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

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

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4 Running title: Sustainable biomass supply in Europe

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31 **ABSTRACT**

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

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

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

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

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

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67 ***Introduction***

68 Biomass is expected to be a major player in the energy transition toward low-carbon
69 economies, in response to the pressing challenges of climate change and dwindling fossil
70 resources. According to the recent IPCC scenarios of energy transition, bioenergy may
71 contribute up to half of total use of primary energy worldwide by 2050 [1]. Such high
72 expectations are reflected in the ambitious bioenergy targets recently set in the EU, the US,
73 Brazil or India, with bioenergy being attributed a 20% to 30% share of the overall energy mix
74 within the next 20 years. This implies a several-fold increase compared to the present
75 production of bioenergy, and poses major challenges for agriculture and forestry, since this
76 expansion will for a large part rely on dedicated energy plants, including lignocellulosic crops
77 and short rotation forestry [2]. In Europe for instance, bio-energy is the fastest growing
78 renewable energy source with a production that almost doubled over the last 15 years,
79 currently supplying 6% of the total primary energy [3]. Around 3.1 Mha in the European
80 Union (EU) are currently used for bioenergy, mainly for biofuel production as biodiesel and
81 ethanol, and biogas, all involving arable food and feed crops. A small proportion is derived
82 from dedicated bioenergy crops. These crops are mostly perennials grown to generate
83 electricity and heating, with the most frequent species being miscanthus, willow, reed canary
84 grass and poplar. They were covering 50 000 to 60 000 ha in Europe in 2008, and about 100
85 000 ha in 2010 [4,3], underlining a rapid development. Such trend is likely to continue since it
86 is estimated that 17-19 million hectares should be converted to bio-energy crops to meet the
87 targets of the SET-plan in the EU, whether for heat, electricity or liquid biofuels production
88 [3]. Meeting this demand raises considerable challenges for feedstock supply chains in terms
89 of competitiveness, reliability and sustainability [5]. First, the availability of terrestrial land to
90 grow the feedstock imposes major constraints on potential biomass supply, and secondly the
91 conditions for a sustainable and reliable supply are yet to be defined [6].

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 an 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 N₂O (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

142 and uptake of new knowledge is necessary, regarding the farming of crops as well as the
143 forms of organisation to be set up over the feedstock supply area and the biomass value-chain.
144 However, there is a paucity of specific social sustainability assessment methodologies. Up to
145 now, assessments have often been conducted through social impact assessment (SIA),
146 extended to include other sustainability pillars, or by extending the framework of
147 environmental impact assessment (EIA) to incorporate social issues.

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

156 ***Feedstock production and environmental impacts***

157 ***Biomass and biofuel yields***

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

166 generation biofuels and expected conversion yields of cellulosic ethanol for dedicated crops
167 and crop residues (Table S1).

168 The yields of arable crops were evaluated using available agricultural statistics since there is
169 no or little difference between the cultivars and crop management practices used for food or
170 bioenergy production. We focused on three different scales: EU-27, France, and an
171 administrative department (6170 km² in area) called “Somme” in northern France, in a region
172 of intensive arable crop production. The hierarchy between crops was identical across the 3
173 scales, with sugar-beet being the most productive crop and oilseed rape the less productive.
174 This ranking also applied to biofuel production, with an output approximately 3 times higher
175 for sugar-beet than for oilseed rape per ha, even though the latter has the highest grains to
176 biofuel conversion yield.

