

Article

A Life Cycle Assessment of Biomass Production from Energy Crops in Crop Rotation Using Different Tillage System

Anna Vatsanidou ^{1,*}, Christos Kavalaris ¹, Spyros Fountas ², Nikolaos Katsoulas ¹
and Theofanis Gemtos ¹

¹ Department of Agriculture Crop Production and Rural Environment, University of Thessaly, 38446 Volos, Greece; chkaval@uth.gr (C.K.); nkatsoul@uth.gr (N.K.); gemtos@uth.gr (T.G.)

² Department of Natural Resources Management and Agricultural Engineering, Agricultural University of Athens, 11855 Athens, Greece; sfountas@aau.gr

* Correspondence: vatsanidou@gmail.com

Received: 30 July 2020; Accepted: 24 August 2020; Published: 27 August 2020



Abstract: A three-year experiment was carried out in Central Greece to assess the use of different tillage practices (Conventional, Reduced, and No tillage) for seedbed preparation, in a double cropping per year rotation of irrigated and rainfed energy crops for biomass production for first- and second-generation biofuel production. A life cycle assessment (LCA) study was performed for the first year of crop rotation to evaluate the environmental impact of using different tillage practices, identifying the processes with greater influence on the overall environmental burden (hotspots) and demonstrating the potential environmental benefits from the land management change. LCA results revealed that fertilizer application and diesel fuel consumption, as well as their production stages, were the hot-spot processes for each treatment. In the present study, different tillage treatments compared using mass- and area-based functional unit (FU), revealing that reduced tillage, using strip tillage for spring crop and disc harrow for winter crops, and no tillage treatment had the best environmental performance, respectively. Comparison between the prevailing in the area monoculture cotton crop with the proposed double energy crop rotation adopting conservation tillage practices, using mass and energy value FU, showed that cotton crop had higher environmental impact.

Keywords: biomass; tillage; crop rotation; energy crops; environmental sustainability

1. Introduction

The potential environmental benefits of bioenergy derived from renewable biomass sources have been the subject of research the last years. Dedicated energy crops have the benefit of providing specific ecosystem services (e.g., C sequestration, biodiversity enhancement, Greenhouse Gas (GHG) emissions mitigation, enhancement of soil quality), the value of which are dependent on the particular bioenergy production system and the reference land use that it displaces [1]. A life cycle assessment (LCA) study offers a clear and comprehensive picture of the flows of energy and materials used as well as waste and emissions released through a system and gives a holistic and objective basis for comparisons. LCA quantify the potential environmental impacts of a product system over the life cycle, help to identify opportunities for improvement, and indicate more sustainable options where a comparison is made. It is widely accepted by the scientific community that LCA is one of the best methodologies to assess both the environmental burdens of biofuel production, and also identify the opportunities for environmental improvement [1].

A great number of studies have dealt with the energy used and the environmental burden of bioenergy production systems using diverse approaches. For example, Mann and Spath [2] published

a comprehensive LCA research of a biomass (from almond trees) gasification combined-cycle power system. They found that carbon closure, defined as the carbon percentage in the biomass recycled in the power plant, was almost 95%. A zero-net CO₂ process is represented by a 100% carbon closure. Since tree growing needs CO₂, the use of biomass power could reduce the net amount of CO₂ added to the atmosphere for each produced electricity unit. Sensitivity analysis showed that the amount of C sequestration into the soil considerably affected C closure (ranged from 83% to 200%); an outcome also supported by other sensitivity cases, where if soil C was not changed the carbon closure would be more than 94%. IEA performed a great number of LCA research studies, revealing a net improvement of GHG ranging 60–120% when using first- and second-generation biofuels compared to conventional transportation fuels [3]. Likewise, other studies revealed similar results [4,5], while going beyond the benefit of reduced GHG emissions, several LCA studies on different thermochemical processes of lignocellulosic biomass (for 2nd generation biofuels) revealed the process having the best performance regarding GHG impact [6]. All the previous and other research studies helped to comprehend the potential environmental impacts and the energy balance of bioenergy systems. On the other hand, several studies indicated significant GHG emissions originated by bioenergy agriculture systems, thus abating the intended mitigation [7,8]. Therefore, the significantly different outcomes generated controversial views among scientists, policy makers, and the public.

Given the variety of processes leading to bioenergy, and the controversial discussion of their 'net benefit', several studies have already been undertaken using LCA methodology to analyze the processes in detail, in order to know which biofuels have more or less environmental impacts [9,10]. Most LCAs found that when biofuels, like bioethanol and biodiesel, replaced conventional diesel and gasoline in transportation, a significant net reduction of fossil energy consumption and GHG emissions was achieved [3,11,12]. In several LCA studies additional to GHG emissions, other impacts were examined, like local air pollution, acidification, eutrophication, ozone depletion, land use, etc. [13,14]. It was then indicated that site specific assumptions could influence the magnitude of the environmental burden when more impact categories than just GHG and energy consumption included, showing that it is not easy to draw simplified conclusions. Studies evaluating environmental issues, like acidification, eutrophication, ozone depletion, land use, etc., concluded that most, but not all, biofuels substituting fossil fuels would lead to increased negative impacts to environment [15,16]. This concerned mainly energy crops where, among others, an intensive use of fertilizers (compounds based on N and P) and pesticides were performed, causing contamination of water and soil resources, while important emissions were neglected like nitrous oxide (N₂O), from feedstock production [8,17]. Therefore, it should always be acknowledged that the positive impacts on GHG emissions (from fossil fuels replacement) may carry a cost in other environmental areas, so that a much more careful analysis is needed to understand the trade-offs in any particular situation.

Management decisions, except biomass crop, could also determine the overall environmental impact of a bioenergy production system. Kulak et al. [18] reviewed several LCA studies evaluating the ratio of production to environmental impact in a low-input eco-efficient cropping system. They stated that low-input cropping systems introduced to reduce the environmental impacts, in most cases, have benefits that were offset by lower yields. Also, they claimed that sustainable management regimes that increase yield could improve further the eco-efficiency. Finally, they concluded that highly eco-efficient cropping systems require application of optimum instead of minimum quantities of external input that either could reduce or increase environmental impacts per product unit. Nemecek et al. [19] investigating eco-efficiency of crop rotations using LCA suggested that eco-efficiency can be improved by reducing N fertilization to non-legume crops, by the same N amount that is gained from the introduction of legumes in a crop rotation. They concluded that diverse crop rotations with reduced N input is a promising way to reduce the environmental impacts of intensive arable crop rotations. Furthermore, the diversification of management practices in field, i.e., reduced or no-tillage, and residue management have been under investigation for influencing the environmental impacts during the production cycle [20–22]. Malhi et al. [20] in an eight-year crop rotation study found that retaining crop

residues along with no-tillage practice, improved some soil properties and also had better environmental behavior, since the higher amount of N fertilization in conventional tillage resulted in increased amount of N losses through nitrous oxide -N (N_2O -N) emissions. Cropping system can influence CO_2 and N_2O emissions by affecting the quality and quantity of crop residue returned to the soil [23]. N fertilization typically has a stimulatory effect on N_2O emissions [24], but a variable effect on CO_2 emissions [25]. Management practices can also indirectly affect GHG (CO_2 , N_2O , and CH_4) emissions by altering soil temperature and water content [26]. Tillage can reduce soil water content through increased evaporation, whereas no-tillage can conserve soil water and reduce temperature because of decreased soil disturbance and increased residue accumulation at the soil surface [27]. Goglio et al. [21] used LCA to evaluate the environmental impacts of three cropping systems characterized by different external input levels in crop rotation production system and found that the highest output–input ratios and the lowest impact for the selected impact categories was achieved by the lowest external inputs to the system. The environmental performance of two cropping systems, single and double crop per year (two crops in sequence) combined with different cultivation practices (conventional tillage, minimum tillage, and no tillage) were analyzed by Bacenetti et al. [22]. The environmental analysis showed that for both cropping systems the environmental burdens were mainly due to crop fertilization (in particular, N application, primarily via organic fertilizers) and mechanization of field operations (diesel fuel emissions). The single crop system had better environmental performance for all the impact categories evaluated except for acidification and eutrophication, while these two categories had lower values in the double crop system due to fewer fertilizer applications and higher total yield. Also, the comparison among tillage cultivation practices showed that reduced and no tillage practices resulted in better environmental performance, compared to conventional soil tillage. The reduction of the environmental load was mainly due to lower diesel fuel consumption and it was higher in the double crop system, where soil preparation was carried out twice a year. Küstermann et al. [28], in a long-term field experiment in Southern Germany, examined the effects of soil tillage and fertilization on resource efficiency and GHG emissions. The results showed that the benefit of reduced soil tillage over conventional was a lower consumption of diesel fuel (reduced by 35%) and fossil energy (by 10%), and an increase in C sequestration and N soil accumulation. However, among reduced tillage treatments, when there was a significant decrease in yield, N and energy efficiency were reduced and also yield-related GHG emissions were increased. In another study, the relative benefits of using land for bioenergy production over 40 years compared with the use of the same land for C sequestration (e.g., forest) [29]. Results showed that a combination of high yielding crop species and efficient fossil fuel substitution by the biomass produced, made the bioenergy crop option more preferable. In contrast, low efficiency in fossil fuel replacement, independent of crops' growth rate, meant that land was better to be used for C sequestration (e.g., forest). Cherubini and Stromman [30] in a review paper concluded that bioenergy production should be preferred over C sequestration if biomass, from high-yielding plantations, was produced and converted efficiently to bioenergy. Thus, this bioenergy could displace GHG-intensive and low-efficiency fossil energy over a number of years.

The present study describes a simplified environmental impact research using the LCA methodology. The LCA was performed for one year of double crop system using different tillage practices compared to the monoculture cotton production prevailing in the area. No other relevant studies have been performed so as to offer a comparison of the existing cropping system with an innovative crop rotation system under reduced tillage cultivation. More specifically, LCA was used in order to:

- Evaluate the environmental profile of the different tillage practice used in a specific crop rotation system for biomass production.
- Identify the stages of the system that presented higher environmental impacts (i.e., hot-spots identification).
- Demonstrate if there were any environmental benefits from the land management change (LMC), transformed from a monoculture cultivation of half year (e.g., cotton crop) to a crop rotation

system with double cropping per year to keep soil covered all year round combined with reduced or no-till.

