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Article

Life Cycle Based Evaluation of Environmental and Economic Impacts of Agricultural Productions in the Mediterranean Area

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Abstract: In recent years, there has been an increasing interest in Life Cycle Assessment (LCA) applied to estimate the *cradle-to-grave* environmental impact of agricultural products or processes. Furthermore, including in the analysis an economic evaluation, from the perspective of an integrated life cycle approach, appears nowadays as a fundamental improvement. In particular, Life Cycle Costing (LCC), is a method that could integrate financial data and cost information with metrics of life cycle approaches. In this study, LCA in conjunction with LCC methods were used, with the aim to evaluate the main cost drivers—environmental and economic—of five widely diffused and market-valued agricultural productions (organic tomato and pear, integrated wheat, apple and chicory) and to combine the results in order to understand the long-term *externalities* impacts of agricultural productions. Data obtained in local assessment show a wide margin of improvement of resources management at farms level in the short-term, but also allow for the investigation of future effects of environmental impacts not expressed in product price on the market. Reaching a real sustainable model for agriculture could be a value added approach firstly for farmers, but also for all the people who live in rural areas or use agricultural products.

Keywords: agricultural systems; environmental impact; life cycle assessment; life cycle costing

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1. Introduction

Agriculture plays a small part in the economies of European Union (EU) member countries, accounting for about 2% of the overall EU gross domestic production (GDP) and 5% of employment [1]. However, its impact on the environment and natural resources is particularly significant, accounting for 45% of EU total land use and over 30% of total water use [2]. Therefore, the vast surface area occupied by agriculture guarantees that any change in management to optimize the resources use would have a very high impact [3].

Environmental impact of agriculture depends largely on farmer production practices, but also on unpredictable and changeable factors such as rainfall and temperature, or quality of soils [4]. Consequently, differently from other sectors where variables are almost exclusively of anthropic origin, the evaluation of sustainability of agricultural production systems needs appropriate indicators, which accounts for natural effects, such as land use, nitrate leaching or ammonia volatilization [5]. In the last decade, to better address its environmental sustainability, several Life Cycle Assessment (LCA) studies on agriculture have been carried out [6–9]. As is well known, LCA is a technique to assess environmental issues associated with all the stages of a product's life *from-cradle-to-grave*, permitting an integral and integrated approach for measuring impacts of products and processes [10,11]. As indicated by the SETAC-Europe framework for Life-Cycle Sustainability Assessment (LCSA) [12], the methodology also has the potential to include both social and economic indicators. The inclusion of social and economic dimensions besides the impacts related only to the biophysical flows would create a framework that have the capacity to address the overall sustainability of a product or a process [13]. It contributes in introducing the concept of *sustainability science* and aimed at understanding the fundamental interactions between nature and society [14,15]. Relative to the social, the economic dimension is further along in its development, and there are several tools currently available, such as total cost assessment or life cycle costing [16]. Life Cycle Costing (LCC) is reported as the method that could integrate existing financial data and specifically cost information with metrics of life cycle approaches [17]. LCC accounts for all costs and benefits that someone (*i.e.*, producer, transporter, consumer or other directly involved stakeholder) has paid for along the life cycle of a product. The use of LCA and LCC together can define the primary cost drivers (environmental and economic) that reflect the real monetary flows encountered by one or more actors during the life cycle of a product [18]. No corresponding code of practice or set of metrics currently exist for the social dimension that includes life cycle thinking [19]. To date, methods attempted to include social aspects in the LCA framework are often inconsistent with one another, and the majority have concluded that more research and development is needed [20–22]. Sometimes, social LCA has been properly referred to the so-called *externalities*, which are changes that may affect external environment but not covered by biophysical or economic impacts of a product or process [23].

Externalities could be considered as side effects of an activity, whereby the costs are not part of the price paid by producers or consumers. Examples are human health or well-being issues, long-term effects of pollution, or landscape value deterioration. When such *externalities* are not included in prices, they distort the market by encouraging activities that leads to substantial private benefits, even if strongly onerous to society [24].

First studies to quantify *externalities* in agriculture, as damage to natural capital—water, air and soil—and damage to human health induced by pesticides, disease agents and phosphate/nitrate released in the environment have been carried out in recent years only in UK and USA [25–27]. As a major exporter of food and feed products, Italy is a country highly concerned with environmental and food safety issues, of international relevance, associated with agricultural production and the food processing industry. Notwithstanding, except for few cases [28–30], the life cycle is not yet recognized as a strategic tool for evaluating environmental, economic and social impact of agriculture.

The typical Italian agricultural system is characterized by intensive farming, supported by the use of large quantities of fertilizers, pesticides and irrigation, which facilitate an increase in the production of feed and food per unit of cultivated land, also contributing to soil and groundwater enrichment with various forms of nitrogen and phosphorus and potentially toxic residues. Intensive farming is an agricultural system that aims to get maximum yield from the available land. Its use has spread worldwide, especially in modern large-scale societies. On the other hand, organic farming is an internationally regulated production system that promotes and enhances biological cycles and soil activity, based on minimal use of off-farm inputs. Its use represents approximately only 9% of total Italian farmland [31], but has a great importance as market niche. The authors carried out a LCA and LCC study aimed at investigating the environmental performances of five market-valued crops in the North-East of Italy, in the Mediterranean area, which is particularly representative as a model for the analysis of the most widely used methods of cultivation, both in industrialized and developing countries. Firstly, the environmental and cost profile of organic tomato and pear, apple, wheat and lettuce productions have been assessed, as to identify for each product *where* and *how* resources are consumed, emissions occur and costs are charged. Secondly, combining the results from LCA and LCC analysis, this study has sought to estimate the *externalities*, as a first attempt to quantify the socio-economic long-term impacts of agricultural products at local level.

The general aim is to support the use of this methodology to the National and European decision-makers, as valuable decision-supporting tool for defining the future development of agriculture and promote the diffusion of short and long-terms sustainable practices.

2. Experimental Section

2.1. Study Area

The project area is the East part of the river Po (Pianura Padana) in the Emilia Romagna region (Italy). The province is comprised of 180,000 ha of utilized agricultural area (UAA), principally cultivated with cereals, fruits and vegetables. In this study, production of wheat (32.9% of overall UAA for cereals), apple and pear (63.0% and 5.2% of overall UAA for fruits, respectively), tomato and chicory (72.3% and 14.9% of overall UAA for vegetables, respectively) have been investigated. A total soil surface of 1500 ha has been monitored, corresponding to a total of 40 farms of different dimension, 8 for each crop. Some farmlands were under the sea level (about 5–10 m), as usual in alluvial lowlands. Tomato and pear were produced according to the organic cultivation protocol, apple, wheat and lettuce under traditional intensive farming system.

