

A land-based approach for the environmental assessment of Mediterranean annual and perennial energy crops

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Highlights

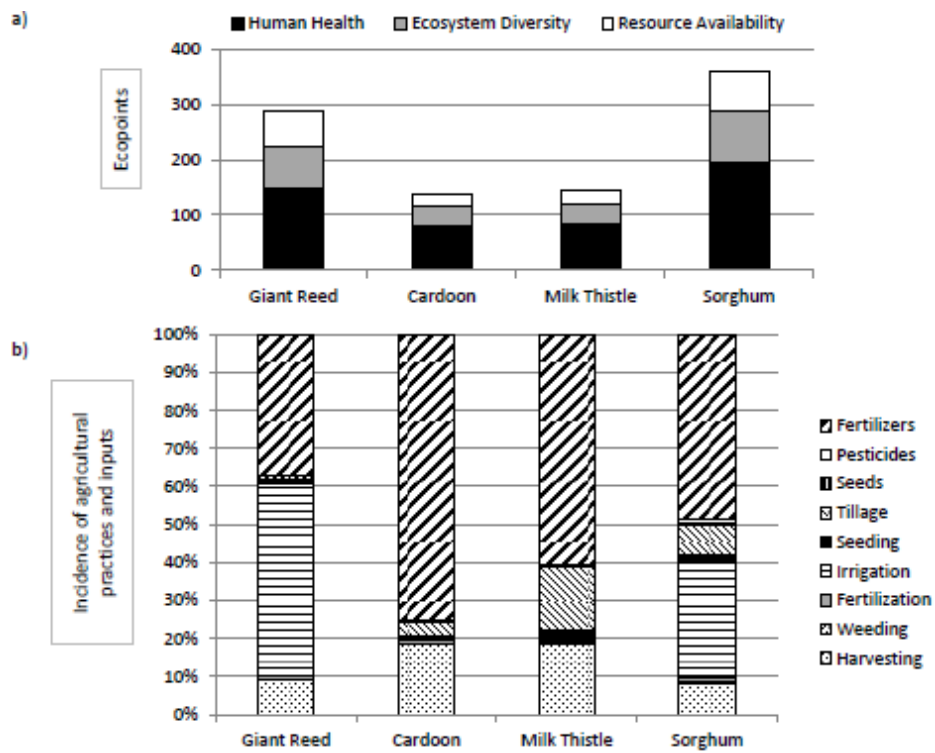
LCA highlights linkage between crop yield, management, and environmental sphere.

Irrigated (rainfed) annual crops are more damaging than the respective perennials.

Except for irrigation, fertilizers had the largest environmental effect in all crops.

Environmental burdens increase more proportionally than yield in all energy crops.

Results identify no winning crop as environmental burdens depend on site specificity.



Environmental damages (Ecopoints) on land basis of four energy crops were allocated between three vulnerable targets (a); incidence (%) of agricultural practices and inputs were evaluated on total Ecopoints for each crop on land basis (b).

1 **A land-based approach for the environmental assessment of Mediterranean annual and**
2 **perennial energy crops**

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38
39 17 **Abstract**

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41 18 Biomass production helps address the worldwide energy demand. However, some controversial
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43
44 19 issues have been identified such as the possible conflict between the goal of increasing
45
46 20 vegetable biomass and food production and the need to limit environmental impacts. In
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48 21 Mediterranean region, where the supply of some natural resources appears significantly limited
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50
51 22 (e.g., water) and the competition for land is higher than it was in the past, the objective of
52
53 23 evaluating environmental burdens at a regional scale represents an important issue, especially
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55
56 24 if the assessment considers the farmer scope of increasing productivity.

57
58 25 Using a Life Cycle Assessment (LCA) “from cradle to field gate” approach, this paper aims to

26 evaluate land-based environmental sustainability related to four energy crop options. We
27 carried out a LCA differentiating between annual and perennial species and between irrigated
28 (giant reed and sorghum) and rainfed crops (cardoon and milk thistle) to determine their
29 performances and impacts within the same context. The findings suggest that irrigated crops
30 generate larger impacts on the environment than rainfed species and that annual crops (both
31 irrigated and rainfed) are more damaging than the respective perennial crops. The damages were
32 expressed in Ecopoints, where one Ecopoint corresponds to one thousandth of the annual
33 overall environmental burden of an average European inhabitant. Ecopoints for sorghum, giant
34 reed, milk thistle and cardoon are equal to 361, 288, 146, and 138, respectively. Except for
35 irrigation, fertilizers were found to be the input with the largest effect, accounting for 37% (giant
36 reed) to 75% (cardoon) of the environmental burden on the system. The results do not suggest
37 the presence of a winning crop option - *i.e.*, a crop that shows the best environmental
38 performances everywhere and in all categories - since regional environmental burdens are
39 simultaneously related to different factors (e.g., land allocation, crop productivity, and degree
40 of practice intensification) that drive farmer choice. Finally, following a dynamic and
41 innovative perspective, we evaluated the trade-off between productivity and environmental
42 burden for each crop simulating an increasing product variation. We found that environmental
43 burdens would increase more proportionally than crop yields done. Especially the latter finding
44 provides interesting suggestions on energy cropping system integration within agricultural
45 planning under stressed natural resource conditions.

46
47 **Keywords:** life cycle assessment, biomass production, agricultural management cropping
48 system, rainfed crop, irrigated crop.

49 50 **1. Introduction**

51 Biomass energy supply is greatly interwoven with the controversial dilemma among food,
52 energy and the environment (Tillman *et al.*, 2009) that in turn has remarkable repercussions in
53 terms of land availability and biomass potential (Thrän *et al.*, 2010; Harvey and Pilgrim, 2011;
54 Popp *et al.*, 2014). Biomass production triggers competition for natural resource use - especially
55 for land and water – assuming its strategic relevance to farmers and policy makers in a given
56 territory (Johansson, 2013; Bonsch *et al.*, 2016; Robledo-Abad *et al.*, 2016; Rosillo-Calle,
57 2016). For example, a crucial issue is identifying what type of lands should be used for energy
58 crops to mitigate the food-energy-environment controversy and, as a consequence, improve the
59 sustainability of biomass production (Allen *et al.*, 2014; Lewis and Kelly, 2014; Mehmood *et*
60 *al.*, 2017). Indeed, a sustainable land-use choice for energy crop cultivation may involve both
61 agricultural land-use intensification and the exploitation of underutilized agricultural lands
62 (Miyake *et al.*, 2012). Furthermore, the use of these lands does not necessarily imply
63 environmental benefits because energy crop cultivation might require natural resource
64 overexploitation to obtain satisfactory productivity (Dauber *et al.*, 2012). More generally, the
65 nature of the land being used (e.g., marginal or highly productive land), the degree of resource
66 use (e.g., intensive or extensive cultivation), the temporal horizon of land use (e.g., annual or
67 perennial crops), and the type of cropping system adopted become triggers that influence farmer
68 choice and drive the magnitude of environmental consequences at a regional scale (Dale *et al.*,
69 2011).

