Energies **2014**, *7*, 6258-6281; doi:10.3390/en7106258

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

LCA Study of Oleaginous Bioenergy Chains in a Mediterranean Environment

Daniele Cocco [1], Paola A. Deligios [2,*], Luigi Ledda [2], Leonardo Sulas [3], Adriana Virdis [4] and Gianluca Carboni [4]

[1] Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Via Marengo 2, 09123 Cagliari, Italy; E-Mail: daniele.cocco@unica.it

[2] Department of Agriculture, University of Sassari, Viale Italia 39, 07100 Sassari, Italy; E-Mail: lledda@uniss.it

[3] National Research Council, Institute for the Animal Production System in Mediterranean Environment (CNR-ISPAAM), Traversa La Crucca 3, Località Baldinca, 07100 Sassari, Italy; E-Mail: l.sulas@cspm.ss.cnr.it

[4] Department of Crop Production, Agricultural Research Agency of Sardinia (AGRIS), Viale Trieste 111, 09123 Cagliari, Italy; E-Mails: avirdis@agrisricerca.it (A.V.); gcarboni@agrisricerca.it (G.C.)

* Author to whom correspondence should be addressed; E-Mail: pdeli@uniss.it; Tel.: +39-079-229-223; Fax: +39-079-229-222.

External Editor: Talal Yusaf

Received: 15 May 2014; in revised form: 8 September 2014 / Accepted: 23 September 2014 / Published: 29 September 2014

Abstract: This paper reports outcomes of life cycle assessments (LCAs) of three different oleaginous bioenergy chains (oilseed rape, Ethiopian mustard and cardoon) under Southern Europe conditions. Accurate data on field practices previously collected during a three-year study at two sites were used. The vegetable oil produced by oleaginous seeds was used for power generation in medium-speed diesel engines while the crop residues were used in steam power plants. For each bioenergy chain, the environmental impact related to cultivation, transportation of agricultural products and industrial conversion for power generation was evaluated by calculating cumulative energy demand, acidification potential and global warming potential. For all three bioenergy chains, the results of the LCA study show a considerable saving of primary energy (from 70 to 86 GJ·ha^{-1}) and greenhouse gas emissions (from 4.1 to 5.2 t CO_2·ha^{-1}) in comparison to power generation from fossil fuels, although the acidification potential of these bioenergy chains may be twice that of conventional power generation. In addition, the study highlights that land use changes due to the cultivation of the abovementioned crops reduce soil organic content and therefore worsen and increase greenhouse gas emissions for all three bioenergy chains. The study also demonstrates that the exploitation of crop residues for energy production greatly contributes to managing environmental impact of the three bioenergy chains.

Keywords: life cycle assessment (LCA); bioenergy chains; oilseed rape; Ethiopian mustard; cardoon

---

1. Introduction

World and EU biodiesel production is expected to increase in the near future because by 2020 a percentage of 10% (by energy basis) of automotive fuels must be substituted for biofuels (Directive 2009/28/EC) [1].

Energy crops include a large number of plant species that can be used to produce biofuels (ethanol, vegetable oil, biodiesel, chipped wood, pellets, *etc.*) for fuelling motor vehicles, heating systems and power generation plants [2]. Among energy crops, oleaginous species, in particular sunflower, soybean, oilseed rape, and palm oil are used worldwide for biodiesel production via transesterification of raw vegetable oils, but many other edible and non-edible species are under evaluation for vegetable oil and biodiesel production [3–5].

Oleaginous species are mainly considered for biodiesel production and many studies concerning the analysis of the biodiesel production process, the emissions of biodiesel fuelled engines as well as the overall biofuel production chain are available [6–9]. However, the raw vegetable oil, other than for biodiesel production, can also be directly used to produce heat in industrial or household boilers [10] and especially to produce power by means of diesel engines [11–15]. In particular, medium-speed diesel units (with power outputs up to 10–15 MW and conversion efficiencies of around 45%–47%) require only minor changes to be fuelled by vegetable oils due to their higher viscosity [16]. Replacing conventional fuels with vegetable oils can lead to lower exhaust gas emissions while maintaining the same conversion efficiency.

Although the oil crops sector is increasingly dominated by a great number of possible crops, only few crops are suitable, under a rainfed regime, for European Mediterranean-climate environments, due to the typical high temperatures and lack of rainfall during late spring and summer, precluding any significant summer cropping without irrigation [17,18]. Moreover, in areas where water is also in short supply (e.g., some Mediterranean countries), the question of whether water should be used to produce food rather than energy crops (e.g., maize) has been raised. Because the per unit-value of biomass is low compared with food, feed and fiber crops, production under minimal input is desirable for growers to profit from producing biomass [19].

Besides oilseed rape (*Brassica napus* L. var. *oleifera* DC.), new crops for Southern Europe have already been identified such as Ethiopian mustard (*Brassica carinata* A. Braun) [20] and cardoon (*Cynara cardunculus* var. *altilis* DC.) [21]. While oilseed rape and Ethiopian mustard are annual species, cardoon is a perennial one which means that sowing operation costs are included only for the planting year.

The above-mentioned bioenergy crops may allow different management practices that could, for example, reduce input use or increase soil cover, thus reducing soil erosion risks (e.g., cardoon being a perennial species). Furthermore, as alternative farming practices, new cropping systems involving feed/food and biomass production in one rotation can also be set up (e.g., oilseed rape and/or Ethiopian mustard in rotation with winter wheat). Innovative bioenergy chains can thus in some cases add to crop diversity and combine relative high yield with lower environmental pressures when compared to intensive food farming systems.

According to Cayuela *et al.* [22], an environmentally compatible bioenergy production could only be assessed by combining main crop yield with its by-products. Harvesting of oleaginous seeds produces a significant amount of agricultural residues (straw), which represent about 70%–90% of the total aboveground biomass weight. The straw is usually left in field but it represents about 65%–85% of the total aboveground biomass energy content. Moreover, the oil content of seeds is around 40%, and therefore the remaining 60% represents the oil production residue (oil press cake). In order to maximize the energy utilization of the cultivated biomass, the agricultural and industrial residues (straw and oil press cake) should be used to produce heat or power [23,24], allowing a more complete exploitation of the bioenergy crop. On the other hand, the different management of crop residues is relevant from an agronomic point of view and for soil fertility issues [25,26]. In fact, crop residues are rich in essential plant nutrients and their continuous removal adversely impacts on soil properties, soil organic matter dynamics, and water as well as crop production [27].

Life cycle assessment (LCA) is a tool widely used to assess the environmental impact of energy production from biomass and its methodology is currently standardized by the ISO 14040 guidelines [28,29] but some areas have been subjected to intense development in recent years [30,31].

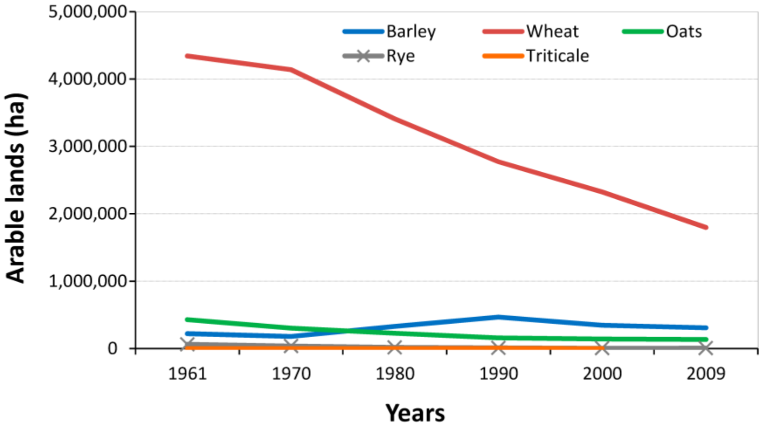
In particular, many recent LCA studies on bioenergy have pointed out that one of the most critical issues concerns the environmental impact of land use changes (LUC) [32–34]. Moreover, the impact related to LUC is usually classified into direct land use change (d-LUC) and indirect land use change (i-LUC). The former takes into account the environmental impact (in particular, the soil organic carbon (SOC) change) related to the substitution of existing crops with others in the region studied while the latter takes into account the environmental impact of land use changes elsewhere in the world induced by different short- or long-term potential decision periods (e.g., changes in food/feed demand) [35].

This paper aims at fully evaluating suitable oleaginous bioenergy chains under Mediterranean environmental conditions. For this reason, the environmental and energy performances of three different oleaginous energy production chains (oilseed rape, Ethiopian mustard and cardoon), were analyzed and compared by means of a LCA approach. These species were carefully selected on the basis of outcomes provided by previous research activities and projects carried out at Italian (BIOENERGIE Project) and regional scale (Biomass Project and Biofuels Project). The study area of this paper is represented by the Sardinia region (Italy).

2. Bioenergy Crops and Input Data

The studied oleaginous chains are based on the cultivation of three different dedicated energy crops: oilseed rape, Ethiopian mustard and cardoon. These bioenergy chains reflect typical operating condition in Mediterranean areas, such as Sardinia region in Southern Italy which was identified as the study area. Indeed, in Southern Italy about 1,000,000 ha of arable land have been abandoned in the last two decades [36,37], according to a progressive and unstoppable trend (Figure 1).

Figure 1. Trend of arable lands in recent decades in Italy, data reported by Roggero *et al.* [36] and re-elaborated for this paper.