2.2. Goal and Scope of LCA and LCC

The purpose of the LCA and LCC analysis is to evaluate the environmental and economic impacts of the agricultural production of the dominant five crops in the project area, and identify the most critical hotspots.

2.3. Functional Unit, System Boundaries and Assumptions

The present study will be based on the assessment of impacts calculated for two different functional units for comparative purposes. This is a common practice in LCAs of agricultural products [32], because the use of multiple functional units can improve the interpretation of the environmental results obtained in LCA studies [33]. The functional unit (FU) was defined as 1 kg of fresh harvested crop, to allow for a comparison of the impacts generated by the production of the same crop produced in different location. Results have been also expressed as 1 ha of arable soil, as to account for the regional character of the impact categories assessed and permit an evaluation of the impact of agriculture in the project region.

The system boundaries were set from seedlings transplanting for tomato and chicory, seeding for wheat, and orchard plantation for pear and apple, up to the delivery to the local agricultural consortia. Boundaries included also materials and machineries production, fertilizers and pesticides life cycles, packaging management and resources (energy/fuel/water) production, transportation, and consumptions (Figure 1). For calculating energy production impact, the Italian energy mix was used [34]. The CO_2 emissions/removal generated by the carbon stock changes in biomass and soil were not included, due to difficulties obtaining a specific spatial estimate without a sampling campaign or validated models [35]. In soils under the sea level, energy and water consumption for land reclamation were included in the calculation.

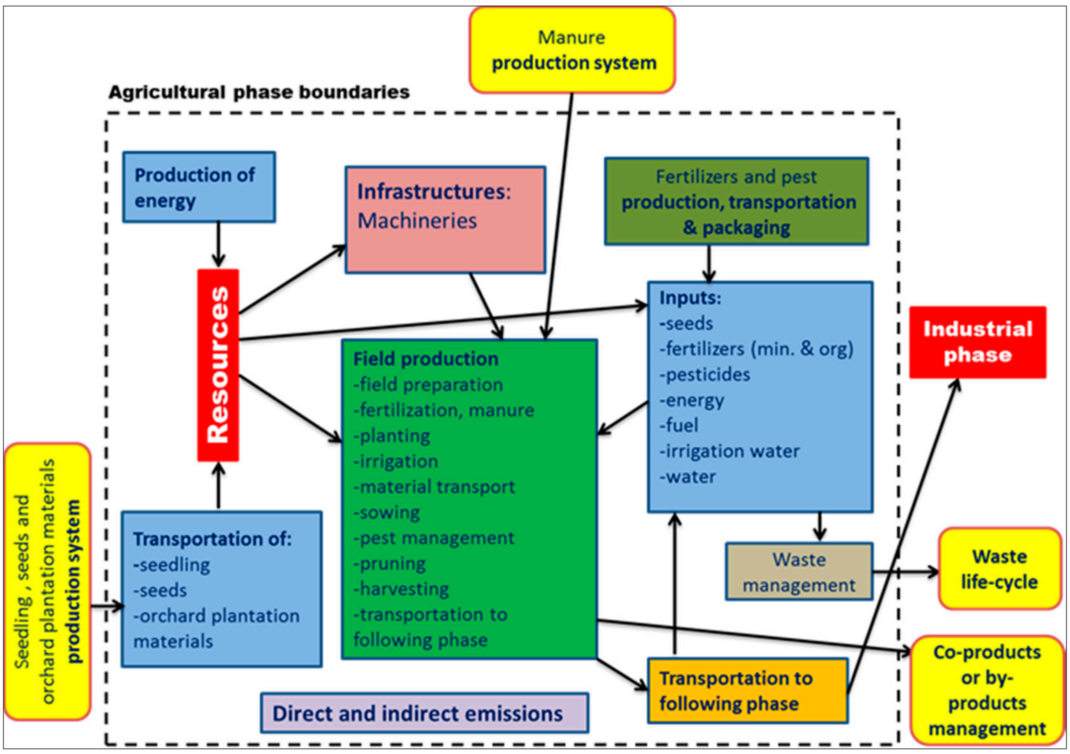

Figure 1. System boundaries for a cradle-to-farm-gate Life Cycle Assessment (LCA) agricultural productions. The figure represents a simplified scheme of all the variables considered in the LCA calculations of agricultural productions.

The same boundaries applied to LCC included also the cost factors not directly related to physical crop production, as labor costs *overheads* (namely, general expenses, assurance costs and taxes, capital costs, financial incomes). Market price of fertilizers, pesticides and materials were considered inclusive of production, packaging and transportation costs.

2.4. Land Use and Crop Yields

It was assumed that soils are arable and used for agriculture for years. Therefore no impacts due to change in land use were taken into account. Soil occupation by the crop was calculated on the basis of cultivation time (months) per year. In the case of perennial crop as orchard (pear and apple), the entire year was accounted. Crop yields were obtained as primary data from farms (see next paragraph).

2.5. Data Collection and Life Cycle Inventory (*LCI)*

The most effort-consuming step of the LCA and LCC studies implementation is the collection of data in order to build the life cycle inventory (LCI). Furthermore, default data for agricultural processes are limited in LCA database, compared to industrial processes [36]. Questionnaires had been elaborated for our specific data collection and were fulfilled by personal interviews with farmers and agronomists. The reference year was 2011. LCA and LCC modeling were done with SimaPro v.7.3.3 using Ecoinvent® v. 2.2 as database [37,38].

Qualitative (general data about farms, overall production, type of machineries or irrigation system), and quantitative inputs (energy, water, materials) and outputs (products) data were collected. In LCA, within the system boundaries, six stages were recognized: (1) land occupation; (2) field operations, (3) production and packaging of fertilizers; (4) production and packaging of pesticides; (5) transportations; (6) other energy, water and fuel consumption by the farm, not directly due to the crop under investigation. Every stage were further divided in sub-unit, because specific field management for each crop were used, depending on the characteristics and method of cultivation (Table 1). Concerning pear and apple cultivation, LCI started with orchard plantation, including manufacturing, transport and planting of concrete poles, reinforcing steel bars and wires, and field harrowing and grooving. Because in both cases the orchard life was 20 years, the impacts derived from plantation have been portioned by the lifetime (20 years) of orchard and allocated to the reference year (2011) using a factor of 1/20. In the case of tomato and chicory, LCI started from the production of seedlings, which are young plants to be bedded out. They are grown in plastic pots, mainly filled with peat. Based on the yield and number of seedlings planted per ha, the amount of transported weight per kg of product from the supplier were calculated. For wheat, production, packaging and freight transport of seeds were included in the LCI.