70 In Mediterranean region, energy cropping systems have also been planned as alternatives to
71 food production on lands typically covered by food/feed crops, thus avoiding the risk of
72 additional lands being abandoned in some cases (Ledda *et al.*, 2013; Cocco *et al.*, 2014). Indeed,
73 certain lands have been abandoned owing to the economic crisis that affected valuable food
74 production, but these areas are far from being unproductive. On the other hand, energy
75 crops have also been introduced on lands unsuitable for food production (e.g. marginal and

76 degraded lands) precisely because these biomass crops are able to grow under stress conditions
1
2 77 (Allen *et al.*, 2014). In these cases, the “food versus fuel” might be a false dilemma because
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4 78 energy crops are not a conflicting factor (Strapasson *et al.*, 2017) whereas, vice-versa,
5
6 79 introduction of these crops can worsen this controversial issue where biomass energy occupy
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8
9 80 lands characterized by high food productivity (Miyake *et al.*, 2015). This dilemma should not
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11
12 81 be considered an issue merely restricted by the land competition, since land is an extremely
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14 82 dynamic and multifunctional resource, the use of which is strongly affected by a set of
15
16 83 complicated interactions (Tomei and Helliwell, 2016).

17
18
19 84 In the unproductive lands, crops that require a low amount of inputs are cultivated, or the inputs
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21
22 85 applied should be increased to achieve profitable energy crop production (Fernando *et al.*, 2015;
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24 86 Schmidt *et al.*, 2015; Bosco *et al.*, 2016). In the fertile lands, cultivation is generally practised
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26
27 87 more intensively and hardly concurs in exploitation of natural resources, such as water, *in*
28
29 88 *primis*, especially in a climate change context (Dono *et al.*, 2013a; 2013b). However,
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31
32 89 intensification of input use and adoption of new techniques may still have negative
33
34 90 environmental consequences (Don *et al.*, 2012). At the same time, increasing productivity might
35
36 91 contrast with the needs of safeguarding biodiversity and natural resources and of mitigating
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38
39 92 climate change (Bagley *et al.*, 2014; Immerzeel, *et al.*, 2014). Furthermore, water scarcity and
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41
42 93 other stress-related conditions suggest that a choice regarding energy cropping systems should
43
44 94 consider both (controversial) outcomes of achieving optimal productivity and minimizing
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46 95 environmental burdens.

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48
49 96 Using a Life Cycle Assessment (LCA) approach, this study aimed to assess the environmental
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51 97 burdens related to the agronomic management of different energy crops in a Mediterranean
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53 98 region to support cropping system choices and agricultural land-use planning. Specifically,
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56 99 the objectives were to (i) compare perennial vs annual crops and irrigated vs rainfed crops in
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58 100 terms of their environmental implications; (ii) identify the main hot spots among adopted

101 agronomic practices that might be responsible for environmental impacts and, as such, might
102 provide useful information to better address choices for farmers and policy makers; and (iii)
103 analyse environmental burdens considering the trade-off with crop productivity considering a
104 dynamic production perspective. With regard to the latter, we consider the needs of achieving
105 satisfactory productivity levels and of limiting natural resources exploitation setting up different
106 agronomic scenarios characterized by increasing use of certain technical inputs and yield
107 obtained by each crop.

108 In the light of this perspective, this study is one of the first attempts at examining the
109 environmental burdens related to progressive increase of product - simulating a yield increase
110 by a unit (tonne) from time to time and considering three alternative scenarios to the status
111 quo - in each energy crop considered in terms of farming and land choices in a complex context,
112 such as the Mediterranean region.

113 The LCA analysis was focused on sorghum (*Sorghum vulgare* Pers.), giant reed (*Arundo donax*
114 L.), milk thistle (*Silybum marianum* (L.) Gaertn) and cardoon (*Cynara cardunculus* L. var.
115 *altilis* D.C.) cultivation in Sardinia (Italy), and they are representative crops of relevant
116 agricultural systems in the Mediterranean area. Indeed, Sardinia can be considered a suitable
117 territory for crop residual biomass energetic exploitation (De Menna *et al.*, 2016) or energy
118 cropping system development owing to the occurrence of land abandonment and conversion
119 of arable land into grasslands even in areas served by irrigation infrastructures (Solinas *et al.*,
120 2015).

121

122 **2. Materials and methods**

123 The LCA approach is a comparative scientific method that identifies and quantifies
124 environmental and health damage that arise from the emissions produced and resources
125 exhausted throughout the entire life cycle of a given product (European Commission, 2010).

126 In this study, the life cycle procedure was performed based on the International Standards
127 Organization (ISO) guidelines (ISO, 2006a, b) using SimaPro 8.0.3.14 software (Goedkoop *et*
128 *al.*, 2013a, b).

129 The need to LCA standards was based on a growing awareness that LCA is considered a useful
130 methodological in individuating environmental issues into the standardized framework (ISO
131 14001) of environmental management systems (Ryding, 1999; Pryshlakivsky and Searcy,
132 2013).

133 Specifically, the main standards for LCA are ISO 14040 and ISO 14044. The former describes
134 the basic information and the framework that should characterized a correct LCA, the latter is
135 focused on requirements necessary for perform each LCA phases (Goal and Scope, Definition,
136 Inventory Analysis, Impact Assessment and Interpretation) providing guidelines to support its
137 implementation (ISO, 2006a, b).

138 These standards emphasise the iterative approach within and between LCA phases (i.e. each
139 step use results of the others) and it permits a satisfactory level of comprehensiveness,
140 transparency, and consistency of the obtained results (Finkbeiner *et al.*, 2006; Heijungs *et al.*,
141 2010). Although the ISO criteria provide a common language about used terms and key
142 methodological requirements (Finkbeiner, 2014), they show also a limited meaning or even
143 failed in case of scientific basis and/or data and formulas are not provided (Heijungs *et al.*,
144 2010).

145 SimaPro is one of the most software tool worldwide used to implement effectively a LCA of a
146 product or service, developed by PRé Consultants, in the Netherlands (Pieragostini *et al.*, 2012).

147 It enables to model a product system by user-friendly and flexible interface that retraces the
148 standardized LCA phases (Colangelo *et al.*, 2018). Basically, the software offers opportunity
149 for analyzing complex life cycles calculating a product system in a transparent
150 way and identifying the hotspots in all aspects of supply chain (Starostka-Patyk, 2015). Using

151 a highly efficient algorithm, SimaPro is able to deal with thousands of processes in a unique
152 calculation into a matrix inversion (Ciroth, 2012). It is also characterized by the availability of
153 various databases and the opportunity to combine this information through different assessment
154 methodologies in line with the product system modeling implemented in the user interface
155 (Herrmann and Moltesen, 2015).

156 *2.1 Functional unit and system boundaries*

157 In this study, the functional unit is the cultivated land (one hectare of land) which was chosen
158 to maintain agricultural production while reducing land-use intensity to minimize
159 environmental burdens per area and per unit of time (Nemecek *et al.*, 2011, 2015). Consistent
160 with this goal, this functional unit enables to highlight the environmental implications of
161 biomass energy crops at farm and land scales. Indeed, set-up production inputs and agricultural
162 land allocation - that together might be the cause and effect of environmental burdens - play a
163 strategic role in the choices of farmers and thus policy maker decisions that often are land-
164 based, such as the conversion of traditional food/feed cropping systems to partial or complete
165 biomass systems (Solinas *et al.*, 2015). However, cropping system planning is affected by
166 policy guidance at a land scale that in turn should also be developed considering the
167 environmental sustainability of energy crop cultivation to minimize natural resource
168 exploitation and to support farmers in maximizing their biomass yields. Using land as
169 functional unit can also enable the identification of a trade-off between environmental burdens
170 and productivity that arise from one hectare of land, which might be an added value that
171 enhances overall land management.

