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.

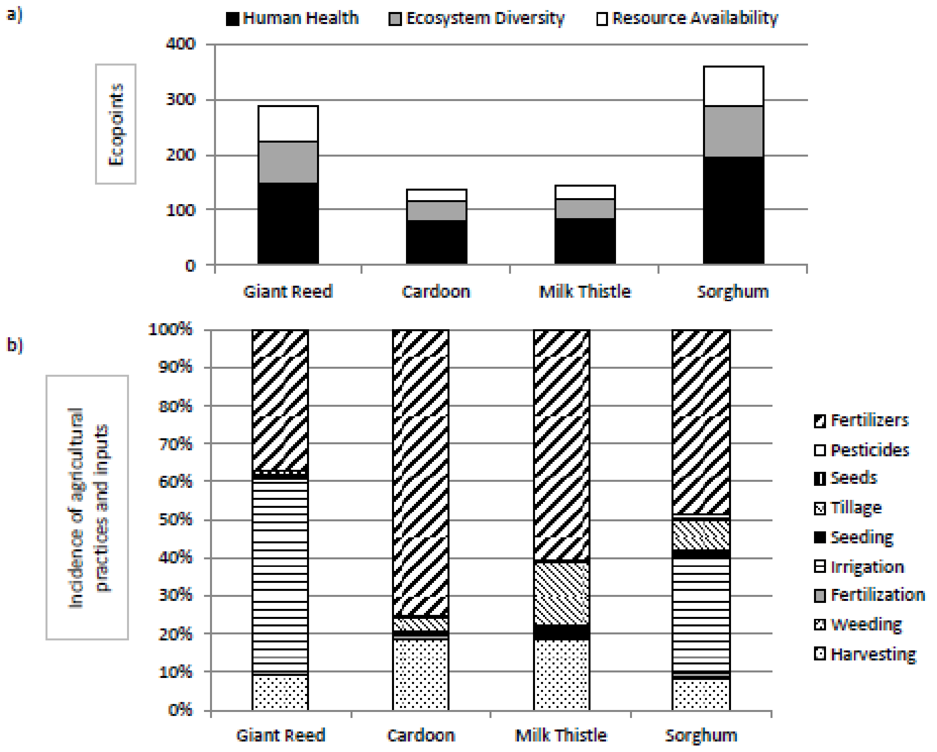
Irrigated (rainfed) annual crops are more damaging than the respective perennials.

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.

Graphical Abstract



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).

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

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Abstract

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

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

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

1. Introduction

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

In Mediterranean region, energy cropping systems have also been planned as alternatives to food production on lands typically covered by food/feed crops, thus avoiding the risk of additional lands being abandoned in some cases (Ledda *et al.*, 2013; Cocco *et al.*, 2014). Indeed, certain lands have been abandoned owing to the economic crisis that affected valuablefood production, but these areas are far from being unproductive. On the other hand, energy crops have also been introduced on lands unsuitable for food production (e.g. marginal and degraded lands) precisely because these biomass crops are able to grow under stress conditions (Allen *et al.*, 2014). In these cases, the “food versus fuel” might be a false dilemmabecause energy crops are not a conflicting factor (Strapasson *et al*., 2017) whereas, vice-versa, introduction of these crops can worsen this controversial issue where biomass energy occupy lands characterized by high food productivity (Miyake *et al.*, 2015). This dilemma should not be considered an issue merely restricted by the land competition, since land is an extremely dynamic and multifunctional resource, the use of which is strongly affected by a set of complicated interactions (Tomei and Helliwell, 2016).

In the unproductive lands, crops that require a low amount of inputs are cultivated, or the inputs applied should be increased to achieve profitable energy crop production (Fernando *et al.*, 2015; Schmidt *et al.*, 2015; Bosco *et al.*, 2016). In the fertile lands, cultivation is generallypractised more intensively and hardly concurs in exploitation of natural resources, such as water, *in primis*, especially in a climate change context (Dono *et al*., 2013a; 2013b). However, intensification of input use and adoption of new techniques may still have negative environmental consequences (Don *et al.*, 2012). At the same time, increasing productivity might contrast with the needs of safeguarding biodiversity and natural resources and of mitigating climate change (Bagley *et al.*, 2014; Immerzeel, *et al.*, 2014). Furthermore, water scarcity and other stress-related conditions suggest that a choice regarding energy cropping systems should consider both (controversial) outcomes of achieving optimal productivity and minimizing environmental burdens.

Using a Life Cycle Assessment (LCA) approach, this study aimed to assess the environmental burdens related to the agronomic management of different energy crops in a Mediterranean region to support cropping system choices and agricultural land-use planning. Specifically, the objectives were to (i) compare perennial vs annual crops and irrigated vs rainfed crops in terms of their environmental implications; (ii) identify the main hot spots among adopted agronomic practices that might be responsible for environmental impacts and, as such, might provide useful information to better address choices for farmers and policy makers; and (iii) analyse environmental burdens considering the trade-off with crop productivity considering a dynamic production perspective. With regard to the latter, we consider the needs of achieving satisfactory productivity levels and of limiting natural resources exploitation setting up different agronomic scenarios characterized by increasing use of certain technical inputs and yield obtained by each crop.