177 The biomass production potential of dedicated lignocellulosic crops has mostly been
178 investigated in experimental plots, mainly in Europe and North America, and involving only
179 one crop type, which makes it difficult to compare crops. As a consequence, dry matter yields
180 found in the literature (Table 1) should not be used to rank crops because of the differences in
181 soil and climate conditions between studies. For instance, fiber sorghum was only
182 investigated in southern Europe whereas willow data originate from northern Europe. The
183 large variability in the literature data for a given crop type (Table 1) also arises from
184 differences in crop management (eg, irrigation and fertilizer inputs) between studies. For the
185 scale of France, Table 1 displays the results of an experimental network (called “Regix”)
186 comparing 6 species in 10 sites located in northern, central and southern France [27]. The data
187 evidence a large variability between sites, due to the interaction between crops and soil and
188 climate conditions, with no consistent ranking of crops across the network of sites. At
189 departmental scale in Somme, the data of Table 1 were obtained in a single experimental site
190 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

215 fertilizers and pesticides. Crop nutrient requirements are of prime importance because
216 nitrogen fertilization has a huge impact of the overall GHG balance of bioenergy crops [11]
217 and because P and K are non-renewable resources that cannot be synthesized. In France in
218 2006, the mean fertilization rates for winter wheat, maize, oilseed rape and sugar beet were
219 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
220 [30].

221 The nutrient requirements of lignocellulosic crops are still poorly known. The yield response
222 of perennial crops to nitrogen fertilization varies between sites. For miscanthus, out of 11
223 studies reviewed by Cadoux *et al.* [31], 6 concluded to a positive but often limited response
224 (an increase of 1 to 6 t DM ha⁻¹ in autumn), while 5 showed an absence of a response. The
225 same variability was shown for switchgrass by Monti *et al.* [32], who reviewed 6 studies with
226 10 locations in the USA. No response or an increase of less than 2 t DM ha⁻¹ was observed in
227 4 sites while in 6 sites an increase of 2 to 11 t DM ha⁻¹ was observed. Among pluriannual
228 forage crops, alfalfa does not require N inputs because of its N-fixing capacity [33], while the
229 N requirements of fescue are high [34]. For annual crops, the yield triticale was shown to
230 increase with N fertilization in 4 locations in Southwest Germany, which is consistent with the
231 relatively high N requirements of this crop [35]. Surprisingly, no effects of N inputs on the
232 yield of fiber sorghum were evidenced in a field trial in northern Italy [36]. Finally, unlike
233 nitrogen, the role of P and K as possible limiting factor of biomass yields has been little
234 investigated for lignocellulosic crops [37].

235 An indirect way of assessing the nutrient requirements of crops is to compare nutrient
236 concentrations at harvest. For a given crop type, the latter can vary because of differences in
237 soil nutrient availability, crop management (harvest time, fertilization) and DM yield. Despite
238 this variability, literature data show that nutrient concentrations are crop-specific and very
239 variable between feedstocks (Table 2). Across the crops considered in this Table, N

240 concentration varies between 3.3 and 31.8 g N kg⁻¹ DM, P concentration between 0.4 and 6 g
241 P kg⁻¹ and K concentration between 2.1 and 21.4 g K kg⁻¹. This variability also exists between
242 arable crops, with sugar-beet having much smaller N and P concentration than the other crops
243 and especially oilseed rape. The differences in N, P and K concentrations between these crops
244 are consistent with the observed mean fertilization rates expressed per ton of harvested
245 biomass. Overall, the highest N concentrations are observed for arable crops except for sugar-
246 beet and forage crops, and the lowest N concentrations are observed for SRC and perennial
247 rhizomatous crops. The same trend applies to P concentrations, with crop residues having also
248 very low P concentrations. For K, forage crops have the highest concentrations, followed by
249 crop residues, while SRC willow and poplar have the lowest concentrations.