172 For this study, a “from cradle to field gate” approach was adopted to emphasize the
173 environmental implications of agricultural practices applied only to biomass energy crop
174 cultivation. Therefore, the LCA analysis neglected product transport operations and stopped
175 at product harvesting; the evaluation does not pertain to activities beyond the edge of the

176 field. Given that all considered crops were completely devoted to biomass production, no
177 allocation of impacts was necessary in this evaluation.

178 2.2 Inventory

179 Agricultural practices typically carried out by local farmers for each energy crop were
180 considered in the data collection for the LCA. The main production inputs generally
181 encompassing fertilizers, pesticides, seeds and machinery were included in the system
182 boundaries defined in the LCA analysis along with agricultural production (Audsley *et al.*,
183 2003; Mourad *et al.*, 2007; Nemecek *et al.*, 2014) (Fig. 1).

185 **Figure 1**

186
187 Because the data were not exhaustive, they were integrated with secondary data (i.e., the
188 upstream and downstream processes of crop cultivation) derived from international databases,
189 primarily the Ecoinvent 3 database. Since its first version, the purpose of Ecoinvent database
190 has mainly been to provide a set of life cycle inventory data - concerning inter alia several
191 processes related to agriculture and renewable energy systems - in order to support evaluation
192 of environmental and socio-economic impacts owed to a product or a service (Frischknecht *et*
193 *al.*, 2005). The quality and robustness of data included in Ecoinvent play an essential role in a
194 LCA study (Pascual-Gonzalez *et al.* 2016). Indeed, consistent and coherent of each dataset is
195 a basic requirement to facilitate the implementation of LCA analysis and to strengthen
196 reliability and consensus of results (Frischknecht *et al.*, 2007). For the reasons set out above,
197 all data undergo a peer review process to ensure their quality and reliability before being
198 included in the Ecoinvent database (Pascual-Gonzalez *et al.* 2016).

199 The structure of the Ecoinvent 3 database is characterized by the basic building blocks (life
200 cycle inventory datasets), namely both the individual unit processes of human activities and

201 their exchanges with the environment (Weidema *et al.*, 2013). This database enables to show
202 two relevant aspects with respect to a certain process: i) all exchanges, namely inputs, co-
203 products and emissions in a single overview; ii) aggregation of life cycle inventory datasets or
204 life cycle impact assessment outputs through applying of system modeling, namely connecting
205 and allocating the unit processes in the basis of a specific set of rules (Wernet *et al.*, 2016). The
206 availability of unit process and data not only limited to Europe, but also from other geographical
207 regions entails an enhanced modeling of global supply chains and a more realistic impacts
208 assessment (Steubing *et al.*, 2016; Wernet *et al.*, 2016).

209 In this study, Ecoinvent 3 database was used in order to include in the evaluation processes
210 regarding technical inputs production (e.g. fertilizers, pesticides, seeds and seedlings) and
211 implementation of mechanical operations such as tillage, sowing, crop maintenance (e.g.
212 fertilization, weeding and irrigation) and harvesting. The data regard consumption of natural
213 resources, raw material, fuels, and electricity, heat production and emissions of chemicals to
214 environment.

215 Direct field measurements were carried out through long-term field trials on different crop
216 management systems (irrigated and rainfed) situated at two sites in Sardinia representative of
217 local agricultural practices and yield performances of the considered energy crops under
218 Mediterranean agro-climatic conditions (Table 1).

219 In the LCA analysis, the main field emissions (NO^- , NH_3 , N_2O and NO) were considered based
220 on mineral fertilizer typology and were expressed as a percentage of the total amount of fertilizer
221 applied and the emission factors reported in technical and scientific literature.

222 Specifically, NO_3^- emissions from urea were computed according to Díez-López *et al.* (2008)
223 and Wu *et al.* (2007), who analysed the effects of nitrate leaching from urea with and without

a nitrification inhibitor. The estimation of NO_3^- losses from ammonium nitrate was considered
59 225 based on Cameron *et al.* (2013), who provided a quantification of NO_3^- leaching under arable

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226 systems. Ammonia volatilization loss was computed following the European Monitoring and
227 Evaluation Programme (EMEP) emission factors (Hutchison *et al.*, 2016). The N₂O and NO
228 emissions were estimated according to the Product Category Rules (PCR) approach for arable
229 crops (EPD, 2016).

230

231 **Table 1**

232

233 Losses of phosphorous were not reported since they were considered negligible in the observed
234 sites. Pesticide emissions were included in the LCA analysis according to the approach in
235 Margni *et al.* (2002) and Schmidt Rivera *et al.* (2017), which is based on the behaviour of
236 pesticides in the air and their transfer between the soil and surface or ground waters, to evaluate
237 the toxic impacts on human health and ecosystems.

238 *2.3 Life cycle impact assessment*

239 Environmental burdens were evaluated by the ReCiPe method, which is the most developed
240 method according to the literature and the European Commission (Mota *et al.*, 2015).
241 Essentially, this method is the follow-up to the methodology for the trade-off between the
242 midpoint level approach of CML2 baseline 2000 and the endpoint level analysis of Eco-
243 indicator 99 one. Indeed, the first method evaluates the total amount of substance-equivalents
244 released or resource-equivalents exhausted that are related to some impact categories. The latter
245 analysis assesses the potential damage to specific areas of protection, namely, Human Health
246 (HH), Ecosystem Diversity (ED) (i.e., loss of biodiversity) and Resource Availability (RA) (i.e.,
247 abiotic resources depletion) (Goedkoop *et al.*, 2013c). Specifically, the life cycle impact
248 assessment (LCIA) of a certain product can be implemented on the basis of two methodological
249 approaches, namely the midpoint and the endpoint that provide environmental
250 indicators at different levels (European Commission, 2011). The midpoint are considered as a

251 point on the cause-effect chain between stressors and endpoints; in contrast, the latter are
252 physical elements which society establish as worthy of protection (e.g. such as human health,
253 ecosystem, and natural resources) (Bare and Gloria, 2008). On the basis of above, the main
254 purpose of ReCiPe is to harmonized the existing midpoint and endpoint approaches to make
255 easier the choice of the LCIA method (Goedkoop *et al.*, 2013c). Basically, the strength of this
256 method is its ability to connect the midpoint and the endpoint levels converting the former into
257 the latter through a set of endpoint characterization factors (Dong and Ng, 2014). The
258 aggregation of eighteen impact categories - reported in Table 2 - into only the three damage
259 categories mentioned above, facilitates results interpretation to the detriment of their
260 uncertainty. This method is also entails normalization (i.e. the relative magnitude of each impact
261 categories) and weighting (i.e. the relevance attributed to each damage categories) phase.
262 ReCiPe enables to express outputs through a single score that can be obtained by the
263 aggregation of results arisen from weighting phase (Itsubo, 2015). This analysis used a single
264 score ranking, "Ecopoints" (1 Ecopoint = one thousandth of the annual overall environmental
265 burden of an average European inhabitant) (PRÉConsultants, 2000).

267 **Table 2**

268
269 Each estimated environmental burden was expressed in annual equivalents. Scores for perennial
270 crops were calculated considering their lifetime average impacts (Fazio and Monti, 2011).

271 *2.4 Uncertainty analysis of LCA results*

272 A Monte Carlo analysis was performed to evaluate the uncertainty of the LCA outcomes. The
273 analysis was also implemented to test possible significant differences in terms of Ecopoints per
274 land unit when comparing the environmental burdens of each biomass energy crop.

