] Fletcher Jr RJ, Robertson BA, Evans J, Doran PJ, Alavalapati JRR, Schemske DW.
1040 Biodiversity conservation in the era of biofuels: risks and opportunities. Frontiers Ecol
1041 Environ 2010;9:161-8.

1042 [75] Dale VH, Kline KL, Wiens J, Fargione J. Biofuels: implications for land use and
1043 biodiversity. Biofuels and Sustainability Reports. The Ecological Society of America,
1044 Washington DC; 2010. www.esa.org/biofuelsreports

1045 [76] Benton TG, Vickery JA, Wilson JD. Farmland biodiversity: is habitat heterogeneity the
1046 key? Trends Ecol Evol 2003;18:182-8.

1047 [77] Sébillote M. Systèmes de culture, un concept opératoire pour les agronomes. In: Combe
1048 L, Picard D, editors. Les Systèmes De Culture, INRA, Paris; 1990, p. 165–196.

1049 [78] Karlen DL, Varvel GE, Bullock DG, Cruse M. Crop rotations for the 21st century.
1050 Advances Agron 1994;53:1-45.

1051 [79] Robson MC, Fowler SM, Lampkin NH, Leifert C, Leitch M, Robinson D et al. The
1052 agronomic and economic potential of break crops for ley/arable rotations in temperate organic
1053 agriculture. Advances Agron 2002;77:369-427.

1054 [80] Saint Clair S, Hillier J, Smith P. Estimating the pre-harvest greenhouse gas costs of

1055 energy crop production. Biomass Bioenergy 2008;32:442-52.

1056 [81] Bennett AJ, Bending GD, Chandler D, Hilton S. Meeting the demand for crop
1057 production: the challenge of yield decline in crops grown in short rotations. Biological Rev
1058 2012;87:52-71.

1059 [82] Ball BC, Bingham I, Rees RM, Watson CA, Litterick A. The role of crop rotations in
1060 determining soil structure and crop growth conditions. Canadian J Soil Sci 2005;85:557-77.

1061 [83] Dufossé K, Drewer J, Gabrielle B, Drouet J-L. Soil carbon and N2O emission dynamics
1062 after destruction of a 20-year old Miscanthus stand, and comparison with a plot under annual
1063 crops. In: Proceedings 20th European Biomass Conference and Exhibition, 20-23 June 2012,
1064 Milan; 2012.

1065 [84] Deytieux V, Nemecek T, Knuchel RF, Gaillard G, Munier-Jolain NM. Is Integrated Weed
1066 Management efficient for reducing environmental impacts of cropping systems? A case study
1067 based on life cycle assessment. Eur J Agron 2012;36:11.

1068 [85] Colbach N, Lucas P, Cavelier N. Influence des successions culturales sur les maladies du
1069 pied et des racines du blé d'hiver. Agronomie 1994;14,525–40.

1070 [86] Hill J. Environmental costs and benefits of transportation biofuel production from food-
1071 and lignocellulose-based energy crops. A review. Agron Sustain Dev 2007;27:1–12.

1072 [87] Thomsen MH, Hauggaard-Nielsen H. Sustainable bioethanol production combining
1073 biorefinery principles using combined raw materials from wheat undersown with clover-grass.
1074 J Industrial Microbiol Biotech 2008;35:303–11.

1075 [88] Nemecek T, von Richthofen JS, Dubois G, Casta P, Charles R, Pahl H. Environmental
1076 impacts of introducing grain legumes into European crop rotations. Eur J Agron 2008;28:380-
1077 93.

1078 [89] Lamb J, Jung H, Sheaffer C, Samac D. Alfalfa leaf protein and stem cell wall
1079 polysaccharide yields under hay and biomass management systems. Crop Sci 2007;47:1407-
1080 15.