Table 2 lists the main primary data on inputs used to cultivate the soil surface for each crops (as average values for 1 kg of fresh product). Secondary data on machineries production, infrastructures, pumping and piping systems were derived from Ecoinvent®.

Except for the case of wheat, irrigation is usually needed the project area, because rainfall is less than the amount of water required by crops. The amount of water supplied by irrigation depends on the crop as well as on soil types and climate parameters as temperature, wind and rainfall. Data on temperature and cumulated monthly rainfall trends were available from Environmental Service of Emilia Romagna Region [39].

Table 1. Process stages and agricultural management for the five crops.

Process stages	Process sub-stages	Tomato	Apple	Pear	Wheat	Chicory
1. Land occupation	Land occupation and cultivation method	■	■	■	■	■
2. Field operations	Orchard plantation		■	■		
	Seedlings transplanting	■				■
	Ploughing	■			■	■
	Harrowing	■			■	■
	Hoeing	■				■
	Pre-cultivation fertilization	■		■		■
	Sowing				■	
	Irrigating	■	■	■		■
	Fertilizing	■	■	■	■	■
	Application of plant protection products	■	■	■	■	■
	Pruning		■	■		
	Wood chopping		■			
	Grass cutting		■	■		
	Harvesting	■	■	■	■	■
3. Fertilizers production and packaging	Production of fertilizers and packaging materials	■	■	■	■	■
4. Pesticides production and packaging	Production of pesticides and packaging materials	■	■	■	■	■
5. Transportation	of fertilizers from supplier to the farm gate	■	■	■	■	■
	of pesticides from supplier to the farm gate	■	■	■	■	■
	of seeds, seedlings or orchard plant. materials to the farm gate	■	■	■	■	■
	to the subsequent phase	■	■	■	■	■
	personnel transportations within the farms	■	■	■	■	■
6. Other resources	Electricity from grid	■	■	■	■	■
	Electricity from renewable	■				
	Fuel (diesel oil and/or gasoline)	■	■	■	■	■
	Tap water	■	■	■	■	■
	Water from river				■	■

Table 2. Life Cycle Inventory of the main inputs for the crops investigated (reported as average values of the data collected from the 8 farms).

Process	Input	Unit	Tomato	Apple	Pear	Wheat	Chicory
Land occupation	Soil surface	ha	450	170	150	590	140
	Yield	kg/ha	88,000	53,800	30,000	7200	20,000
Field operations	Diesel	kg/ha	572	803	4000	60	200
	Gasoline	kg	-	-	-	-	-
	Electricity	MJ	-	-	38	-	-
	Water	m^3/ha	6000	12,700	2500	-	1250
	Machine time	h/ha	170	188	270	8	40
	Wood pole	kg/ha	-	120	-	-	-
	Cement pole	kg/ha	-	-	250	-	--
	Metallic devices	kg/ha	-	230	54	-	-
	Irrigating tube (PE)	kg/ha	-	-	35	-	-
Seeds production and packaging	Seeds	kg/ha	-	-	-	200	-
	Packaging (Bag, PE)	kg/ha	-	-	-	2	-
Fertilizers production and packaging	Chemical N	kg/ha	-	270	-	500	800
	Chemical P	kg/ha	-	40	-	-	
	Organic N	kg/ha	1020	-	800	-	5000
	Packaging (Bottle, PE)	kg/ha	1	-	3	-	
	Packaging (Bag, PE)	kg/ha	3	1	2	2	3
Pesticides production and packaging	Pesticides	kg/ha	-	80	-	6	10
	Pesticides of natural origin	kg/ha	24	-	65	-	-
	Packaging (Bottle, PE)	kg/ha	1	5	5	1	2
	Packaging (Paper bag)	kg/ha	1	-	2	-	1
Transportation	Diesel	kg	100	200	430	120	800
Other resources	Electricity	MJ/year	2520	4320	7500	12,000	2000
	Fuel	kg/year	2000	3000	2300	7000	1650
	Water	m^3/year	600	800	300	6000	750

Ammonium sulfate, ammonium nitrate, potassium chloride and urea were used as fertilizers for wheat, apple and chicory, while compost and vinasses-derived were permitted in organic cultivation (tomato and pear). Direct and indirect N_2O/NH_4 emissions were calculated using emission models developed by national inventory of emissions in agriculture [40], based on IPCC guidelines [41]. Emissions in atmosphere deriving from the use of fertilizing machineries were included in the field operations stage.

Direct emissions deriving from the use of 52 different type of pesticide were accurately modeled based on Mackay model [42]. In most cases, individual pesticide data source were the producer websites or products label, when not available, the generic pesticide process "pesticide unspecified, at regional storehouse" from Ecoinvent® was used.

In LCC, a steady-state cost model was set up, which means that no discounting and depreciation were taken into account [43]. Stages identified for LCA were considered in the different perspective of being cost centers. Therefore, for each crop, costs were accounted as: (1) field operations; (2) fertilizers; (3) pesticides; (4) transportation; (5) other resources (energy/water/fuel); (6) overheads. Official 2011 prices for gasoline and diesel oil were examined [34] machineries values were assessed on the basis of average market price and lifetime (22.5 years), while electric energy and labor costs were asked with the questionnaires and were different from farm to farm.

Inputs (materials, fertilizers and pesticides) suppliers and receiving distributors had all an average distances from farms of less than 70 km. EURO 3 standard trucks with cargo weight <16 t was generally reported to be used.

2.6. Allocation

In this study, co-products and by-products were excluded from the system boundaries, thus no allocation process was needed.