2. Materials and Methods

2.1. Experiments

The present study analyzed data originated from the first of the three-year research project focusing on environmentally friendly biomass production. During this project, several experiments were carried out to assess the effect of the proposed cropping practices to soil fertility, environment, energy, and economic balance. Primary data in the present LCA study were derived from the experiment dealt with crop rotation system of irrigated and rain-fed energy crops, while using conventional and conservation tillage practices Conservation tillage concern reduced tillage practices (without soil turning) in several depths, as well as no tillage practice. In Figure 1, the production steps of the five different tillage systems used (treatments) are shown:

1. Conventional tillage (CT): Seedbed preparation for sunflower as spring crop using ploughing at 25–30 cm and two passes of a disk harrow at 7–9 cm. For winter crop, one ploughing at 25–30 cm, two passes of a disk harrow at 7–9 cm, and two passes of a light cultivator at 6–8 cm for seedbed preparation.
2. Reduced tillage I (RT I): Seedbed preparation using a heavy cultivator at a depth of 20–25 cm and one pass of a disk harrow or a light cultivator for each crop.
3. Reduced tillage II (RT II). Seedbed preparation before planting sunflower using strip tillage, where only a part of soil is cultivated while the other is not disturbed. A strip tillage machine developed in the laboratory of Farm Mechanization was used for spring crops. Primary and secondary tillage carried out by a disk harrow at 6–8 cm for the winter crops. A total of three passes; two passes for weed destruction and initial soil disturbance and one for seedbed preparation before planting the crop.
4. Reduced tillage III (RT III) with one pass of a rotary cultivator at 10–15 cm for primary tillage, and a second pass with disk harrow for the spring crop and one pass of rotary cultivator for winter crop.
5. No-tillage (NT). Direct planting using a no till pneumatic drilling machine for winter crops and a pneumatic drilling machine for spring row crops.

The rest of cultural practices were homogeneously applied, i.e., planting date, fertilizer rates, and irrigation water quantity, for all the five treatments in order to achieve the same conditions in all plots for comparison. It should be noted that having applied the same inputs in all plots even in those with lower yields, that action favored conventional tillage treatment with the higher yields. The same applies for the time of sowing, as reduced tillage or no tillage could have been sown earlier. In all treatments, except no till, sowing was carried out by conventional pneumatic planting or drilling machines. For no till plots, a pneumatic no till drilling machine and a pneumatic no till row crop planting machine was used. Fertilizer was applied by a drilling machine to achieve accurate and homogeneous application rate. Irrigation was applied by a traveler irrigator with a gun sprinkler for seedling emergence and drip irrigation system was installed thereafter that offered better application homogeneity. Harvesting of the seed producing crops was carried out by a plot combine harvester of 1.50 m width harvesting the middle two rows of the plots. For the other crops, a hay harvesting machine was used. Therefore, the measured yield should reflect the characteristics of a normal harvest condition in field, where whole plant was removed for biomass production that will eventually be used for 1st- and 2nd-generation biofuels.

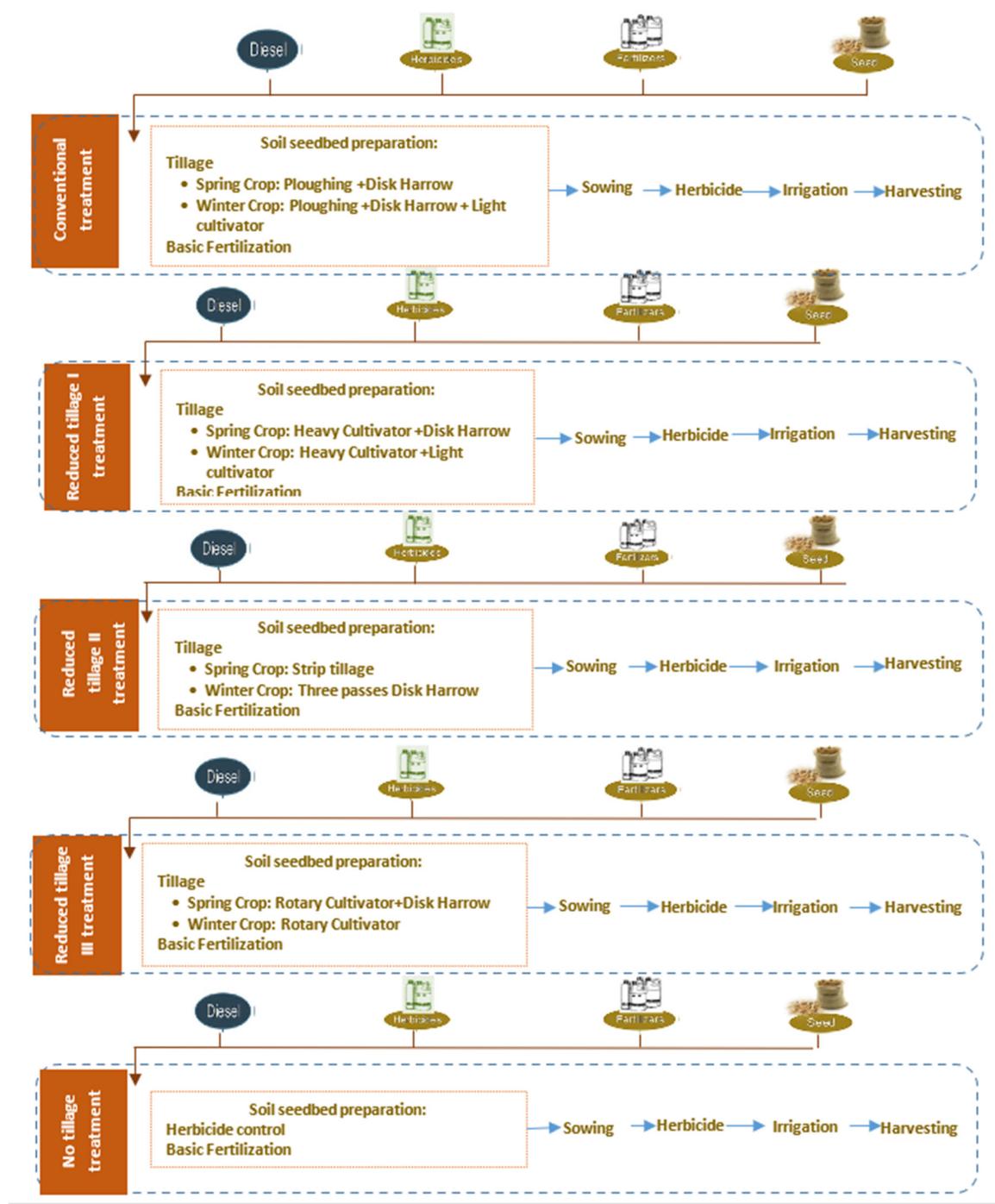


Figure 1. Flowchart depicting the five experimental treatments.

2.2. Life Cycle Analysis

The goal of the study was to perform a multiple impact category LCA following the ISO standards for LCA 14040 [31] and 14044 [32] as close as possible. The LCA was performed for one year of a double cropping per year rotation of irrigated and rainfed energy crops using different tillage systems and compared to the monoculture cotton production prevailing in the area. The software SimaPro 8 (PRé Consultants, Amersfoort, Netherland) was used to analyze the characterization step of the life cycle impact assessment (LCIA).

The main objective of the present study was to compare the environmental profile of the different agricultural practices in a crop rotation system used for biomass production. The ultimate

aim was to reveal and compare the environmental impacts of using different tillage practices for seedbed preparation (conventional and conservation tillage) in an innovative crop rotation system, combining winter and spring crops, in order to achieve a continuous over the years soil coverage of the field. Crop residue management and land use management changes, from monoculture (using conventional tillage and, in most cases, burning or removal of the residues) to a crop rotation using conservation tillage (reduced and no-till tillage) were also issues under consideration in the current study. The reference scenario of the monoculture conventional crop corresponded to the cotton cultivation.

2.2.1. System's Functions and Functional Unit

The functional unit (FU) is an important step of any LCA, since it provides the reference to which all other data in the assessment are normalized. In many LCA studies of agricultural production systems, the FU is the area (e.g., 1 ha). Nevertheless, the mass-based FU is prevalent in LCA studies of agricultural systems, since it takes into account the important element of productivity. In the present study, a mass-based FU was defined as the 1 kg dry matter of biomass production at farm gate. This means that the LCA study is a cradle-to-gate study, which means that it includes all the processes, the input used, and emission released until the biomass is harvested at the farm.

2.2.2. System Boundary

The study under analysis was a cradle-to-gate study, meaning an assessment of a partial life cycle of a product, from the extraction of raw materials (cradle) up to the production of the product, at the farm, "gate". In the current study, the phase of the "gate" was the biomass production in the field, including the whole aboveground plant part of the plant in its entirety. Thus, all emissions and resource uses during biomass production and the supply chains of all inputs were included (e.g., fertilizer production from raw materials and fertilizer application equipment, production, maintenance, etc.). It is pointed out that the CO₂ uptake of the plants was included, but reported separately, because the carbon is released as CO₂ when the biomass is used for generating energy, which nullifies this positive effect. The CO₂ captured in the soil due to land use change was also included and reported separately. Seed, fertilizer, and herbicide production were also included and the agricultural practices of soil seedbed preparation, sowing, irrigation, harvesting, baling, loading bales, and, finally, transporting the biomass at the field temporary storage area. In the case of capital goods (or ancillaries), the production, use, and maintenance phase of the machinery were analyzed, as well as the farming infrastructure (e.g., buildings, irrigation infrastructure, etc.), its production, use, and maintenance. The environmental impacts of field operations by human labor were not considered, as well as the transportation of human labor to the field. All the processes included to the cradle-to-gate analysis are presented in Figure 2.

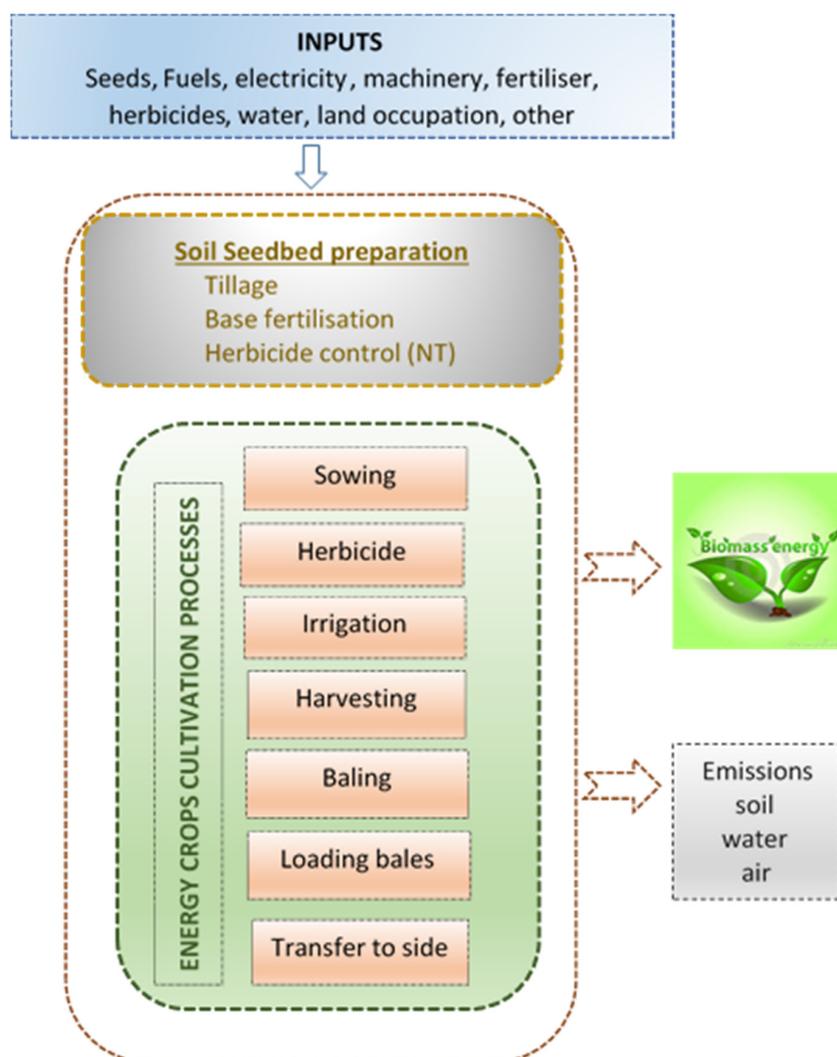


Figure 2. The processes included to the system boundaries for the biomass production.