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

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

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

264 *Environmental impacts*

265 The choice of a given feedstock has implications on its environmental impacts at the field
266 scale. Among them, biosphere-atmosphere exchanges of GHG in the field a crucial item for
267 the overall GHG balance of bioenergy chains. The main fluxes include soil N₂O emissions
268 and CO₂ balance, as controlled by changes in soil and biomass C pools [3]. Although there is
269 a large body of work on these fluxes for arable crops, little data is available for lignocellulosic
270 crops. In their review, Don *et al.* [3] presented the results of 5 European studies comparing
271 N₂O emissions from arable and perennial lignocellulosic crops (willow SRC, poplar SRC and
272 miscanthus), concluding the latter had significantly lower N₂O emissions than the former.
273 This was not only an effect of lower N input rates with perennial crops but also of the
274 reduction of the ratio of emissions to fertilizer rates (emission factor). However, in one of the
275 5 sites, the emission factor for miscanthus was more than 3 times higher than for winter rye
276 [40]. A recent study comparing GHG emissions from miscanthus, willow and maize at two
277 fertilization rates (0-240 kg N ha⁻¹ for maize and 0-80 kg N ha⁻¹ for miscanthus and willow)
278 also lead to contrasted conclusions [41]. The emission factors were 0.95% for maize, 1.1% for
279 miscanthus and only 0.04% for willow. Two other recent studies showed a large increase of
280 N₂O emissions from perennial crops (miscanthus and switchgrass) with increasing fertilizer N
281 input rates [42,43]. It seems that the latter are a key point for controlling N₂O emissions from
282 perennial bioenergy crops and that a balance has to be found between increasing biomass
283 yields and minimizing N₂O emissions per ton of feedstock produced.

284 Changes in soil organic carbon (SOC) content depends on crop type and management but also
285 on the former land-use history. Conversion of forest or grassland to annual crops leads to very
286 high SOC losses, creating a carbon debt equivalent to 17 to 420 times the annual GHG
287 reduction resulting from the displacement of fossil fuel by first generation biofuels [44].
288 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

314 nitrogen leached under established miscanthus, switchgrass or willow SRC, with nitrate
315 concentration in drainage water usually below 25 mg NO₃ l⁻¹ [51, 52, 53, 54 55, 56]. Nitrate
316 concentration was little affected by the N input rates, except in one study with miscanthus for
317 the highest N rate [53]. However, high nitrate concentrations were observed during the
318 establishment phase of miscanthus and SRC willow (one or two years after establishment),
319 with nitrate concentrations in some cases higher than 100 mg l⁻¹. This was probably due to an
320 imbalance between the soil mineralization rate and the low N uptake rates of these crops in
321 this period. Another increase in nitrate concentration was also observed after the destruction
322 and replanting of a SRC [54].

323

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

333 *Impacts on biodiversity*

334 While annual crops have been extensively studied with respect to their impact on biodiversity,
335 fewer studies address the impacts of lignocellulosic plants. Yet, the introduction of perennial
336 bioenergy crops in a European agricultural landscape dominated by annual crops will
337 certainly lead to marked changes to agrosystems and arable landscapes, especially when

338 perennial crops such as miscanthus or switchgrass, and/or short rotation coppices of woody
339 species, such as poplars or willows, will be grown besides annual crops. It is likely that
340 processes maintaining biodiversity in both space and time would subsequently change, but
341 this remains largely under-evaluated.

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

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

363 20% of the local species pool do actually express annually in cultivated fields [62].

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

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

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

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

385 A scarcely considered aspect is the potential increase in the introduction of invasive alien
386 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.

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

414

415 ***Integration into cropping systems***

416 *Why considering bioenergy crops within a cropping system?*

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

420 The introduction of bioenergy crops could generate several effects at cropping system level
421 [78, 79]. These effects may be assessed through relevant performance criteria, which include
422 dry matter yield and quality (especially *vis-a-vis* the pre-treatment and conversion process),
423 energy balance, environmental impacts (such as GHG emissions, soil C dynamics, N losses
424 and water consumption), production costs and profitability. These criteria may be calculated
425 for a particular bioenergy crop but are strongly dependent on the cropping system it is
426 integrated into. For instance, the former land use (cropland, grassland or woodland)
427 determines whether energy crops are a net source or sink of GHG [3, 80].