Land abandonment is particularly evident in areas where agricultural productivity is limited [38,39]. Production of biomass crops on so-called "marginal" lands has been proposed so that it does not compete with other crops for better farmland [19]. According to Dauber *et al.* [40], a variety of concepts for bioenergy production based on minimal or no land competition has been developed, e.g., [41–46].

For all three bioenergy chains, grain was considered as the main final product, while crop residues were regarded as final co-products. In particular, once harvested, the seeds of each species are subjected to extraction to obtain oil for power generation through diesel engines. For each species, the straw was baled, removed from the field and used for power generation in a steam power plant.

In the present study, we used accurate data on field practices, that were either directly measured or collected during a three-year study carried out following a common experimental protocol from 2007 to 2010 at two sites, Ussana and Ottava (Table 1) in Sardinia.

The sites are different for geographical, lithopedologic, thermopluviometric conditions. Both site have a typical Mediterranean climate with rainfall mainly occurring during the autumn and spring months. From 2007, the three different energy crops were arranged in 500 m^2 plots (100 m long and 5 m wide).

Several studies demonstrate that changes in land use and management can strongly affect soil organic carbon stock [47,48]. Increasing intensities of harvests from existing agricultural and forestry systems and replacing pasture with short rotation energy crops may deplete soil carbon [49]. Therefore, in this LCA study the environmental impact related to land use change (LUC) was implemented by addressing the potential changes in soil organic carbon (SOC) [50–52].

Table 1. Location and pedoclimatic conditions of the two study sites in Sardinia (Italy).

Site	Location Coordinates	Elevation (m a.s.l.) *	USDA Soil Description	Silt (%)	Clay (%)	Organic C (%)	pH	FAO Climate Description	Long-Term Rainfall Average (mm)
Ottava	40° 46' N, 8° 29' E	81	Lithic Xerorthents	12.9	17.9	1.22	8.3	Thermomediterranean attenuated	554
Ussana	39° 24' N, 9° 05' E	110	Petrocalcic Palexeralf	29.2	31.3	1.01	8.2	Thermomediterranean accentuated	432

* m a.s.l. means metres above sea level; USDA means United States Department of Agriculture; FAO means Food and Agriculture Organization.

3. LCA Methodology

The energy and environmental performance analysis of the three bioenergy chains based on oleaginous crop cultivation was carried out using the life cycle assessment (LCA) methodology. The LCA methodology is based on ISO 14040 guidelines and allows assessment of the environmental impact (use of energy and materials, as well as the polluting emissions) of a product throughout its overall life cycle, from raw material extraction, to production, use and final disposal [28,29]. The definition of the goal and scope, the system boundaries and the assumptions of the study are described below.

3.1. Goal and Scope Definition

The main goal of this study is to compare the energy and environmental performance of energy production from three different oleaginous crop chains (oilseed rape, Ethiopian mustard and cardoon) cultivated under Mediterranean climate conditions.

This study is based on an attributional LCA and therefore the use of average data instead of marginal data was preferred in evaluating the environmental impact avoided by the electrical energy produced by the bioenergy chains [30]. As with many other LCA studies previously developed [53], the functional unit chosen was 1 ha of cultivated field because it is the most straightforward basis for a similar comparative study.

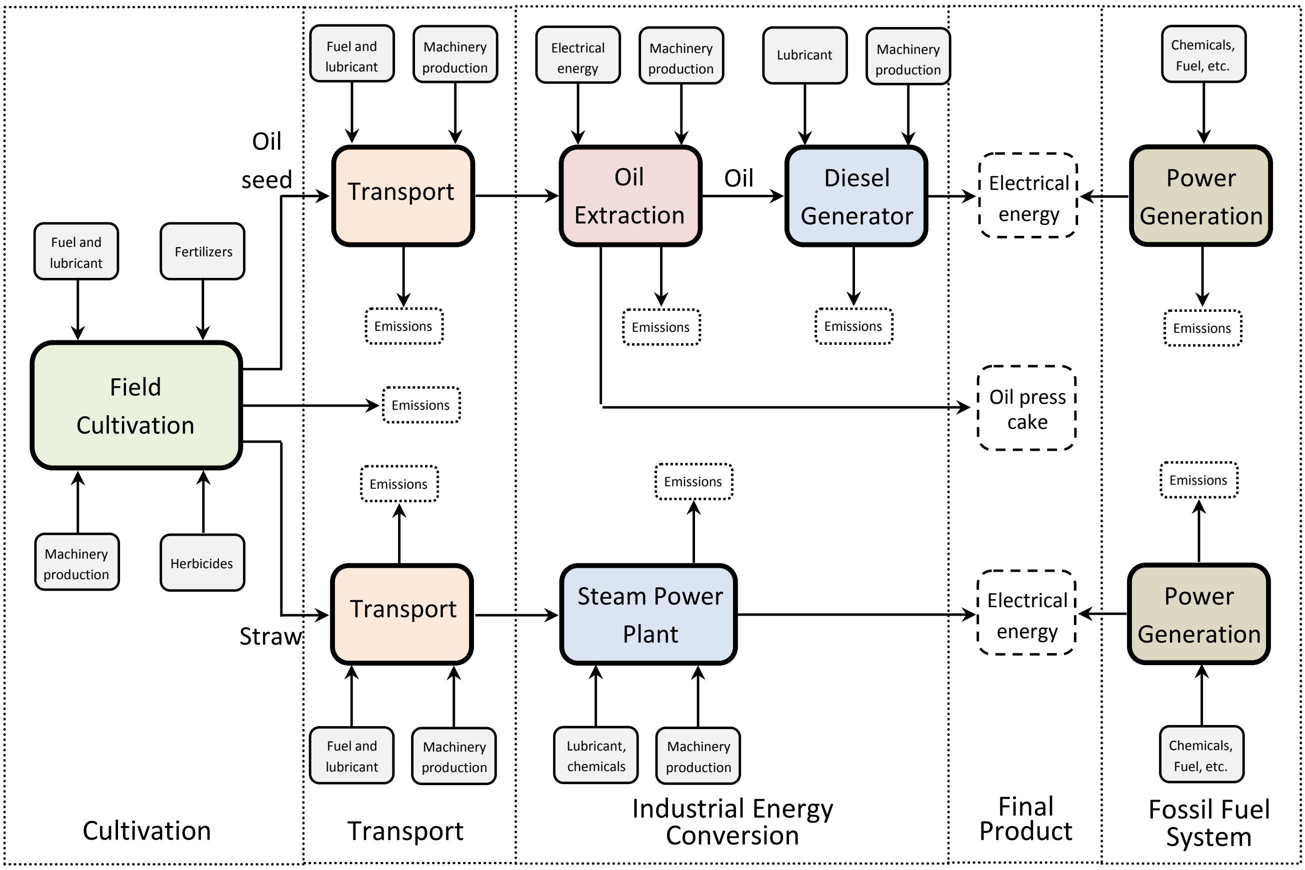
The bioenergy production systems studied here are based on power generation from oleaginous crops which show different yields in terms of vegetable oil, oil press cake and straw. The vegetable oil produced by oleaginous seeds is used for power generation in medium-speed diesel engines whereas crop residues are used for energy production in steam power plants. As better explained below, the boundaries of the system are expanded to include the unit processes required to produce the same final product (electrical energy in this case).

This study includes d-LUC but not i-LUC, because it is focused mainly on differences between the overall bioenergy chain emissions of the three crops that will be grown mainly in marginal and abandoned lands that have a relatively low carbon stock and a minimum productivity potential, so avoiding competition with food crops [54]. The main audience of this study is represented by researchers involved in the study of energy crops as well as policy-makers engaged in defining future assets in biomass production and use. Only the energy and environmental aspects are considered herein; economic and social aspects are not covered.

3.2. System Description

Figure 2 shows the boundaries of the bioenergy system considered. In particular, the bioenergy production chain was split into three main phases: cultivation, transportation of agricultural products and their industrial conversion for power generation. Each phase includes one or more unit processes that require input flows (materials, energy, intermediate products) and produce output flows (intermediate products, environmental emissions, final products).

Figure 2. Boundaries of the bioenergy production system.



The cultivation phase is very similar for the three oleaginous crops considered here and includes all agricultural activities, such as tillage, sowing, fertilization, weeding, harvesting, raking and baling. Cultivation is carried out with conventional farm machinery and requires the availability of diesel oil, lubricants, fertilizers, seeds and herbicides. After harvesting, oleaginous seeds are transported to the industrial processing plant by means of heavy-duty trucks. For all three oleaginous crops, at harvest large amounts of straw are available and could be used for energy production, although only the cardoon straw is ordinarily collected. The vegetable oil is extracted by means of a mechanical press and then directly utilized for power generation. The oil extraction process requires electrical energy and produces an oil press cake residue that contains about 40%–60% of overall energy content of oilseeds. The oil press cake can be often used in animal feeding as a substitute for other protein-rich supplements, although in the case of Ethiopian mustard, the oil press cake is unsuitable for use as fodder owing to high levels of glucosinolates. For this reason, this study assumes that the oil press cake is used outside the boundaries of the bioenergy systems but without a detailed specification. Therefore, allocation of the environmental impact with the expansion of the system boundaries for including the same unit process (the production of fodder) for all three chains was impossible and, as usually carried out in LCA studies [30], the environmental impact of the overall oil production process was allocated between oil and oil press cake according to the corresponding energy contents.