2.2.3. Inventory Analysis

The data used to make the inventory were collected from one year of a three-year crop rotation (Table 1). Crop rotation used energy crops with double crops per year, one rain fed and one irrigated, in order to keep the soil covered all year round and simulate the conditions that will be created when second-generation biofuels will be adopted. Three categories of data were used in this study: The foreground data, the background data, and the semi-specific data. The attributional modelling approach will also be used here for compiling the inventory of the system under study. The foreground data concerned the primary data from the energy crop cultivation and were obtained via questionnaire-based interview during the growing seasons. These foreground data included amounts of all the crop production input/inflows categories—fertilizers, machinery, irrigation, fuel consumption, and transportation of agro-chemicals from the production site to the store and from the store to the farm. These data were highly detailed data when different production inputs within an input category was used, e.g., N ammonium nitrate and N in urea for N fertilizers.

Table 1. Life cycle inventory: Inputs–outputs biomass production for both crops: Sunflower and oat/vetch. Cultivation period: One year—spring 2012 to winter 2013.

Inputs	CT *	RT I	RT II	RT III	NT
Resources					
Precipitation (m ³ /ha)	6300	6300	6300	6300	6300
Land Transformation (m ²)	10,000	10,000	10,000	10,000	10,000
Land Occupation (m ²)	10,000	10,000	10,000	10,000	10,000
Energy in biomass (MJ)	240,300	219,420	271,800	224,460	209,160
Carbon dioxide. in air (kg)	19,778.3	18,026.7	19,981.72	18,035.96	17,161.21
N ₂ fixation (kg)	78.47	72.87	86.8	63.28	71.05
Materials/Processes					
Tillage Treatments in Kg of fuel consumption					
a. Plough (kg)	81.6	x **	x	x	x
b. Heavy cultivator (kg)	x	44.22	x	x	x
c. Rotary cultivator (kg)	x	x	x	55.74	x
d. Strip (kg)	x	x	28.45	x	x
e. Medium cultivator (kg)	29.6	x	x	x	x
f. Disk harrow (kg)	28.8	12	17.97	6	x
Sowing/Fertilising (fuel consumption) (kg)	21.6	22.29	22.29	22.29	21.6
Sunflower seeds (kg)	6.24	6.24	6.24	6.24	6.24
Oat/Vetch seeds (kg)	230	230	230	230	230
Fertilisers					
a. N (all types) (Kg)	179.9	179.9	179.9	179.9	179.9
b. P ₂ O ₅ (kg)	106.65	106.65	106.65	106.65	106.65
c. K ₂ O (kg)	106.65	106.65	106.65	106.65	106.65
Herbicide application (fuel consumption) (kg)	0.998	0.998	0.998	0.998	
Herbicides (kg)	2.88	2.88	2.88	2.88	5.88
Irrigation (m ³)	3870	3870	3870	3870	3870
Transportation of inputs to field (fuel consumption) kg	0.45	0.45	0.45	0.45	1.996
Transportation of inputs to agriculture store(tkm)	2777.67	2777.67	2777.67	2777.67	2786.7
Harvesting (fuel consumption) (kg)	14.4	14.4	14.4	14.4	14.4
Baling (fuel consumption) (kg)	12.44	12.44	12.44	12.44	12.44
Bale loading pieces (p)	48	44	54	43	42
Transfer to side (fuel consumption)(kg)	5.4	5.4	5.4	5.4	5.4
Outputs					
Biomass in Kg of dry matter	13,350	12,190	15,100	12,470	11,620
Emissions to air, water, soil					

* CT = Conventional tillage; RT I = Reduced tillage I, using heavy cultivator; RT II using strip tillage; RT III using rotary cultivator; NT = No-tillage. ** x: no treatment.

The background data concerned all the information about the inputs production stage from raw material including the machinery and infrastructure production and all the operations under specific conditions. These data were taken from the Ecoinvent database, cut-off (also called recycled content) system model version 3.1 [33]. The semi-specific data concerned data coming from the Ecoinvent background database adapted for the conditions of the present study.

In the farm machinery input category, the processes from the Ecoinvent data like, “Tillage, ploughing”, “Tillage rotary and spring harrowing”, “Tillage chiseling and rotary cultivator”, “Sowing”, “fertilizing by broadcaster”, “Baling”, and “Transfer to side” were adapted to the data of the study, mainly for fuel consumption. All the other characteristics of the machines, like tractor, agricultural implement, shed production and maintenance, etc., remained the same as in the background data. This semi-specified farm machinery process was used as input for all the machinery use phase of the present study. For the fertilizers and herbicides application the background data were used, where different amounts of inputs within the input’s categories were distinguished, e.g., for N fertilizers N from urea was used, ammonium sulphate, and ammonium nitrate, while for pesticides the pesticides’ unspecified production and active ingredient compounds were used. Also, for the seed production, the background data were used. The irrigation process was adapted from the Ecoinvent database ‘Spanish irrigation market’ process, using the Greek conditions for irrigation, and a ground well for pumping water as a source. Energy use for pumping included electricity-powered pumps, which were modelled with country-specific datasets using the country’s electricity consumption mix and from diesel-powered pumps, generic data were used (diesel market ‘Europe, without Swiss’). Regarding transportation from the place of production to the point of sale, global freight process from

the background Ecoinvent database was used. The herbicides were assumed to have been produced in European countries and came to retail points by lorry. Likewise, the fertilizers were assumed to either have been produced in EU or the raw materials were extracted in European countries and came to Greece by lorry. Transport passenger car was used as semi-specific process for the transportation of the fertilizers and pesticides from the agri-store to the field.

The inputs of water from precipitation, the land occupation, the land transformation, the C captured as CO₂ from the crops, and the N₂ formed in the rhizobia of the cover winter crop, were considered inputs from natural resource (resource use type of elementary flows) meaning materials that had been drawn from the environment without previous human transformation or interventions that affect land dependent ecosystems. These resource uses cannot be categorized like the inputs from other human activities. Precipitation was taken from weather data of the closest weather station. The fixed N₂ produced in the rhizobia formations of the winter crop was taken from literature, where it accounted for 70% of the N uptake for Oat/vetch mix crop [34]. The CO₂ fixation from the atmosphere was estimated from the C-content in dry matter multiplied by the stoichiometric factor 44/12, based on the assumption that the C in the biomass is completely sourced from the air. The CO₂ bound from atmosphere was represented in the datasets as the exchange with the environment “carbon dioxide, in air”.

For land transformation, which is a change from one land use type to another as a result of a human activity, we used the area of 1 ha, the area required to produce the biomass of crops of the present study. For land occupation (occupied area multiplied by time), the resource flow occupation “occupation arable” was chosen to represent the cultivation of energy crops. It should be noted that the two cultivations, spring crop and winter crop, occupied six and a half and five and a half months, respectively, completing a whole year of cultivation.

The quantitative data of product output in the present study were defined as the kg dry matter of biomass produced in one ha and one year of cultivation. In the analyzed cropping system, the biomass and the seeds were collected together, so the agricultural harvesting work included the collection of the whole aboveground plant mass.

The emissions from the different agricultural practices into the environment (water, air, and soil) were estimated using the appropriate equations and emission factors (EF) (Table 2).

Table 2. Life cycle inventory—emissions.

Inputs	CT	RT I	RT II	RT III	NT	Emission Factors/Parameters	Equation used
Outputs: Emissions							
a. Emission to air							
Water m ³	9981.35	9981.35	9981.35	9981.35	9981.35		ETc = ET _o × Kc
Ammonia (kg) NH ₃	13.1	12.28	12.96	11.81	12.19	NPK – N = 0.04 kgNH ₃ – N/kgN AS – N = 0.08 kgNH ₃ – N/kgN Urea – N = 0.15 kgNH ₃ – N/kgN Conversion: NH ₃ – N to NH ₃ = 1.21 kgNH ₃ /kg NH ₃ – N	NH ₃ = kg N × EF × 1.21
Nitrous oxide or Dinitrogen monoxide N ₂ O (kg)	4.64	4.40	4.53	4.20	4.39	NH ₃ EF = 0.01 kg N ₂ O – N/kgNH ₃ – N NO ₃ – N EF = 0.0075 kg N ₂ O – N/kg NO ₃ – N N ₂ O EF = 0.01 kg N ₂ O – N/kg N Conversion: N ₂ O – N to N ₂ O = 1.57 kg N ₂ O/kg N ₂ O – N	N ₂ O = 1.57 × kg N (f + r) × (direct EF N ₂ O + indirect EF NH ₃ × NH ₃ – N + indirect EF NO ₃ × NO ₃ – N) f = fertilizer, r = rhizobia
Nitrogen oxides, NO _x (kg)	1	0.9	1	0.9	0.9	NO _x EF = 0.21 kg NO _x /kgN ₂ O	NO _x = 0.21 V × kg N ₂ O
CO ₂ fossil (kg)	114.83	114.83	114.83	114.83	114.83	1 kg of Urea – N = 1.57 kg CO ₂	CO ₂ = kg Urea – N × 1.57
CO ₂ land transformation (kg)	x	1367	1766	1430	2266		ΔCMineral = (SOC0 – SOC(0 – T))/D
b. Emission to water							
Water m ³	187.65	187.65	187.65	187.65	187.65		(Irrig + precipit) – ETc = GroundWater
Phosphate (PO ₄ ^{3–}) (kg)	0.07	0.07	0.07	0.07	0.07	Constant value of PO ₄ ^{3–} for a land use category = 0.07 kg/ha/a	P _{gw} = P _{gwl} × F _{gw} (Nemeck and Schnetzer 2012) P _{gwl} = average P leached to ground water, F _{gw} = correction factor for fertilisation by slurry
Nitrate NO ₃ [–] (kg) (leaching)	60.3	67.81	34.9	48.52	75.95		
c. Emission to soil							
Herbicides (kg)	2.88	2.88	2.88	2.88	5.88		

2.2.4. Impact Assessment

LCIA is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system [32]. Impact assessment phase was analyzed with respect to the methods used to quantify the impacts in different stages of the cause-effect, endpoint, and midpoint methods. Midpoints are used for a more specific and detailed analysis, whereas endpoints are useful to communicate the results obtained to broader audience. Typically, for an ISO-compatible study, results are presented at the midpoint level.