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

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

2. Materials and methods

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

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

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

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

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

SimaPro is one of the most software tool worldwide used to implement effectively a LCA of a product or service, developed by PRé Consultants, in the Netherlands (Pieragostini *et al.*, 2012). It enables to model a product system by user-friendly and flexible interface that retraces the standardized LCA phases (Colangelo *et al.*, 2018). Basically, the software offers opportunity for analyzing complex life cycles calculating a product system in a transparent way and identifying the hotspots in all aspects of supply chain (Starostka-Patyk, 2015). Using a highly efficient algorithm, SimaPro is able to deal with thousands of processes in a unique calculation into a matrix inversion (Ciroth, 2012). It is also characterized by the availability of various databases and the opportunity to combine this information through different assessment methodologies in line with the product system modeling implemented in the user interface (Herrmann and Moltesen, 2015).

2.1 Functional unit and system boundaries

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

For this study, a “from cradle to field gate” approach was adopted to emphasize the environmental implications of agricultural practices applied only to biomass energy crop cultivation. Therefore, the LCA analysis neglected product transport operations and stopped at product harvesting; the evaluation does not pertain to activities beyond the edge of the field. Given that all considered crops were completely devoted to biomass production, no allocation of impacts was necessary in this evaluation.

2.2 Inventory

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

Figure 1

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

The structure of the Ecoinvent 3 database is characterized by the basic building blocks (life cycle inventory datasets), namely both the individual unit processes of human activities and their exchanges with the environment (Weidema *et al*., 2013). This database enables to show two relevant aspects with respect to a certain process: i) all exchanges, namely inputs, co-products and emissions in a single overview; ii) aggregation of life cycle inventory datasets or life cycle impact assessment outputs through applying of system modeling, namely connecting and allocating the unit processes in the basis of a specific set of rules (Wernet *et al*., 2016). The availability of unit process and data not only limited to Europe, but also from other geographical regions entails an enhanced modeling of global supply chains and a more realistic impacts assessment (Steubing *et al*., 2016; Wernet *et al*., 2016).

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

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

In the LCA analysis, the main field emissions (NO_3^-, NH_3, N_2O and NO) were considered based on mineral fertilizer typology and were expressed as a percentage of the total amount offertilizer applied and the emission factors reported in technical and scientific literature.

Specifically, NO_3^- emissions from urea were computed according to Díez-López *et al.* (2008) 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 based on Cameron *et al.* (2013), who provided a quantification of NO_3^- leaching under arable systems. Ammonia volatilization loss was computed following the European Monitoring and Evaluation Programme (EMEP) emission factors (Hutchison *et al*., 2016). The N_2O and NO emissions were estimated according to the Product Category Rules (PCR) approach for arable crops (EPD, 2016).

Table 1

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

2.3 Life cycle impact assessment

Environmental burdens were evaluated by the ReCiPe method, which is the most developed method according to the literature and the European Commission (Mota *et al.*, 2015). Essentially, this method is the follow-up to the methodology for the trade-off between the midpoint level approach of CML2 baseline 2000 and the endpoint level analysis of Eco-indicator 99 one. Indeed, the first method evaluates the total amount of substance-equivalents released or resource-equivalents exhausted that are related to some impact categories. The latter analysis assesses the potential damage to specific areas of protection, namely, Human Health (HH), Ecosystem Diversity (ED) (i.e., loss of biodiversity) and Resource Availability (RA) (i.e., abiotic resources depletion) (Goedkoop *et al.*, 2013c). Specifically, the life cycle impact assessment (LCIA) of a certain product can be implemented on the basis of two methodological approaches, namely the midpoint and the endpoint that provide environmental indicators at different levels (European Commission, 2011). The midpoint are considered as a point on the cause-effect chain between stressors and endpoints; in contrast, the latter are physical elements which society establish as worthy of protection (e.g. such as human health, ecosystem, and natural resources) (Bare and Gloria, 2008). On the basis of above, the main purpose of ReCiPe is to harmonized the existing midpoint and endpoint approaches to make easier the choice of the LCIA method (Goedkoop *et al.*, 2013c). Basically, the strength of this method is its ability to connect the midpoint and the endpoint levels converting the former into the latter through a set of endpoint characterization factors (Dong and Ng, 2014). The aggregation of eighteen impact categories - reported in Table 2 - into only the three damage categories mentioned above, facilitates results interpretation to the detriment of their uncertainty. This method is also entails normalization (i.e. the relative magnitude of each impact categories) and weighting (i.e. the relevance attributed to each damage categories) phase. ReCiPe enables to express outputs through a single score that can be obtained by the aggregation of results arisen from weighting phase (Itsubo, 2015). This analysis used a single score ranking, "Ecopoints" (1 Ecopoint = one thousandth of the annual overall environmental burden of an average European inhabitant) (PRéConsultants, 2000).