1081 [90] Petersson A, Thomsen MH, Hauggaard-Nielsen H, Thomsen AB. Potential bioethanol
1082 and biogas production using lignocellulosic biomass from winter rye, oilseed rape and faba
1083 bean. Biomass Bioenergy 2007;31:812-9.

1084 [91] Martin C, Thomsen MH, Hauggaard-Nielsen H, Thomsen AB. Wet oxidation
1085 pretreatment, enzymatic hydrolysis and simultaneous saccharification and fermentation of
1086 clover-ryegrass mixtures. Bioresour Technol 2008;99:8777-82.

1087 [92] Lançon J, Wery J, Rapidel B, Angokaye M, Gerardeaux E, Gaborel C. An improved
1088 methodology for integrated crop management systems. Agron Sustain Dev 2007;27:101-10.

1089 [93] Miguez FE, Villamil MB, Long SP, Bollero G. Meta-analysis of the effects of
1090 management factors on Miscanthus × giganteus growth and biomass production. Agric Forest
1091 Meteorol 2008;148:1280-92.

1092 [94] Sadok W, Angevin F, Bergez JE, Bockstaller C, Colomb B, Guichard L. MASC: a
1093 qualitative multi-attribute decision model for ex ante assessment of the sustainability of
1094 cropping systems. Agron Sustain Dev 2009;29:447-61.

1095 [95] Blaschke T, Biberacher M, Gadocha S, Zocher D, Mittlböck M, Haslauer E et al. Virtual
1096 Power Plants: Spatial Energy Models in Times of Climate Change. In: Ehlers M, Behncke K,
1097 Gerstengarbe F-W, Hillen F, Koppers L, Stroink L et al. editors, Digital Earth Summit on
1098 Geoinformatics. Potsdam, Germany. Deutsch Nationalbibliothek, Wichmann Heidelberg;
1099 2008, p. 61-7.

1100 [96] Hellmann F, Verburg P. Spatially explicit modelling of biofuel crops in Europe. Biomass
1101 Bioenergy 2011;35,2411-24.

1102 [97] Vereecken H, Kasteel R, Vanderborght J, Harter T. Upscaling hydraulic properties and
1103 soil water flow processes in heterogeneous soils: a review. Vadose Zone J 2007;6:1-28.

1104 [98] Turner II BL, Lambin EF, Reenberg A. The emergence of land change science for global
1105 environmental change and sustainabiltiy. Proc Natl Acad Sci USA 2007;104:20666-71.

1106 [99] Simon S, Wiegmann K. Modelling sustainable bioenergy potentials from agriculture for
1107 Germany and Eastern European countries. Biomass Bioenergy 2009;33:603-9.

1108 [100] Farine DR, O'Connell DA, John Raison R, May BM, O'Connor MH, Crawford FD et al.
1109 An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission
1110 reduction in Australia. GCB Bioenergy 2012;4:148-75.

1111 [101] Campbell JE, Lobell DB, Genova RC, Field CB. The global potential of bioenergy on
1112 abandoned agriculture lands. Environ Sci Technol 2008;42:5791-94.

1113 [102] Lovett AA, Sunnenberg GM, Richter GM, Dailey AG, Riche AB, Karp A. Land Use
1114 Implications of Increased Biomass Production Identified by GIS-Based Suitability and Yield
1115 Mapping for Miscanthus in England. Bioenergy Res 2009;2:17-28.

1116 [103] Fischer G, Prieler S, van Velthuizen H, Berndes G, Faaij A, Londo M et al. Biofuel
1117 production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land
1118 use scenarios. Biomass Bioenergy 2010;34:173-87.

1119 [104] UNCTAD. Price Formation in Financialized Commodity Markets: The Role of
1120 Information. Study prepared by the secretariat of UNCTAD, UNCTAD/GDS/2011/1, New
1121 York and Geneva; 2011.

1122 [105] Gaucherel C, Griffon S, Misson L, Houet T. Combining process-based models for
1123 future biomass assessment at landscape scale. Landscape Ecol 2010;25:201-15.