276 SimaPro 8.0.3.14 software was employed to run the Monte Carlo simulation (Goedkoop *et al.*,
277 2013a,b). It was used at a 95% confidence interval, and 1000 reiterations were performed.
278 The analysis was performed comparing all considered crops.

279

280 **3. Results**

281 Two different sets of findings were calculated to provide detailed information on the
282 environmental burdens caused by cultivation of the studied annual and perennial energy crops.

283 The first group consists of all impact categories at a midpoint level, which is the total amount
284 of substance-equivalent released or resource-equivalent consumed. Both measures are classified
285 into the environmental themes to which they potentially contribute (Supplementary Material).

286 The latter group identifies the potential environmental damages derived from the emissions and
287 resources depletion at the endpoint level, namely, certain vulnerable targets (e.g., human health,
288 ecosystems and natural resources).

289 *3.1 Damage categories assessment*

290 The estimated single score for the endpoint assessment, expressed in Ecopoints, is reported in
291 Fig. 2. HH was the most affected damage category for each crop, with a contribution ranging
292 from 52% to 58%. The next most affected categories were ED and RA, which did not exceed
293 27% and 22%, respectively.

294

295 **Figure 2**

296

297 The findings at the endpoint level were consistent with the impact category analysis reported
298 in Figs. S1 and S2. Indeed, human toxicity and ecosystem quality were the most affected
299 environmental factors, although high emission levels impacting the ecological and human

300

301 toxicity categories do not necessarily mean high levels of damage. The overall environmental
burden related to one hectare of sorghum corresponded to 361 Ecopoints (i.e., the impact
equivalent to 0.36 EU inhabitants). Among the energy crops, relative to the sorghum
performance, the incidence of giant reed was 80% (288 Ecopoints) followed by milk thistle
(146 Ecopoints equal to 41%) and cardoon (138 Ecopoints equal to 38%). These results were
due to the implementation of some agricultural operations and input use, mainly irrigation and
fertilizers, and they were consistent with the impact category analysis (Fig. 3). These results
showed incidence of agricultural practices and production inputs on environmental burdens for
the considered crops. All crops were most affected by fertilizers that ranged from 37% to 75%,
although irrigation had the highest effect on the giant reed (50%). Among the rainfed crops, the
factor with the second largest impact was tillage (16%) for milk thistle and harvesting (19%)
for cardoon. Tillage operations for milk thistle showed a contribution 4 times greater than
tillage for cardoon.

Figure 3

An additional analysis focused on an environmental damage assessment with respect to a
marginal product variation in each crop through the development of four different scenarios.
The baseline scenario (BS) involved the traditional agronomic practices that were generally
used for every crop in Sardinia and that were also considered in this study. The other three
alternative scenarios (AS1, AS2 and AS3) assumed increases in yield equalling one, two and
three tonnes, respectively, modifying N input doses for the analysed crops given an equal use
of all the other production inputs. In other terms, productivity increase was handled as
progressive increase in yields (from time to time): if n is the yield in BS, then the yield in
AS1, AS2, and AS3 is equal to $n + 1t$, $n + 2t$, $n + 3t$, respectively. Specifically, the N quantity

326 increment of AS1 was hypothesized based on experimental measurements that represented the
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2 327 BSs of each crop. AS2 was developed by raising the N dose of AS1 by 50%, which in turn
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5 328 increased by 75% and was used for setting up AS3 (Table 3).
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7 329

8
9 **Table 3**

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12 331
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14 332 Setting up of the scenarios allows us to dispose of a measure reflecting the trade-off between
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17 333 productivity increase and environmental burdens into a dynamic perspective (progressive
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19 334 increase of marginal yield).

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21 335 All crops showed increasing damage values in terms of Ecopoints moving from BS to ASs (Fig.
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23
24 336 4). The overall environmental burden was raised more than proportionally with respect to each
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26
27 337 considered additional production level. The cardoon had the worst performances followed by
28
29 338 milk thistle since their increased rates were higher than the irrigated crops. This finding might
30
31 339 be explained considering the incidence of fertilizers that - as reported in Fig. 3 - was greater for
32
33
34 340 the rainfed crops than the other crops where irrigation had the most relevance. Since the unitary
35
36 341 product variation was considered modifying only for N-input dose, it is likely that the variation
37
38
39 342 in fertilizers affected the rainfed crop more than irrigated crops, therefore causing a relevant
40
41 343 Ecopoints variation. Specifically, the environmental burden of cardoon and milk thistle
42
43
44 344 increased by 32% and by 16%, respectively, concerning an additional one tonne production.
45

46 345

47
48 **Figure 4**

49 346

50
51 347
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53 348 The increase rate of cardoon and milk thistle continued to increase moving from AS2 to AS3
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56 349 (46% for cardoon and 30% for milk thistle). The performances of the giant reed and sorghum
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351 were lower than the previous species although their environmental damages sustained the
1
2 352 previous upward trend. Indeed, the giant reed caused incremental damage equal to 7% for the
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4 353 additional one tonne produced, and it increased 16% going from AS2 to AS3. The same values
5
6 354 were shown for sorghum in terms of the transition from BS to AS1 and from AS2 to AS3 (7%
7
8 355 and 15%, respectively). Among the damage categories, for all crops, HH and ED showed a
9
10 356 slight increase more than proportionally with respect to the RA category that therefore
11
12 357 decreased its incidence through each AS. The HH and ED performances might be due to the
13
14 358 increase in the N-input doses, which were used less by crops moving from BS to the different
15
16 359 ASs. The unexploited N-input part might be a pollution source, which might harm ED and
17
18 360 HH in the short and long run, respectively, whereas it might affect the RA less.
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23 361 *3.2 Uncertainty analysis results*

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25
26 362 To evaluate the uncertainty of the LCA outcomes, a Monte Carlo analysis was performed by
27
28 363 pair-to-pair comparison between each crop in terms of Ecopoints per land unit. The analysis
29
30 364 showed that sorghum, namely the most damaging crop, was significantly higher (by $\alpha = 0.10$)
31
32 365 compared to each of the others except for giant reed. In contrast, milk thistle revealed significant
33
34 366 difference only related to sorghum. Hence, it could not be considered a winning crop option
35
36 367 because probability of expecting milk thistle to be the least environmental damaging was not
37
38 368 significant. As regards the single damage categories, the Monte Carlo analysis highlighted that
39
40 369 the RA category showed highly significant differences by each comparison except for cardoon
41
42 370 vs milk thistle. The differences detected in ED were mostly significant except for comparisons
43
44 371 between the irrigated crops (i.e. sorghum vs giant reed) and the rainfed ones (i.e. cardoon vs
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46 372 milk thistle). Finally, no comparisons showed significant differences in the HH category.
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55 374 **4. Discussion**

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376 A LCA was applied in this study in order to evaluate environmental burdens of four energy
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2 377 crops in a Mediterranean region. We analysed irrigated and rainfed crop systems characterized
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5 378 by both annual and perennial crops in order to perform an environmental evaluation on the basis
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7 379 of different needs in terms of natural resources and land use. Furthermore, a trade-off between
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9 380 environmental burdens and crop yield was carried out in order to assess the variation of
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11 381 environmental burdens on the basis of possible increase of productivity. The main key findings
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13 382 suggest that LCA analysis detected no winning crop option - *i.e.*, a crop that shows the best
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15 383 environmental performances everywhere and in all categories - even though sorghum and
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17 384 cardoon are the most and the less impacting crop on environment, respectively. Then we found
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19 385 that environmental burdens tend to increase more proportionally than production level.
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22 386 Furthermore, the hot spots owed to agricultural management detected by LCA application are
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24 387 discussed in order to underline their main implications on natural resources exploitation from
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27 388 each crop and on energy crop systems planning.
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30 31 389 *4.1 Hot spots influencing environmental crop performance* 32