2.7. LCA Impact Categories

This study is mainly focused on the following input-related environmental indicators: (1) Abiotic resource depletion (ARD); (2) Cumulated energy consumption (CED); (3) Water Consumption (WC), and on the following output-related indicators: (4) Global Warming Potential with a time frame of 100 years (GWP100); (5) Eutrophication potential (EP); (6) Acidification potential (AP); (7) Human Toxicity Potential (HTP) and (8) Eco Toxicity Potential (ETP). We modeled the LCA in SimaPro® Software using impact assessment method CML baseline 2 2002, adjusted with 2007 Intergovernmental Panel on Climate Change (IPCC) indicators for global warming potential (GWP) [37].

Photochemical Oxidation and Ozone Layer Depletion indicators were calculated but not reported here, because of the negligible values obtained in all cases ($<10^{-9}$, as order of magnitude). *1,4-dinitrobenzene* was taken as reference substance to measure toxicity, as well as *antimony* for abiotic resource depletion.

LCC assessment. To obtain exhaustive results, costs of life cycle were classified both on the basis of the (1)–(6) aforementioned cost centers and on the basis of cost types (fixed and variables). Overheads, energy and water costs are by their nature fixed costs that is independent by production, while materials costs are strictly related to the amount of product. Allocation of labor costs as fixed or variables has been a hot topic even before LCC debates. According to Oi [44] and Becker [45] here they were considered as fixed costs and included in the field operations. Calculations have been carried out customizing the SimaPro® software, according to the recommendations of GreenDelta GmbH (Berlin, Germany).

3. Results and Discussion

3.1. LCA

Agri-food production systems contribute to a wide range of environmental impacts besides climate change. Climate change potential (GWP100) accounts for relevant effect on agriculture, but from an environmental point of view, the analysis of individual issue does not permit a conclusion on the preference for one or another production strategy. The other complementary potential impacts, conveniently covered by LCA analysis and integrated with, contribute to an overall evaluation of environmental effect of an agricultural production.

For the base year 2011, the comparative results of the LCA, as *cradle-to-gate* impacts, for the selected five crops are shown in Table 3 (expressed as 1 kg of fresh harvested product).

The results of this study could be basically used for benchmarking actions of regional agri-foods products and put in evidence the differences among agricultural practices, methods of cultivation and type of farm management.

Table 3. Potential environmental impacts due to agricultural phase for the production of 1 kg of selected crops.

	Tomato	Apple	Pear	Wheat	Chicory
Land occupation (%)	58.4	100	100	60.0	42.0
GWP_{100} (kg CO_2 eq.)	6.30×10^{-2}	9.70×10^{-2}	3.76×10^{-1}	5.09×10^{-1}	3.27×10^{-1}
EP (kg PO_4^{3-} eq.)	2.25×10^{-4}	5.80×10^{-4}	1.26×10^{-3}	4.24×10^{-3}	2.01×10^{-3}
AP (kg SO_2 eq.)	3.22×10^{-4}	1.42×10^{-3}	4.13×10^{-3}	1.79×10^{-3}	1.36×10^{-3}
CED (MJ)	8.69×10^{-1}	12.00×10^{-1}	60.72×10^{-1}	30.98×10^{-1}	41.20×10^{-1}
WC (m^3)	1.80×10^{-1} (0.33×10^{-1})	2.53×10^{-1} (0.07×10^{-1})	4.63×10^{-1} (0.08×10^{-1})	3.45×10^{-1} (0)	11.09×10^{-1} (0.80×10^{-1})
HTP (kg 1–4, DB eq.)	6.80×10^{-2}	1.47×10^{-1}	1.69×10^{-2}	1.33×10^{-1}	2.48×10^{-1}
ETP (kg 1–4, DB eq.)	33.61	87.70	58.14	68.49	123.36
marine aquatic	33.56	87.53	58.05	68.46	123.29
freshwater aquatic	4.25×10^{-2}	1.66×10^{-1}	8.70×10^{-2}	2.90×10^{-2}	7.10×10^{-2}
terrestrial aquatic	8.57×10^{-4}	3.37×10^{-3}	1.00×10^{-3}	9.82×10^{-4}	1.16×10^{-3}
ARD (kg Sb eq.)	3.59×10^{-4}	5.01×10^{-4}	2.36×10^{-3}	1.18×10^{-3}	1.59×10^{-3}

ARD: Abiotic resource depletion; CED: Cumulated energy consumption; WC: Water Consumption; GWP_{100}: Global Warming Potential with a time frame of 100 years; EP: Eutrophication potential; AP: Acidification potential; HTTP: Human Toxicity Potential; ETP: Eco Toxicity Potential.

In an organic farming system, particular field operations as harrowing and hoeing are introduced instead of chemicals, to assure protection against weeds. In spite of an increase of inorganic emissions deriving from fuel combustion (SO_2, NO_x, CO, NH_3, particles) that have a potential toxic effect in humans [46], this provides an overall positive effect of lowering the HTP/ETP impact values, for both organic pear and tomato. Moreover, even if the increase in fuel consumption results in an increase in emissions of CO_2 eq., the compensation due to the large decrease in the use of fertilizers produces an overall positive balance in favor of organic farming [47].

In fact, a comparison with the case of open-field tomato cultivated in conventional farming in Italy [48], shows an increase of GWP100 to 0.74 kg CO_2 eq, combined with HTP of 0.43 kg 1–4, dichlorobenzene equivalent (1–4,DB eq.), ETP of 0.51 kg 1–4, DB eq. and EP of 2.1 kg PO_4^{3-} eq., for 1 kg of fresh product. In Northern regions (Sweden, Denmark), where open-field system is not permitted for climate, studies on tomato cultivated in glass greenhouses reported GWP100 values of 3.3–9.4 kg CO_2 eq./kg of fresh product and CED of 42–125 MJ/kg of fresh product [49,50]. In these cases, about 97% of the energy used is for heating and lighting greenhouses, for extending the growing season.

Previous *cradle-to-grave* analysis performed on pear production evidenced a GWP100 of 0.25 kg CO_2 eq./kg fresh product for organic system, and 0.68 kg CO_2 eq./kg fresh product for conventional farming [51]. In our case, pear cultivation has shown a higher value of CO_2 eq. emissions, probably because of the typical regional high-density planting layout (130 plants/ha), which requires particularly strong and time-consuming operations, *i.e.*, for pruning and harvesting (see Table 2 for machine time and diesel consumption values). Data on planting layout is not reported in the cited study.

Results on apple cultivation are consistent with those found in other LCA studies of conventional apple orchards (0.06–0.09 kg CO2eq./kg of product) [52,53].