1124 [106] Scheffran J, BenDor T. Bioenergy and land use: a spatial-agent dynamic model of

1125 energy crop production in Illinois. Int J Environ Pollution 2009;39:4-27.

1126 [107] Rindfuss RR, Walsh SJ, Turner BL, Fox J, Mishra V (2004) Developing a science of
1127 land change: Challenges and methodological issues. Proc Natl Acad Sci USA
1128 2004;101:13976-81.

1129 [108] Valbuena D, Verburg PH, Bregt AK, Ligtenberg A. An agent-based approach to model
1130 land-use change at a regional scale. Landscape Ecol 2010;25:185-99.

1131 [109] Bocquého G, Jacquet F. The adoption of switchgrass and miscanthus by farmers: Impact
1132 of liquidity constraints and risk preferences. Energy Policy 2010;38:2598-2607.

1133 [110] McCormick K, Käberger T. Key barriers for bioenergy in Europe: Economic conditions,
1134 know-how and institutional capacity, and supply chain co-ordination. Biomass Bioenergy
1135 2007;31:443-52.

1136 [111] Cooper J, Braster M, Woolsey E. Overview of the Chariton Valley switchgrass project: a
1137 part of the biomass power for rural development initiative. Proceedings of the conference
1138 BioEnergy '98: Expanding Partnerships. Madison, WI; 1998.

1139 [112] Madlener R. Innovation diffusion, public policy, and local initiative: The case of wood-
1140 fuelled district heating systems in Austria. Energy Policy 2007;35:1992-2008.

1141 [113] Adams P, Hammond G, McManus M, Mezzullo W. Barriers to and drivers for UK
1142 bioenergy development. Renew Sustain Energy Rev 2011;15:1217-27.

1143 [114] GBEP 2011. The Global Bioenergy Partnership Sustainability Indicators for Bioenergy.
1144 First Edition. ISBN 978-92-5-1072493.

1145 http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/Indicators/The_GBEP_Sust
1146 ainability_Indicators_for_Bioenergy_FINAL.pdf

1147 (last visited: 2 April 2013)

1148 [115] UNEP. Guidelines for Social Life Cycle Assessment Products. UNEP-SETAC Life-
1149 Cycle Initiative. Nairobi, Kenya; 2009.

1150 [116] Thornley P, Rogers J, Huang Y. Quantification of employment from biomas power
1151 plants. Renew Energy 2008;33:1922-7.

1152 [117] Rutz D, Janssen R. Socioeconomic Impacts of different scales of biofuel production in
1153 Africa. In: Rutz D, Janssen, R, editors. Bioenergy for Sustainable Development in Africa.
1154 Springer Dordrecht Heidelberg London New York; 2012.

1155 [118] Ten Raa, T. The Economics of Input-Output Analysis, Cambridge University Press,
1156 Cambridge; 2005.

1157 [119] Neuwahl F, Löschel A, Mongelli I, Delgado L. Employment impacts of EU biofuels
1158 policy: combining bottom-up technology information and sectoral market simulations in an
1159 input-output framework. Ecol Econ 2008;68:447-60.

1160 [120] Burdge R. The concepts, process and methods of SIA. The Social Ecology Press,
1161 Middleton, WI; 2004.

1162 [121] Griesshammer R, Benoît C, Dreyer LC, Flysjö A, Manhart A, Mazijn Bet al. Feasibility
1163 Study: Integration of social aspects into LCA. Discussion paper from UNEP-SETAC Task
1164 Force Integration of Social Aspects in LCA meetings in Bologna (January 2005), Lille (May
1165 2005) and Brussels (November 2005), Freiburg, Germany; 2006.

1166 [122] Crate SA. Cows, Kin and Globalization: An Ethnography of Sustainability. Altamira
1167 Press, Plymouth, UK; 2006.