According to the LCA methodology, the boundaries of the system are expanded to include the unit processes used to produce fuels, lubricants, fertilizers, chemicals, seeds, agricultural machinery and electricity. In particular, agricultural machinery, pesticide, fertilizer and seed production were included in the agricultural phase of this LCA. Moreover, to compare energy production from oleaginous crops and from fossil fuels, the boundaries of the systems are expanded to include the unit processes required to produce the same final product (electricity in this case).

3.3. Environmental Impact Categories

In this study, only the mandatory elements of the Life Cycle Impact Assessment (LCIA) phase were included [28,29]. The impact categories considered in the LCIA phase are cumulative energy demand (CED), global warming potential (GWP) and acidification potential (AP), so the energy balance, greenhouse and acid gas emissions of the different unit processes were evaluated. The characterization phase is based on the calculation of primary energy consumption (from renewable and fossil sources), global warming potential for a 100-year time horizon (Intergovernmental Panel on Climate Change (IPCC) model) [55] and acidification potential (Regional Air Pollution Information and Simulation (RAINS) 10 model) [55]. The category indicators are energy demand (expressed in MJ of primary energy), equivalent CO_2 and SO_2 emissions (expressed in kg of CO_2 and SO_2).

3.4. Input Data and Assumptions

The input and output flows of the different unit processes were evaluated using the Simapro software Version 7.3 and the Ecoinvent database Version 2.0 [55,56]. The Ecoinvent database includes most of the processes required by the LCA study of energy production from oleaginous crops. However, input and output data of the different processes were adapted to take into account the specific features of oleaginous crop cultivation under Mediterranean conditions.

The main assumptions for the cultivation phase of the three oleaginous crops are shown in Table 2. The field operations were almost the same for all three crops. An average grain yield of 1.8, 1.9 and 0.75 $t \cdot ha^{-1}$ and 6.2, 8.1 and 10.0 $t \cdot ha^{-1}$ of straw was considered here for oilseed rape, Ethiopian mustard and cardoon, respectively. As cardoon is a perennial crop, tillage, sowing and weeding were included only for the planting year during its five-year crop cycle considered.

Table 2 includes fuel and lubricant consumption of the different cultivation activities, as well as the operation time and the weight of tractors and agricultural equipment. In fact, as in many other LCA studies, the environmental impact related to the manufacture of agricultural machinery was evaluated here according to the fraction of machinery weight used in the cultivation phase [23]. The latter was calculated starting from the weight of the machinery, the operation time of each field operation and the lifetime of the machinery (7000 h for tractors, 1000 h for agricultural equipment and 1300 h for the harvester). Emissions related to the use of fertilizers were evaluated by assuming that the ammonia emissions are 0.17 $kg \cdot kg^{-1}$ of N in urea and 0.0215 $kg \cdot kg^{-1}$ of N in diammonium phosphate. N_2O emissions are 0.0251 $kg \cdot kg^{-1}$ of N in fertilizers and 0.346 $kg \cdot t^{-1}$ of seed produced. Moreover NO_X emissions were 10% of N_2O emissions [23,57].

Table 2. Main assumptions for the cultivation phase of the three oleaginous crops.

Field Operations	**Machinery**	**Oilseed rape**		**Ethiopian mustard**		**Cardoon** [a]	
		Time (h)	Fuel, Lubr. [b] (kg·ha^{-1})	Time (h)	Fuel, Lubr. [b] (kg·ha^{-1})	Time (h)	Fuel, Lubr. [b] (kg·ha^{-1})
Ploughing	Tractor (3,970 kg) Plough (580 kg)	3.05	Fuel = 37.6 Lubr. = 0.1	3.05	Fuel = 37.6 Lubr. = 0.1	3.05	Fuel = 37.6 Lubr. = 0.1
Harrowing	Tractor (3,970 kg) Harrow (1,050 kg)	1.00	Fuel = 12.8 Lubr. = 0.03	1.00	Fuel = 12.8 Lubr. = 0.03	1.00	Fuel = 12.8 Lubr. = 0.03
Sowing	Tractor (3,970 kg) Seeder (500 kg)	1.05	Fuel = 10.0 Lubr. = 0.1 Seed = 8.0	1.05	Fuel = 10.0 Lubr. = 0.1 Seed = 10.0	1.00	Fuel = 12.0 Lubr. = 0.1 Seed = 4.0
Rolling	Tractor (3,970 kg) Roller (820 kg)	0.50	Fuel = 3.6 Lubr. = 0.01	0.50	Fuel = 3.6 Lubr. = 0.01	0.50	Fuel = 3.6 Lubr. = 0.01
Fertilization	Tractor (2,620 kg) Spreader (100 kg)	0.33	Fuel = 4.4 Lubr. = 0.01 N = 110.0 P_2O_5 = 92.0	0.33	Fuel = 4.4 Lubr. = 0.01 N = 120.0 P_2O_5 = 92.0	0.39	Fuel = 5.0 Lubr. = 0.01 N = 140.0 P_2O_5 = 92.0
Weeding	Tractor (3,970 kg) Sprayer (90 kg)	0.45	Fuel = 4.0 Lubr. = 0.01 Metaz. [c] = 1.5	0.45	Fuel=4.0 Lubr. =0.01 Metaz. =1.5	0.45	Fuel = 4.0 Lubr. = 0.01 Linur. [d] = 1.5
Harvesting	Harvest (12,400 kg, for cardoon 13,500 kg)	1.00	Fuel = 12.0 Lubr. = 0.01 Seed = 1,800	1.30	Fuel = 18.0 Lubr. = 0.02 Seed = 1,900	1.00	Fuel = 36.8 Lubr. = 0.03 Seed = 750
Raking	Tractor (3,970 kg) Gyro Rake (230 kg)	0.55	Fuel = 6.0 Lubr. = 0.02	0.55	Fuel=6.5 Lubr. = 0.02	0.55	Fuel = 7.0 Lubr. = 0.02
Baling	Tractor (6,890 kg) Baler (12,560 kg)	0.33	Fuel = 7.0 Lubr. = 0.02	0.42	Fuel = 9.0 Lubr. = 0.02 Straw = 8,100	0.50	Fuel = 11.0 Lubr. = 0.025 Straw = 10,000

[a] Ploughing, harrowing, sowing, rolling and weeding have been considered only for the planting year; [b] Lubr.: Lubricant; [c] Metaz.: Metazachlor; [d] Linur.: Linuron.

The transportation phase of seeds and straw was evaluated by taking 50 km as the average distance. The vegetable oil is extracted by means of a mechanical press with 80% oil extraction efficiency and an electricity consumption of 32 kWh·t_{SEED}^{-1}. Moreover, other than the oil press cake used outside the boundaries of the bioenergy systems, a solid waste mass equal to 2% of inlet seeds was also considered as waste product. As mentioned, since the oil press cake can be used externally, the energy demand and the environmental impact of the overall oil production process (oilseed cultivation, transport and extraction) were allocated between the two products (oil and oil press cake) according to their energy content. Vegetable oil and straw are both converted to electricity but with different conversion technologies (Diesel engines and steam power plants) and therefore with very different conversion efficiencies and environmental emissions. Pure Vegetable Oil (PVO) produced from all three oleaginous crops is very similar and therefore, the Lower Heating Value (LHV) of PVO from rapeseed oil reported by [5] was assumed. In particular, the LHV is 37.6 MJ·kg^{-1} for PVO for all three crops. The LHV of oil press cake is 18.6 MJ kg^{-1} according to values reported by [58] for oilseed rape.

The same value was considered for Ethiopian mustard, while for cardoon the LHV of oil press cake was reduced to 17.7 $MJ \cdot kg^{-1}$ due to its lower residual oil content.

The LCA impact of power generation was evaluated with reference to the use of pure vegetable oil in medium-speed diesel engines (44% of average conversion efficiency, [16]) and the straw in small size steam power plants (25% of average efficiency, [59]). It is to be noted that to reduce NO_X emission both power generation systems were equipped with a Selective Catalytic Reaction (SCR) unit using urea as reducing agent.

Table 3 shows the emission factors (in terms of mass of pollutant per kWh of electrical energy produced) used here to evaluate the environmental impact of the diesel engine and the steam power plant. The emission factors of the diesel engine were assumed starting from those given by the Ecoinvent database for diesel engines with SCR fuelled with diesel oil. According to Russo *et al.* [5], use of PVO in diesel engines produces emissions very similar to those of fossil fuels. Overall, we assume an increase of 5% in NO_X emissions and a reduction of 90% in SO_X emissions (owing to the lower sulphur content of PVO). Emission factors for the steam power plant were assumed starting from those given by the Ecoinvent database for boilers using chipped biomass and modified for the use of straw according to data of [60].

As mentioned, the electrical energy produced by vegetable oil and straw substitutes an equal amount of energy produced elsewhere and therefore the boundaries of the three bioenergy production systems are expanded to include the unit processes required to produce the same amount of electrical energy by the Italian power generation mix. In this way, the environmental emissions related to the latter energy production (hereinafter called avoided emissions) contribute to reducing the emissions of the overall bioenergy production chain.

Table 3. Environmental emission factors for diesel engines fuelled with vegetable oil and steam power plants fuelled with straw (From [5,55,56,60]).