Intensive farming of wheat suffers for the greatest GWP100 value because, although not requiring strong field operations, uses a large amount of chemical N fertilizers, to assure high yields [54]. Literature data on conventional wheat cultivation reported GWP100 values from 0.38 to 0.46 kg CO2 eq./kg of product [55], excluding from LCI computation the other resources consumed by farms. CED was 2.70 MJ/kg and WC not calculated. In our study, the water consumption indicator (WC) accounts for both direct (irrigation) and indirect water amount used to produce 1 kg of product. Indirect water includes consumptions for production, packaging and transportation of all the inputs (materials and energy) supplied for the functional unit production. Inherently, the American neologism “Watergy” [56] perfectly highlights the narrow links between the production of an electric unit (*i.e.*, kWh) and a certain amount of water consumed or used in its production. In Italy more than 65% of the electricity derives from thermal 256 power plants and fossil fuels, burdening significantly on the life cycle of all products [57]. In addition to energy, a realistic life cycle calculation must take into account water consumption related to the manufacture of materials, fertilizers and pesticides. This water is only indirectly attributable to the functional unit, but unexpectedly can get to burden on it more heavily than the water used for irrigation. In fact, thanks to LCA analysis, our study has revealed that only a very small percentage (<3%) of the total WC used for the production of 1 kg of fresh product could be directly allocated to irrigation step. The case study of wheat is particularly interesting because WC is 0.253 m^3, even though it was not irrigated during 2011.

Chicory represents an interesting example of manual harvesting, carried out to preserve product characteristics to the market. Manual harvesting might be expected to have a minimal impact on GWP100, but the slowness of tractor and trailer, that must follow the speed of the operators, causes a high fuel consumption, and so a great impact on GWP100.

Similar data have been obtained for open-field conventional cultivation of Spanish lettuce (GWP100 from 0.31 to 0.55 kg CO2 eq./kg of fresh product), whilst for greenhouse growing in UK an increase to 2.6–3.75 kg CO2 eq./kg of fresh product is reported [58].

Consumption of fossil fuels shows negative effects also on ARD, deriving from the correlated abiotic resources (*i.e.*, coal, natural gas) depletion and on AP for sulfites eq. emissions, besides the already mentioned effects on toxicity indicators (HTP/ETP), for the release of toxic residues of combustion in atmosphere.

The principal effect of fertilization is to increase eutrophication potential (EP), imputable to nitrate and phosphorus leaching [59]. As provided by organic protocol of cultivation, only wood ash based fertilizers, compost and manure is permitted, whilst in conventional agriculture chemical nitrate, ammonia, urea and phosphate are currently used. Our findings seems to confirm that a lower fertilizer input level supports the expectation of lower nitrate and phosphorus losses, and consequently lower EP values, irrespective of farming systems: organic tomato and conventional apple crops showed the lowest EP. In fact, leaching to groundwater of nutrients depends on several other factors, as soil properties (*i.e.*, compaction, organic matter content, aeration) and climate, indirectly correlated on soil management [60]. Mineral and organic fertilizers contain a small quantity of heavy metals (*i.e.*, Cd, Cu, Ni, Cr, Pb, Zn), that can be released to soils and remain in soil after harvest. In the case of long-standing cropping systems (*i.e.*, orchard) their potential effects on toxicity indicators have been accounted, as suggested by Audsley [61].

Plant protection substances are applied to control certain organisms (e.g., weeds, fungi, and insects) in order to improve the productivity of arable farming. However, via wind drift, evaporation, leaching, and surface run-off, part of the applied agro-chemicals may be release upon terrestrial and aquatic environments, generating a potential toxicity on ecosystems and humans. Depending on the great biodiversity (species and functions) of flora and fauna, pesticides residues determine a wide range of different effects on environment that are in turn different from effects on humans.

Overall, marine aquatic ecosystems appears for being the most sensitive to chemical residues of pesticides. In apple and chicory, where the use of pesticides are usually high, the impact on toxicity indicators appears straightforward, whereas the use of biocompatible pesticides (*i.e.*, pyrethrum) shows a positive effect on toxicity potentials of organic tomato and pear cultivation.

LCA is permitted to discriminate the sole contribution of transportation on environmental impact, and so to perform scenario analysis, changing data inputs. This could be an important aspect for evaluating the trade-off beyond which transportation burdens on product more than production stage, and so quantifying the maximum acceptable distance for a sustainable agricultural supply chain. In our case study, transports had a generalized negligible effect due to the very short distances involved (<70 km). Nevertheless, simulating a scenario of distribution of 1 kg of fresh product to northern European customers (which could be one of the end markets for Italian fruits and vegetables), a distance between farmer and customers of 2000 km, creates burdens on CO_2 eq. emissions of up to 5–10 kg functional units, overloading the production.

When applying LCA to agriculture, great attention has to paid to the functional unit used, as the numerical results can be markedly affected and led to distorted interpretations. We have chosen to conveyed LCA values on 1 kilograms of harvested product to conveniently facilitate comparisons with results generated by the production of the same crop in other regions, but it is worthwhile noting the difference of numerical values of the principal impact categories if expressed on 1 hectare of arable soil (Figure 2). Producing 1 kg of tomato gives lower contributions to GWP100 than 1 kg of wheat, but cultivating 1 ha of tomato creates a greater burden on CO_2 eq. emissions than cultivating 1 ha of wheat. The higher yield per hectare of tomato "spreads" the effect on a very high quantity of product, unlike to what happens in the case of wheat, which has an average yield per hectare 10–15 fold lower.