1168 [123] Orlikowski W. Knowing in Practice: Enacting a collective capability in distributed
1169 organizing. Organization Sci 2002;13:249-73.

1170 [124] Mathur VN, Price ADF, Austin S. Conceptualising stakeholder engagement in the

1171 context of sustainability and the assessment process. Construc Manag Econ 2008;26,601-9.

1172 [125] Matsaert H. Institutional analysis in natural resources research. Natural Resources
1173 Institute, University of Greenwhich; 2002.

1174 [126] ESF. Biomasa y desarrollo. Oportunidades de la biomasa para mejorar el acceso local a
1175 la energía en comunidades aisladas de América Latina, Fundacion Energia sin Fronteras,
1176 Madrid ; 2012.

1177 [127] De Cara S, Goussebaïle A, Grateau R, Levert F, Quinemer J, Vermont B. Critical review
1178 of studies evaluating the effect of land-use changes on the environmental balances of biofuels.
1179 Environment and Energy Agency (ADEME), Angers, France; 2012 (in French).

1180 [128] Havlık P, Schneider UA, Schmid E, Böttcher H, Fritz S, Skalský R et al. Global land-
1181 use implications of first and second generation biofuel targets. Energy Policy 2010;39:5690-
1182 5702.

1183 [129] Aylott MJ, Casella E, Tubby I, Street NR, Smith P, Taylor G. Yield and spatial supply of
1184 bioenergy poplar and willow short-rotation coppice in the UK. New Phytol 2008;178:358-70.

1185 [130] Kern J, Hellebrand HJ, Scholz V, Linke B. Assessment of nitrogen fertilization for the
1186 CO(2) balance during the production of poplar and rye. Renew Sustain Energy Rev
1187 2010;14:1453-60.

1188 [131] Heaton E, Voigt T, Long SP. A quantitative review comparing the yields of two
1189 candidate C 4 perennial biomass crops in relation to nitrogen, temperature and water. Biomass
1190 Bioenergy 2004;27:21-30.

1191 [132] Tilvikienė V., Kadžiulienė Ž., Dabkevičius Z. The evaluation of tall fescue, coksfoot
1192 and reed canary grass as energy crops for biogas production. Grassland Sci Eur 2010;15:304–
1193 6.

1194 [133] Scholz V, Ellerbrock R. The growth productivity, and environmental impact of the
1195 cultivation of energy crops on sandy soil in Germany. Biomass Bioenergy 2002;23:81-92.

1196 [134] Habyarimana E, Laureti D, Ninno MD, Lorenzoni C. Performances of biomass sorghum
1197 [Sorghum bicolor (L.) Moench] under different water regimes in Mediterranean region. Indus
1198 Crops Prod 2004;20:23-28.

1199 [135] Sakellariou-Makrantonaki MS, Papanikolaou CD, Mygdakos E. Fiber sorghum biomass
1200 yield, water use efficiency and economic results under different levels of water using
1201 subsurface and surface irrigation systems. Fresenius Environ Bull 2009;18:1624-31.

1202 [136] Banowetz GM, Griffith SM, Steiner JJ, Ei-Nashaar HM. Mineral accumulation by
1203 perennial grasses in a high-rainfall environment. Energy Fuels 2009;23:984-8.

1204 [137] Beaudoin N, Saad JK, Van Laethem C, Machet JM, Maucorps J, Mary B. Nitrate
1205 leaching in intensive agriculture in Northern France: Effect of farming practices, soils and
1206 crop rotations. Agric Ecosyst Environ 2005;111:292-310.

1207 [138] Christian DG, Riche AB, Yates NE. The yield and composition of switchgrass and
1208 coastal panic grass grown as a biofuel in Southern England. Bioresour Technol 2002;83:115-
1209 24.

1210 [139] Comifer. Teneurs en P, K et Mg des organes végétaux récoltés. COMIFER, La Défense,
1211 France; 2007.