Table 2

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

2.4 Uncertainty analysis of LCA results

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

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

3. Results

Two different sets of findings were calculated to provide detailed information on the environmental burdens caused by cultivation of the studied annual and perennial energy crops. The first group consists of all impact categories at a midpoint level, which is the total amount of substance-equivalent released or resource-equivalent consumed. Both measures areclassified into the environmental themes to which they potentially contribute (Supplementary Material). The latter group identifies the potential environmental damages derived from the emissions and resources depletion at the endpoint level, namely, certain vulnerable targets (e.g., human health, ecosystems and natural resources).

3.1 Damage categories assessment

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

Figure 2

The findings at the endpoint level were consistent with the impact category analysis reported in Figs. S1 and S2. Indeed, human toxicity and ecosystem quality were the most affected environmental factors, although high emission levels impacting the ecological and human 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 increment of AS1 was hypothesized based on experimental measurements that represented the BSs of each crop. AS2 was developed by raising the N dose of AS1 by 50%, which in turn increased by 75% and was used for setting up AS3 (Table 3).

Table 3

Setting up of the scenarios allows us to dispose of a measure reflecting the trade-off between productivity increase and environmental burdens into a dynamic perspective (progressive increase of marginal yield).

All crops showed increasing damage values in terms of Ecopoints moving from BS to ASs (Fig. 4). The overall environmental burden was raised more than proportionally with respectto each considered additional production level. The cardoon had the worst performances followed by milk thistle since their increased rates were higher than the irrigated crops. This finding might be explained considering the incidence of fertilizers that - as reported in Fig. 3 -was greater for the rainfed crops than the other crops where irrigation had the most relevance. Since the unitary product variation was considered modifying only for N-input dose, it is likely that the variation in fertilizers affected the rainfed crop more than irrigated crops, therefore causing a relevant Ecopoints variation. Specifically, the environmental burden of cardoon and milk thistle increased by 32% and by 16%, respectively, concerning an additional one tonne production.

Figure 4

The increase rate of cardoon and milk thistle continued to increase moving from AS2 to AS3 (46% for cardoon and 30% for milk thistle). The performances of the giant reed and sorghum were lower than the previous species although their environmental damages sustained the previous upward trend. Indeed, the giant reed caused incremental damage equal to 7% for the additional one tonne produced, and it increased 16% going from AS2 to AS3. The same values were shown for sorghum in terms of the transition from BS to AS1 and from AS2 to AS3 (7% and 15%, respectively). Among the damage categories, for all crops, HH and ED showed a slight increase more than proportionally with respect to the RA category that therefore decreased its incidence through each AS. The HH and ED performances might be due to the increase in the N-input doses, which were used less by crops moving from BS tothe different ASs. The unexploited N-input part might be a pollution source, which mightharm ED and HH in the short and long run, respectively, whereas it might affect the RA less.

3.2 Uncertainty analysis results

To evaluate the uncertainty of the LCA outcomes, a Monte Carlo analysis was performed by pair-to-pair comparison between each crop in terms of Ecopoints per land unit. The analysis showed that sorghum, namely the most damaging crop, was significantly higher (by $\alpha = 0.10$) compared to each of the others except for giant reed. In contrast, milk thistle revealedsignificant difference only related to sorghum. Hence, it could not be considered a winning crop option because probability of expecting milk thistle to be the least environmental damaging was not significant. As regards the single damage categories, the Monte Carlo analysis highlighted that the RA category showed highly significant differences by each comparison except for cardoon *vs* milk thistle. The differences detected in ED were mostly significant except for comparisons between the irrigated crops (i.e sorghum *vs* giant reed) and the rainfed ones (i.e. cardoon *vs* milk thistle). Finally, no comparisons showed significant differences in the HH category.

4. Discussion

A LCA was applied in this study in order to evaluate environmental burdens of four energy crops in a Mediterranean region. We analysed irrigated and rainfed crop systemscharacterized by both annual and perennial crops in order to perform an environmental evaluation on the basis of different needs in terms of natural resources and land use. Furthermore, a trade-off between environmental burdens and crop yield was carried out in order to assess the variation of environmental burdens on the basis of possible increase of productivity. The main key findings suggest that LCA analysis detected no winning crop option - *i.e.*, a crop that shows the best environmental performances everywhere and in all categories - even though sorghum and cardoon are the most and the less impacting crop on environment, respectively. Then we found that environmental burdens tend to increase more proportionally than production level.