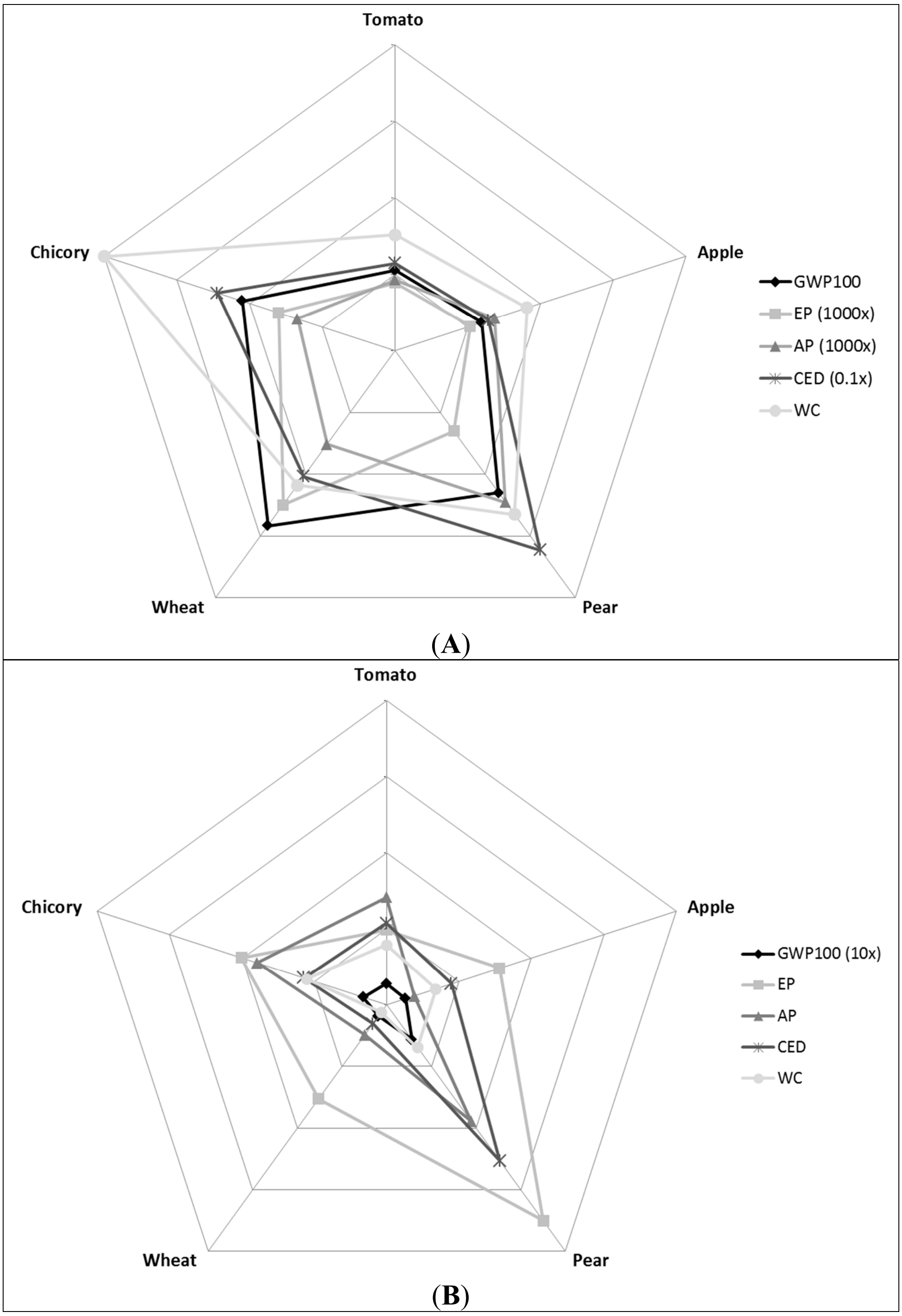

Figure 2. Comparative values of impact categories (**A**) for 1 kg of selected crop and (**B**) for 1 ha of cultivated soil. The figure represents a graphical visualization of the different relative results of impact categories depending on the functional unit used.

3.2. LCC

Based on official 2011 tariffs for electric energy and fuels [34], and on specific financial costs collected from questionnaires, life cycle costing analysis for each crop was carried out (Table 4). Cost related to field operations never accounts for less than 45% of total costs of life cycle, principally due to the high costs of Italian labor and fuel. Pear production was the most expensive, due to the fuel mix used (gasoline and diesel oil). Overheads contributes for about 15%–20% of the life cycle costs. Costs are distributed between fixed and variables as 75:25 for all crops, except for pear (50:50) and wheat (45:55), where variables costs are more significant (due to fuel in the former case and to fertilizers in the latter).

Table 4. Economic impacts of agricultural phase for the production of selected crops. Data are expressed in €cent/kg.

	Tomato	Apple	Pear	Wheat	Chicory
Cost of field operations	**1.27**	**2.29**	**20.41**	**5.23**	**13.51**
Orchard plantation	-	0.67	0.77	-	-
Seeds	-	-	-	1.55	-
Machineries	0.56	1.05	5.70	1.75	11.13
Fuel	0.71	0.57	13.97	0.60	0.80
Labor	1.36	1.36	3.28	1.33	1.58
Cost of fertilizers	**0.30**	**0.32**	**3.83**	**2.21**	**1.62**
Cost of pesticides	**0.29**	**2.45**	**10.04**	**1.92**	**1.70**
Cost of transports	**0.01**	**0.19**	**0.56**	**0.35**	**0.81**
Cost of other resources	**0.06**	**0.07**	**0.07**	**0.08**	**0.26**
Cost of overheads	**1.51**	**1.27**	**4.75**	**1.71**	**3.55**
Total costs of life cycle	**4.80**	**7.95**	**42.96**	**11.50**	**21.45**

Total costs of the life cycle obtained for the five model crops were higher both in production costs declared by farmers for 2011 and in the selling price of products in the same year in Italy. Even in a steady state model, this showed that changing the perspective on costs in terms of LCC allows obtaining economic data and margins evaluation more realistic than in the case of conventional costs analysis. LCC is confirmed to be able to capture hidden costs, usually overlooked without considering the full life cycle.

3.3. Integrated LCC and LCA

LCA analysis permitted to measure the environmental impacts of five local crops, and to identify key stages with highest contribution to different impact categories. This is in itself an important result from the perspective of a local benchmarking of the environmental impact of agricultural productions, or for a comparison with different production systems in other regions.

Nevertheless, we identify as the key point of this analysis the possibility to combine and *superimpose* the two life cycle set of values generated by the LCA/LCC analysis, to build a model for a semi-quantitative assessment of *externalities* in agriculture. In fact, understanding and identifying the relationship between economical and physical impacts of a product could lay the foundation for investigate the impact of the related social costs [62,63]. To the best authors' knowledge, this study represents the first attempt to apply an integrated life cycle approach to evaluate the overall sustainability of Italian agriculture. Departing from a local level, the final aim of this strategy will be to join to the general regional effort of creating a "waterfall effect" in the diffusion of a culture of social responsibility, through the promotion of an environmental context that is more safeguarded and livable, therefore more sustainable.