Emission Factors	Diesel Engine	Steam Power Plant
CO ($g \cdot kWh^{-1}$)	1.3949	2.7692
NO_X ($g \cdot kWh^{-1}$)	0.6835	1.7723
CH_4 ($g \cdot kWh^{-1}$)	0.1116	0.0988
N_2O ($g \cdot kWh^{-1}$)	0.0465	0.0594
SO_2 ($g \cdot kWh^{-1}$)	0.0465	4.4308
NH_3 ($g \cdot kWh^{-1}$)	0.0093	0.0554
NMVOC ($g \cdot kWh^{-1}$)	0.4650	0.0100
PM2.5 ($g \cdot kWh^{-1}$)	0.0093	1.0135
HF ($g \cdot kWh^{-1}$)	–	0.0554
HCl ($g \cdot kWh^{-1}$)	–	0.2769

3.5. Land Use Change and Carbon Stock

The potential impact related to d-LUC was estimated starting from a carbon stock baseline of 53.7 $t \cdot C \cdot ha^{-1}$ measured in a representative grassland area of Sardinia [48]. Moreover, the average carbon stock values of 44.7 $t \cdot C \cdot ha^{-1}$ for oilseed rape [61], 44.1 $t \cdot C \cdot ha^{-1}$ for Ethiopian mustard and 50.3 $t \cdot C \cdot ha^{-1}$ for cardoon were also considered [62].

According to the IPCC 2006 guidelines for National Greenhouse Gas Inventories [63], the SOC changes between crops (expressed in $kg\cdot C\cdot ha^{-1}$) were multiplied by 3.67 ($44\ kg\cdot CO_2/12\ kg\cdot C$) to express the environmental impact in terms of GWP ($kg\cdot CO_2\cdot ha^{-1}$). Then, the GWP impact related to SOC changes, based on the above mentioned assumptions, was annualized over a period of 100 years.

4. Results and Discussion

The main results of the LCA study of the three oleaginous bioenergy chains are presented and discussed with reference to the main unit processes.

4.1. Oleaginous Crop Cultivation

Table 4 gives the results of the LCA study for the cultivation phase of the three oleaginous crops, with reference to 1 ha of cultivated land. In Table 4, the LCA impact (fuel, lubricating and machinery construction) of ploughing, harrowing and rolling operations was grouped into the tillage operation. Other than LCA impact due to fuel, lubricant and machinery construction, the sowing, fertilization and weeding control operations also include those related to seed, fertilizers and herbicides, respectively.

As shown in Table 4, the LCA impact of the cultivation phase is very similar for the three oleaginous crops because the field operations are almost the same for all three. Moreover, the LCA impact of the cultivation phase is mainly affected by fertilization and in particular by fertilizer production. Oilseed rape and Ethiopian mustard fertilization accounts for around 53%–54% of CED, 75%–76% of GWP and around 89% of AP. This large impact of fertilization on oilseed rape and Ethiopian mustard cultivation is similar to other studies [23,51]. For cardoon, fertilization accounts for about 66% (CED), 83% (GWP) and 93% (AP), respectively.

Table 4. Main LCA results for the cultivation phase (for 1 ha of cultivated land).

Cumulative Energy Demand ($MJ\cdot ha^{-1}$)						
Bioenergy chains	Tillage	Sowing	Fertilization	Weeding	Harvesting	Total
Oilseed rape	3,717.2	1,005.8	9,347.3	396.2	2,799.4	17,266.0
Ethiopian mustard	3,717.2	1,083.8	10,010.1	396.2	3,629.6	18,837.9
Cardoon	744.5	316.3	11,372.1	189.9	4,702.7	17,325.6
Global Warming Potential 100y ($kg\ CO_2eq\cdot ha^{-1}$)						
Bioenergy chains	Tillage	Sowing	Fertilization	Weeding	Harvesting	Total
Oilseed rape	238.8	57.9	1508.7	22.4	163.8	1,991.6
Ethiopian mustard	238.8	61.4	1626.3	22.4	214.0	2,162.9
Cardoon	47.8	17.2	1725.7	9.9	289.0	2,089.7
Acidification Potential ($kg\ SO_2eq\cdot ha^{-1}$)						
Bioenergy chains	Tillage	Sowing	Fertilization	Weeding	Harvesting	Total
Oilseed rape	1.54	0.45	26.77	0.34	1.01	30.12
Ethiopian mustard	1.54	0.49	29.63	0.34	1.34	33.34
Cardoon	0.31	0.15	35.34	0.08	1.98	37.85

However, as previously mentioned, the three oleaginous crops compared here show different seed yield and straw production. Although an overall range of 80–250 $g\cdot m^{-2}$ potential of seed yield is reported for cardoon [64], the average grain yield of 0.75 $t\cdot ha^{-1}$ and 10 $t\cdot ha^{-1}$ for straw considered in this paper is in accordance with the recent findings of [65]. In fact, those authors reported a mean seed yield of 603 kg·ha^{-1} in a large scale cultivation (77 ha) of the cardoon in southern Portugal and confirmed that this species is suitable for biomass production in Mediterranean regions. Average grain yields of 1.8 t·ha^{-1} and 1.9 t·ha^{-1} were considered in for oilseed rape and Ethiopian mustard, respectively, although both species show a high seed yield variability within years and among cultivation sites [20]. CED values in MJ·ha^{-1} for Ethiopian mustard and oilseed rape were relatively low due to the low fertilization ratios applied on the basis of the expected yields. Similar CED values were reported for the latter crop in Romania, where its seed yields were about twice than in Sardinia [66].

As stated before, the LCA results of Table 4 refer to a case study where the vegetable oil was used in a diesel generator while the cultivation residues were collected and used in a steam power plant. Therefore, for the oleaginous bioenergy crops studied here, all the aboveground biomass (seeds and straw) was used for energy production. For this reason, Table 5 summarizes the results of the LCA study of the cultivation phase and the LCA impact indicators are reported with reference to 1 ha of cultivated land, 1 t of seeds and 1 GJ of collected biomass energy (seeds and straw). The energy content of oleaginous seeds and residual straw was evaluated here on the basis of their LHV. In particular, the LHV of seeds and straw was assumed to be 25.0 and 15.0 MJ·kg^{-1} respectively, for oilseed rape and Ethiopian mustard [58] and 22.5 and 13.0 MJ·kg^{-1} for cardoon [67].

Table 5. LCA impact for the cultivation phase with reference to 1 ha of cultivated land, 1 t of seeds and 1 GJ of collected biomass energy (seeds and straw).

Cultivation Phases		**Oilseed rape**	**Ethiopian mustard**	**Cardoon**
Seed production (t·ha^{-1})		1.80	1.90	0.75
Straw production (t·ha^{-1})		6.15	8.10	10.00
Seed energy (GJ·ha^{-1})		45.00	47.50	16.88
Straw energy (GJ·ha^{-1})		92.25	121.50	130.00
LCA Impacts		**Oilseed rape**	**Ethiopian mustard**	**Cardoon**
CED	MJ·ha^{-1}	17,266.0	18,836.8	17,325.6
	MJ·t$_{\text{SEED}}^{-1}$	9,592.2	9,914.1	23,100.8
	MJ·GJ$_{\text{PROD}}^{-1}$	125.80	111.46	117.96
GWP-100y	kg·CO$_2$·ha^{-1}	1,991.6	2,162.9	2,089.7
	kg·CO$_2$·t$_{\text{SEED}}^{-1}$	1,106.4	1,138.3	2,786.2
	kg·CO$_2$·GJ$_{\text{PROD}}^{-1}$	14.51	12.80	14.23
AP	kg·SO$_2$·ha^{-1}	30.1	33.3	37.9
	kg·SO$_2$·t$_{\text{SEED}}^{-1}$	16.7	17.5	50.5
	kg·SO$_2$·GJ$_{\text{PROD}}^{-1}$	0.22	0.20	0.26

If the LCA impact indicators are calculated with reference to the mass of oilseed, Table 5 demonstrates that cardoon gives the worst environmental performance owing to its low seed yield. In particular, the corresponding CED, GWP and AP impact indicators for cardoon are 2.3–3 times those for oilseed rape and Ethiopian mustard. However, as shown in Table 5, the energy content of the residual straw is very high for all three oleaginous crops and in particular for cardoon. Therefore, Table 5 shows that if the LCA impact indicators refer to the overall energy content of the collected biomass, the LCA impact of the cultivation phase for the three oleaginous crops shows smaller differences (by about 12%–13% for CED and GWP and by about 30% for AP). Overall, the cultivation phase of Ethiopian mustard produces the lowest LCA impact. These results highlight that cardoon cannot be considered an actual oleaginous crop but its seed production is only a secondary product compared to its potential biomass production. In addition, the exploitation of straw plays such an important role in determining the oilseed chain that it makes Ethiopian mustard more effective. The latter is a relatively "new" oilseed crop and has the lowest LCA impact owing to its higher production in straw. In this case, indeed, the oilseed rape, which is the most widespread crop among the three considered and the most promising species for oilseed production thanks to breeding activities in recent decades, is the most efficient (in terms of CED) crop for oilseed production but its lower biomass production compared to Ethiopian mustard penalizes its performance in terms of CED and GWP with respect to the energy content of the collected products.

