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LIFE CYCLE ASSESSMENT OF SUNFLOWER AND RAPESEED CULTIVATION FOR BIODIESEL PRODUCTION

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SUMMARY

A Life Cycle Assessment for sunflower and rapeseed cultivation was performed in order to assess the environmental impacts both in terms of greenhouse gas emissions balance and global ecological burden and to quantify the GHG emissions mitigation, thanks to the return to the field of crop residues. The analysis considered all field operations and 1 MJ of biodiesel (obtainable from the oleaginous seeds) energy content was assumed as functional unit. Inventory data were obtained from EcoInvent database and from an Umbrian farm which cultivates oleaginous species. As regards the carbon and nitrogen emissions produced by tillage operations and nitrogen fertilizers application, the DNDC (DeNitrification and DeComposition) model was used. DNDC simulates a full carbon and nitrogen balance, including different C and N pools, and the emissions of all relevant trace gases from soils. Specific climate data, soil properties and cropping practices were used to run the model. All input and output data were collected to carry out the environmental analysis, using a detailed LCA software (Simapro 7.0) and adopting EcoIndicator 99 as environmental impact assessment method. Results showed that rapeseed cultivation was characterized by an higher environmental impact, both in terms of GHG balance and global ecological burden.

INTRODUCTION

Agricultural activity is responsible for environmental concern, causing high nitrate concentrations in water, emitting ammonia into the atmosphere and contributing to increase *GHG* concentration in the atmosphere.

Actually recommended procedures for the estimation of these emissions have a large uncertainty range, above all because of their lack of models to differentiate site-specific conditions.

Therefore it would be interesting to develop models able to simulate the complex interactions occurring between the environment and anthropogenic activities.

The EU Directive on the promotion of Renewable Energy [1] increased attention towards the environmental performance of energy crops for biofuel production: only biofuels that achieve greenhouse emissions savings of 35% will be eligible for inclusion in the 2020 target of 10% for the share of biofuels.

In particular, the cultivation phase is considered as one of the main difficult to quantify from the *GHG* emission balance point of view.

In this paper it was analyzed the environmental impact (in terms of ecological and *GHG* emission balance), through Life Cycle Assessment (*LCA*) methodology [2, 3], of two oleaginous crops, sunflower and rapeseed, dedicated to biodiesel production.

The analysis was site-specific with inventory data taken from an Umbrian farm and fluxes of carbon and nitrogen from the soil obtained applying the *DNDC* (Denitrification Decomposition) model [4], that has been shown to be especially sensitive to soil organic matter (*SOM*) content and nitrogen fertilizer application rates.

LIFE CYCLE ASSESSMENT

Life Cycle Assessment was carried out with the assistance of a commercial *LCA* software package, SimaPro 7.0. It is an open structure program that can be used for different types of life cycle assessments. The production stage, the use stage and the end of life scenario can be specified in as much detail as necessary by selecting processes from the database and by building processes trees, which can be drawn by the program.

LCA studies are composed of several interrelated components: goal definition and scoping, inventory analysis, impact assessment and improvement assessment. In the following, each step is described with regard to this work.

Goal and scope definition

In this paper it was analyzed the environmental impact of the cultivation of sunflower and rapeseed crops, dedicated to biodiesel production. In particular the influence on the *GHG* emission balance of crop residues return into the soil was evaluated. Incorporating crop residues into the ploughed layer of soil affects the dynamics of carbon and nitrogen. A precise quantification of its short-term effect in agricultural fields is difficult, because biological and physical processes interact and take place simultaneously. The functional unit of the life cycle analysis was 1 MJ of biodiesel (in terms of the energy content of biofuel).

The systems under consideration in this study include the agricultural operations for the cultivation of sunflower and rapeseed. Fig. 1 shows a diagram of the production stages of the two crops.

The construction of the machineries for crops cultivation was not taken into account as well as the impact associated with the production of the oleaginous seeds.