1212 [140] Da Silva Perez D, Briand S, Leygue J, Laboubée C, Chabbert B, Labalette F et al.
1213 Comparison of agricultural and forest biomass with the regard to biological processes fo
1214 bioethanol production of second generation. In: Proceedings 18th European Biomass
1215 Conference & Exhibition, Lyon, France; 2010, p. 506-510.

1216 [141] Dien BS, Jung HJG, Vogel KP, Casler MD, Lamb JFS, Iten L et al. Chemical
1217 composition and response to dilute-acid pretreatment and enzymatic saccharification of

1218 alfalfa, reed canarygrass, and switchgrass. Biomass Bioenergy 2006;30:880-91.

1219 [142] El-Nashaar HM, Banowetz GM, Peterson CJ, Griffith SM. Genetic variability of
1220 elemental concentration in winter wheat straw. Energy Fuels 2010;24:2020-7.

1221 [143] Energy Research Centre of the Netherlands. PHYLLIS, the composition of biomass and
1222 waste. Web-based data base: http://www.ecn.nl/phyllis2 (last visited 2 April 2013). ECN-
1223 Biomass, Petten, NL; 2012.

1224 [144] Gallejones P, Castellon A, Del Prado A, Unamunzaga O, Aizpurua A. Nitrogen and
1225 sulphur fertilization effect on leaching losses, nutrient balance and plant quality in a wheat-
1226 rapeseed rotation under a humid Mediterranean climate. Nutr Cycl Agroecosyst 2012;93:337-
1227 55.

1228 [145] Heckman JR, Sims JT, Beegle DB, Coale FJ, Herbert S, Bruulsema TW et al. Nutrient
1229 removal by corn grain harvest. Agron J 2003;95:587-91.

1230 [146] Jenkins BM, Baxter LL, Miles Jr TR, Miles TR. Combustion properties of biomass.
1231 Fuel Process Technol 1998;54:17-46.

1232 [147] Johnson JMF, Wilhelm WW, Karlen DL, Archer DW, Wienhold B, Lightle DT et al.
1233 Nutrient Removal as a Function of Corn Stover Cutting Height and Cob Harvest. BioEnergy
1234 Research 2010;3:342-52.

1235 [148] Kanapeckas J, Lemeziene N, Butkute B, Stukonis V. Evaluation of tall fescue (Festuca
1236 arundinacea Schreb.) varieties and wild ecotypes as feedstock for biogas production.
1237 Zemdirbyste (Agriculture) 2011;98:149-56.

1238 [149] Kauter D, Lewandowski I, Claupein W. Quantity and quality of harvestable biomass
1239 from Populus short rotation coppice for solid fuel use—a review of the physiological basis
1240 and management influences. Biomass & Bioenergy 2003;24:411-27.

1241 [150] Lavado RS, Porcelli CA, Alvarez R. Nutrient and heavy metal concentration and
1242 distribution in corn, soybean and wheat as affected by different tillage systems in the
1243 Argentine Pampas. Soil Till Res 2001;62:55-60.

1244 [151] Ledin S. Willow wood properties, production and economy. Biomass & Bioenergy
1245 1996;11:75-83.

1246 [152] Lemus R, Brummer EC, Moore KJ, Molstad NE, Burras CL, Barker MF. Biomass yield
1247 and quality of 20 switchgrass populations in southern Iowa, USA. Biomass & Bioenergy
1248 2002;23:433-42.

1249 [153] Lloveras J, Ferran J, Boixadera J, Bonet J. Potassium fertilization effects on alfalfa in a
1250 Mediterranean climate. Agron J 2001;93:139-43.

1251 [154] Propheter JL, Staggenborg SA, Wu X, Wang D. Performance of annual and perennial
1252 biofuel crops: yield during the first two years. Agronomy J 2010;102:806-14.

1253 [155] Setiyono TD, Walters DT, Cassman KG, Witt C, Dobermann A. Estimating maize
1254 nutrient uptake requirements. Field Crops Research 2010;118:158-68.