Furthermore, the hot spots owed to agricultural management detected by LCA application are discussed in order to underline their main implications on natural resources exploitation from each crop and on energy crop systems planning.

4.1 Hot spots influencing environmental crop performance

Some clarifications need to be made in terms of describing the nature of the findings. The strong and various interactions occurring among site specific factors (i.e., edaphic and climatic conditions, agro-techniques, resource availability and crop lifespan) did not enable usto obtain a unique crop performance in terms of environmental sustainability. In other terms, it was hard to identify a winning crop option from the environmental point of view. However, this prerogative is common to other LCA applications aimed at comparing environmental burdens among more energy crops since different studies detected that no crop showed the best (or the worst) in all environment categories under consideration (Fazio and Monti, 2011; González-García *et al*., 2013; Cocco *et al*., 2014; Solinas *et al*. 2015; Parajuli *et al*., 2017). On the other hand, the LCA approach has limitations that might affect the accuracy of the results

(Curran, 2013). It mainly depends on the lack of a well-defined procedure to encompass and estimate important site-specific factors (e.g., land-use change, carbon stock and soil quality) closely related to both agricultural management and environmental performance of cropping systems in the LCA analysis (Garrigues *et al.*, 2012; Goglio *et al.*, 2015; Nitschelm *et al.*, 2016). It is a given that biomass production is considerably affected by natural resource availability, which in turn is limited by both overexploitation and climate change effects (Speirs *et al.*, 2015). Specifically, this statement is even more applicable with respect to the Mediterranean region as it is already characterized by a shortage of natural resources (Allen *etal.*, 2013). Our study underlined the key role of irrigation for the giant reed and sorghum and the relevance of fertilizer use with respect to both rainfed and irrigated crops in terms of environmental burdens as is the case for progressive unitary product variation. These results suggested that the environmental performance of the giant reed might be enhanced by reducing nitrogen fertilization or by less intensive use of irrigation. Similar findings were detected by Fernando *et al*. (2018), although they highlighted that the possible reduction in N inputs might jeopardize crop yield and that the high impact in terms of water depletion is due to the water needs of the giant reed. However, as reported by Cosentino *et al*. (2014), thegiant reed showed a high production level by enhancing its water-use efficiency with stressed irrigation treatments. Indeed, the deep root system of the giant reed enables water uptake fromthe deeper and moist soil layers and thus helps the plant to tolerate drought occurrence. In the same study on fertilization, it was found that N input might be reduced guaranteeing the achievement of a proper biomass production level because of a nitrogen-use efficiency improvement. Furthermore, the giant reed rhizome can accumulate nutrients and remobilize them to support the growing phase (Nassi o Di Nasso *et al.*, 2013). Hence, giant reed might bea suitable crop for tackling water scarcity and extreme soil conditions (e.g., salinity and nutrient availability) that generally characterize the Mediterranean region, specifically its marginal lands (Fagnano *et al.*, 2015; Alexopoulou *et al.*, 2015). However, as reported by Bosco *et al.* (2016), the environmental performance of the giant reed cultivated in marginal soil was worse than cultivation in fertile soil; although in both cases, the environmental burdens might be enhanced by acting on N fertilization management.

The greater negative environmental performance of sorghum than that of the giant reed was basically due to its higher input requirements. The trade-off between biomass production and the environmental performance of sorghum appeared remarkable. On the one hand, the annual crop seems to be inherently adequate for intensive cropping systems. On the other hand, the achievement of a good yield requires high input management, which is the main cause of the considerable environmental burden. However, this annual irrigated crop was able to provide higher biomass production than the perennial crop with the available water supply beingequal. The greater productivity of sorghum than that of the giant reed might be due to a more efficient use of intercepted photosynthetically active radiation. Specifically, the radiation-use efficiency for giant reed showed high values for only limited period throughout the growing crop cycle, whereas the same parameter for sorghum did not show much variation (Ceotto *et al.*, 2013). Furthermore, water scarcity could be responsible for a reduction in efficiency in the conversion of intercepted radiation by biomass, especially in the Mediterranean area (Garofalo *et al.*, 2011). However, sorghum is capable of attaining high biomass yields in well-drained and fertile soils, but it was found to also be productive under soil water deficit conditions (Cosentino *et al.*, 2012a; Garofalo and Rinaldi, 2013; Sawargaonkar *et al.*, 2013). Depending on genotype, this crop is well suited to drought and stress conditions such as waterdeficit stress, it is versatile to soil properties, and it also shows salinity and alkalinity tolerance (Vasilakoglou *et al.*, 2011; Zegada-Lizarazu and Monti, 2012; Regassa and Mortmann, 2014). Sorghum also has an efficient N use response, implying the possibility of limiting N fertilizer use without jeopardizing biomass production (Cosentino *et al.*, 2012a; Amaducci *et al.*, 2016) and minimizing the environmental load (Calviño and Messing, 2012). Some studies have emphasized that water and soil stress conditions and low or moderate input management do not substantially affect cardoon and milk thistle capacity in terms of biomass and bioenergy production (Gominho *et al.*, 2011; Mauromicale *et al.*, 2014; Afshar *et al.*, 2015; Andrzejewska *et al.*; 2015). The yield differences are consistent with the results reported for Sardinia by Sulas *et al.* (2008) and Ledda *et al.* (2013), who highlighted that the lifespan of annual species might enable a high flexibility degree compared to perennial species in terms of being included in traditional cropping systems and in underutilized lands. However, the shortness of the life cycle of milk thistle is not a constraint for achieving higher productivity than cardoon, although the capital requirement for cardoon is greater than that for milk thistle. Nutrient availability was the main factor responsible for the environmental performances of both rainfed crops. Nevertheless, cardoon has promising biomass and energy yields, specifically with low and medium fertilization levels beyond which it did not show productivity variation in some cases (Ierna *et al.*, 2012). Furthermore, cardoon roots can use nutrients from deep soil layers and enrich the topsoil as root residue biomass (Francaviglia *et al.*, 2016). However, milk thistle is a competitive crop that tends to occupy the soil by removing other species through shading or competition for nutrients and water resources (Berner *et al.*, 2002; Khan *et al.*, 2009). Nonetheless, milk thistle showed a low to moderate demand for nutrients because of its capacity to adapt to poor quality soils (Karkanis *et al.*, 2011).