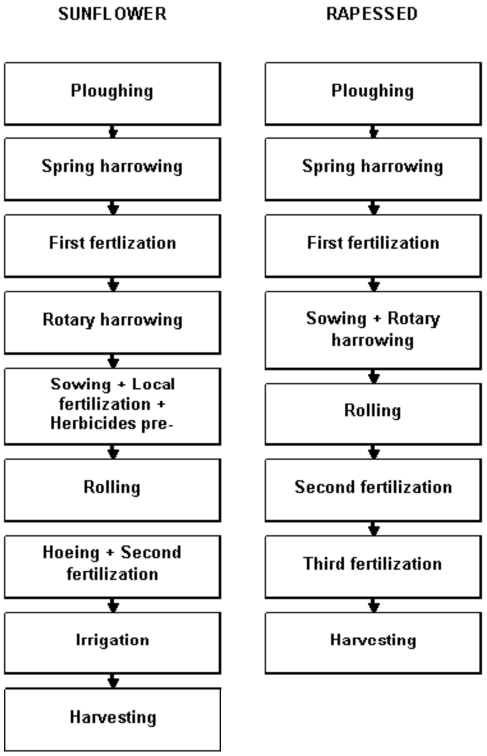

Figure 1: Agricultural operation for the cultivation of sunflower and rapeseed

Inventory analysis

The inventory analysis is the quantitative description of all material and energy flows across the system boundary either into or out of the system itself. Data for the agricultural operations (tab. 1, 2) were drawn from an Umbrian farm, located in Spoleto, characterized by an extent of about 1.000 hectares. The number of irrigation cycles and the period of each agricultural operation were established considering the situation in the mean climate conditions; the following emissions in air, soil and water produced by farm management practices were considered: air emissions produced by diesel engines [5], heavy-metal soil emissions from tyre abrasion [5], ammonia, dinitrogen monoxide and NO_x air emissions from the application of nitrogen fertilizers, phosphates water emissions from the application of phosphate fertilizers [6], *VOC* air emissions from the application of herbicides [7] and soil pollution deriving from herbicides remained into the soil [7]

All energy and mass flows were referred to 1 ha of cultivated soil and then were ascribed to the considered function unit, assuming the following hypothesis:

- sunflower: 0.435 kg oil/kg seed [8];
- rapeseed: 0.405 kg oil/kg seed [8];
- Lower Heating Value of biodiesel: 37.2 MJ/kg oil [8].

Air emissions produced by diesel engines.

Emissions to air from combustion of the fuel in agricultural machineries were calculated applying the methodology described in [5], multiplying the fuel consumption of each work process by the relative emission factor.

Soil emissions from tyre abrasion.

The heavy-metal (zinc, lead and cadmium) emissions from tyre abrasion were calculated taking into account the number of tyre sets used during the lifetime of the machinery, according to [5].

Nitrogen compound emissions from fertilizer applications.

Emissions of NH_3, N_2O e NO_X due to the nitrogen fertilizer applications were estimated through the application of the biogeochemistry model *DNDC* (DeNitrification DeComposition), which allows to simulate *GHG* fluxes, carbon stock changes and the nitrogen budget of the agricultural soil.

Emissions of phosphorus into the water.

A part of the phosphorus applied with mineral fertilizers is lost to water due to run-off of soluble phosphate to surface water. The methodology used to calculate phosphate emissions is described in [6] and results were: 0.39 kg/ha for sunflower and 0.22 kg/ha for rapeseed.

Emissions from herbicides applications.

The method [7] employed for estimating *VOC* emissions in air and remaining herbicides in soil uses the vapor pressure of the active ingredient to determine the appropriate emission factor, the amount of herbicide applied and the percent of the active ingredient in the herbicide applied. Results for sunflower cultivation were 59 g/ha of *VOC* in air and 180 g/ha of herbicide in soil.