4.2. Transportation of Agricultural Products

The transportation phase of collected products simply includes the transport of seeds and straw from the field to the biomass processing plant. For both transport phases, an average distance of 50 km was considered here. Obviously, environmental emissions and energy consumption for 1 t of transported product are the same for the three bioenergy chains. However, owing to the different seed and straw yield, in Table 6 the LCA impact indicators for the transportation phase refer to 1 ha of cultivated land, 1 t of seeds and 1 GJ of collected biomass energy. As shown in Table 6, because of the higher mass of collected straw, the overall LCA impact of the transportation phase for the cardoon bioenergy chain is slightly higher than those for oilseed rape and Ethiopian mustard. To our knowledge, other results on cardoon LCA are almost lacking, except for the study carried out in Greece [68]. Those authors concluded that the dominant operation that adversely affected the LCA of cardoon was the transportation of seeds to the biomass processing plant (biodiesel production). However, the transportation distance considered by the latter study was three times as long as the distance reported in our study.

Table 6. LCA impact for the transportation phase with reference to 1 ha of cultivated land, 1 t of seeds and 1 GJ of collected biomass energy.

LCA Impacts		Unit	Oilseed rape	Ethiopian mustard	Cardoon
CED	Oilseed	$\mathrm{MJ \cdot ha^{-1}}$	203.5	214.8	84.8
		$\mathrm{MJ \cdot t_{SEED}^{-1}}$	113.1	113.1	113.1
		$\mathrm{MJ \cdot GJ_{PROD}^{-1}}$	1.48	1.27	0.58
	Straw	$\mathrm{MJ \cdot ha^{-1}}$	1004.5	1323.1	1633.4
		$\mathrm{MJ \cdot t_{SEED}^{-1}}$	558.06	696.37	2177.87
		$\mathrm{MJ \cdot GJ_{PROD}^{-1}}$	7.3	7.8	11.1
GWP-100y	Oilseed	$\mathrm{kg \cdot CO_2 \cdot ha^{-1}}$	12.0	12.7	5.0
		$\mathrm{kg \cdot CO_2 \cdot t_{SEED}^{-1}}$	6.7	6.7	6.7
		$\mathrm{kg \cdot CO_2 \cdot GJ_{PROD}^{-1}}$	0.09	0.08	0.03
	Straw	$\mathrm{kg \cdot CO_2 \cdot ha^{-1}}$	59.7	78.6	97.0
		$\mathrm{kg \cdot CO_2 \cdot t_{SEED}^{-1}}$	33.2	41.4	129.3
		$\mathrm{kg \cdot CO_2 \cdot GJ_{PROD}^{-1}}$	0.44	0.47	0.66

Table 6. *Cont.*

LCA Impacts		Unit	Oilseed rape	Ethiopian mustard	Cardoon
AP	Oilseed	$kg{\cdot}SO_2{\cdot}ha^{-1}$	0.07	0.07	0.03
		$kg{\cdot}SO_2{\cdot}t_{SEED}^{-1}$	0.039	0.038	0.040
		$kg{\cdot}SO_2{\cdot}GJ_{PROD}^{-1}$	0.0005	0.0004	0.0002
	Straw	$kg{\cdot}SO_2{\cdot}ha^{-1}$	0.33	0.43	0.53
		$kg{\cdot}SO_2{\cdot}t_{SEED}^{-1}$	0.183	0.226	0.707
		$kg{\cdot}SO_2{\cdot}GJ_{PROD}^{-1}$	0.0024	0.0025	0.0036

4.3. Vegetable Oil Extraction Process

The LCA impact evaluation of the oil extraction process takes into account the manufacture of the mechanical press and its electricity consumption. The oil extraction process considered here is the same for the three oleaginous crops but the corresponding LCA impact changes depending on the seed oil content. The overall LCA impact of the oil extraction process is summarized in Table 7, where the impact indicators are calculated with reference to 1 t of vegetable oil and to 1 ha of cultivated land. As shown in Table 7, the LCA impact of the oil extraction process for cardoon is higher than that for oilseed rape and Ethiopian mustard owing to the low oil content of cardoon seeds.

It is to be noted that the oil extraction process produces two useful products, the vegetable oil and the oil press cake, and therefore the LCA impact of the oilseed cultivation, transport and oil extraction phases was allocated according to the energy content of oil and oil press cake. Therefore, the LCA impact allocated to the vegetable oil is around 51.8% for oilseed rape, 50.5% for Ethiopian mustard and 40.8% for cardoon.

Table 7. LCA impact for the oil extraction process with reference to 1 ha of cultivated land and 1 t of vegetable oil.

Oil extraction Process		Oilseed rape	Ethiopian mustard	Cardoon
Vegetable oil ($kg{\cdot}ha^{-1}$)		612	608	180
Vegetable oil ($GJ{\cdot}ha^{-1}$)		23.01	22.86	6.77
Oil press cake ($kg{\cdot}ha^{-1}$)		1152	1254	555
Oil press cake ($GJ{\cdot}ha^{-1}$)		21.43	23.32	9.82
LCA Impacts		**Oilseed rape**	**Ethiopian mustard**	**Cardoon**
CED	$MJ{\cdot}t_{OIL}^{-1}$	987.79	1045.96	1375.28
	$MJ{\cdot}ha^{-1}$	604.53	635.95	247.55
GWP	$kg{\cdot}CO_2{\cdot}t_{OIL}^{-1}$	15.93	16.70	21.04
	$kg{\cdot}CO_2{\cdot}ha^{-1}$	9.75	10.15	3.79
AP	$kg{\cdot}SO_2{\cdot}t_{OIL}^{-1}$	0.08	0.09	0.11
	$kg{\cdot}SO_2{\cdot}ha^{-1}$	0.05	0.05	0.02

4.4. PVO Diesel Generator

As mentioned, in this study the vegetable oil was directly used in a medium-speed diesel engine for power generation with a net conversion efficiency of 44% (that is, a specific fuel consumption of about 0.218 $kg{\cdot}kWh^{-1}$). As shown in Table 8, on the basis of the PVO yield, the electricity production is about 2812 kWh·ha^{-1} for the oilseeds' rape chain, 2794 kWh·ha^{-1} for Ethiopian mustard and 827 kWh·ha^{-1} for cardoon. As mentioned, the boundaries of the system were extended because the latter energy production replaces an equal amount of electrical energy produced by the Italian power generation mix and therefore avoids the corresponding environmental impact and fossil fuel energy consumption (hereinafter called avoided impact). The overall LCA impact of the power generation process from PVO for the three oleaginous crops is summarized in Table 8. Specific fuel consumption and environmental emission factors of the diesel engine (Table 3) are the same for the three vegetable oils and therefore the LCA impact is the same for the three oleaginous crops. However, because of the different oil production, the direct and avoided LCA impact indicators are reported with reference to 1 ha of cultivated land. As reported in Table 8, the direct CED of power generation by PVO is about 8% of the CED required by the Italian power generation mix; GWP is about 9% and AP about 20%.

Table 8. Energy and environmental impact for the diesel generator with reference to 1 ha of cultivated land.

Energy Production		**Oilseed rape**	**Ethiopian mustard**	**Cardoon**
Vegetable oil (kg·ha^{-1})		612	608	180
Electrical energy (kWh·ha^{-1})		2,812.48	2,794.10	827.20
LCA Impacts		**Oilseed rape**	**Ethiopian mustard**	**Cardoon**
CED (MJ·ha^{-1})	Direct	2,150.35	2,136.30	632.46
	Avoided	−26,765.30	−26,590.39	−7,872.15
GWP (kg CO_2·ha^{-1})	Direct	163.48	162.41	48.08
	Avoided	−1,778.55	−1,766.93	−523.10
AP (kg SO_2·ha^{-1})	Direct	1.70	1.69	0.50
	Avoided	−8.33	−8.28	−2.45

4.5. Steam Power Plant

The straw is used for power generation in a small size (10–15 MW) steam power plant with an electrical efficiency of 25% (that is, a specific fuel consumption of about 1.11 kg·kWh^{-1} for the cardoon straw and about 0.96 kg·kWh^{-1} for oilseed rape and Ethiopian mustard straw). In Table 9, the direct and avoided LCA impact indicators of the steam power plant are calculated with reference to 1 ha of cultivated land. Table 9 also reports the avoided environmental impact related to the electricity produced from straw. On the basis of the assumptions of this study, electrical energy production from cultivation residues varies from 6406 kWh·ha^{-1} (oilseed rape) to 9028 kWh·ha^{-1} (cardoon) and substitutes an equal amount of electrical energy produced by the Italian power generation mix. For all three oleaginous crops, the CED of power generation by residual straw is about 9%–10% with respect to power generation by using the Italian power generation mix, while GWP is about 11%–12%. However, Table 9 also shows that the acidification potential related to straw combustion is almost twice that of Italian power generation mix owing to its higher SO_X and NO_X emissions.

Table 9. Energy and environmental impact for the steam power plant with reference to 1 ha of cultivated land.

Energy Production		**Oilseed rape**	**Ethiopian mustard**	**Cardoon**
Straw (kg·ha^{-1})		6,150	8,100	10,000
Electrical energy (kWh·ha^{-1})		6,406.25	8,437.50	9,027.78
LCA Impacts		**Oilseed rape**	**Ethiopian mustard**	**Cardoon**
CED (MJ·ha^{-1})	Direct	5,683.75	7,485.92	9,140.72
	Avoided	−60,965.85	−80,296.48	−85,913.95
GWP (kg CO_2·ha^{-1})	Direct	425.81	560.82	685.40
	Avoided	−4,051.18	−5,335.70	−5,708.98
AP (kg SO_2·ha^{-1})	Direct	34.95	46.03	56.80
	Avoided	−18.97	−24.99	−26.74

4.6. Comparison of the Three Bioenergy Systems

Table 10 summarizes the direct LCA impact of the entire bioenergy chains, as well as the avoided impact with the substitution of power generation when compared to the Italian power mix.