Leaving aside the specific incidence of technical inputs and agricultural operations required for each considered crop, we found that environmental burdens are sensitively high. This result suggests that energy crops in the Mediterranean area should not be handled as complementary to food crops and not necessarily be cultivated on underutilized lands.

4.2 Implications on farming systems

Biomass production from dedicated energy crops is expected to play a strategic role as bioenergy sources into the future (Krasuska *et al.*, 2010; Cosentino *et al.*, 2012b). Hence, an increase in biomass per unit of land will be necessary to satisfy energy and food demands and to mitigate climate change (Bentsen and Felby, 2012). This fact implies that energy cropping systems are capital intensive, and we built LCA inventories considering this perspective. However, we found that environmental burdens are substantial, and they might dramatically increase the number of farmers who have to obtain higher yields than the yields they generally achieve. Our findings emphasize the absolute necessity of contextualizing the choice of energy crops, specifically in terms of cropping systems and land allocation. Well- defined spatio-temporal boundaries and well-contextualized data should be deemed a key step to better understanding both complicated interactions and the mutual effects that might occur among food security, bioenergy and resource management (Kline *et al*., 2017). However, some energy crops showed a capacity for adaptation in terms of resources and land availability; thus, choosing suitable agricultural management and species should be site specific to maximize yields and minimize inputs and land-use competition (Zegada-Lizarazu*et al.*, 2010; Kline *et al*., 2017). Hence, a bioenergy production system should be set up considering site specificity to optimize agricultural management and land-use efficiency andto safeguard natural resources and the traditional farming system (Zegada-Lizarazu *et al.*, 2013). Moreover, rational strategies aimed at guaranteeing sustainability from a long-term perspective should be based on combining the use of biomass produced by more areasfollowing a cropping system approach. Potentially, this strategy would enable biomass to be obtained from both fertile and marginal lands, reducing the risk of competition in land use between energy and food/feed crops - mainly typical of fertile lands - and at the same time

optimizing the possibility to achieve high income production (Bosco *et al.*, 2016).

Furthermore, the introduction or adoption of energy crops within cropping system planning and land allocation raises different issues for which farmers and policy makers - the latter called to support sustainability of the sector overcoming the main bottlenecks that affect it - cannot disregard. It must be emphasized, however, that LCA is not a predictive tool for the middle to long term; thus, the results are suitable for policy makers to use for only short-term decisions (Arodudu, 2017). First, the practice of irrigated energy crops can reduce the amount of land used even though they result in higher environmental burdens. Given that landallocation is one of the main variables that affect a farmer's choice, higher costs and environmental burdens related to irrigated crops might be overcome by the higher efficiency in land use (or in water use). Basically, a more efficient use of land and technical inputs in thedisposability of farmers might both reduce costs and environmental burdens due to reduction of wastes, irrigation water *in primis*.

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

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

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

5. Conclusions

The findings stress the difficulty of denoting a unique crop performance from environmental perspective. We found that performances vary not only according to crop and to implementation of irrigation (irrigated crops show higher burdens than rainfed ones), but also according to level of inputs supplied (e.g., relevance of fertilizers in affecting burdens) and to productivity (environmental burdens increase more proportionally than yield in all considered crops). Hence, the overall LCA results should be interpreted with caution since they might not properly consider the influence of edaphic, climatic conditions, crop inputs requirement and, as a consequence, agricultural management on environmental performances and potential biomass production.