The ReCiPe midpoint (hierarchist) method was used in this study as the default method and IMPACT 2002+ midpoint as the second method to verify the robustness of the results. ReCiPe method, endpoint, and midpoint do not contain a water scarcity indicator, thus the regionally specific Pfister et al. [35] water scarcity method was also used. The two methods have the option to explore the results at endpoint. This analysis was added to the interpretation of the results for the selection of relevant impact categories. The results of a product LCA with an endpoint method can show the relative contribution of the “midpoint categories” to human health, ecosystems, and resources. Categories that have insignificant contribution to these endpoint categories are left out of the results at midpoint. It should be noted that emissions of fossil CO₂ can be determined accurately, but the CO₂ emissions/uptake from land transformation are difficult to be measured or calculated with much precision and are very uncertain. This is the reason that we reported them separately. The kinds of CO₂ emissions described here are:

- Fossil-based C emissions: C originating from fossil fuels that are used for producing and transporting agricultural inputs, for fueling the tractor, and from application of urea fertilizer.
- C emissions or uptake due to land transformation: Directly related to the crops.
- CO₂ uptake by the crops: CO₂ that is stored in plants as they grow, while the carbon taken up is released again when the biomass is used for generating energy, which nullifies the positive effect.

It should be pointed out that all the practices and materials used for completing the inventory were grouped in the impact assessment in groups representative of the data included. In the present energy crops study, the groups were: (1) Biomass production, (2) fertilizer production, (3) operations, (4) energy/fuel production, (5) capital goods, (6) seed production, and (7) pesticide production.

3. Results

3.1. Endpoint Method

The results of the Impact Assessment using the ReCiPe endpoint method combined with the Pfister et al. [35] method for scarcity in water are presented in Figure 3 for all the treatments of the study. In the endpoint level, the impact categories are aggregated into three endpoint categories:

- (a) Damage to human health (HH),
- (b) Damage to ecosystem diversity (ED),
- (c) Damage to resource availability (RA).

Figure 3 shows that the RT II (Disk harrow/strip tillage) treatment of the energy crop study had better performance compared to other treatments in the three areas of protection (AoPs), meaning that it was the least harmful treatment, according to the adapted ReCiPe endpoint method.

The results of the analysis per impact category are presented in Table S1. The purpose of the endpoint calculations was to determine the most important impact categories for the study by selecting those categories that contribute to the environmental impacts more than 1% of the total contribution for the present energy crops study per endpoint category. This is a helpful step to determine which impact categories are distinguished in the midpoint level, where a more detailed and specific analysis is applied. Thus, Table S1 presents the impact categories, where if a threshold of 1% is applied, then only seven impact categories remain in the endpoint level of the ReCiPe method: Climate

change, human toxicity, particulate matter formation, agricultural land occupation, metal depletion, fossil depletion, and water scarcity.

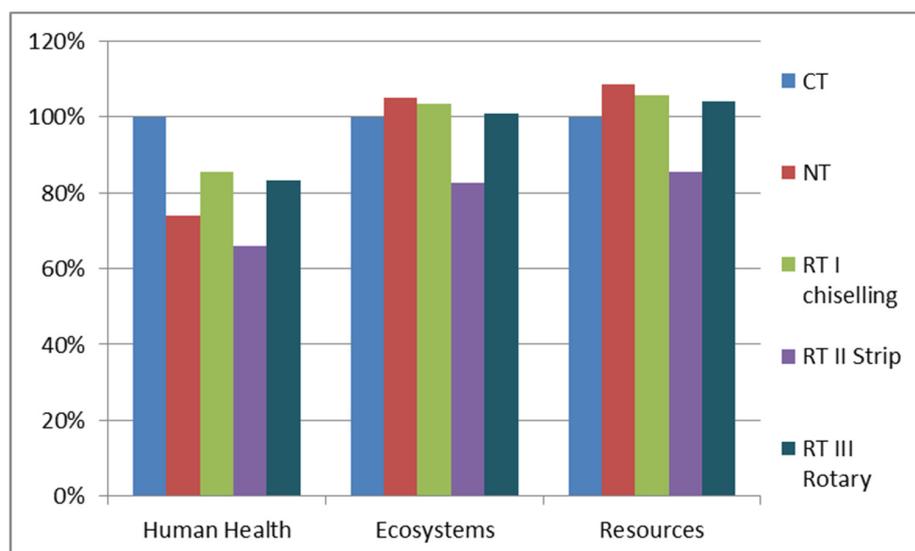


Figure 3. Results of impact assessment applied on energy crops study at the endpoint level using FU 1 kg of dry biomass.

3.2. Midpoint Method

The most important impact categories distinguished from the endpoint level analysis are the categories that will further be analyzed in the midpoint level analysis. The results of the impact assessment using the adapted ReCiPe midpoint method (combined with Pfister method) are presented in the Table 3 and in Figures 4 and 5.

Table 3. Impact assessment results for each treatment of the energy crop study; using ReCiPe midpoint 1.11 + Pfister et al. [35] water method.

Impact Category	Unit	CT	NT	RT I C	RT II S	RT III R
Fossil CO ₂ eq	kg CO ₂ eq	0.498	0.508	0.507	0.409	0.502
CO ₂ eq from land transformation	kg CO ₂ eq	0.000	−0.195	−0.112	−0.117	−0.114
CO ₂ uptake	kg CO ₂ eq	−1.524	−1.522	−1.524	−1.521	−1.520
CO ₂ eq Fossil + Land transform	kg CO ₂ eq	0.498	0.313	0.395	0.292	0.388
Human toxicity	kg 1.4-DB eq	0.046	0.049	0.047	0.038	0.047
Particulate matter formation	kg PM10 eq	0.001	0.001	0.001	0.001	0.001
Agricultural land occupation	m ²	0.839	0.958	0.915	0.739	0.895
Water depletion	m ³	0.201	0.230	0.220	0.177	0.215
Metal depletion	kg Fe eq	0.049	0.045	0.046	0.039	0.048
Fossil depletion	kg oil eq	0.119	0.116	0.118	0.095	0.116

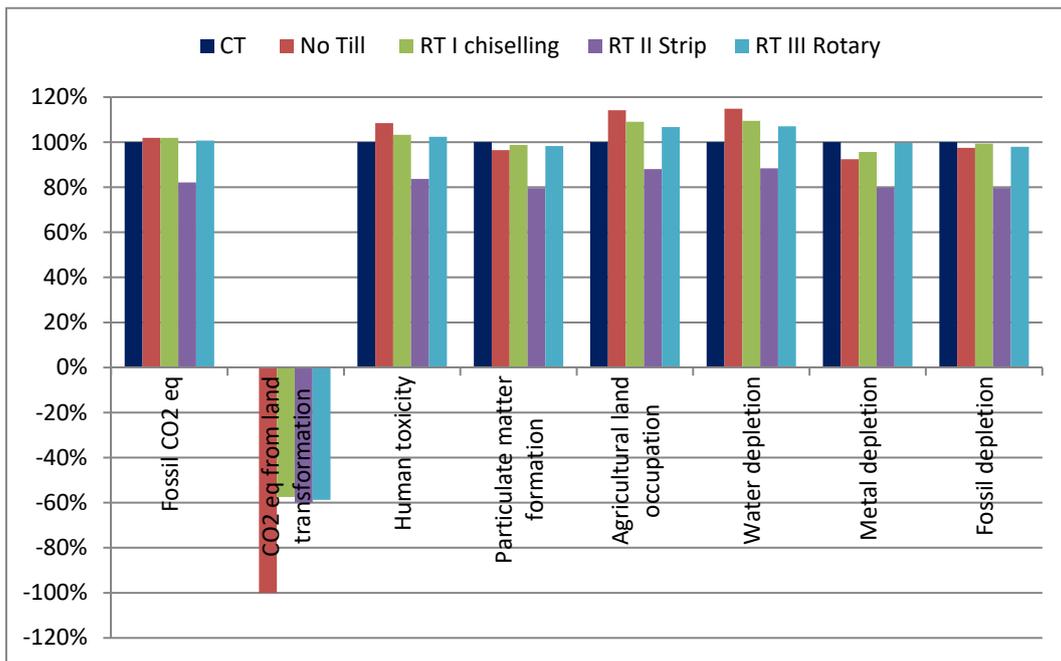


Figure 4. Comparison among the different tillage treatments to most important impact categories using as functional unit (FU) 1 kg of dry biomass.

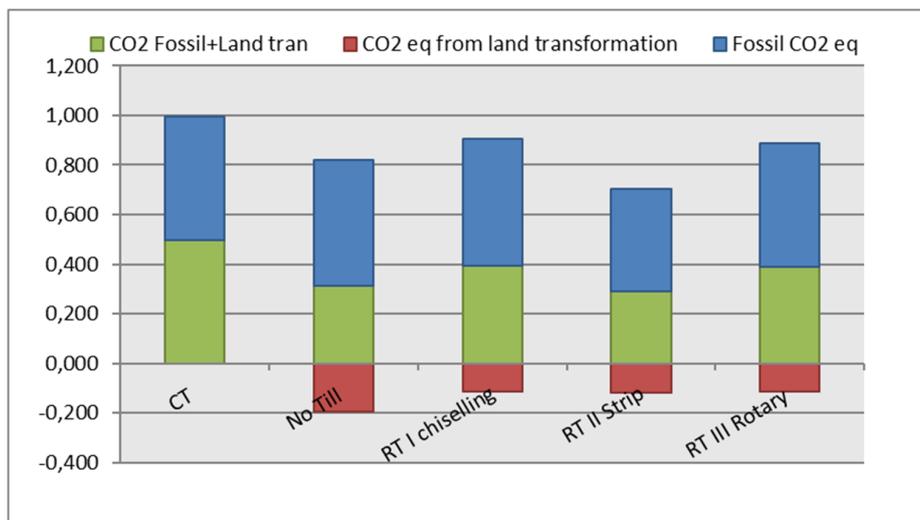


Figure 5. Total amount of CO₂ emission resulting from the addition of the two impact categories, that of Fossil CO₂ and CO₂ from Land transformation, using FU 1 kg of dry biomass.

CO₂ emissions are presented in two categories separately due to the high uncertainty of calculating CO₂ from land management transformation. The values of CO₂ uptake were almost the same for all the treatments, having a negative sign (Table 3) due to binding of CO₂ from the atmosphere to the biomass. As it was explained earlier, there is no advantage of CO₂ uptake at all, because at the use phase of agricultural products (which it is not included in the system boundary of the present study) the entire CO₂ uptake is lost to the air again due to combustion or digestion later in the life cycle of the product. In particular, in the use phase, when biomass will be investigated as a substitute for fossil fuels, as far as CO₂ emissions is concerned, the potential benefits will then be revealed. Thus, due to this nullifying effect, the CO₂ uptake impact category will not be further analyzed. CO₂ from land transformation has also a negative sign (Table 3, Figure 4). This means that C was sequestered into the soil for all the tillage treatments except of the conventional treatment. It is worthwhile to mention

that the biggest reduction at the CO₂ levels of the atmosphere was made by No Tillage treatment. Fossil CO₂ values (Figure 4) were at the same level for all the tillage treatments of the study (higher yield was combined with higher energy inputs or lower yield with lower energy inputs) except RT II (strip tillage), which was lower than the rest, probably due to the higher biomass production and the lower energy inputs.