1255 [156] Sweeney DW, Moyer JL, Havlin JL. Multinutrient fertilization and placement to
1256 improve yield and nutrient concentration of tall fescue. Agron J 1996;88:982-6.

1257 [157] Tharakan PJ, Volk TA, Abrahamson LP, White EH. Energy feedstock characteristics of
1258 willow and hybrid poplar clones at harvest age. Biomass & Bioenergy 2003;25:571-80.

1259 [158] Thomason WE, Raun WR, Johnson GV, Taliaferro CM, Freeman KW, Wynn K et al.
1260 Switchgrass response to harvest frequency and time and rate of applied nitrogen. J Plant Nutr,
1261 2004;27:1199-1226.

1262 [159] US Department of Energy. Biomass Feedstock Composition and Property Database.
1263 Web-based data base: http://www.afdc.energy.gov/biomass/progs/search1.cgi (last visited 25

1264 April 2013); 2004.

1265 [160] Vassilev SV, Baxter D, Andersen LK, Vassileva CG. An overview of the chemical
1266 composition of biomass. Fuel 2010;89:913-33.

1267 [161] Vos J, Van Der Putten PEL. Nutrient cycling in a cropping system with potato, spring
1268 wheat, sugar beet, oats and nitrogen catch crops. I. Input and offtake of nitrogen, phosphorus
1269 and potassium. Nutr Cycl Agroecosyst 2000;56:87-97.

1270 [162] Ericsson K, Nilsson LJ. Assessment of the potential biomass supply in Europe using a
1271 resource-focused approach. Biomass Bioenergy 2006;30:1-15.

1272 [163] Haughton AJ, Bond AJ, Lovett AA, Dockerty T, Sünnenberg G, Clark SJ et al. A novel,
1273 integrated approach to assessing social, economic and environmental implications of changing
1274 rural land-use: a case study of perennial biomass crops. J Applied Ecol 2009;46:315-22.

1275 [164] Sudha P, Ravindranath NH. Land availability and biomass production potential in India.
1276 Biomass and Bioenergy 1999;16:207-21.

1277 [165] Fischer G, Prieler S, van Velthuizen H, Lensink SM, Londo M, de Wit M. Biofuel
1278 production potentials in Europe: Sustainable use of cultivated land and pastures. Part I: Land
1279 productivity potentials. Biomass Bioenergy 2010;34:159-72.

1280 [166] Jager HI, Baskaran LM, Brandt CC, Davis EB, Gunderson CA, Wullschleger SD.
1281 Empirical geographic modeling of switchgrass yields in the United States. GCB Bioenergy
1282 2010;2:248-57.

1283 [167] Piketty MG, Wichert M, Fallot A, Aimola L. Assessing land availability to produce
1284 biomass for energy: The case of Brazilian charcoal for steel making. Biomass and Bioenergy
1285 2009;33:180-90.

1286 [168] Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC. A bottom-up assessment

1287 and review of global bio-energy potentials to 2050. Progr Energy Combustion Sci 2007;33:
1288 56-106.

1289 [169] De Wit M, Faaij A. European biomass resource potential and costs. Biomass and
1290 Bioenergy 2010;34:188-202.

1291 [170] Ballarin A,Vecchiato D, Tempesta T, Marangon F, Troiano S. Biomass energy
1292 production in agriculture: A weighted goalprogramming analysis. Energy Policy
1293 2011;39:1123-31.

1294 [171] Callesen I, Grohnheit PE, Ostergard H. Optimization of bioenergy yield from cultivated
1295 land in Denmark. Biomass and Bioenergy 2010;34:1348-62.

1296 [172] Fiorese G, Guariso G. A GIS-based approach to evaluate biomass potential from energy
1297 crops at regional scale. Environ Model Software 2010;25:702-11.