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

436 *Introducing annual/pluriannual crops versus perennial crops into cropping systems*

437 Energy crops provide an opportunity to farmers to increase their crop portfolios and access
438 new markets, albeit with specific challenges. Introducing annual/pluriannual crops for
439 bioenergy production implies that cropping systems are only partly dedicated to bioenergy, as
440 other crops within the crop sequence may still be grown for food and feed production.
441 Moreover, such energy crops may be more easily introduced by farmers in usual crop
442 sequences, allowing (i) combined food and feed production on the same field (thus mitigating
443 the competition between food and non-food purposes), (ii) higher flexibility for farmers
444 compared to perennial crops, which are established for at least 15 years [25], and (iii) a
445 diversification of arable crop sequences with positive impacts on weed pressure [84], pest and
446 disease risks [85], soil fertility and structure, and yields [25–81]. However, annual
447 lignocellulosic crops often have a higher reliance on chemical inputs than perennial crops [3,
448 8, 86]. Reducing this reliance implies a move towards agronomical low-inputs principles,
449 starting with a diversification of crops within the cropping system: (i) over the crop sequence,
450 (ii) within a growing season through species mixtures (possibly with mixed uses of the
451 different crops, i.e. food/feed and bioenergy; 67), and (iii) with the introduction of cover
452 crops.

453 In particular, the introduction of legumes and their conversion to energy deserves further
454 investigation [33]. Given their capacity to fix atmospheric N, legumes allow a significant
455 reduction of N fertilisation at the cropping system scale (no N fertilisation on a sole legume,
456 or reduced N fertilisation on a legume-other species intercropping, and reduced N fertilisation
457 on a crop following a legume). This reduces upstream GHG emissions due to fertilizer
458 manufacturing and field emissions of N₂O resulting from fertilizer N applications, along with
459 the energy consumption of the cropping system [33, 88]. Other benefits were observed in
460 terms of ecosystem services, such as soil structure improvement, increase in C sequestration

461 (due to higher soil organic N content) or lower nitrate leaching under pluriannual legumes
462 with deep root systems [33]. Given these advantages, legumes could play a role in the
463 production of biomass for bioenergy [33]. Valorisations for second-generation bioethanol
464 have already been investigated, based either on whole plants [87] or co-products (alfalfa
465 stems; 89). However, the use of sole legumes as energy crops incurs potential drawbacks such
466 as lower soil fertility in the case of whole-plant harvesting, lower yields compared to other
467 energy crops, and biomass quality constraints with respect to the conversion processes [87,
468 90, 91]). Intercropping legumes with other energy crops could be a way of achieving higher
469 yields and better quality, which remains to be investigated on a commercial scale. The choice
470 of species and cultivars as well as crop management are important issues, as well as the
471 impact of the introduction of such intercrops in cropping systems.

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

482 Compared to (pluri-)annual crops, the advantages of perennial crops are the production of
483 high amounts of biomass per hectare with low inputs, together with low environmental
484 impacts compared to arable crops (e.g., [3, 27]). However, some concerns should be raised,
485 for instance on the impacts after their cultivation (e.g. on GHG emissions, soil fertility and on

486 the establishment of succeeding crops), or the location of these crops (current cropland vs.
487 other types of lands). The competition between food and energy crops provides an incentive
488 for establishing perennial lignocellulosic crops on alternative lands (marginal lands,
489 including contaminated soils, fields that are far from the farm headquarters or difficult to
490 manage).

491 *Future research needs*

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

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

509 To implement an *ex ante* assessment of innovative cropping systems including bioenergy

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

522

523 ***Upscaling from local to supply-area scale***

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

530 The spatial allocation of bioenergy crops, as any other agricultural land-use change, is a
531 complex process driven by biophysical, economic and social factors (e.g.: soil type, land use
532 competition, social acceptability; [98]). The biophysical context (agro-pedo-climatic
533 conditions) first determines if and where a given crop specie can be grown together with its

534 corresponding potential yield. As many crop species may be grown on the same tract of land,
535 resulting in a competition between crops, land-use allocation is theoretically determined by
536 the relative profitability of these crops (income minus production cost), assuming that prices
537 result from the balance between biomass supply and demand. However, as opposed to wheat
538 grains, biomass feedstock is an emerging commodity for which there is currently no real
539 market price. For lignocellulosic crops to be adopted by farmers, their farm-gate price should
540 cover at least their production cost plus the foregone revenues due to land-use substitution –
541 what is termed “opportunity costs”. Stakeholders' characteristics and behavior (e.g. risk
542 aversion, social embeddedness), as well as technical and policy constraints at the plot, farm or
543 landscape levels (e.g., plot size and distance to the farm headquarters) should also be taken
544 into account to determine the availability of biomass. Lastly, on the demand side, the
545 biorefinery-gate cost includes at least transportation costs. All these factors have to be
546 accounted for, and determine the relative location of biomass crops and biorefineries, as well
547 as the feedstock supply mix and price.