In all the impact categories, the analysis showed that RT II S (strip tillage) treatment had lower percentages in the environmental impacts compared to the other tillage treatments of the study. The variations presented by impact categories for the rest experimental treatments were due to the yield variations among the treatments. It should be mentioned again that the analysis concerned the environmental impacts derived from one year of full cultivation with two successive crops, the spring 2012 sunflower and the winter 2013 oat/vetch crop. Also, it should be noted that the same inputs were used for each experimental treatment (materials and practices) except for the tillage practice. Therefore, the amount of fertilizer and irrigation water was the same. Only herbicide application was different among the treatments in the spring crop, where only in the No Till treatment was applied for seed bed preparation. The experimental design resulted in a handicap for the No-tillage and for some RT treatments, due to the reduced biomass production. Nevertheless, in Figure 5, the NT treatment is very close to RT II S treatment, concerning the total amount of CO₂ emitted in the atmosphere. This result mean that the low biomass production of the NT treatment was compensated by the decrease in fuel consumption (reduced by 71% compared to CT) presenting a similar performance with the RT II S treatment as far as CO₂ emissions is concerned.

The environmental profile of each tillage treatment of the energy crop study is presented in Appendix A (Figures A1–A5) for all the tillage treatments. Each graph depicts the contribution of each process group to the most important impact categories for the study. All the emissions of substances to air, water, and soil from the biomass production phase in the different tillage treatments were represented by CT, RTI, RTII, RTIII, and NT biomass group. The biomass production phase was almost exclusively responsible for the emissions in the Agricultural land occupation category and CO₂ from land transformation. These results were due to land use for specific period, during growth cultivation and to the C sequestration in soil from land management change of use, respectively. Also, biomass production group covered a part of Fossil CO₂ category with similar percentages (23–25%) in all tillage treatments, and a part of Particulate matter formation ranged 25–29% also for all the tillage treatments. The biomass production phase had no contribution to Human toxicity, meaning that production phase was not responsible for emissions included in this impact category. The diesel consumption in tractor uses, gasoline consumption in transportation, and electricity use in irrigation were represented from the Operation in the graphs. As it is depicted mainly in the Water Depletion impact category and consequently in Particulate matter formation and Fossil CO₂, the operations showed significant contribution, with CT tillage treatment having higher amounts in Particulate matter formation and Fossil CO₂ (17% and 10%, respectively), while the lowest was recorded in No-tillage treatment (7% and 4%). The agricultural machinery production and maintenance of all the equipment and machinery used were included in the Capital goods group and had an important contribution percentage in the majority of the impact categories in all the treatments. Contribution analysis showed that the three most contributing processes were biomass production (CT = 23%, RTI = 33%, RTII = 33%, RTIII = 33%, No Till = 34%), the irrigation (11% in all treatments), and agricultural machinery (CT = 10%, all RT = 8%, NT = 9%).

3.3. Comparison with Monoculture Cotton Crop Using Different Functional Units

The results of the crop rotation system with two successive crops in one year is compared with the prevailing monoculture cotton crop system. The same adapted ReCiPe midpoint method was used for this comparison following the steps of the impact assessment analysis conducted earlier. Thus, an existing cotton production process with data originating from USA was analyzed initially with ReCiPe endpoint method, to distinguish the most important impact categories, and afterwards with

adapted ReCiPe midpoint method. The endpoint analysis revealed as most important the same impact categories with the energy crops studied plus the Terrestrial ecotoxicity, mainly due to many pesticide usage in a cotton cultivation. The cotton crop is a multi-output process (cotton fiber and cotton seed) that had been under economic allocation. The results coming from midpoint analysis are presented in the Table 4.

Table 4. Impact assessment results cotton production, using ReCiPe midpoint 1.11 + Pfister et al. [32] water method.

Impact Category	Unit	Total	Cotton Fibre {US} Cotton Production Alloc Rec, Adapted	Cotton Seed {US} Cotton Production Alloc Rec, Adapted
Fossil CO ₂ eq	kg CO ₂ eq	1.533	1.226	0.307
Human toxicity	kg 1.4-DB eq	0.211	0.169	0.042
Particulate matter formation	kg PM10 eq	0.004	0.003	0.001
Terrestrial ecotoxicity	kg 1.4-DB eq	0.100	0.080	0.020
Agricultural land occupation	m ²	4.204	3.363	0.841
Water depletion	m ³	0.492	0.393	0.098
Metal depletion	kg Fe eq	0.105	0.084	0.021
Fossil depletion	kg oil eq	0.382	0.306	0.076

Agricultural systems are multi-functional needing more than a single FU to be adequately described. Thus, three FU was proposed by Nemecek et al. [36] that consider important aspects of agricultural production:

- Land management function: Describes the cultivation of land with the hectare × year. This function could minimize the environmental impacts in terms of area and time, while maintaining agricultural production.
- Productive function: Agricultural activities aim at producing food, feed, or biomass for other uses (bioenergy, renewable materials). The goal is to minimize the environmental impacts in terms of product units (e.g., impact per kg of dry matter (DM) or MJ of energy produced).
- Financial function: From the perspective of the farmer, income is the main motivation for agricultural production. The FU of impact per euro is measured with different economic indicators.

In the present study, the first two functional units will be used in the comparison of the two cropping systems, cotton monoculture and biomass crop rotation. In Figures 6 and 7, the impact from using a FU of 1 kg of dry biomass and 1 MJ, and in Figure 8 using FU of 1 ha, are presented.

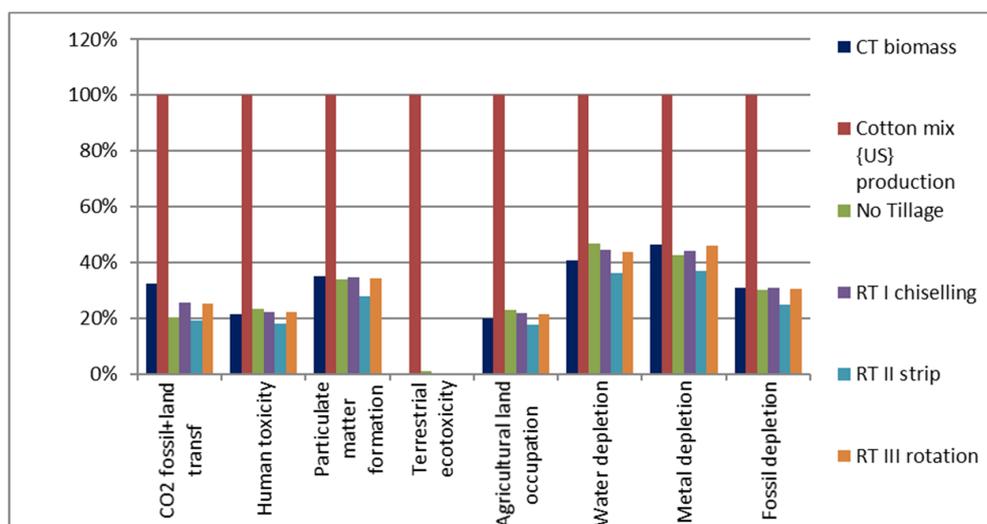


Figure 6. Comparison of environmental impacts to most important impact categories between cotton crop monoculture system and energy crops in crop rotation system using as FU 1 kg of dry biomass production.

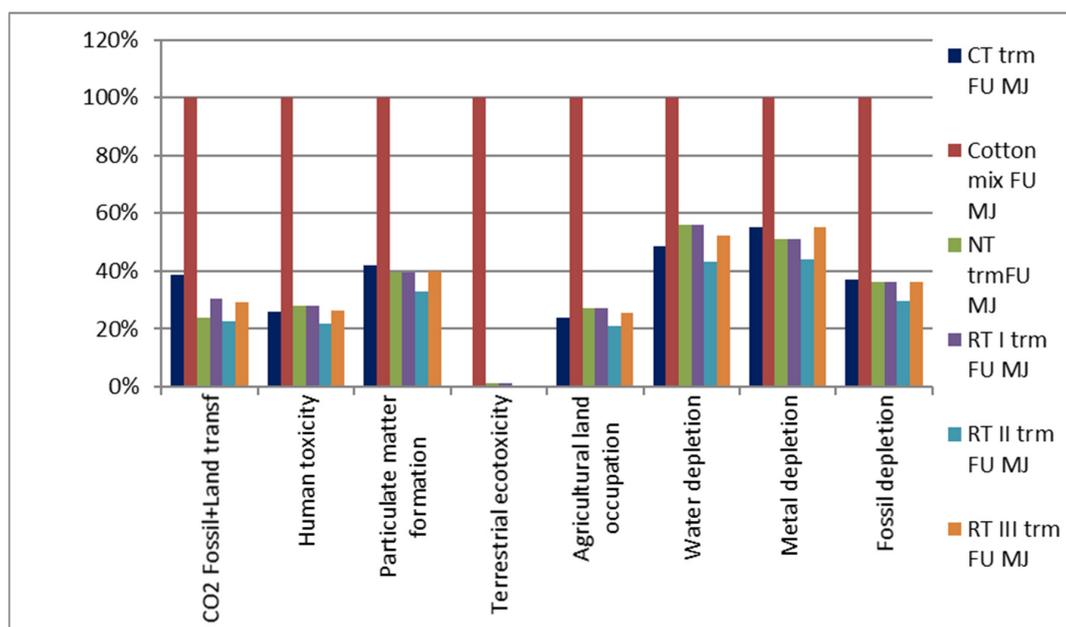


Figure 7. Comparison of environmental impacts to most important impact categories between cotton crop monoculture system and energy crops in crop rotation system using as FU. FU is 1 MJ.

It is clear that the monoculture cotton crop had a bigger environmental impact than the energy crops when the FU is 1 kg of biomass production or 1 MJ. It should be noted that cotton yield was very low compared to the yield of the two energy crops. Nevertheless, the purpose of cultivating energy crops was to produce biomass for combustion or other transformation process. Cotton crop production, though, had different use purpose. Thus, the comparison using FU 1kg of biomass production cannot interpret the results correctly, due to different end products between the two cropping systems. Additionally, when the mass-based FU 1 MJ was used then we had the same end use, that is energy from crops (biomass combustion) and the results were also the same (higher percentages in all impact categories for all the treatments in the cotton crop). On the other hand, when the FU used for the impact assessment analysis is 1 ha (Figure 8), the end use is also the same, the comparison of land use; but this is a not a life cycle analysis anymore.