However, findings suggest that choice of energy crops would be contextualized on the basisof cropping systems and land allocation approaches. Theoretically, selection of crops according to the specific context would allow to exploit both fertile and marginal lands for producing biomass. This would enable to optimize agricultural management and land-use efficiency and safeguarding natural resources and the traditional farming. For example, environmental burdens related to irrigated crops might be overcome by the higher efficiency in land and/or water use.

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

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Figure 1
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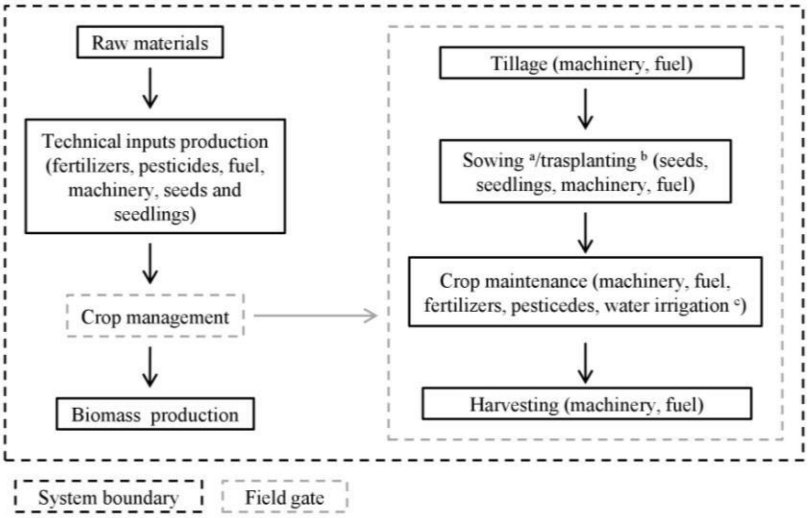

Fig. 1 Flow chart of analysed processes. The system boundary on the land basis (black dotted line) included both upstream steps and typical agricultural processes (grey dotted line) for the considered crops.

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

Figure 2
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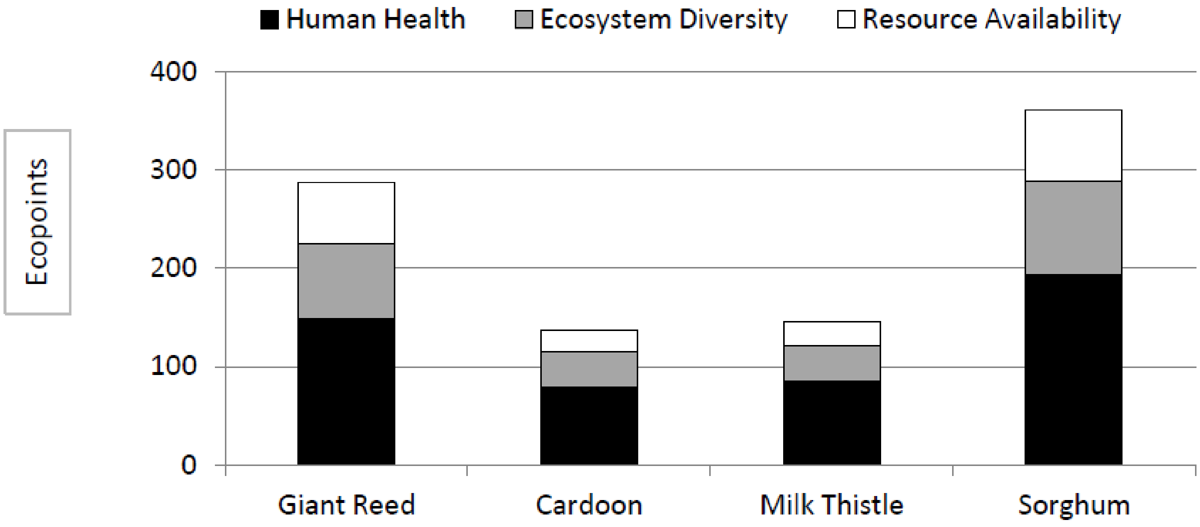

Fig. 2 Ecopoints on land basis (1 Ecopoint = one thousandth of the annual environmental burdens of average European inhabitant, Ecoindicator 99).