1298 [173] Tenerelli A, Carver S. Multi-criteria, multi-objective and uncertainty analysis for agro-
1299 energy spatial modelling. Applied Geog 2012;32:724-36.

1300 [174] De La Torre Ugarte DG, Ray DE. Biomass and bioenergy applications of the POLYSYS
1301 modeling framework. Biomass and Bioenergy 2000;18:291-308.

1302 [175] Geyer R, Stoms DM, Lindner JP, Davis FW, Wittstock B. Coupling GIS and LCA for
1303 biodiversity assessments of land use. Int J Life Cycle Assessment 2010;15:454-67.

1304 [176] Hellwinckel CM, West TO, De La Torre Ugarte DG, Perlack RD. Evaluating possible
1305 cap and trade legislation on cellulosic feedstock availability. GCB Bioenergy 2010;2:278-87.

1306 [177] Krasuska E, Cadorniga C, Tenorio JL, Testa G, Scordia D. Potential land availability for
1307 energy crops production in Europe. Biofuels Bioproducts Biorefining-Biofpr 2010;4,658-73.

1308 [178] Forster M, Helms Y, Herberg A, Köppen A, Kunzmann K, Radtke D et al. A site-related
1309 suitability analysis for the production of biomass as a contribution to sustainable regional

land-use. Environ Manag 2008;41:584-98.

[179] Shi X, Elmore A, Li X, Gorence NJ, Jin H, Zhang X et al. Using spatial information technologies to select sites for biomass power plants: A case study in Guangdong Province, China. Biomass Bioenergy 2008;32:35-43.

[180] van der Hilst F, Dornburg V, Sanders JPM, Elbersen B, Graves A, Turkenburg WC et al. Potential, spatial distribution and economic performance of regional biomass chains: The North of the Netherlands as example. Agric Syst 2010;103:403-17.

[181] Tittmann PW, Parker, NC, Hart QJ, Jenkins BM. A spatially explicit techno-economic model of bioenergy and biofuels production in California. J Transport Geog 2010;18:715-28.

[182] Bryan BA, Ward J, Hobbs T. An assessment of the economic and environmental potential of biomass production in an agricultural region. Land Use Policy 2008;25:533-49.

[183] Egbendewe-Mondzozo A, Swinton SM, Izaurralde CR, Manowitz DH, Zhang X. Biomass supply from alternative cellulosic crops and crop residues: A spatially explicit bioeconomic modeling approach. Biomass Bioenergy 2011;35:4636-47.

[184] Bauen AW, Dunnett AJ, Richter GM, Dailey AG, Aylott M, Casella E et al. Modelling supply and demand of bioenergy from short rotation coppice and Miscanthus in the UK. Bioresource Technology 2010 ;101:8132-43.

[185] ADEME. Life cycle assessments applied to first generation biofuels used in France. Environment and Energy Agency (ADEME), Angers, France ; 2010 (in French).

[186] Amaducci S, Amaducci MT, Benati R, Venturi G. Crop yield and quality parameters of four annual fibre crops (hemp, kenaf, maize and sorghum) in the North of Italy. Industrial Crops and Products 2000;11:179-86.

[187] Guidi W, Tozzini C, Bonari E. Estimation of chemical traits in poplar short-rotation

coppice at stand level. Biomass Bioenergy 2009;33:1703-09.

[188] Lee D, Owens VN, Boe A, Jeranyama P. Composition of Herbaceous Biomass Feedstocks. South Dakota State University, Brookings ; 2007.

[189] Stolarski MJ, Szczukowski S, Tworkowski J, Wroblewska H, Krzyzaniak M. Short rotation willow coppice biomass as an industrial and energy feedstock. Industrial Crops and Products 2011;33:217-23.