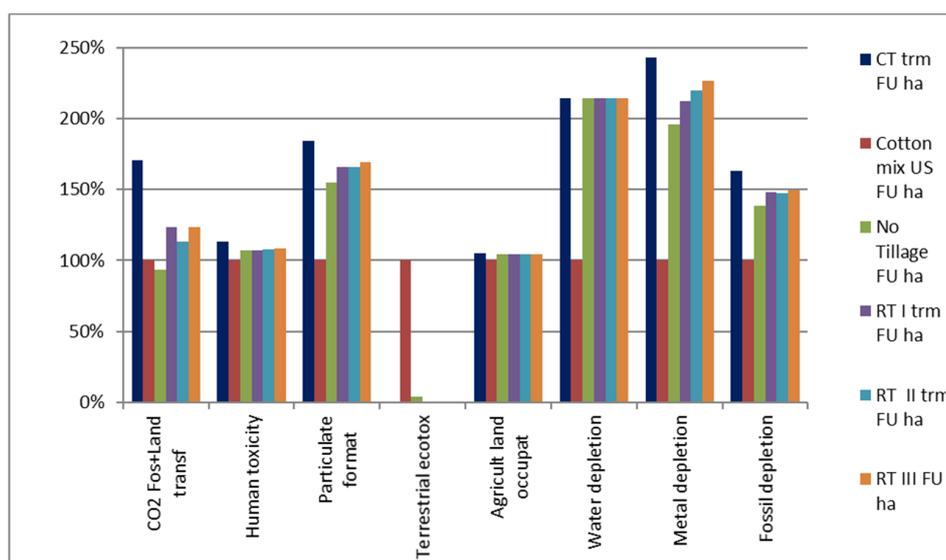


Figure 8. Comparison between cotton monoculture crop and energy crops in crop rotation, if the FU is 1 ha.

The comparison depicted in Figure 8 shows that No tillage treatment had the best environmental performance in relation to the total CO₂ emissions, and better environmental performance in the most impact categories compared to other treatments in the energy crop study. It should be kept in mind that cotton is cultivated one year, growing in the field for half year. The energy crops in the present study were cultivated for one year, growing in the field the whole year (double crop/year). This means that many of the agricultural practices are doubled, i.e., machinery use, fertilizer amount, while irrigation was applied only for spring energy crop but with three times more irrigation water than cotton crop (Water depletion). Thus, Metal and Fossil depletion, as well as CO₂ emissions and Particulate matter formation, had increased values compared cotton crop with FU 1ha. However, Human toxicity had small variations among cotton crop and biomass production, since this impact category represented background processes and is almost always dominated by waste treatment of coal power plants and coal mining. Also, Agricultural land occupation was almost the same for all the crops, since the land use is 1 ha. One issue that should be highlighted is that the increased values in the related to fertilization impact categories (CO₂ emissions and Particulate matter formation) was merely due to the inclusion of the rhizobium symbiotic crop (oat/vetch) in the crop rotation of the energy crop study. The amount of biological nitrogen fixation had been accounted in the total amount of synthetic nitrogen applied in the present study. This additional amount of N may end up increasing the related environmental emissions, i.e., (N₂O, NH₃ and NO₃), as other studies have found. Tuomisto et al. [37], in a cropping system used in Spain, introduced grain legumes into low-input crop rotation with sunflower, leading to an increase in most of the environmental impacts considered, since no mineral fertilizer was replaced in the process.

4. Discussion

A large amount of site specific data was collected for all inputs and agricultural practices taking place in the present energy crop study. The most important emissions from the field (N₂O, NO_x, NH₃, CO₂) were calculated based on the collected and available data according to the most recent scientific insights for conducting agricultural LCAs (Table 2). Potential limitation in the present study was the one-year analysis, which may result in inaccurate calculation of carbon changes in soil. It should be kept in mind that ΔSOC (difference in soil carbon) is difficult to be determined and may increase the uncertainty in the analysis. If more years of data will be available then a more accurate assessment of the tillage effect to the SOC will be made. Another potential limitation, concerning the comparison of the tillage treatments, could be the use of the same inputs like, fertilization, herbicide application, and irrigation (spring crop). However, the diversification of the inputs in relation to the tillage treatment according to the expected yield, which is generally lower in no till and the reduced tillage (except disk harrow-strip tillage reduced tillage treatment), could influence the outcome in a way that the results could not be attributed to the tillage practice. Finally, one more limitation of the study could be the use of the specific cotton production process, which is not a full representative of a cotton production system in the area of Thessaly. However, given that there are no other relevant studies, this could offer a comparison between the existing cropping system and the proposed innovative crop rotation.

The impact categories contributing most to the total environmental impact according to the impact assessment analysis were Climate Change (mainly CO₂ and N₂O emissions), Human toxicity, Particulate matter Formation, Agricultural land occupation, and Water, Metal, and Fossil depletion (Table 3). The results from the adapted midpoint method for each treatment (Appendix A, Figures A1–A5) showed that background processes (i.e., groups of fertilizer, energy/fuel, seed production, and capital goods, attributed to background processes) were almost exclusively responsible for the impacts of Human toxicity (this impact category is almost always dominated by waste treatment from coal power plants and coal mining wastes), and Metal and Fossil depletion impact categories (because the mineral and fossil resource extraction take place in the mining processes). Regarding the Fossil depletion impact category, it should be clarified that fossil resources were needed for production and transportation of agricultural inputs and for machinery production. The foreground processes

were represented by biomass production and operations groups. The biomass production group (including all inputs, land use, and agricultural practices required for biomass production) was responsible for a substantial amount of Fossil CO₂ emissions (CT = 23%, RTI, II, III = 24%, NT = 25%; Appendix A, Figures A1–A5), mainly due to fertilization. Also, it was exclusively responsible for CO₂ emissions from land transformation (resulting from land management change) and Agriculture land occupation categories. Biomass production group had a quite large participation in the Particulate matter formation (CT = 25%, RTI, III = 27%, RTII = 28%, NT = 29%; Appendix A, Figures A1–A5), also due to fertilizer applications, but a small contribution to Water depletion. Water depletion impact category is attributed to the operation group mainly due to energy (electricity) needed for pumping the water. Also, operation group (including fuel and electricity consumption) contributes to Fossil CO₂ (CT = 10%, RT I, III = 7%, RT II = 6%, NT = 4%; Appendix A, Figures A1–A5), and to Particulate matter formation impact categories (CT = 17%, RTI, II = 11%, RT III = 12%, NT = 7%; Appendix A, Figures A1–A5), revealing the contribution of fuel consumption and the machinery exhaust gases, respectively, to Fossil CO₂ and Particulate matter impact categories. In Tables S2–S11, the inventory substances' emissions are presented for Fossil CO₂ and Particulate matter formation impact categories, and only for foreground processes, resulting from the primary data of the study in groups of Biomass production and Operation. Fossil CO₂ and Particulate matter formation impact categories depict the use of fertilizers. For all the tillage treatments, N₂O emissions to air from Fossil CO₂ category, and NH₃ emissions to air from Particulate matter formation category were totally responsible for the impact to the environment of the Biomass production group. Also, CO₂ fossil emission to air from Fossil CO₂ category and the N₂O from Particulate matter formation category were totally responsible for Operation group impact to the environment. Thus, fertilization was revealed to be the main driver for environmental impacts followed by fuel consumption during the biomass production for all the treatments. These results agree with the recent LCA study of Nemecek et al. [19], where, in an LCA eco-efficient crop rotation with crop combination study, they found that N management was the key driver for the environmental impact, revealing a strong correlation between them. They suggested that diverse crop rotations with reduced N inputs are a promising way to reduce the environmental impacts of intensive arable crops. Furthermore, Becenetti et al. [22], in a similar study to the present study, analyzed the environmental performance of three different tillage practices—conventional tillage, minimum tillage, and no tillage—of two cropping systems (single crop system: Only one crop cultivated in one season and double crop system: Two crops grown in sequence) in cereal production. They found that the fertilizer application and diesel consumption and production were the main processes with the greater influence on the overall environmental burden.

When tillage treatments were compared, the results with ReCiPe endpoint and midpoint methods, respectively, revealed that the RT II S (Reduced Tillage II using strip tillage) treatment presented the best environmental performance compared to all the other tillage treatments in all the important impact categories. This result is in agreement with several studies [22,28,38,39]. However, the differences in the methodology and the way the “Reduced” and “No Tillage” agricultural practices are defined (even the conventional tillage found to use other than ploughing machinery) makes it difficult to have identical results. In a general perspective, though, it is highlighted that with respect to conventional tillage, reduced tillage and no tillage could achieve better environmental performances [22,28,38,39]. The reduction of the environmental load was mainly due to lower diesel fuel consumption and secondly to other inputs like fertilization, water, and seed use. Moreover, Küsterman [28], after conducting a more thorough research, revealed the benefits of reduced tillage over conventional in relation to lower consumption of diesel fuel (reduced by 35%) (direct input of diesel fuel and electricity) and fossil energy (by 10%) (indirect input of fossil energy), as well as to C sequestration and N accumulation in the soil. When two different reduced tillage treatments were compared (a chisel plow 18 cm and 8 working depth), the key factor for better environmental impacts was yield. They stated that the significant decrease in yield reduced the nitrogen and energy efficiency and raised yield-related GHG emissions in comparison to other treatment. Similar results were also found in the present study,

where the comparison among the RT (chiseling, disk harrow/strip, rotary cultivator) treatments showed that RT using strip tillage had lower CO₂ emissions compared to other due to higher yield. Generally, RT II (disk harrow/strip) presented the lowest emissions in all impact categories due to highest yield (15.1 t/ha) and the reduced fuel consumption compared to CT (reduced by 48%). It should be noted that NT treatment had the lowest fuel consumption compared to CT (reduced by 71%). However the lowest biomass production of this treatment was responsible for its medium environmental performance.

An important issue that should be highlighted concerns the C accumulation in soil. The carbon soil depletion is an extremely important factor for GHG emissions of cropping systems [28]. Numerous investigations reported using methods of no or conservation tillage supported C sequestration, while conventional tillage led to soil organic carbon (SOC) decline and CO₂ released to the atmosphere [28,29,40]. In the present study, the highest SOC reserves were obtained in NT treatment, followed by RTII (disk harrow/strip), RTIII (rotary), and RTI (chiseling). SOC reserves were inversely correlated to the tillage intensity and the depth of soil disturbance. The lowest SOC levels were in the CT ploughed treatment. However, annual SOC changes are relatively small compared to the total SOC pool. According to Körschens [41], long-term field experiments (minimum of 10 years) should be arranged in order to detect differences in humus content. The annual changes in C content are spatial variable and generally small. In addition to this, Baker et al. [42] stated that errors may occur in sampling depth, sample preparation, and laboratory analyses, concluding that “Studies that have involved deeper than 30 cm sampling generally show no C sequestration benefit for conservation tillage, often show more C in conventionally tillage systems”. In the present study, samples were taken from a maximum soil depth of 30 cm, which suggests that the significant effects of tillage on the SOC reserves were taken into account (soil depth of 0–30 cm is the depth that the majority of the studies consider in their experiments). The measured Δ SOC in the present study concerned an intermediate measurement, and another measure of SOC will take place at the end of a three-year experiment resulting in more precise calculations of Δ SOC, revealing more accurate effects of tillage treatments to the SOC.