Figure 3
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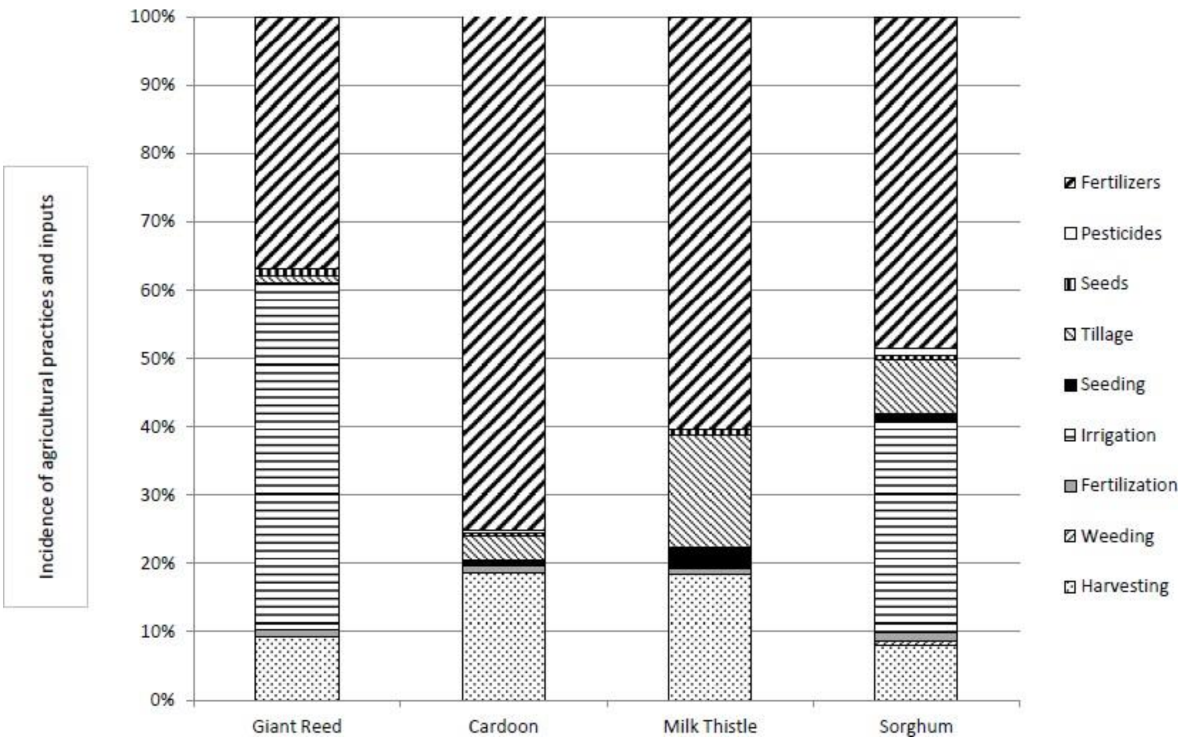

Fig. 3 Incidence (%) of agricultural operations and inputs on total Ecopoints for each crop - land basis (ha).

Figure 4
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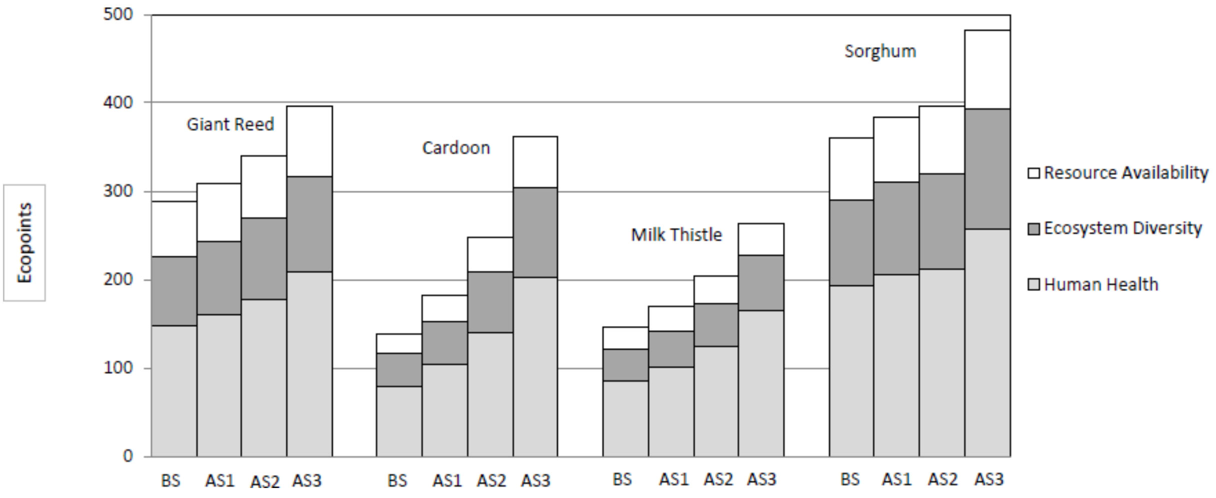

Fig. 4 Damages categories assessment of BS and ASs for each crops in terms of Ecopoints