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34 390 Some clarifications need to be made in terms of describing the nature of the findings. The strong
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36 391 and various interactions occurring among site specific factors (*i.e.*, edaphic and climatic
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38 392 conditions, agro-techniques, resource availability and crop lifespan) did not enable us to obtain
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40 393 a unique crop performance in terms of environmental sustainability. In other terms, it was hard
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42 394 to identify a winning crop option from the environmental point of view. However, this
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44 395 prerogative is common to other LCA applications aimed at comparing environmental burdens
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46 396 among more energy crops since different studies detected that no crop showed the best (or the
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48 397 worst) in all environment categories under consideration (Fazio and Monti, 2011; González-
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50 398 García *et al.*, 2013; Cocco *et al.*, 2014; Solinas *et al.* 2015; Parajuli *et al.*, 2017). On
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53 399 the other hand, the LCA approach has limitations that might affect the accuracy of the results
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401 (Curran, 2013). It mainly depends on the lack of a well-defined procedure to encompass and
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2 402 estimate important site-specific factors (e.g., land-use change, carbon stock and soil quality)
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4 403 closely related to both agricultural management and environmental performance of cropping
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6 404 systems in the LCA analysis (Garrigues *et al.*, 2012; Goglio *et al.*, 2015; Nitschelm *et al.*, 2016).
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9 405 It is a given that biomass production is considerably affected by natural resource availability,
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12 406 which in turn is limited by both overexploitation and climate change effects (Speirs *et al.*, 2015).
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14 407 Specifically, this statement is even more applicable with respect to the Mediterranean region as
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16 408 it is already characterized by a shortage of natural resources (Allen *et al.*, 2013). Our study
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19 409 underlined the key role of irrigation for the giant reed and sorghum and the relevance of
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22 410 fertilizer use with respect to both rainfed and irrigated crops in terms of environmental burdens
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24 411 as is the case for progressive unitary product variation. These results suggested that the
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27 412 environmental performance of the giant reed might be enhanced by reducing nitrogen
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29 413 fertilization or by less intensive use of irrigation. Similar findings were detected by Fernando
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31 414 *et al.* (2018), although they highlighted that the possible reduction in N inputs might jeopardize
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34 415 crop yield and that the high impact in terms of water depletion is due to the water needs of the
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36 416 giant reed. However, as reported by Cosentino *et al.* (2014), the giant reed showed a high
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39 417 production level by enhancing its water-use efficiency with stressed irrigation treatments.
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41 418 Indeed, the deep root system of the giant reed enables water uptake from the deeper and moist
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44 419 soil layers and thus helps the plant to tolerate drought occurrence. In the same study on
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46 420 fertilization, it was found that N input might be reduced guaranteeing the achievement of a
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49 421 proper biomass production level because of a nitrogen-use efficiency improvement.
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51 422 Furthermore, the giant reed rhizome can accumulate nutrients and remobilize them to support
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53 423 the growing phase (Nassi o Di Nasso *et al.*, 2013). Hence, giant reed might be a suitable crop
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56 424 for tackling water scarcity and extreme soil conditions (e.g., salinity and
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58 425 nutrient availability) that generally characterize the Mediterranean region, specifically its
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426 marginal lands (Fagnano *et al.*, 2015; Alexopoulou *et al.*, 2015). However, as reported by Bosco
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2 427 *et al.* (2016), the environmental performance of the giant reed cultivated in marginal soil was
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5 428 worse than cultivation in fertile soil; although in both cases, the environmental burdens might
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7 429 be enhanced by acting on N fertilization management.

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10 430 The greater negative environmental performance of sorghum than that of the giant reed was
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12 431 basically due to its higher input requirements. The trade-off between biomass production and
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14 432 the environmental performance of sorghum appeared remarkable. On the one hand, the annual
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17 433 crop seems to be inherently adequate for intensive cropping systems. On the other hand, the
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19 434 achievement of a good yield requires high input management, which is the main cause of the
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22 435 considerable environmental burden. However, this annual irrigated crop was able to provide
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24 436 higher biomass production than the perennial crop with the available water supply being equal.

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27 437 The greater productivity of sorghum than that of the giant reed might be due to a more efficient
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29 438 use of intercepted photosynthetically active radiation. Specifically, the radiation-use efficiency
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31 439 for giant reed showed high values for only limited period throughout the growing crop cycle,
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34 440 whereas the same parameter for sorghum did not show much variation (Ceotto *et al.*, 2013).

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36 441 Furthermore, water scarcity could be responsible for a reduction in efficiency in the conversion
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39 442 of intercepted radiation by biomass, especially in the Mediterranean area (Garofalo *et al.*, 2011).

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41 443 However, sorghum is capable of attaining high biomass yields in well-drained and fertile soils,
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44 444 but it was found to also be productive under soil water deficit conditions (Cosentino *et al.*,
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46 445 2012a; Garofalo and Rinaldi, 2013; Sawargaonkar *et al.*, 2013). Depending on genotype, this
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48 446 crop is well suited to drought and stress conditions such as water deficit stress, it is versatile to
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51 447 soil properties, and it also shows salinity and alkalinity tolerance (Vasilakoglou *et al.*, 2011;
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53 448 Zegada-Lizarazu and Monti, 2012; Regassa and Mortmann, 2014). Sorghum also has an
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56 449 efficient N use response, implying the possibility of

450 limiting N fertilizer use without jeopardizing biomass production (Cosentino *et al.*, 2012a;
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2 451 Amaducci *et al.*, 2016) and minimizing the environmental load (Calviño and Messing, 2012).
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5 452 Some studies have emphasized that water and soil stress conditions and low or moderate input
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7 453 management do not substantially affect cardoon and milk thistle capacity in terms of biomass
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9 454 and bioenergy production (Gominho *et al.*, 2011; Mauromicale *et al.*, 2014; Afshar *et al.*,
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11 2015; Andrzejewska *et al.*; 2015). The yield differences are consistent with the results
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13 455 reported for Sardinia by Sulas *et al.* (2008) and Ledda *et al.* (2013), who highlighted that the
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15 456 lifespan of annual species might enable a high flexibility degree compared to perennial
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17 457 species in terms of being included in traditional cropping systems and in underutilized lands.
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19 458 However, the shortness of the life cycle of milk thistle is not a constraint for achieving higher
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21 459 productivity than cardoon, although the capital requirement for cardoon is greater than that for
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23 460 milk thistle. Nutrient availability was the main factor responsible for the environmental
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25 461 performances of both rainfed crops. Nevertheless, cardoon has promising biomass and energy
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27 462 yields, specifically with low and medium fertilization levels beyond which it did not show
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29 463 productivity variation in some cases (Ierna *et al.*, 2012). Furthermore, cardoon roots can use
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31 464 nutrients from deep soil layers and enrich the topsoil as root residue biomass (Francaviglia *et*
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33 465 *al.*, 2016). However, milk thistle is a competitive crop that tends to occupy the soil by
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35 466 removing other species through shading or competition for nutrients and water resources
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37 467 (Berner *et al.*, 2002; Khan *et al.*, 2009). Nonetheless, milk thistle showed a low to moderate
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39 468 demand for nutrients because of its capacity to adapt to poor quality soils (Karkanis *et al.*,
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41 469 2011).
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44 470 Leaving aside the specific incidence of technical inputs and agricultural operations required for
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46 471 each considered crop, we found that environmental burdens are sensitively high. This result
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48 472 suggests that energy crops in the Mediterranean area should not be handled as
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50 473 complementary to food crops and not necessarily be cultivated on underutilized lands.
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475 4.2 Implications on farming systems