The comparison among the tillage treatments revealed that reduced tillage (RT) II disk harrow (DH)/strip tillage (STR) treatment resulted in the best environmental performance compared to all the other tillage treatments in all the important impact categories. RT II DH/STR treatment used a strip tillage machine for seedbed preparation before planting spring crops. For winter crops, primary and secondary tillage was carried out by a disk harrow at 6–8 cm. RT II DH/STR treatment had the highest yield (15.1 t/ha) and at the same time a substantial decrease in fuel consumption compared to conventional tillage (CT) (reduced by 48%). Therefore, RT II S presented the lowest emissions in all impact categories per kg biomass produced. It should be noted, though, that no tillage (NT) treatment had the lowest fuel consumption compared to CT (reduced by 71%) but produced the lowest biomass and ended with a medium environmental performance. The tested double cropping rotation system for biomass production compared to the prevailing in the area cotton crop using conventional tillage presented reduced environmental impact in all categories when a mass-based functional unit (FU) was used (Figure 7). That is, when the mass-based FU was used (1 kg DM or 1 MJ), the monoculture single cotton crop had higher environmental impact than the energy crops. However, when a comparison between monoculture cotton crop system and a crop rotation system of energy crops was made using different FU for the LCIA analysis, the results could be interpreted differently. Therefore, when 1 ha of a cotton crop cultivation was compared with 1 ha of the tested energy crops, cultivation using reduced input levels, as it was cotton crop, had better environmental performance in almost all impact categories except CO₂. This means that when comparing cropping systems based on yield production (mass-based FU), the system with higher production has better environmental impact profile, as in our case of study. On the other hand, when area-based FU was used, yield is no more the key driver of the comparison. Productivity per hectare is an important parameter that influences the impact per unit of the product. Productivity is also related to the amount of inputs that is used. Using hectare as the FU does not take the productivity into account. Then, the amounts of inputs used are considered the key issue. However, this is not an LCA analysis anymore, since LCA is a product-based method of

assessment. It is clear that the productivity of crops is the most important factor for the production of food, and thus humans' survival, and in this factor the LCA is based. Additionally, when FU was 1 ha, NT treatment had the best environmental performance in relation to the total CO₂ emissions between the two cropping systems, but also presented better environmental performance among the tillage treatments of the energy crop study in the most impact categories. NT treatment using direct planting with a no till pneumatic drilling machine for winter crops and a pneumatic planting machine for spring row crops resulted in reduced fuel consumption compared to CT (reduced by 71%) and the other tillage treatment. It is clear from the results that a land use change from cotton monoculture to crop rotation for energy crops (which can also be animal feed) could be beneficial for the environment when considering yield. The area-based analysis gave some advantage to cotton monoculture but did not take into account the productivity that is a prerequisite to cover human needs. From this point of view, no till or reduced tillage biomass production gave the best overall results.

Monoculture cropping system have been the dominant cropping system in the tested area for a long time. Adopting an innovative double crop rotation system of energy crops, using conservation tillage is aimed to improve the environmental and economic performance of the cropping system, while leading to more sustainable cultivation by improving soil organic matter content, i.e., C sequestration, decreasing soil erosion, reducing fertilizer use by using N-fixing legume crops, and finally, reducing pesticides inputs by restricting pest presence and damage, using crop rotation. Many environmental research studies have focused on the environmental profile of specific crops [9,22], while a substantial number was concerned with the environmental impacts from different agricultural practices or different cropping systems [21,22,38,39]. Crop residue management and land use management changes, from monoculture (using conventional tillage and, in most cases, burning or removal of the residues) to a crop rotation using conservation tillage (reduced and no-till tillage) were also issues under consideration in the current study. The reference scenario of the monoculture conventional crop corresponded to the cotton cultivation. Planting winter cover crops can compensate of some disadvantages (i.e., soil organic carbon levels and soil erosion) occurring when removing crop residues in energy crops. Cover crops also permit crop residues to be harvested without adverse effects to the environment, like soil erosion. Thus, utilization of crop residues and winter cover crops can improve the eco-efficiency of the cropping systems [11]. In the present study, an LCA methodology was used to support the experimental results, revealing the benefit of lower environmental impact when adopting the proposed such novel cropping system.

5. Conclusions

In the present study, a crop rotation combined with reduced or no tillage treatment and presented as a possible solution to initially substitute the monoculture cropping system prevailing in the area and secondly to alleviate the effects of whole biomass (whole crop or crop residues) removal from the field as expected to happen with second-generation biofuels production. An LCA methodology was adopted to assess the environmental implication of a new technology in agriculture, which is conservation tillage agriculture, and also to evaluate the environmental benefit of introducing an innovative double crop rotation per year system. The LCIA characterization results used primary data of one year, including two successive crops—spring and winter crops. The main conclusions emerged from the present LCA study are summed up below:

- When the cropping system was analyzed concerning inputs and outputs, the fertilization was the main driver for environmental impacts followed by fuel consumption during the biomass production for all the treatments.
- When the different tillage practices were compared, RT II S treatment presented the best environmental performance (lowest emissions per kg biomass produced) compared to all the other tillage treatments in all the most important impact categories.
- When the mass-based FU was used (1 kg DM or 1 MJ), the monoculture single cotton crop had higher environmental impact than the energy crops.

- When the area-based FU was used (1 ha) No tillage treatment had the best environmental performance in relation to the total CO₂ emissions between the two cropping systems, as well as presenting better environmental performance among the tillage treatments of the energy crop study in the most impact categories.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/17/6978/s1>, Table S1: title: Impact assessment results using ReCiPe 1.11 + Pfister et al. (2009) endpoint method, Table S2, S4, S6, S8, S10: Fossil CO₂ Inventory substances' contribution to impact category having a threshold of 2% (cut off 2%), for CT, RTI, RTII, RTIII and NT treatments, Table S3, S5, S7, S9, S11: Particulate Matter formation Inventory substances' contribution to impact category having a threshold of 2% (cut off 2% for CT, RTI, RTII, RTIII and NT treatments).

Author Contributions: Conceptualization, A.V., T.G. and S.F.; methodology, A.V.; data curation C.K.; writing—original draft preparation, A.V. and T.G.; writing—review and editing, S.F., N.K. and T.G.; supervision, T.G. All authors have read and agreed to the published version of the manuscript

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

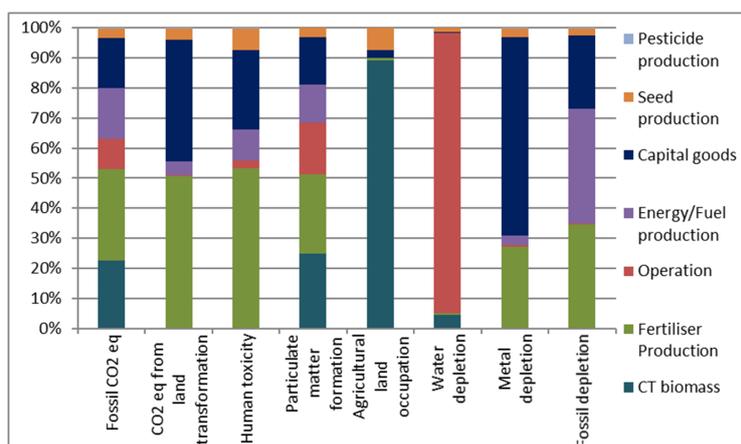


Figure A1. Processes contribution to the most significant impact categories for Conventional tillage treatment.

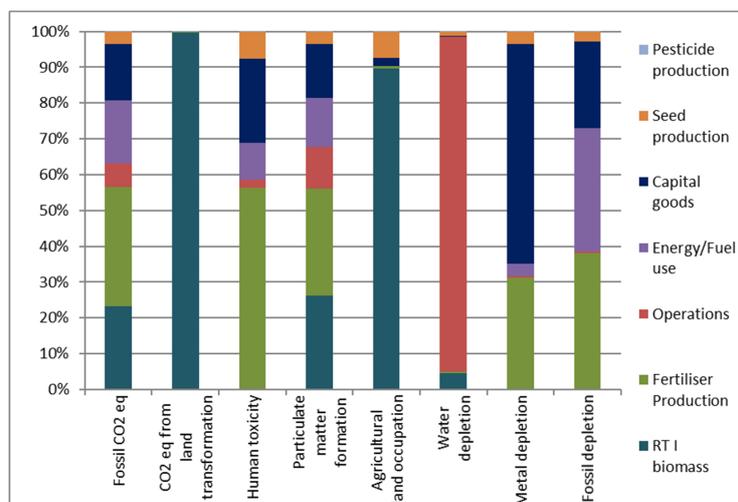


Figure A2. Processes contribution to the most significant impact categories for Reduced tillage I (chiselling) treatment.

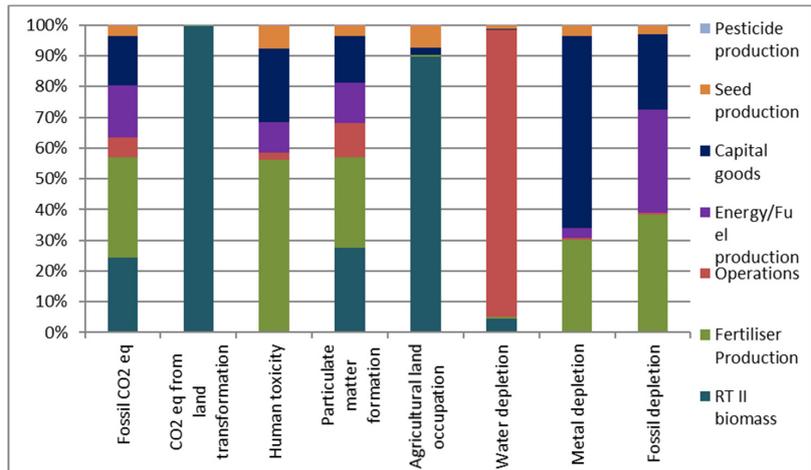


Figure A3. Processes contribution to the most significant impact categories for Reduced Tillage II S (disk harrow/strip) treatment.

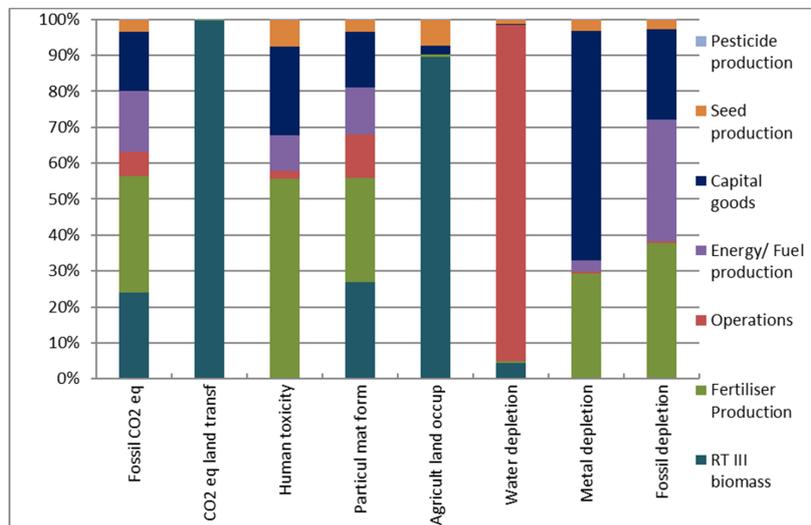


Figure A4. Processes contribution to the most significant impact categories for Reduced Tillage III (Rotary).