DNDC model

DNDC is a biogeochemistry model for agro-ecosystems that can be applied both at the plot-scale and at the regional scale. It consists of three major sub-models: (1) soil climate, (2) crop growth and (3) soil biogeochemistry, including sub-modules for decomposition of organic material, nitrification, denitrification, and fermentation [4]. It is able to track the fate of nitrogen, carbon and water in the rooting zone of the soil, simulating all relevant fluxes including, for the example of nitrogen, uptake and export with the harvest, recycling through decomposition of crop residues, losses below the rooting zone and to the river system through leaching and run-off and gaseous losses of NH_3, NO_x, N_2O, and N_2. The model is driven by environmental (daily weather), ecological (nitrogen deposition) and management (land use, fertilizer application, field operations) factors and simulates the controlling processes on the basis of the characteristics in the soil profile, which must be initialized with information on soil organic carbon content, pH, bulk density and texture.

The crop growth module covers crop development, photosynthesis, root growth and biomass partitioning. Nitrogen uptake by vegetation is the key process linking crop growth with climate and soil status. It is regulated by four factors: (i) the crop potential maximum yield, which is defined as the optimum grain carbon-yield of a crop growing with sufficient water and nitrogen supply; (ii) the crop C:N ratio; (iii) the crop growth curve; (iv) the availability of dissolved inorganic nitrogen in the soil. Decomposition is simulated with a pool model for litter, microbial biomass and humads of different resistances to degradation, respectively.

Biogeochemistry in *DNDC* follows the production and consumption of NO, N_2O and N_2 in the nitrification-denitrification chain. Emissions of NO and N_2O from nitrification are calculated as a function of the predicted nitrification rate and temperature. Both methane production during fermentation of organic matter and methane oxidation by methanotrophic bacteria are represented in the model, as well as the transport of methane in paddy soils. Emissions of NH_3 are instead calculated as fluxes from the soil, related to the clay content and the NH_3 concentration and as releases from the plants.

Table 1: Agricultural operations for sunflower cultivation.

Agricultural operations	Diesel (l/ha)	Materials	Date	Notes
Ploughing	30		27 September	Depth: 25-30 cm
Spring harrowing	20		15 January	Depth: 40-45 cm
First fertilization	0,5	diammonium phosphate: 200 kg/ha	10 March	
Rotary harrowing	20		12 March	Depth: 5-7 cm
Sowing + Local fertilization + Herbicides pre-emergency	5,5	monoammonium phosphate: 20 kg/ha Oxyfluorfen: 0,5 kg/ha	10 April	
Rolling	3		15 April	
Hoeing + Second fertilization	10	urea: 300 kg/ha	7 May	
Irrigation	176,5	water: 4200 m^3/ha	15 May – 31 August	Number of cycles: 15 Water ph: 7.3
Harvesting	30		15 September	
Transports	11,25			

Table 2: Agricultural operations for rapeseed cultivation.

Agricultural operations	Diesel (l/ha)	Materials	Date	Notes
Ploughing	30		5 July	Depth: 25-30 cm
Spring harrowing	20		1 September	Depth: 40-45 cm
First fertilization	0,5	NPK (8-24-24): 300 kg/ha	15 September	
Sowing + Rotary harrowing	22,5		30 September	Depth: 5-7 cm
Rolling	3		5 October	
Second fertilization	0,5	ammonium sulphate: 200 kg/ha	15 February	
Third fertilization	0,5	ammonium nitrate: 200 kg/ha	15 March	
Harvesting	30		20 June	
Transports	11,25			

Input data for the *DNDC* model.

The site-specific input data for *DNDC* includes climate data, soil properties, farm management activities (defined in tables 1 and 2) and crop properties.

The main parameters introduced in the model about climate were: latitude (42.77°), daily low temperature, daily high temperature, daily precipitation (fig. 2) and daily solar radiation (fig. 3). Data were drawn from the National Agro-meteorological Data Bank [9], referring to a meteorological station located at Marsciano. In particular, for each input, mean data for the last five years was considered.