Figure S1

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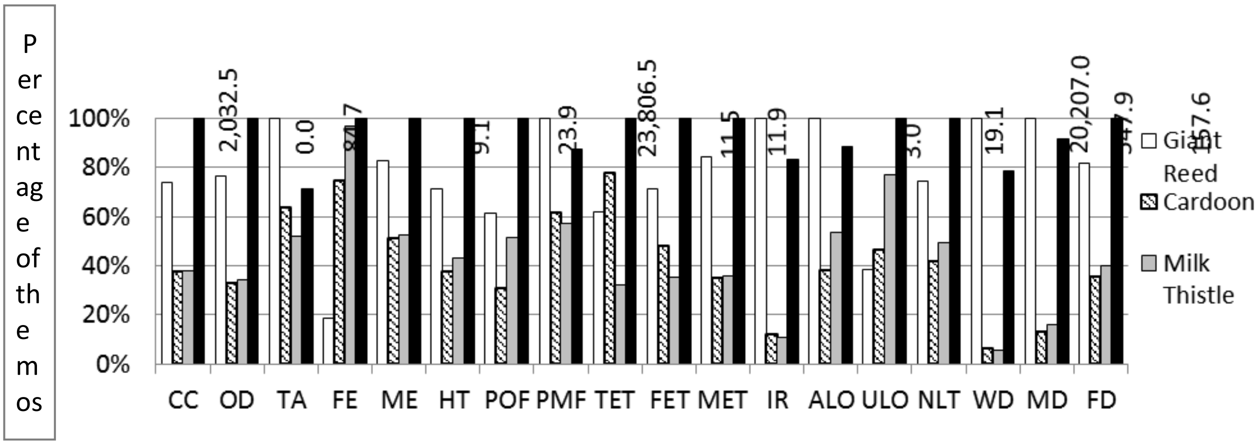

Fig. S1 Characterization on the most impacting scenario on land basis (ReCiPe method). The values are expressed as percentage of the most impacting scenario in each category (i.e. Sorghum = 100% in all the considered impact categories apart from the TA, PMF, IR, ALO, WD and MD categories where Giant Reed = 100%). The standardized values in kg of substance-equivalents for all impact categories except ALO and ULO (m^2a), NLT (m^2) and WD (m^3) are reported on top of thehistograms; the absolute values are referred to the impacts of the most impacting scenario. See Table 2 for abbreviation details.

Figure S2

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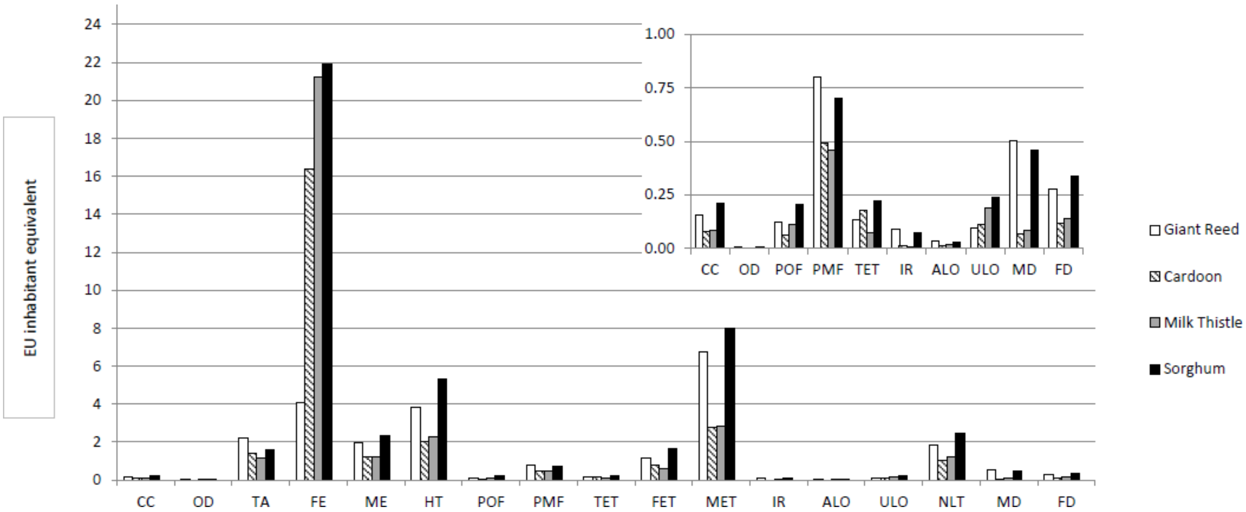

Fig. S2 Normalized impacts per unit land - EU inhabitant equivalent. The histograms on the top report the normalized values range from 0 to 1 for all categories which are not clear in the main graph. See Table 2 for abbreviation details.

Table 1

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 ($Mg \cdot ha^{-1}$ (DM)**)
Giant Reed	12	1	449	578	10.4
Cardoon	5	1	631	0	8.9
Milk Thistle	1	5	573	0	16.2
Sorghum	1	4	127	425	25.0

*: mean value referred to crops lifespan. **: Dry Matter.

Table 2

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^2a
Urban Land Occupation	ULO	m^2a
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

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