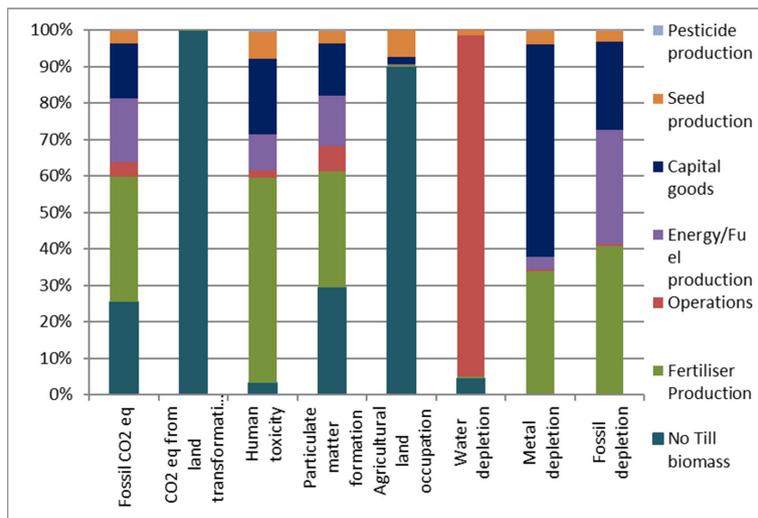


Figure A5. Processes contribution to the most significant impact categories for No-tillage treatment.

References

1. Cherubini, F.; Neil, D.; Birda, D.N.; Cowie, A.; Jungmeier, G.; Schlamadinger, B.; SusanneWoess-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. [CrossRef]
2. Mann, M.K.; Spath, P.L. Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System. Report. Available online: <https://www.osti.gov/biblio/567454> (accessed on 25 August 2020).
3. Sims, R.; Taylor, M.; Saddler, J.; Mabee, W. From 1st to 2nd Generation Biofuel Technologies. An Overview of Current Industry and RD&D Activities. Available online: <http://task39.sites.olt.ubc.ca/files/2013/05/From-1st-to-2nd-generation-biofuel-technologies.pdf> (accessed on 25 August 2020).
4. Christoforou, E.; Fokaides, P.A.; Koroneos, C.J.; Recchia, L. Life Cycle Assessment of first-generation energy crops in arid isolated island states: The case of Cyprus. *Sustain. Energy Technol. Assess.* **2016**, *14*, 1–8. [CrossRef]
5. Weldemichael, Y.; Assefa, G. Assessing the energy production and GHG (greenhouse gas) emissions mitigation potential of biomass resources for Alberta. *J. Clean. Prod.* **2016**, *112*, 4257–4264. [CrossRef]
6. Ubando, A.T.; Rivera, D.R.T.; Chen, W.H.; Culaba, A.B. A comprehensive review of life cycle assessment (LCA) of microalgal and lignocellulosic bioenergy products from thermochemical processes. *Bioresour. Technol.* **2019**, *291*, 121837. [CrossRef]
7. Crutzen, P.J.; Mosier, A.R.; Smith, K.A.; Winiwarter, W. N₂O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys.* **2008**, *8*, 389–395. [CrossRef]
8. Smith, K.A.; Searchinger, T.D. Crop-based biofuels and associated environmental concerns. *GCB Bioenergy* **2012**, *4*, 479–484. [CrossRef]
9. Gasol, C.M.; Gabarrell, X.; Anton, A.; Rigola, M.; Carrasco, J.; Ciria, P. Life cycle assessment of a Brassica carinata bioenergy cropping system in southern Europe. *Biom. Bioenergy* **2007**, *31*, 543–555. [CrossRef]
10. Quintero, J.A.; Montoya, M.I.; Sanchez, O.J.; Giraldo, O.H.; Cardona, C.A. Fuel ethanol production from sugarcane and corn: Comparative analysis for a Colombian case. *Energy* **2008**, *33*, 385–399. [CrossRef]
11. Kim, S.; Dale, B.E. Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. *Biomass Bioenergy* **2005**, *29*, 426–439. [CrossRef]
12. von Blottnitz, H.; Curran, M.A. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *J. Clean. Prod.* **2007**, *15*, 607–619. [CrossRef]
13. Pimentel, D.; Patzek, T. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Nat. Res.* **2005**, *14*, 65–76. [CrossRef]
14. Farrell, A.E.; Plevin, R.J.; Turner, B.T.; Jones, A.D.; O'Hare, M.; Kammen, D.M. Ethanol can contribute to energy and environmental goals. *Science* **2006**, *311*, 506–508. [CrossRef] [PubMed]
15. Larson, E. A review of LCA studies on liquid biofuels for the transport sector. In Proceedings of the Scientific and Technical Advisory Panel of the Global Environment Facility (STAP) Workshop on Liquid Biofuels, New Delhi, India, 29 August–1 September 2005.
16. Zah, R.; Boni, H.; Gauch, M.; Hischier, R.; Lehmann, M.; Wager, P. Life Cycle Assessment of Energy Products: Environmental Assessment of Biofuels. Available online: <https://www.osti.gov/etdweb/biblio/21208801> (accessed on 25 August 2020).
17. Del Grosso, S.; Smith, P.; Galdos, M.; Hastings, A.; Parton, W. Sustainable energy crop production. *Curr. Opin. Environ. Sustain.* **2014**, *9*, 20–25. [CrossRef]
18. Kulak, M.; Nemecek, T.; Frossard, E.; Gaillard, G. How eco-efficient are low-input cropping systems in western Europe, and what can be done to improve their eco-efficiency? *Sustainability* **2013**, *5*, 3722. [CrossRef]
19. Nemecek, T.; Hayera, F.; Bonnin, E.; Carrouee, B.; Schneider, A.; Viviere, C. Designing eco-efficient crop rotations using life cycle assessment of crop combinations. *Eur. J. Agron.* **2015**, *65*, 40–51. [CrossRef]
20. Malhi, S.S.; Lemke, R.; Wang, Z.H.; Chhabra, B.S. Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. *Soil Tillage Res.* **2006**, *90*, 171–183. [CrossRef]
21. Goglio, P.; Bonari, E.; Mazzoncini, M. LCA of cropping systems with different external input levels for energetic purposes. *Biomass Bioenergy* **2012**, *42*, 33–42. [CrossRef]
22. Bacenetti, J.; Fusi, A.; Negri, M.; Fiala, M. Impact of cropping system and soil tillage on environmental performance of cereal silage productions. *J. Clean. Prod.* **2015**, *86*, 49–59. [CrossRef]

23. Sainju, U.M.; Stevens, W.B.; Caesar-Tonthat, T.; Jabro, J.D. Land use and management practices impact on plant biomass carbon and soil carbon dioxide emission. *Soil Sci. Soc. Am. J.* **2010**, *74*, 1613–1622. [[CrossRef](#)]
24. Robertson, G.P.; Vitousek, P.M. Nitrogen in agriculture: Balancing the cost of an essential resource. *Annu. Rev. Environ. Res.* **2009**, *34*, 97–125. [[CrossRef](#)]
25. Al-Kaisi, M.M.; Kruse, M.L.; Sawyer, J.E. Effect of nitrogen fertilizer application on growing season carbon dioxide emission in a corn-soybean rotation. *J. Environ. Qual.* **2008**, *37*, 325–332. [[CrossRef](#)] [[PubMed](#)]
26. Liebig, M.A.; Tanaka, D.L.; Gross, J.R. Fallow effects on soil carbon and greenhouse gas flux in central North Dakota. *Soil Sci. Soc. Am. J.* **2010**, *74*, 358–365. [[CrossRef](#)]
27. Al-Kaisi, M.M.; Yin, X. Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn-soybean rotation. *J. Environ. Qual.* **2005**, *34*, 437–445. [[CrossRef](#)] [[PubMed](#)]
28. Küsterman, B.; Munch, J.C.; Hólsbergen, K.J. Effects of soil tillage and fertilization on resource efficiency and greenhouse gas emissions in a long-term field experiment in Southern Germany. *Eur. J. Agron.* **2015**, *49*, 61–73. [[CrossRef](#)]
29. Bird, N.D.; Cherubini, F.; Cowie, A.; Fijan-Parlov, S.; Moellersten, K.; Pingoud, K.; Rueter, S.; Schlamadinger, B.; Soimakallio, S.; Van Stappen, F.; et al. Bioenergy: The relationship with greenhouse gases in agriculture and forestry. In Proceedings of the 16th European Biomass Conference & Exhibition, Valencia, Spain, 2–6 May 2008.
30. Cherubini, F.; Strømman, A.H. Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresour. Technol.* **2011**, *102*, 437–451. [[CrossRef](#)]
31. ISO 14040. In *Environmental Management—Life Cycle Assessment—Principles and Framework*; International Standard Organization: Geneva, Switzerland, 2006.
32. ISO 14044. In *Environmental Management—LCA—Requirements and Guidelines*; International Standard Organization: Geneva, Switzerland, 2006.
33. Ecoinvent Database. Ecoinvent Data v3.1, Life Cycle Inventory Database. Available online: <https://www.ecoinvent.org/database/older-versions/ecoinvent-31/ecoinvent-31.html/> (accessed on 25 July 2020).
34. Smith, M.S.; Scott, W.W.; Varco, J.J. Legume Winter Cover Crops. In *Advances in Soil Science*; Springer: New York, NY, USA, 1987; Volume 7, pp. 95–132.
35. Pfister, S.; Saner, D.; Koehler, A. The environmental relevance of freshwater consumption in global power production. *Int. J. Life Cycle Assess.* **2011**, *16*, 580–591. [[CrossRef](#)]
36. Nemecek, T.; Schnetzer, J. Methods of Assessment of Direct Field Emissions for LCIs of Agricultural Production Systems. Available online: https://scholar.google.com/scholar?q=Methods+of+assessment+of+direct+field+emissions+for+LCIs+of+agricultural+production+systems&hl=zh-CN&as_sdt=0&as_vis=1&oi=scholar (accessed on 24 August 2020).
37. Tuomisto, H.; Hodge, I.; Riordan, P.; Macdonald, D. Comparing global warming potential, energy use and land use of organic, conventional and integrated winter wheat production. *Ann. Appl. Biol.* **2012**, *161*, 116–126. [[CrossRef](#)]
38. Houshyar, E.; Grundmann, P. Environmental impacts of energy use in wheat tillage systems: A comparative life cycle assessment (LCA) study in Iran. *Energy* **2017**, *122*, 11–24. [[CrossRef](#)]
39. Pratibha, G.; Srinivas, I.; Rao, K.V.; Raju, B.M.; Shanker, A.K.; Jha, A.; Kumar, M.U.; Rao, K.S.; Reddy, K.S. Identification of environment friendly tillage implement as a strategy for energy efficiency and mitigation of climate change in semiarid rainfed agro ecosystems. *J. Clean. Prod.* **2019**, *214*, 524–535. [[CrossRef](#)]
40. Lal, R. Soil carbon sequestration to mitigate climate change. *Geoderma* **2004**, *123*, 1–22. [[CrossRef](#)]
41. Körschens, M. Simulationsmodelle für den Umsatz und die Reproduktion der organischen Substanz im Boden. *Bodennutz. Bodenfruchtbar.* **1992**, *206*, 140–154.
42. Baker, J.M.; Ochsner, T.E.; Venterea, R.T.; Griffis, T.J. Tillage and soil carbon sequestration—What do we really know? *Agric. Ecosyst. Environ.* **2007**, *118*, 1–5. [[CrossRef](#)]