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2 476 Biomass production from dedicated energy crops is expected to play a strategic role as
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5 477 bioenergy sources into the future (Krasuska *et al.*, 2010; Cosentino *et al.*, 2012b). Hence, an
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7 478 increase in biomass per unit of land will be necessary to satisfy energy and food demands and
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10 479 to mitigate climate change (Bentsen and Felby, 2012). This fact implies that energy cropping
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12 480 systems are capital intensive, and we built LCA inventories considering this perspective.
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14 481 However, we found that environmental burdens are substantial, and they might dramatically
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17 482 increase the number of farmers who have to obtain higher yields than the yields they generally
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19 483 achieve. Our findings emphasize the absolute necessity of contextualizing the choice of energy
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22 484 crops, specifically in terms of cropping systems and land allocation. Well- defined spatio-
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24 485 temporal boundaries and well-contextualized data should be deemed a key step to better
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27 486 understanding both complicated interactions and the mutual effects that might occur among
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29 487 food security, bioenergy and resource management (Kline *et al.*, 2017). However, some energy
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32 488 crops showed a capacity for adaptation in terms of resources and land availability; thus,
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34 489 choosing suitable agricultural management and species should be site specific to maximize
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36 490 yields and minimize inputs and land-use competition (Zegada-Lizarazuet *et al.*, 2010; Kline *et*
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39 491 *al.*, 2017). Hence, a bioenergy production system should be set up considering site specificity
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41 492 to optimize agricultural management and land-use efficiency and to safeguard natural resources
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44 493 and the traditional farming system (Zegada-Lizarazu *et al.*, 2013). Moreover, rational strategies
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46 494 aimed at guaranteeing sustainability from a long-term perspective should be based on
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49 495 combining the use of biomass produced by more areas following a cropping system approach.
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51 496 Potentially, this strategy would enable biomass to be obtained from both fertile and marginal
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53 497 lands, reducing the risk of competition in land use between energy and food/feed crops -
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56 498 mainly typical of fertile lands - and at the same time
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58 499 optimizing the possibility to achieve high income production (Bosco *et al.*, 2016).
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500 Furthermore, the introduction or adoption of energy crops within cropping system planning and
501 land allocation raises different issues for which farmers and policy makers - the latter called to
502 support sustainability of the sector overcoming the main bottlenecks that affect it - cannot
503 disregard. It must be emphasized, however, that LCA is not a predictive tool for the middle to
504 long term; thus, the results are suitable for policy makers to use for only short-term decisions
505 (Arodudu, 2017). First, the practice of irrigated energy crops can reduce the amount of land
506 used even though they result in higher environmental burdens. Given that land allocation is one
507 of the main variables that affect a farmer's choice, higher costs and environmental burdens
508 related to irrigated crops might be overcome by the higher efficiency in land use (or in water
509 use). Basically, a more efficient use of land and technical inputs in the disposability of farmers
510 might both reduce costs and environmental burdens due to reduction of wastes, irrigation water
511 *in primis*.

512 Second, the irrigated (rainfed) annual energy crop was found to have a greater impact from an
513 environmental point of view than that of the irrigated (rainfed) perennial crop. However, a
514 farmer's behaviour might be more influenced by the perspective of the time of investment.
515 Specifically, the introduction of an annual crop might be based on a short-term decision that
516 does not necessarily force the farmer to abandon own cropping system planning. In contrast,
517 the adoption of perennial energy crops obligates a switch from a given (food/feed) cropping
518 system to another (energy) system. This long-term perspective suggests some policy
519 implications such as perennial energy crop cultivation in abandoned lands.

520 Finally, we found that environmental burdens increase more proportionally than yield in all
521 considered crops. In our opinion, this important issue represents a novel contribution into the
522 scientific debate arisen from this study because it basically provides a measure of the trade-off
523 between the controversial needs of achieving satisfactory yields and of guaranteeing
524 application of eco-friendly agricultural practices (given a technological horizon).

525 The linkage between a possible increase in energy crop yield and environmental burdens might
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2 526 play a crucial role with respect to crop system planning and land allocation. Additional research
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5 527 might provide a measure of how much biomass production could increase given a certain level
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7 528 of burden. For example, it might be a helpful tool for assessing the maximum quantity of
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10 529 produced biomass in the presence of a given threshold in terms of the environmental burdens
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12 530 produced, especially considering the possibility that normative constraints might be introduced
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14 531 into Mediterranean agriculture in the future.

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18 533 **5. Conclusions**

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22 534 The findings stress the difficulty of denoting a unique crop performance from environmental
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24 535 perspective. We found that performances vary not only according to crop and to implementation
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27 536 of irrigation (irrigated crops show higher burdens than rainfed ones), but also according to level
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29 537 of inputs supplied (e.g., relevance of fertilizers in affecting burdens) and to productivity
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31 538 (environmental burdens increase more proportionally than yield in all considered crops). Hence,
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34 539 the overall LCA results should be interpreted with caution since they might not properly
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36 540 consider the influence of edaphic, climatic conditions, crop inputs requirement and, as a
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39 541 consequence, agricultural management on environmental performances and potential biomass
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44 543 However, findings suggest that choice of energy crops would be contextualized on the basis of
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46 544 cropping systems and land allocation approaches. Theoretically, selection of crops according
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49 545 to the specific context would allow to exploit both fertile and marginal lands for producing
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51 546 biomass. This would enable to optimize agricultural management and land-use efficiency and
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53 547 safeguarding natural resources and the traditional farming. For example, environmental burdens
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56 548 related to irrigated crops might be overcome by the higher efficiency
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58 549 in land and/or water use.

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550 In conclusion, more research – specifically using a LCA approach- need to be done in order to
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2 551 opportunely support farmers and makers for short-term decisions since the introduction or
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4 552 adoption of energy crops within cropping system planning and land allocation raises thorny
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7 553 issues that cannot be neglected.
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29 562

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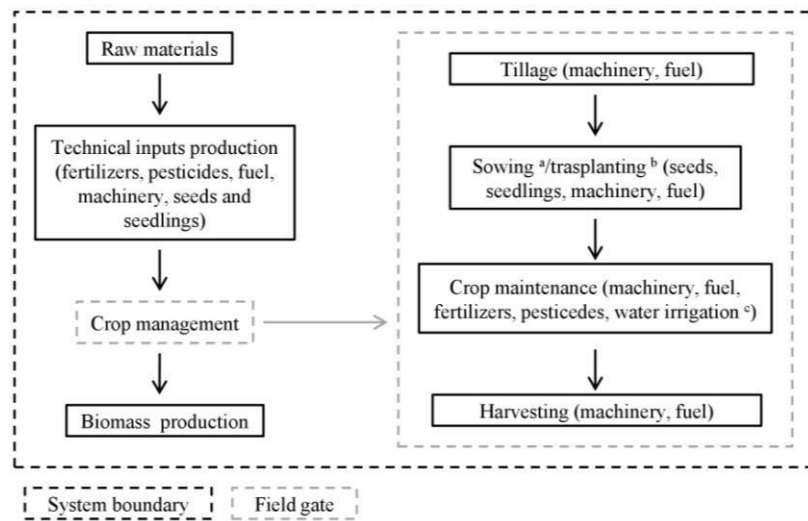


Fig. 1 Flow chart of analysed processes. The system boundary on the land basis (black dotted line) included both upstream steps and typical agricultural processes (grey dotted line) for the considered crops.