As shown in Table 10, the cultivation phase greatly affects the performance of the bioenergy chains. In particular, the cumulative energy demand of the cultivation phase is about 49% for the oilseed rape, 45% for Ethiopian mustard and 38% for cardoon. Power generation with the diesel engine and the steam power plant accounts for about 43% (oilseed rape), 46.5% (Ethiopian mustard) and 52.5% (cardoon) of CED. The transportation phase of straw accounts for about 5.5%–8.8% of the overall CED, while only marginal amounts of primary energy are required by the oil extraction process and the seed transportation phase. Similarly, the cultivation phase contributes greatly to the GWP (by about 50%–60%) of the overall bioenergy chain, while straw combustion in the steam power plant is the main factor responsible (by about 66%–72%) for the acidification potential.

As demonstrated in Table 10, power generation from vegetable oil and cultivation residue allows avoiding a noteworthy amount of primary energy (88–107 GJ·ha^{-1}), greenhouse (5830–7100 kg·CO_2·ha^{-1}) and acid gas emissions (27–33 kg·SO_2·ha^{-1}). The use of residual straw for power generation contributes greatly to the avoided environmental impact of the three bioenergy chains (about 70% of the overall energy saving for oilseed rape, 75% for Ethiopian mustard and about 92% for cardoon, for example). However, the agronomic sustainability of power generation from residual straw should be studied in depth because crop residue removal may reduce nutrient pools and alter soil chemical properties [51]. Obviously, the actual energy and environmental saving of the bioenergy chain can be calculated by subtracting the direct impact from the avoided one. Overall, the oleaginous bioenergy chains allow a saving of about 70–86 GJ·ha^{-1} (that is about 79%–80% with respect to conventional power generation) and a reduction of the GWP impact by about 71%–73% (about 4138 kg·CO_2eq·ha^{-1} for oilseed rape, 5219 kg·CO_2eq·ha^{-1} for Ethiopian mustard and 4545 kg·CO_2eq·ha^{-1} for cardoon). However, for all three oleaginous crops, power generation from PVO and residual straw increases the acidification potential mainly due to the higher SO_X and NO_X emissions related to straw combustion. In particular, AP impact produced by the oilseed rape and Ethiopian mustard chains is about 1.9 times that produced by conventional power generation and about 2.7 times for the cardoon bioenergy chain.

Table 10. LCA impact for the entire bioenergy chains with reference to 1 ha of cultivated land.

Phases	**CED (MJ·ha^{-1})**			**GWP (kg CO_2·ha^{-1})**			**AP (kg SO_2·ha^{-1})**		
	Oilseed rape	Ethiopian mustard	Cardoon	Oilseed rape	Ethiopian mustard	Cardoon	Oilseed rape	Ethiopian mustard	Cardoon
Cultivation	8,943.8	9,324.2	7,068.8	1,031.6	1,070.6	852.6	15.60	16.51	20.59
Seed transportation	105.4	106.3	34.6	6.2	6.3	2.0	0.03	0.03	0.01
Straw transportation	1,004.5	1,323.1	1,633.4	59.7	78.6	97.0	0.33	0.43	0.53
Oil extraction	313.1	314.8	101.0	5.0	5.0	1.5	0.03	0.03	0.01
Diesel generator	2,150.4	2,136.3	632.5	163.5	162.4	48.1	1.70	1.69	0.50
Steam power plant	5,683.8	7,485.9	9,140.7	425.8	560.8	685.4	34.95	46.03	56.80
LCA Impacts	Oilseed rape	Ethiopian mustard	Cardoon	Oilseed rape	Ethiopian mustard	Cardoon	Oilseed rape	Ethiopian mustard	Cardoon
Direct impact (*a*)	18,201.0	20,690.6	18,611.0	1,691.9	1,883.7	1,686.7	52.64	64.71	78.44
Avoided impact by Diesel generator	26,765.3	26,590.4	7,872.1	1,778.6	1,766.9	523.1	8.33	8.28	2.45
Avoided impact by steam power plant	60,965.8	80,296.5	85,914.0	4,051.2	5,335.7	5,709.0	18.97	24.99	26.74
Avoided impact (*b*)	87,731.2	106,886.9	93,786.1	5,829.7	7,102.6	6,232.1	27.31	33.27	29.19
Saved impact (*b* − *a*)	69,530.2	86,196.2	75,175.1	4,137.9	5,218.9	4,545.4	−25.33	−31.45	−49.25

As mentioned, GWP impact of bioenergy chains may be significantly affected by SOC variation caused by land use changes. As reported in Section 3.5, the highest SOC changes obtained for annual crops (oilseed rape and Ethiopian mustard) showed a reduction of 20%–21% with respect to the baseline values, whereas SOC changes were about half (10%) for cardoon.

Although the lack of certain data related to soil carbon storage has been claimed [32], the estimated SOC changes have confirmed previous results [51], thus suggesting that oilseed rape has a higher detrimental impact because of the differences between initial and final SOC [51]. This is in agreement with other researchers [62,69–71], who stated that annual cropping systems are the most damaging in terms of SOC contents and structure due to higher soil revolving, short permanence and litter removal. Consequently, impacts in terms of SOC in a bioenergy chain are slightly different depending on whether the chain is based on annual or perennial crops and the latter results in higher environmental benefits than the former [32].

The values of carbon stock used in this work are considered for soil conditions after 20 years of continuous cultivation. As already stated by [72], for oilseed rape and winter wheat in the UK, it should also be noted that from an agronomic point of view it is unlikely that oilseed rape, Ethiopian mustard or cardoon would be grown exclusively for so long a time. As the predicted SOC contents in oilseed rape, Ethiopian mustard and other extensive crops usually in rotation with them (e.g., durum wheat) are very close, we can consider the carbon stock of our arable land quite representative of a standard rotation for a Mediterranean area. On the other hand, the agronomically expected interruption of cardoon crops (after 5 years of cultivation) with other extensive annual crops (e.g., durum wheat) following in the rotation, could determine a partial and temporary increase in CO_2 emission due to SOC oxidation. Consequently, the actual GWP related to d-LUC of cardoon may be slightly larger than the value estimated for this bioenergy chain.

SOC reduction leads to CO_2 emissions during the first years of cultivation. In this study, CO_2 emissions from SOC are about 33.0 t $CO_2 \cdot ha^{-1}$ for oilseed rape, 35.2 t $CO_2 \cdot ha^{-1}$ for Ethiopian mustard and 12.5 t $CO_2 \cdot ha^{-1}$ for cardoon. According to [73], the latter CO_2 emissions represent a “Biofuel Carbon Debt” that is repaid over time by the CO_2 savings of the bioenergy chain. Starting from the CO_2 savings in Table 10, the carbon debt would take about 8 years to repay for oilseed rape, 6.7 years for Ethiopian mustard and less than 3 years for cardoon.

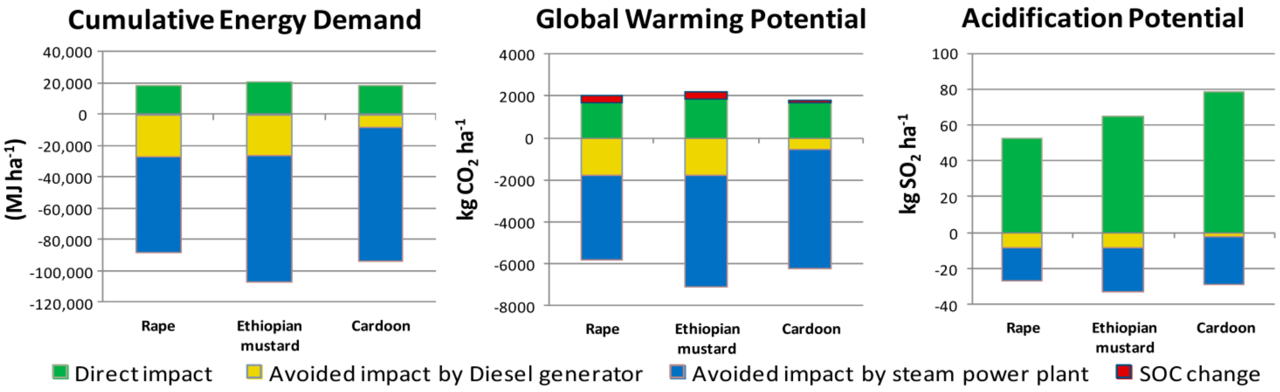
Table 11 summarizes the GWP impact of the three bioenergy chains by including the CO_2 emissions related to SOC changes and also considering the environmental impact due to d-LUC. For all three bioenergy chains, the SOC changes reduce the greenhouse gas emission saving in comparison to the data in Table 10. The GWP impact due to SOC changes accounts for about 16% of the overall GWP impact for oilseed rape and Ethiopian mustard and only 7% for cardoon. Overall, the GWP saving of Ethiopian mustard is about 9% higher than that of cardoon and 22% higher than that of oilseed rape.