DNDC requires also some soil properties (i.e. bulk density, *SOC* content, texture, pH); Data adopted in our database were in part collected from geological report and chemical-physical analysis of the soil while in part were assumed default data, because of the lack of information. Soil data constitute a major source f uncertainty for the simulations, because of some of them, such as especially initial *SOC* content, are the most sensitive factors for estimating *SOC* dynamics. Soil data obtained from direct analysis were:

- soil texture: clay loam, with a clay fraction of 0.417;
- bulk density: 1.81 g/cm^3;
- soil pH: 7.91;
- macro-pores: absent;
- water logging problem: absent;
- depth of water retention layer: 2.2 m;
- highest groundwater table depth: 3.6 m;
- *SOC* at surface soil (0-5 cm): 0.012 kgC/kg;
- depth of top soil with uniform *SOC* content: 0.3 m;
- bulk C/N: 9.5;
- slope: 4%.

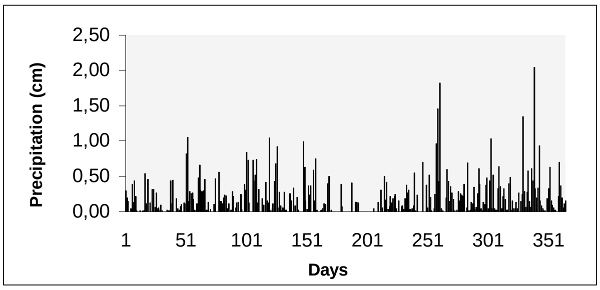

Figure 2: Daily precipitation at Marsciano meteorological station (mean values in the period 2003-2007).

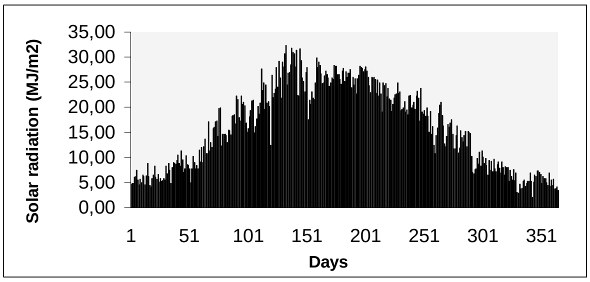

Figure 3: Daily solar radiation at Marsciano meteorological station (mean values in the period 2003-2007).

Crop parameters were taken from the default values provided by *DNDC* (potential biomass yield; grain:shoot:root biomass ratios; tissue C:N ratios; water use efficiency; crop growth and crop phenology) only modifying the maximum production yield of seeds (3 t/ha with a moisture content of 12%, both for sunflower and rapeseed). In tables 3 and 4 the main assumptions for the two crops are reported.

Results of the *DNDC* model.

Simulation was conducted for one year for sunflower and for two years for rapeseed (because it was sowed at 30 September and harvested at 20 June), evaluating carbon, nitrogen and water balances.

Table 3: Crop parameters for sunflower.

Crop parameters	Seed	Leaf+stem	Root
Maximum biomass (kgC/ha)	1073.6	2397.7	107.4
Biomass fraction	0.3	0.67	0.03
Biomass C/N ratio	10	45	50
Total N demand (kgN/ha)	162.8		
Thermal degree days	1500		
Water demand (gH_2O/gDryMatter)	495		
N fixation index	1		
Maximum LAI	3		

Table 4: Crop parameters for rapeseed.

Crop parameters	Seed	Leaf+stem	Root
Maximum biomass (kgC/ha)	1056	3168	367.3
Biomass fraction	0.23	0.69	0.08
Biomass C/N ratio	12	45	52
Total N demand (kgN/ha)	165.5		
Thermal degree days	700		
Water demand (gH_2O/gDryMatter)	450		
N fixation index	1		
Maximum LAI	4		

As regards seed yield, a lower value than the theoretical maximum was obtained, perhaps because of presence of temperature stress: 2.25 t/ha for sunflower and 1.90 t/ha for rapeseed. Tab. 5 shows the summary output results of the simulation for sunflower and rapeseed crops.

Table 5: Main parameters of crops growth, obtained from *DNDC* simulation.