^a: Sorghum, milk thistle and cardoon; ^b: Giant reed; ^c: Sorghum and giant reed.

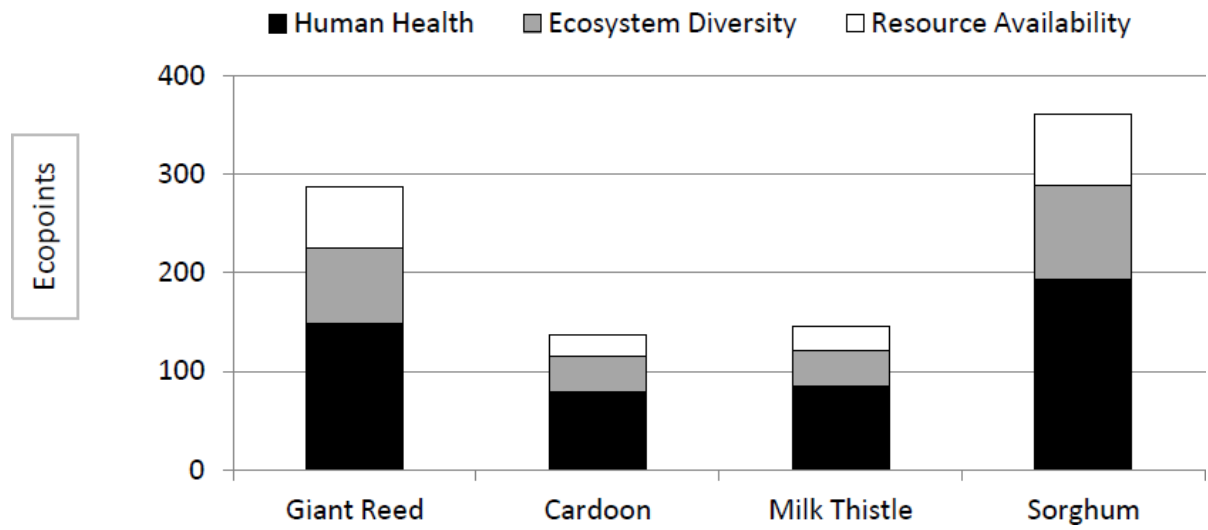


Fig. 2 Ecopoints on land basis (1 Ecopoint = one thousandth of the annual environmental burdens of average European inhabitant, Ecoindicator 99).

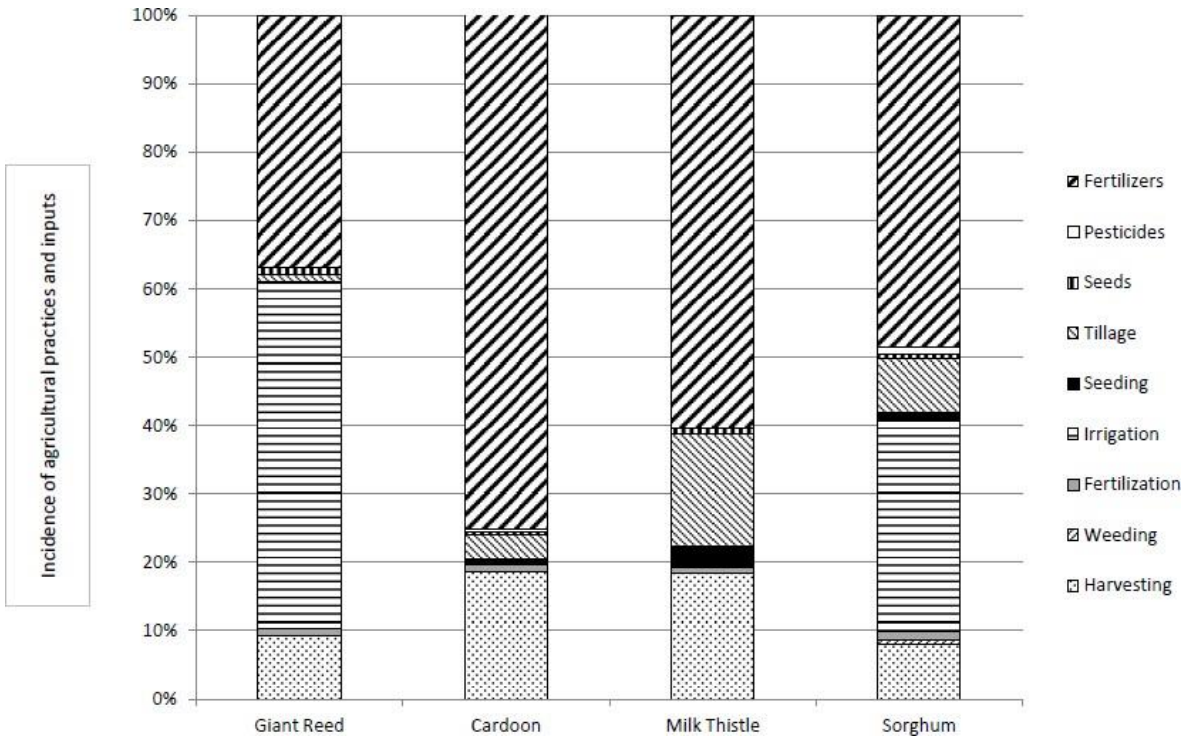


Fig. 3 Incidence (%) of agricultural operations and inputs on total Ecopoints for each crop - land basis (ha).

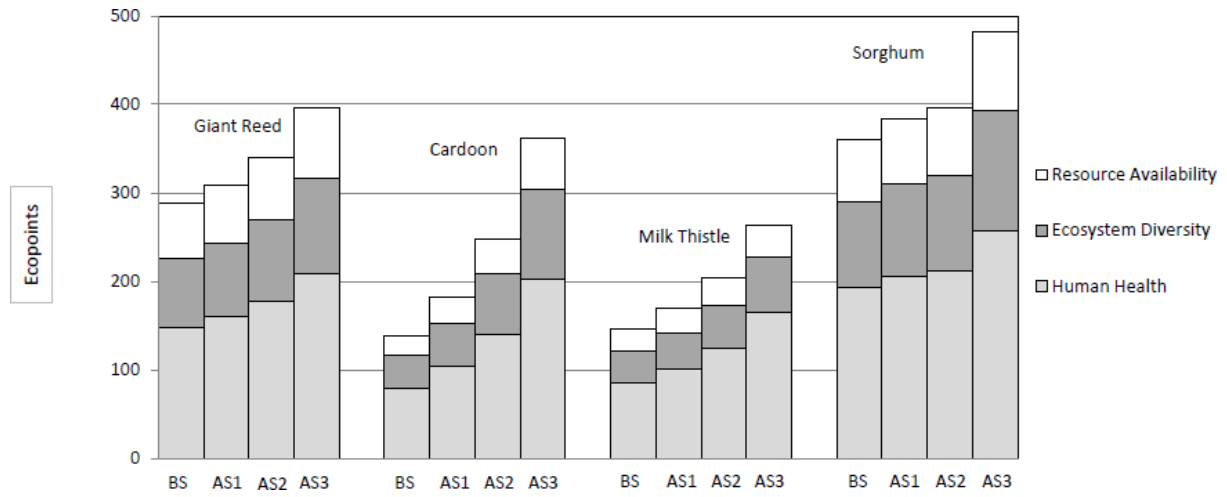


Fig. 4 Damages categories assessment of BS and ASs for each crops in terms of Ecopoints