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

555

556 First, some studies focus on the production potential of biomass without taking into account
557 an overall demand for feedstock (whether in quantity or price) or the economic context, nor
558 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 biophysical
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 world, 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

683 affected by the bioenergy value chain–, but also the indirect effects –that is the impact on
684 those other sectors that supply goods and services to the other sector that are directly affected.
685

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

699

700 However, one must go beyond the pure quantitative figures and also consider, for example,
701 the qualitative attributes of such employment (for example: what is their qualification,
702 duration, gender, etc). Social Impact Assessments (SIA) have been often used to complement
703 the more quantitative results derived from an input-output model. Burdge [120] defines SIA
704 as the systematic appraisal of “impacts on the day-to-day quality of life or persons and
705 communities whose environment is affected by a proposed policy, plan, programme or
706 project”. Guidelines for SIA have been developed, among others, by the World Bank and the
707 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. Therefore, 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 “stretched” 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 throughout 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 simultaneously 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 production and use of modern
755 bioenergy, the Global Bioenergy Sustainability Partnership (GBEP) proposed 24 indicators of
756 sustainability intended to inform policy-making and facilitate the sustainable development of

757 bioenergy [114]. These indicators do not provide answers or correct values of sustainability
758 but rather present the right questions to ask in assessing the effect of modern bioenergy
759 production and use in meeting nationally defined goals of sustainable development (Figure 2).
760 With regards to the social pillar, GBEP considers that the themes that are most relevant are: (i)
761 price and supply of a national food basket, (ii) access to land, water and other natural
762 resources, (iii) labour conditions, (iv) rural and social development, (v) access to energy, (vi)
763 human health and (vii) safety (Figure 2).

764

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

769 ***Consequences at global scales: direct and indirect land-use*** 770 ***changes***

771 At a global scale, displacing food crops with energy crops in Europe may result in net
772 emissions of GHG through changes in land-use worldwide. A higher demand for agricultural
773 commodities such as bioenergy feedstock leads to higher prices and larger incentives for
774 farmers to increase their output, possibly through the conversion of non-agricultural land. The
775 resulting land-use changes (LUC) may cause the release of the below- and above-ground
776 carbon into the atmosphere. LUC emissions are direct if they result from for conversions of
777 land for the production of biomass for bioenergy, and indirect if they are due to conversions to
778 other land uses that would not have occurred without the development of biofuels. These
779 emissions may negate the GHG benefits of substituting fossile energy sources with biomass
780 [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 CO₂eq. MJ⁻¹). When including life-cycle GHG

806 emissions due to feedstock production, transformation and distribution of biofuels, the total
807 emissions are greater than that of the reference fossil fuel for more than half of the collected
808 evaluations. Thirdly, the collected evaluations are characterized by a large variability of the
809 d+iLUC factor both between and within studies. This large variability actually reflects the
810 diversity of approaches, definitions, and assumptions (relative to land-use changes,
811 representation of underlying market mechanisms, biofuel chains, etc.) adopted in the studies.
812 Significant differences occurred among feedstock types, biofuel types, supply regions and the
813 regions of origin for biofuel demand. For example, the gap between biodiesel and bioethanol
814 ranged from 22 to 27 g CO₂eq. MJ⁻¹ depending on the methodology used to approach LUC
815 effects.