Parameters	Sunflower	Rapeseed
Maximum grain (kgC/ha)	1074	1056
Actual grain (kgC/ha)	826	673
Maximum leaf+stem (kgC/ha)	2398	3168
Actual leaf+stem (kgC/ha)	1845	2018
Maximum root (kgC/ha)	107	367
Actual root (kgC/ha)	83	234
Water demand (mm)	821	355
Water uptake (mm)	646	309
N demand (kgN/ha)	163	165
N uptake (kgN/ha)	125	105
Temperature demand (°C)	1500	700
Thermal degree days (°C)	1512	703

Results of nitrogen compounds emissions and *SOC* balance, in the case in which all crop residues are left in the field after harvest, are reported in table 6.

Among the nitrogen compounds emitted in the atmosphere, N_2O is one of the most important gases contributing to the greenhouse effect, so its estimation is of primary importance.

Table 6: Nitrogen and carbon balances, obtained from *DNDC* simulation.

Substances	Sunflower	Rapeseed
	Air	
N_2O (kg/ha)	1.34	2.04
NO_x (kg/ha)	3.66	1.50
NH_3 (kg/ha)	4.87	48.08
N_2 (kg/ha)	0.20	0.03
	Water	
NO_3 (kg/ha)	84.58	44.55
	Soil	
Change in C storage (kgC/ha)	790.50	736.40

The main methodology to determine N_2O emissions from fertilizers application was developed by the Intergovernmental Panel on Climate Change (IPCC) [10]. The methodology provides a framework for the calculation of the total N inputs from agriculture (fertilizers, animal excreta, crop residues). The N input in each component is multiplied by an emission factor (EF) (which specifies the proportion of N input emitted as N_2O), to give a total emission. The EF for fertilizer is 0.0125 kg N_2O-N per kg N applied.

This approach is obviously generalized and simple, since it is intended for global application. However, the IPCC methodology is not sufficiently flexible to allow mitigation options to be assessed. In addition, the EF is drawn from international datasets and it is therefore general and not necessarily specific to the soils, climate and farming practices of the considered soil.

Ammonia (NH_3) is the dominant gaseous base in the atmosphere and a principal neutralizing agent for atmospheric acids. Ammonia volatilization from nitrogen fertilizer application is site-specific, like N_2O emissions; in fact actual NH_3 emission factors are determined by fertilizer placement, application period, soil temperature, soil moisture, wind, precipitation and soil pH. For these reasons the use of an emission factor, depending only on the nitrogen content of fertilizer (15% of N-content, for urea) [10], determines a substantial error.

Impact assessment methodology

Impact assessment was carried out considering eleven impact categories (carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals, fossil fuels). Finally, the application of weighting factors to determine the relative importance, or seriousness, of a category results may be represented as a single score, in eco-indicator points (Pt).

In this study the impact assessment and characterization has been performed by the *LCA* method EcoIndicator 99 [11]. The index chosen for the impact assessment is the hierarchist's version, with average weighting set, which represents the most balanced view amongst all the perspectives on nature.

RESULTS AND DISCUSSION

Table 7 shows the global eco-scores for sunflower and rapeseed cultivation for each impact categories. It can be noted that in both cases about 80% of the ecological effects of the crop production are related to land use category.

Table 7: Ecological impacts for Impact Categories (in *mPt*)

Impact category	Rapeseed	Sunflower
Total	40.6	29.9
Respiratory organics	0.0	0.0
Respiratory inorganics	4.2	1.5
Climate change	0.3	0.2
Radiation	0.0	0.0
Ozone layer	0.0	0.0
Ecotoxicity	0.2	0.1
Acidification/Eutrophication	2.2	0.3
Land use	31.3	24.6
Minerals	0.0	0.0
Fossil fuels	2.1	3.1
Total	***40.6***	***29.9***

As this category is a qualitative and not a quantitative indicator like the other mass and energy flows, its implementation into the overall assessment is quite complicated. Within the agricultural production system, the influence of the impact category land use is very strong, in comparison to all other ecological effects on the overall result. On one hand, large areas are needed for the production of energy crops; this has a multiplying effect on the results per unit area: the intensive arable production leads to decrease in biodiversity, which is close to the decrease caused by a sealed surface. Therefore this form of production is calculated with heavy ecological burdens. On the other hand, it must be recognized that there would also be arable production, even if no energy crops would be produced. Hence, stopping the production of energy crops would not lead to an overall reduction of ecological effects from arable farming.