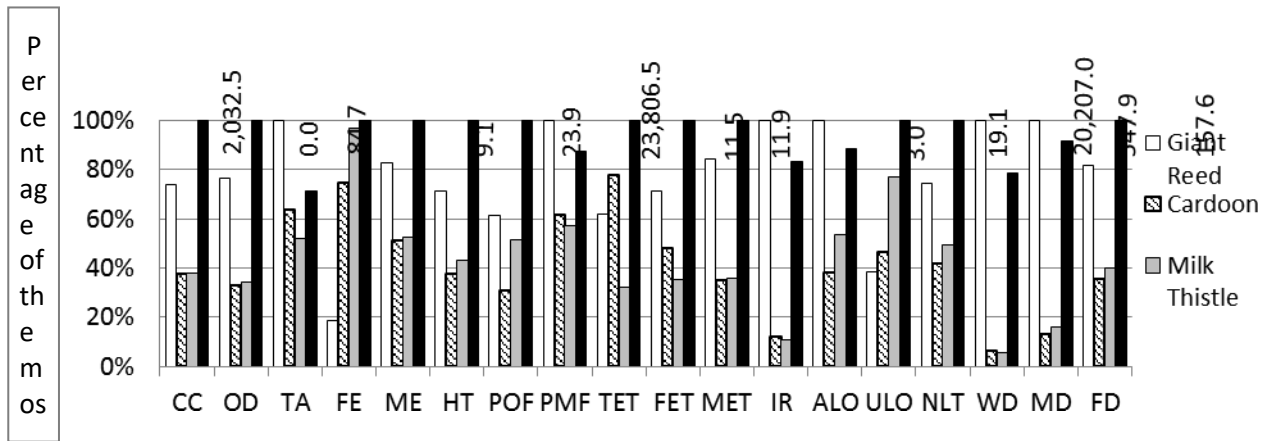


Fig. S1 Characterization on the most impacting scenario on land basis (ReCiPe method). The values are expressed as percentage of the most impacting scenario in each category (i.e. Sorghum = 100% in all the considered impact categories apart from the TA, PMF, IR, ALO, WD and MD categories where Giant Reed = 100%). The standardized values in kg of substance-equivalents for all impact categories except ALO and ULO (m²a), NLT (m²) and WD (m³) are reported on top of the histograms; the absolute values are referred to the impacts of the most impacting scenario. See Table 2 for abbreviation details.

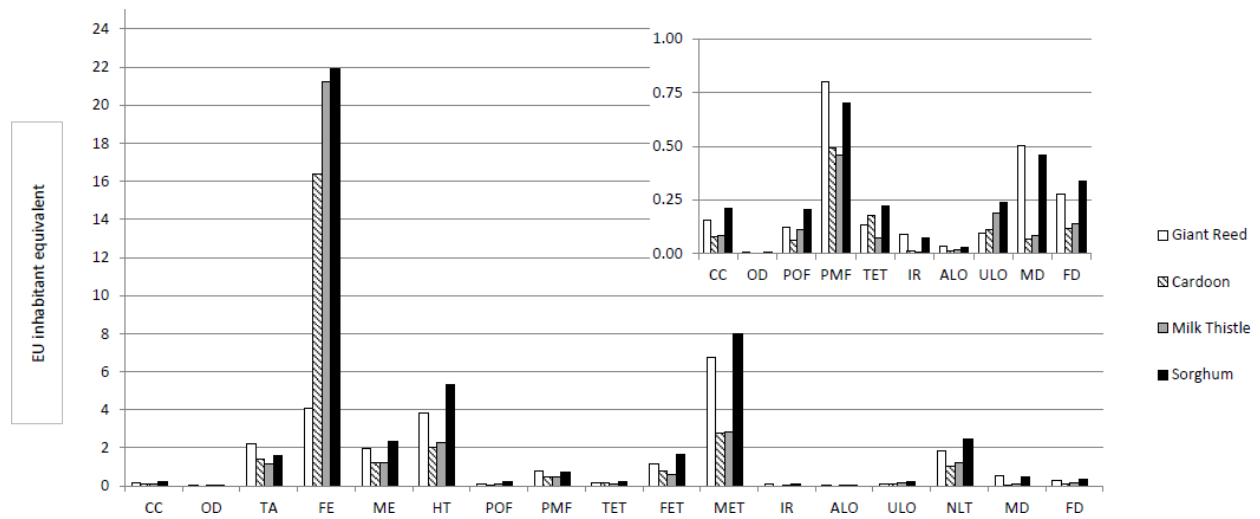


Fig. S2 Normalized impacts per unit land - EU inhabitant equivalent. The histograms on the top report the normalized values range from 0 to 1 for all categories which are not clear in the main graph. See Table 2 for abbreviation details.

Table 1 Energy crops key characteristics

Crops	Crop cycle duration (years)	Considered crop cycles (n.)	Average annual rainfall (mm)*	Average annual irrigation (mm) *	Average annual yield (Mg·ha ⁻¹ (DM)**)
<i>Giant Reed</i>	12	1	449	578	10.4
<i>Cardoon</i>	5	1	631	0	8.9
<i>Milk Thistle</i>	1	5	573	0	16.2
<i>Sorghum</i>	1	4	127	425	25.0

*: mean value referred to crops lifespan.

**: Dry Matter.

Table 2 The main impact categories based on ReCiPe method

Impact categories	Abbr.	Unit-equivalent
Climate Change	CC	kg CO ₂ eq
Ozone Depletion	OD	kg CFC-11 eq
Terrestrial Acidification	TA	kg SO ₂ eq
Freshwater Eutrophication	FE	kg P eq
Marine Eutrophication	ME	kg N eq
Human Toxicity	HT	kg 1,4-DB eq
Photochemical Oxidant Formation	POF	kg NMVOC
Particulate Matter Formation	PMF	kg PM10 eq
Terrestrial Ecotoxicity	TET	kg 1,4-DB eq
Freshwater Ecotoxicity	FET	kg 1,4-DB eq
Marine Ecotoxicity	MET	kg 1,4-DB eq
Ionising Radiation	IR	kBq U235 eq
Agricultural Land Occupation	ALO	m ² a
Urban Land Occupation	ULO	m ² a
Natural Land Transformation	NLT	m ²
Water Depletion	WD	m ³
Metal Depletion	MD	kg Fe eq
Fossil Depletion	FD	kg oil eq

Source: Goedkoop *et al.*, 2013c

Table 3 Baseline (BS) and alternative scenarios (AS) description

Species/Fertilizer/Title NP	BS	AS1	AS2	AS3
N input (kg ha ⁻¹ yr ⁻¹)				
Giant Reed				
Diammonium phosphate (18-46) *	5	7	10	15
Urea (46)	84	101	126	170
Cardoon				
Urea (46)	57	96	155	258
Milk Thistle				
Diammonium phosphate (18-46)	36	54	80	126
Sorghum				
Diammonium phosphate (18-46) **	36	36	36	36
Ammonium nitrate (26)	74	94	124	177

*: it is used only the first year.

**: the fertilizer dose is not modified depending on the different scenarios.

Supplementary material

[Click here to download Supplementary material for on-line publication only: Supplementary Material.docx](#)