During the agricultural year, field operations and the use of inputs caused relevant "environmental costs", measured by LCA indicators. Otherwise, LCC accounts for the economic costs of a product by *internalizing* all the incurred expenses during its life cycle, even including expenses only indirectly related to resources flows (*i.e.*, overheads and labor costs). The gap between these two sets of cost values could shows the presence of negative *externalities* related with an agricultural production. Figure 3 shows a comparison among normalized LCA impact categories that have the major potential direct effect on environment (GWP100, EP and HTP/ETP) and LCC costs, per functional unit. In the case of tomato and pear, CO_2 eq. emissions and 1,4-DB eq. due to field operations had an incidence on respective indicators higher than the costs sustained by farmers for their execution and purchase. For chicory production, the use of labor for harvesting and the high incidence of production/use of fertilizers and pesticides, could have contributed to reduce the overall weight of CO_2 eq. emissions for field operations with respect to their monetary costs. Except for wheat, where the most relevant impact is due to fertilizers and pesticides, in the other cases the gap between CO_2 eq. emissions and related costs is unbalanced to the detriment of environment. In all five study cases, nitrate and phosphate leaching and chemical residues of pesticides induced environmental impacts that were much more of a burden than the costs incurred by farmers to purchase and use their respective inputs. The different percentage weight between environmental and economic impacts could be accounted as side effects of the agricultural activity, and their costs are indeed external to the price paid by producers or not directly accounted to consumers. To date, such *externalities* have not been included in final prices, even if undoubtedly they have a long-term effect to distort the market by encouraging activities focused on private benefits, while having hidden and increasing costs for environment and society. Despite the difficulties of quantifying the current and future value of natural capital, several attempts for putting a cost on these non-market goods has been proven [64,65]. Using average costs of abatement, restoration or replacement of ecosystems and depuration of drinking water, evaluated as about 40€ for 1 kg of nitrogen emitted [66] and about 50€ for 1 kg of active ingredients in pesticides [67]. Table 5 shows a possible quantification of *externalities* connected to the fertilizers and pesticides emissions, modeled as input data for the five crops. Organic farming systems seems to have a lessen *externalities* costs, due to the lower toxicity and polluting potential of pesticides of natural. Nevertheless, at an overall glance, comparing the results obtained with LCC costs of fertilizers and pesticides, and also with the total costs of life cycle, it is worthwhile noting the order of magnitude of the hidden costs related to agricultural productions, that burden on society and environment.

Table 5. Quantification of *externalities* costs deriving from fertilizers and pesticides use.

	Tomato	Apple	Pear	Wheat	Chicory
Modeled fertilizers emissions (kg-N/kg)	3.29×10^{-4}	10.05×10^{-4}	15.63×10^{-4}	97.17×10^{-4}	41.87×10^{-4}
***Externalities* calculated from fertilizers emissions** (€cent/kg)	**1.38**	**4.23**	**6.58**	**40.93**	**17.62**
Modeled pesticides emissions (kg-active ingredients/kg)	2.86×10^{-4}	14.09×10^{-4}	8.12×10^{-4}	19.22×10^{-4}	16.54×10^{-4}
***Externalities* calculated from pesticides emissions** (€cent/kg)	**1.42**	**7.05**	**4.06**	**96.41**	**32.70**