Therefore it seemed to be more interesting to compare the ecological impacts of the two chains excluding land use category from the assessment. In this way, rapeseed cultivation is characterized by an ecological impact of 9.3 *mPt*, while the value for sunflower is equal to 5.3 *mPt*.

For both crops, the main impact categories are represented by Respiratory Inorganics (rapeseed: 46% of the total impact, sunflower: 28%), Acidification/Eutrophication (rapeseed: 24%, sunflower: 6%), Fossil fuels (rapeseed: 23%, sunflower: 58%) and Climate change (rapeseed: 3%, sunflower: 4%). For rapeseed, the main contribution to the Respiratory Inorganics category is represented by ammonia emission (67%) from nitrogen fertilizers application, while for sunflower particulate emission from diesel combustion amount to 47%. The impact of Acidification/Eutrophication category is mostly due to ammonia and nitrogen oxides emissions from nitrogen fertilizer application (94% and 6% respectively for rapeseed, 59% and 40% for sunflower). The score of Fossil Fuels category is produced by natural gas and oil crude consumptions (42% and 58% respectively for rapeseed, 35% and 65% for sunflower). At last, for rapeseed the main contributions to the climate change category are constituted by GHG emissions from nitrogen fertilizers application (31%) and from ammonium nitrate production (26%), while for sunflower GHG emissions from diesel consumption in the irrigation step and nitrogen fertilizers application amount to 26% and 22% respectively. In particular it seemed interesting to report GHG emissions, in terms of gCO_2eq/MJ, according to IPCC (100-years) methodology; the score obtained for rapeseed cultivation is equal to 67 gCO_2eq/MJ against 50 gCO_2eq/MJ for sunflower.

CONCLUSIONS

The *LCA* analysis of rapeseed and sunflower cultivation was carried out, considering the overall process, from field preparation to seed harvesting. Data for each phase were obtained from an Umbrian farm, from the Literature (energy and mass flows of life-cycle production of employed materials) and by calculation.

The environmental analysis was conducted in terms of ecological impact, applying the EcoIndicator 99 method, and of GHG balance, adopting the IPCC (100-years) methodology. In particular, site-specific nitrogen and carbon balances were performed, employing *DNDC* model; the contribution to the carbon storage in the field of crop residues incorporation into the soil was also evaluated.

The ecological analysis showed that sunflower cultivation was characterized by a lower impact than rapeseed farming, both including land use impact category (-26.4%) and excluding it (-43.0%); the difference between the two scenarios was due to the higher oil yield of sunflower than rapeseed. Results obtained for rapeseed crop were biased by the climate data considered, bringing about a lower seed yield than Literature data [12] (2.5-3 t/ha).

As regards GHG balance evaluation, rapeseed farming showed higher GHG emissions than sunflower (+25.4%). Scores obtained for the two crops were higher than those reported in the EU Directive (49 gCO_2eq/MJ for rapeseed and 39 gCO_2eq/MJ for sunflower) in terms of absolute values. The main differences in the input data concern diesel consumption, nitrogen fertilizer application rate and mainly seed yield (3.1 t/ha for rapeseed and 2.4 t/ha for sunflower).

This study represent a first attempt to determine the environmental impact of biofuel crops, assuming site-specific data relative to climate conditions and soil properties of the Umbria region. Therefore, considering the Italian next acknowledgement of EU Directive, this analysis would be extended to other climate regions and to other biofuel crops, using more thorough input data; in this way it could be obtained default values of GHG emissions of cultivation phase for Italian regions.

NOMENCALTURE

DNDC: DeNitrification and DeComposition;
GHG: GreenHouse Gas;
LCA: Life Cycle Assessment;
mPt: milliPoint;
SOC: Soil Organic Carbon [kg C/kg soil];
SOM: Soil Organic Matter;
VOC: Volatile Organic Compounds.

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