816 Even there are far fewer references for first generation biofuels than for lignocellulosic
817 feedstocks, the emissions related to LUC are lower by a factor of 2 to 10 with the latter type
818 of feedstock [127]. As discussed in the 'Feedstock production' section of this paper, the
819 conversion of arable food crops to lignocellulosics results in lower N₂O emissions and a
820 temporary sequestration of C in the soil, ie negative dLUC emissions. Indirect LUC effects
821 deserve further investigation with lignocellulosic feedstocks, but their burden is unlikely to
822 significantly offset the GHG benefits from substituting fossile energy with bioenergy,
823 especially if the feedstock is grown on marginal land [128].

824

825 ***Conclusion and outlook***

826 Ensuring a reliable and sustainable supply of biomass to meet policy targets in Europe raises
827 considerable challenges both in terms of research and practical implementation. While the
828 limits of bioenergy chains based on food crops are clearly appearing [9], lignocellulosic
829 crops will be a key component of future feedstock supply chains, complementing other
830 sources of biomass such as residues and waste streams. There is a potential for large-scale

831 development of such species but there are still many unknowns in terms of yield potentials in
832 a wide range of soil and climate conditions, on marginal lands or in the face of climate
833 change. Based on current evidence, the performance of these crops appear promising but is
834 still uncertain. Further research on yield drivers, optimal management at crop or cropping
835 system level, spatial distribution and environmental impacts is therefore warranted to guide
836 the design of feedstock supply chains.

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

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1348 Figure captions

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1350 Figure 1: Drivers and performance criteria for bioenergy value chains, from plot to global
1351 scales. Blue boxes = drivers; orange boxes = performance criteria.

1352 Figure 2: Proposed indicators under the Social Pillar of the Global Bioenergy Sustainability
1353 Partnership (GBEP). Source: ref 114.

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 lignocellulosic crops
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	Biomass yields (t DM ha ⁻¹ yr ⁻¹)			CY ^a	Biofuel yields (toe ha ⁻¹ yr ⁻¹)		
Arable crops: <i>Current mean yields</i>							
	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: <i>Estimated current mean yields</i>							
	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): <i>Total of conventional crops + crops residues</i>							
	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 lignocellulosic crops : <i>Experimental yields</i>							
	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
Switchgrass 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

1377 *median (min-max)

1378 a CY = conversion yield

1379 b Miscanthus and switchgrass: E = early harvest (September to November) and L = late
1380 harvest (January to April).

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1382 Biomass yields for conventional crops (grain yields) are from Eurostat mean yields (for the
1383 period 2000-2009) for EU-27 and Agreste mean yields (for the period 2000-2009) for France
1384 and Somme (sugar beet yields are calculated from fresh yields at 16% sugar content with an
1385 hypothesis of 20% dry matter content). Biomass yields for crop residues are calculated from
1386 grain yields and straw/grain ratios from ref. [29]. Biomass yields for dedicated
1387 lignocellulosic crops are taken from:

1388 - Literature data: literature reviews and compilations of individual studies (ref 129 for willow;
1389 refs 129 and 130 for poplar; ref 31 for miscanthus; ref 131 for switchgrass; refs 34 and 132
1390 for fescue; ref 34 for alfalfa; refs 35, 37, and 35 and 133 for triticale; refs 36, 134 and 135 for
1391 fiber sorghum.

1392 - Regix: experimental network of the French research project Regix (10 sites located in
1393 northern, central and southern France, years 2007-2008; ref 27)

1394 - B&E: INRA experimental site “Biomass & Environment” located in the Somme department,
1395 years 2007-2010 [28]

1396 Biofuel yields were obtained by multiplying biomass yield by an actual (conventional crops)
1397 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.

1400

	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 lignocellulosic 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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1411 Table 3. Classification framework for biomass supply models. Key to land-use (LU) hypotheses: 1: a few studies make soft hypotheses;

1412 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			Conversion yield	
	Cellulose	(g kg ⁻¹ DM)*	Starch	Ethanol	toe t ⁻¹ DM
		Hemi-cellulose		(kg 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	326 ± 19	227 ± 45		255	0.16
sorghum					

* 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.