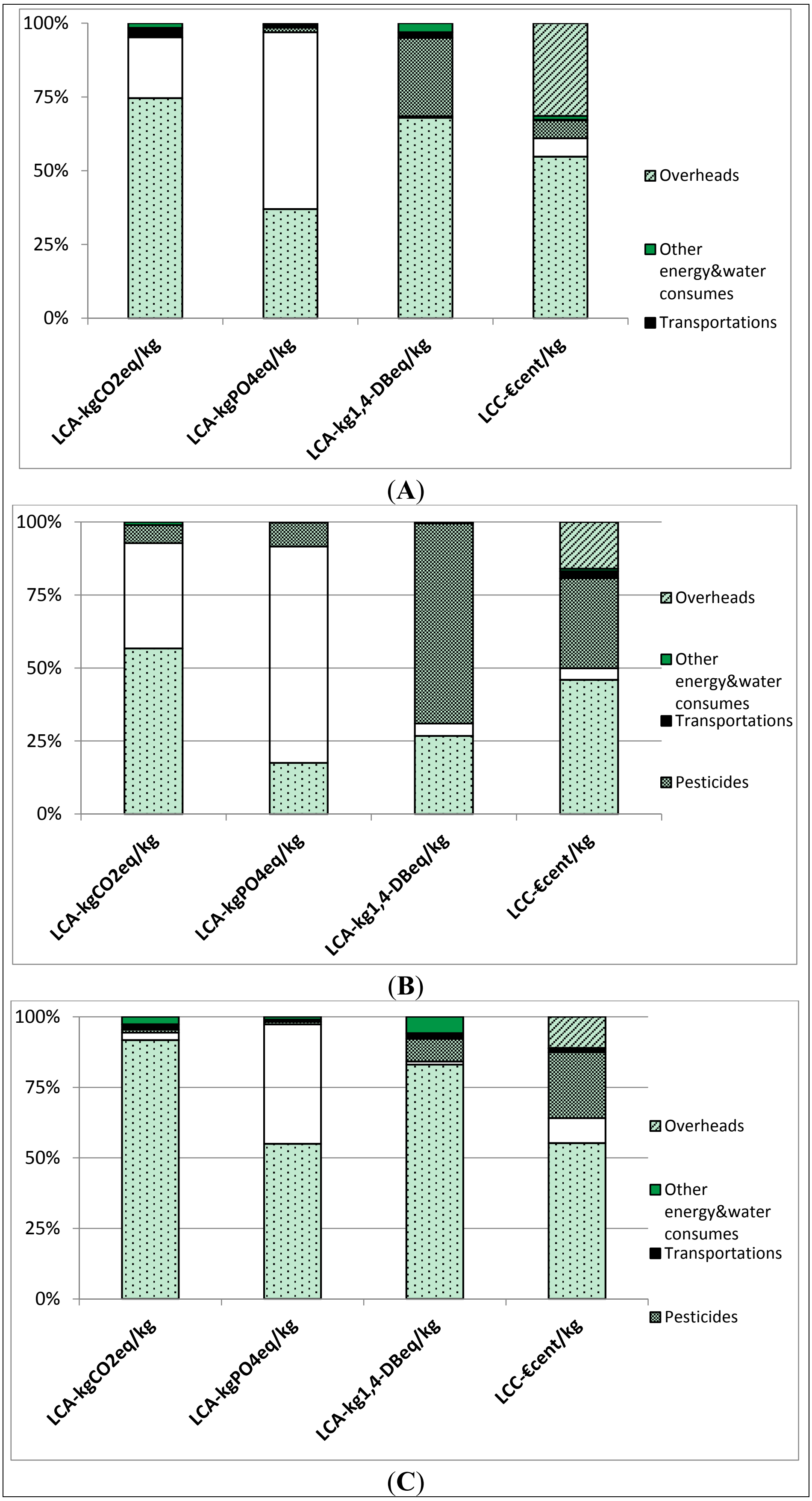

Figure 3. *Cont.*

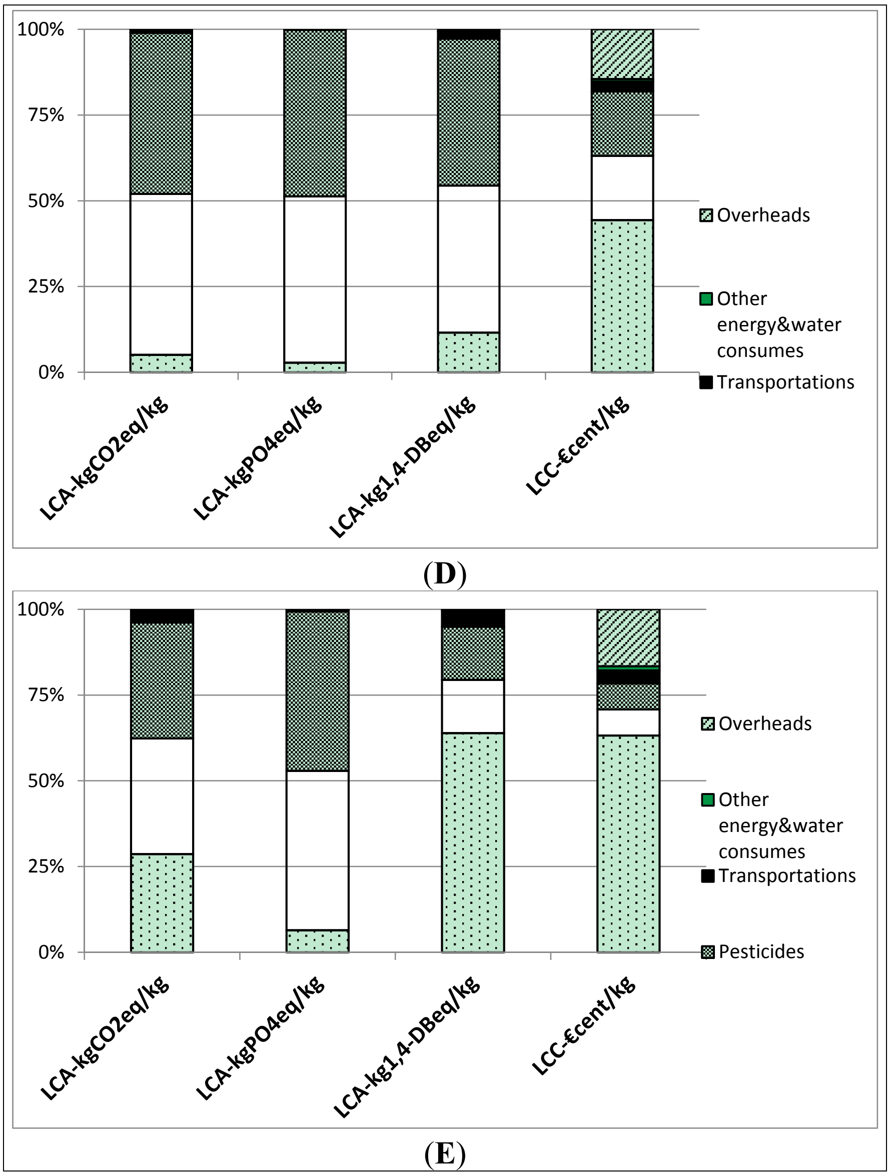

Figure 3. Comparison among contributions of normalized impacts values in LCA and LCC for (**A**) tomato; (**B**) apple; (**C**) pear; (**D**) wheat and (**E**) chicory. The figure shows a percentage-based comparison between economic and environmental resulted impact of the principal categories, for the different macro-phases in which the processes have been divided.

4. Conclusions

Even when the effects of environmental degradation are reasonably well proved, calculating their costs to society remains a difficult task, because of they often occur with a time lag, do not damage specific groups of stakeholders and the identity of the producer is rarely identifiable. Some of the costs in principle can be quantified, but many others involve non-market goods and depend on highly controversial judgments such as the monetary value of returning the environment or human health to pristine conditions. Nevertheless, an evaluation of the order of magnitude of the problem could be attempted, even though it needs further development and investigation, especially for the assessment of national values of *externalities*. In the near future, public awareness cannot avoid taking this direction. These issues raise also important policy questions and an in-depth analysis could permit to find ways to integrate policy tools into effective packages that will increase the supply of desired environmental and social goods, whilst ensuring farmers' economic sustainability.

This perspective becomes even more interesting considering that in the new programming of the new Common Agricultural Policy (CAP) for the period 2014–2020 is given much prominence to the theme of "greening", namely, the commitment of the farm in relation to the conservation of the natural environment.

We are convinced that our study could represent a starting point in the direction of gaining effective sustainability in agricultural production, thanks to the integrated approach based on life cycle results. LCA has been already recognized as a methodology to support agricultural activities assessment year after year, but the possibility to effectively compare and combine LCA with LCC data has permitted us to lay the ground for a general methodology for investigating and (in a next future) quantifying even the long-term effects of resource use and management practices in agriculture.

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Author Contributions

Elena Tamburini was the EU project's scientific supervisor and she has collected and elaborated all the results, supporting by Giuseppe Castaldelli, expert in the field of nitrogen balance in agriculture and eutrophication; Elisa Anna Fano, full professor of ecology and ecosystems, and Maria Gabriella Marchetti, who has great experience of local agriculture and production. Paola Pedrini, as the supervisor of the group, defined the general statement of the research.

Conflicts of Interest

The authors declare no conflict of interest.

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