Finally, Figure 3 summarizes the overall environmental impact of the three bioenergy chains compared here.

Table 11. Overall GWP impact for the three bioenergy chains with reference to 1 ha of cultivated land.

GWP-100y (kg CO_2·ha^{-1})	**Bioenergy Chains**		
	Oilseed rape	Ethiopian mustard	Cardoon
Direct impact (*a*)	1692	1884	1687
SOC change (*b*)	330	352	125
Overall impact ($c = a + b$)	2022	2236	1811
Avoided impact (*d*)	5830	7103	6232
Saved impact ($d - c$)	3808	4867	4421

Figure 3. Comparison of the environmental impact of the three bioenergy chains.



5. Conclusions

For the three bioenergy chains, the results show that their potential in terms of primary energy production and savings of greenhouse gas emissions, is encouraging compared to power generation from fossil fuels.

Although the energy and environmental performances of the energy chains differ, the results also demonstrate that success of the supply chain depends on the full exploitation of its biomass residues.

In fact, the use of biomass residues for energy production and oil cakes for external uses can contribute to reduce environmental emissions and increase the energy efficiency of supply chains but, long-term effects on soil fertility, due to the systematic removal of crop residues, need to be taken into account.

However, it was found that the impact in terms of acidification potential coming from power generation from PVO and residual straw could be larger than conventional power generation, up to 1.9 and 2.7 times for Ethiopian mustard and cardoon bioenergy chains, respectively. In addition, our study highlights that land use changes reduce SOC and therefore worsen GWP impact for the three bioenergy chains. Moreover, the impact in terms of land use change is affected by the biological cycle (annual *vs.* perennial) of the bioenergy crop.

Further studies should focus on the evaluation of economic and environmental sustainability of the three energy chains, also considering a scenario option where only grain is harvested and all crop residues are left in the field (this would lead to a significant reduction in fertilizer input).

Finally, it is to be emphasized that some by-products can be used as valuable animal feed (e.g., cardoon and oilseed rape oil cakes) or to obtain high added-value bio-products.

Acknowledgments

This work was jointly financed by the Italian Ministry of Agricultural, Food and Forestry Policies (BIOENERGIE Project), and by the Sardinia Region (Biomass Project and Biofuels Project). The authors are grateful to the technicians of the experimental farms for their technical support.

Author Contributions

The manuscript has been read and approved by all named authors. Each co-author gave the same contribution to the reported research and writing the paper.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. *Promotion of the Use of Energy from Renewable Sources*; Directive 2009/28/EC; European Commission: Brussels, Belgium, 2009.
2. Koçar, G.; Civaş, N. An overview of biofuels from energy crops: Current status and future prospects. *Renew. Sustain. Energy Rev.* **2013**, *28*, 900–916.
3. Nigam, P.S.; Singh, A. Production of liquid biofuels from renewable resources. *Prog. Energy Combust. Sci.* **2011**, *37*, 52–68.
4. Hossain, A.K.; Davies, P.A. Plant oils as fuels for compression ignition engines: A technical review and life-cycle analysis. *Renew. Energy* **2010**, *35*, 1–13.
5. Russo, D.; Dassisti, M.; Lawlor, V.; Olabi, A.G. State of the art of biofuels from pure plant oil. *Renew. Sustain. Energy Rev.* **2012**, *16*, 4056–4070.
6. Aransiola, E.F.; Ojumu, T.V.; Oyekola, O.O.; Madzimbamuto, T.F.; Ikhu-Omoregbe, D.I.O. A review of current technology for biodiesel production: State of the art. *Biomass Bioenergy* **2014**, *61*, 276–297.
7. Atabani, A.E.; Silitonga, A.S.; Badruddin, I.A.; Mahlia, T.M.I.; Masjuki, H.H.; Mekhilef, S. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2070–2093.
8. Ashraful, A.M.; Masjuki, H.H.; Kalam, M.A.; Rizwanul Fattah, I.M.; Imtenan, S.; Shahir, S.A.; Mobarak, H.M. Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: A review. *Energy Convers. Manag.* **2014**, *80*, 202–228.
9. Malça, J.; Coelho, A.; Freire, F. Environmental life-cycle assessment of rapeseed-based biodiesel: Alternative cultivation systems and locations. *Appl. Energy* **2014**, *114*, 837–844.
10. San Josè Alonso, J.F.; Lopez Sastre, J.A.; Romero-Avila, C.; Lopez Romero-Avila, E.; Izquierdo Iglesias, C. Using mixtures of diesel and sunflower oil as fuel for heating purposes in Castilla y Leon. *Energy* **2005**, *30*, 573–582.
11. Altin, R.; Cetinkaya, S.; Yucesu, H.S. The potential of using vegetable oil fuels as fuel for diesel engines. *Energy Convers. Manag.* **2001**, *42*, 529–538.

12. De Almedia, S.C.A.; Belchior, C.R.; Nascimento, M.V.G.; Vieira, L.S.R.; Fleury, G. Performance of a diesel generator fuelled with palm oil. *Fuel* **2002**, *81*, 2097–2102.
13. Sidibé, S.S.; Blin, J.; Vaitilingom, G.; Azoumah, Y. Use of crude filtered vegetable oil as a fuel in diesel engines state of the art: Literature review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2748–2759.
14. Misra, R.D.; Murthy, M.S. Straight vegetable oils usage in a compression ignition engine—A review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 3005–3013.
15. Soo-Young, N. Inedible vegetable oils and their derivatives for alternative diesel fuels in CI engines: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 131–149.
16. Wartsila, Liquid Biofuel Power Plants. Available online: http://www.wartsila.com (accessed on 5 April 2014).
17. Katerji, N.; Mastrorilli, M.; Rana, G. Analysis and improvement of water use efficiency for crops cultivated in the Mediterranean regions: The state of the art. Available online: http://om.ciheam.org/om/pdf/a72/00800724.pdf (accessed on 2 May 2014).
18. Turner, N.C. Sustainable production of crops and pastures under drought in a Mediterranean environment. *Ann. Appl. Biol.* **2004**, *144*, 139–147.
19. Knoll, J.E.; Anderson, W.F.; Strickland, T.C.; Hubbard, R.K.; Malik, R. Low-input production of biomass from perennial grasses in the Coastal Plain of Georgia, USA. *Bioenergy Resour.* **2012**, *5*, 206–214.
20. Lazzeri, L.; D'Avino, L.; Mazzoncini, M.; Antichi, D.; Mosca, G.; Zanetti, F.; del Gatto, A.; Pieri, S.; de Mastro, G.; Grassano, N.; *et al.* On farm agronomic and first environmental evaluation of oil crops for sustainable bioenergy chains. *Italian J. Agron.* **2010**, *4*, 171–180.
21. Ledda, L.; Deligios, P.A.; Farci, R.; Sulas, L. Biomass supply for energetic purposes from some Cardueae species grown in Mediterranean farming systems. *Ind. Crops Prod.* **2013**, *7*, 218–226.
22. Cayuela, M.L.; Oenema, O.; Kuikman, P.J.; Bakker, R.R.; van Groenigen, J.W. Bioenergy by-products as soil amendments? Implications for carbon sequestration and greenhouse gas emissions. *GCB Bioenergy* **2010**, *2*, 201–213.
23. Gasol, C.M.; Gabarrell, X.; Anton, A.; Rigola, M.; Carrasco, J.; Ciria, P.; Solano, M.L.; Rieradevall, J. Life cycle assessment of a Brassica carinata bioenergy cropping system in southern Europe. *Biomass Bioenergy* **2007**, *31*, 543–555.
24. Cocco, D. Life cycle assessment of bioenergy production systems from oilseed rape crops. *J. Power Energy* **2011**, *225*, 63–73.
25. Weiser, C.; Zeller, V.; Reinicke, F.; Wagner, B.; Majer, S.; Vetter, A.; Thraen, D. Integrated assessment of sustainable cereal straw potential and different straw-based energy applications in Germany. *Appl. Energy* **2014**, *114*, 749–762.
26. Whittaker, C.; Borrion, A.L.; Newnes, L.; McManus, M. The renewable energy directive and cereal residues. *Appl. Energy* **2014**, *122*, 207–215.
27. Blanco-Canqui, H. Energy crops and their implications on soil and environment. *Agron. J.* **2010**, *102*, 403–419.
28. *Environmental Management—Life Cycle Assessment—Principles and Framework*; EN ISO 14040; International Organization for Standardization (ISO): Geneva, Switzerland, 2006.

29. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; EN ISO 14044; International Organization for Standardization (ISO): Geneva, Switzerland, 2006.
30. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in life cycle assessment. *J. Environ. Manag.* **2009**, *91*, 1–21.
31. Cherubini, F.; Strømman, A.H. Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresour. Technol.* **2011**, *102*, 437–451.
32. Fazio, S.; Monti, A. Life cycle assessment of different bioenergy production systems including perennial and annual crops. *Biomass Bioenergy* **2011**, *35*, 4868–4878.
33. Tonini, D.; Hamelin, L.; Wenzel, H.; Astrup, T. Bioenergy production from perennial energy crops: A consequential LCA of 12 bioenergy scenarios including land use changes. *Environ. Sci. Technol.* **2012**, *46*, 13521–13530.
34. Hamelin, L.; Jørgensen, U.; Petersen, B.M.; Olesen, J.E.; Wenzel, H. Modelling the carbon and nitrogen balances of direct land use changes from energy crops in Denmark: A consequential life cycle inventory. *GCB Bioenergy* **2012**, *4*, 889–907.
35. Curran, M.A.; Mann, M.; Norris, G. The international workshop on electricity data for life cycle inventories. *J. Clean. Prod.* **2005**, *13*, 853–862.
36. Roggero, P.P.; Bagella, S.; Deligios, P.; Ledda, L.; Gutierrez, M. Gestione dell'abbandono dei seminativi italiani in aree svantaggiate. In Proceedings of the Giornata di studio: Situazione dei seminativi nel quadro dell'agricoltura italiana, Firenze, Italy, 18 November 2010; pp. 147–173. (In Italian)
37. Niedertscheider, M.; Erb, K. Land system change in Italy from 1884 to 2007: Analysing the North–South divergence on the basis of an integrated indicator framework. *Land Use Policy* **2014**, *39*, 366–375.
38. Baldock, D.; Beaufoy, G.; Brouwer, F.; Godeschalk, F. *Farming at the Margins: Abandonment of Redeployment of Agricultural Land in Europe*; Institute for European Environmental Policy (IEEP)/Agricultural Economics Research Institute (LEI-DLO): London, UK; The Hague, The Netherlands, 1996.
39. Krasuska, E.; Cadorniga, C.; Tenorio, J.L.; Testa, G.; Scordia, D. Potential land availability for energy crops production in Europe. *Biofuels Bioprod. Biorefin.* **2010**, *4*, 658–673.
40. Dauber, J.; Brown, C.; Fernando, A.L.; Finnan, J.; Krasuska, E.; Ponitka, J.; Styles, D.; Thran, D.; van Groenigen, K.J.; Weih, M.; *et al*. Bioenergy from "surplus" land: Environmental and socio-economic implications. *BioRisk* **2012**, *7*, 5–50.
41. Field, C.B.; Campbell, J.E.; Lobell, D.B. Biomass energy: The scale of the potential resource. *Trends Ecol. Evolut.* **2008**, *2*, 65–72.
42. Cotula, L.; Dyer, N.; Vermeulen, S. *Fuelling Exclusion? The Biofuels Boom and Poor People's Access to Land*; International Institute for Environment and Development (IEED): London, UK, 2008.
43. Campbell, J.E.; Lobell, D.B.; Genova, R.C.; Field, C.B. The global potential of bioenergy on abandoned agriculture lands. *Environ. Sci. Technol.* **2008**, *42*, 5791–5794.
44. *Towards Sustainable Production and Use of Resource: Assessing Biofuels*; United Nations Environment Programme (UNEP): Nairobi, Kenya, 2009.

45. Dale, V.H.; Kline, K.L.; Wiens, J.; Fargione, J. Biofuels: Implications for Land Use and Biodiversity. Biofuels and Sustainability Reports. Available online: http://www.esa.org/biofuelsreports/ (accessed on 16 April 2014).
46. Zhuang, D.F.; Jiang, D.; Liu, L.; Huang, Y.H. Assessment of bioenergy potential on marginal land in China. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1050–1056.
47. Chiti, T.; Gardin, L.; Perugini, L.; Quaratino, R.; Vaccari, F.P.; Miglietta, F.; Valentini, R. Soil organic carbon stock assessment for the different cropland land uses in Italy. *Biol. Fertil. Soils* **2012**, *48*, 9–17.
48. Francaviglia, R.; Benedetti, A.; Doro, L.; Madrau, S.; Ledda, L. Influence of land use on soil quality and stratification ratios under agro-silvo-pastoral Mediterranean management systems. *Agric. Ecosyst. Environ.* **2014**, *183*, 86–92.
49. Cowie, A.L.; Smith, P.; Johnson, D. Does soil carbon loss in biomass production systems negate the greenhouse benefits of bioenergy? *Mitig. Adapt. Strateg. Glob. Change* **2006**, *11*, 979–1002.
50. Van-Camp, L.; Bujarrabal, B.; Gentile, A.-R.; Jones, R.J.A.; Montanarella, L.; Olazabal, C.; Selvaradjou, S.K. *Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection*; EUR 21319 EN/1; Office for Official Publications of the European Communities: Luxembourg City, Luxembourg, 2004.
51. Brandão, M.; Milà i Canals, L.; Clift, R. Soil organic carbon changes in the cultivation of energy crops: Implications for GHG balances and soil quality for use in LCA. *Biomass Bioenergy* **2011**, *35*, 2323–2336.
52. Brandão, M.; Milà i Canals, L. Global characterisation factors to assess land use impacts on biotic production. *Int. J. Life Cycle Assess.* **2013**, *18*, 1243–1252.
53. Muench, S.; Guenther, E. A systematic review of bioenergy life cycle assessments. *Appl. Energy* **2013**, *112*, 257–273.
54. Börjesson, P.; Tufvesson, L.M. Agricultural crop-based biofuels—Resource efficiency and environmental performance including direct land use changes. *J. Clean. Prod.* **2011**, *19*, 108–120.
55. SimaPro LCA Software, Version 7.3. Available online: http://www.simapro.co.uk/index.html (accessed on 25 September 2014).
56. SimaPro Database Manual. Methods Library. Available online: http://www.simapro.co.uk/index.html (accessed on 25 September 2014).
57. Iriarte, A.; Rieradevall, J.; Gabarrell, X. Life cycle assessment of sunflower and rapeseed as energy crops under Chilean conditions. *J. Clean. Prod.* **2010**, *18*, 336–345.
58. Stolarski, M.J.; Szczukowski, S.; Tworkowski, J.; Krzyżaniak, M.; Gulczyński, P.; Mleczek, M. Comparison of quality and production cost of briquettes made from agricultural and forest origin biomass. *Renew. Energy* **2013**, *57*, 20–26.
59. Biomass Combustion and Co-Firing: An Overview. Available online: http://www.ieabcc.nl/publications/t32.pdf (accessed on 3 April 2014).
60. Kabir, M.R.; Kumar, A. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. *Bioresour. Technol.* **2012**, *124*, 394–405.
61. Cherubini, F.; Bird, N.D.; Cowie, A.; Jungmeier, G.; Schlamadinger, B.; Woess-Gallasch, S. Energy and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resour. Conserv. Recycl.* **2009**, *53*, 434–447.

62. Fernando, A.L.; Duarte, M.P.; Almeida, J.; Boléo, S.; Mendes, B. Environmental impact assessment of energy crops cultivation in Europe. *Biofuels Bioprod. Biorefin.* **2010**, *4*, 594–604.
63. *IPCC Guidelines for National Greenhouse Gas Inventories*; Institute for Global Environmental Strategies (IGES): Hayama, Japan, 2006.
64. Archontoulis, S.V.; Struik, P.C.; Yin, X.; Bastiaans, L.; Vos, J.; Danalatos, N.G. Inflorescence characteristics, seed composition, and allometric relationships predicting seed yields in the biomass crop *Cynara cardunculus*. *GCB Bioenergy* **2010**, *2*, 113–129.
65. Gominho, J.; Lourenco, A.; Palma, P.; Lourenco, M.E.; Curt, M.D.; Fernández, J.; Pereira, H. Large scale cultivation of *Cynara cardunculus* L. for biomass production—A case study. *Ind. Crops Prod.* **2011**, *33*, 1–6.
66. Buţurcă, R.-C.; Gasol, C.M.; Gabarrell, X.; Scarpete, D. Comparative Life Cycle Assessment of rapeseed oil and biodiesel from winter rape produced in Romania. *Int. J. Environ. Ecol. Geol. Min. Eng.* **2013**, *7*, 547–552.
67. Fernández, J.; Curt, M.D.; Aguado, P.L. Industrial applications of *Cynara cardunculus* L. for energy and other uses. *Ind. Crops Prod.* **2006**, *24*, 222–229.
68. Abeliotis, K.; Makrinika, K.; Detsis, V.; Lasaridi, K. Life cycle assessment of *Cynara cardunculus* L. oilseeds production. In Proceedings of the 11th International Conference on Environment Science and Technology, Chania, Crete, Greece, 3–5 September 2009; pp. A1–A6.
69. Börjesson, P. Environmental effects of energy crop cultivation in Sweden—I: Identification and quantification. *Biomass Bioenergy* **1999**, *16*, 137–154.
70. Zan, C.S.; Fyles, J.W.; Girouard, P.; Samson, R.A. Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. *Agric. Ecosyst. Environ.* **2001**, *86*, 135–144.
71. Deligios, P.A.; Farci, R.; Ledda, L. Annual and perennial crops for bioenergy: Soil and environmental issues. In *Advances in fertilizer technology I: Synthesis*; Sinha, S., Pant, K.K., Eds.; Studium Press LLC: Houston, TX, USA, 2014; pp. 635–658.
72. Hillier, J.; Whittaker, C.; Dailey, G.; Aylott, M.; Casella, E.; Richter, G.M.; Riche, A.; Murphy, R.; Taylor, G.; Smith, P. Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses. *GCB Bioenergy* **2009**, *1*, 267–281.
73. Fargione, J.; Hill, J.; Tilman, D.; Polasky, S.; Hawthorne, P. Land clearing and the biofuel carbon debt. *Science* **2008**, *319*, 1235–1238.