Figure captions

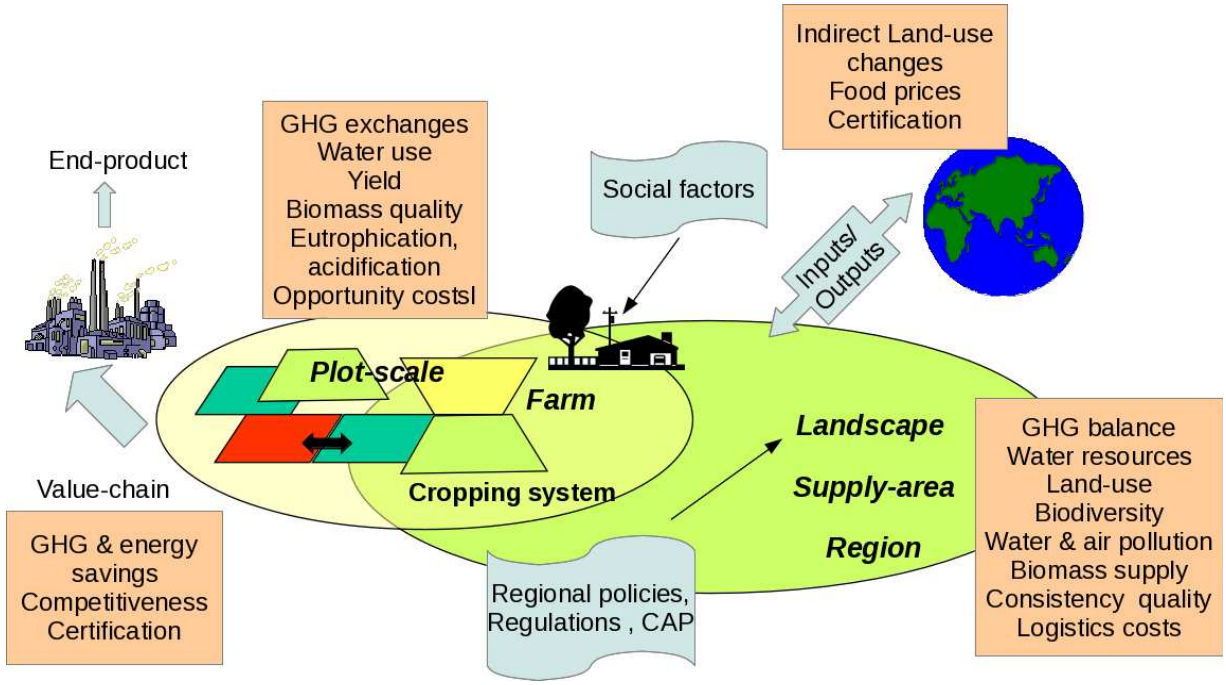
Figure 1: Drivers and performance criteria for bioenergy value chains, from plot to global scales. Blue boxes = drivers; orange boxes = performance criteria.

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

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1355 Figure 1. Drivers and performance criteria for bioenergy value chains, from plot to global
1356 scales. Blue boxes = drivers; orange boxes = performance criteria.

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1370 Figure 2. Proposed indicators under the Social Pillar of the Global Bioenergy Sustainability

1371 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

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1374 Table 1. Biomass and biofuel yields of arable crops, crop residues and dedicated
1375 lignocelllulosic crops
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	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*							
	Literature*	France Regix*	Somme B&E	toe t^{-1}DM	Literature*	France Regix*	Somme 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).

1398 Table 2: Mean N, P, K concentration and N/C, P/C, K/C removal per toe of biofuel produced

1399 for conventional crops, crop residues and dedicated lignocellulosic crops.

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	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 lignocelllulosic 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

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1403 Values (mean ± standard error) for nutrient concentration are from refs 5, 27, 28, 35, 36, 37,
1404 133, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152,
1405 153, 154, 155, 156, 157, 158, 159, 160, 161, and Machet, JM (INRA Laon), pers. Comm.,
1406 2012,. Standard errors are calculated when three or more references are available for a given
1407 feedstock.

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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]

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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.