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Organic production systems: Sustainability assessment of rice in Italy

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ABSTRACT

Even though organic practices are getting more and more widespread, there is scant of information on their environmental impacts. A comprehensive approach is needed in order to take into account, on the one hand, the lower amount of inputs normally used (e.g. pesticides) in organic systems and, on the other hand, the lower yield they usually imply.

The aim of this study is to assess the environmental profile of organic rice cultivation in a farm located in Pavia district (Lombardy). To this purpose, a Life Cycle Assessment methodology, with a cradle-to-field gate perspective, was applied. Inventory data were collected in a rice farm located in Lomellina where organic rice has been cultivated over about 70 ha in the past 15 years.

The environmental profile of organic rice was analysed in terms of 11 different impact categories: climate change (CC), ozone depletion (OD), particulate matter (PM), human toxicity (HT), Photochemical ozone formation (POF), terrestrial acidification (TA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FEx), and mineral and fossil resource depletion (MFRD).

The results suggest that the main environmental hotspots for organic rice are: the emissions of methane from the flooded fields, the production of compost, the nitrogen emissions associated with the application of fertiliser and the mechanisation of the field operations.

Finally, different mitigation strategies have been proposed and investigated. Among these strategies, the substitution of organic compost with cattle manure appears to bring the greatest benefits in 9 out of 11 impact categories. Such benefits range from approximately 13% up to 51%, depending on the impact categories considered. The introduction of aerations during the cultivation period can reduce only climate change (about −9%) but increase all the other environmental effects.

1. Introduction

There is general consensus that food production and consumption are related to negative effects on the environment and that they must become more sustainable (Defra, 2005; Renzulli et al., 2015). Considering the remarkable share of the agricultural activities in the environmental impact of food products, in the last years, several researches have evaluated the agricultural processes from an environmental perspective (CEC, 2003; Roy et al., 2009; Renzulli et al., 2015). More recently increasing attention has been paid to assess the benefits arising from the implementation of mitigation strategies (Roy ey al., 2007; Harada et al., 2007; Weiss and Leip, 2012; Bacenetti et al., 2015b).

Among cereals, maize, wheat and rice are the most analysed crops from an environmental perspective (FAO, 2013a, 2013b); nevertheless, most of the available studies assessed the conventional cultivation systems of these cereals, whilst the organic practices are less investigated (Hokazono and Hayashi, 2012; Renzulli et al., 2015; Hokazono and Hayashi, 2015).

As regard to rice, in Italy, 219,500 ha were cultivated in 2014 (+1.38% respect to 2013, with a total production of 1,466,000 t) mainly in Northern Italy and, in particular, in the districts of Pavia, Vercelli and Novara (Enterisi, 2013; Enterisi, 2014). In Europe, where about 425,000 ha are cultivated to rice (Enterisi, 2014), Italy represents the major rice producer with Northern Italy accounting for about 55% of European rice area. The conventional cultivation is by far the most common agricultural system; however, the organic one is becoming more and more important. According to the SINAB (2015), in 2014, the rice area dedicated to organic rice was 9,528 ha

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(4.3% of the overall rice area) with a total production of 57,070 t (3.5% of the rice production).

Rice cultivation system, both conventional and organic, causes a considerable environmental impact (Milà i Canals et al., 2006; Leip, 2007; Blengini and Busto, 2009; Xu et al., 2013; Hatcho et al., 2012; Fusi et al., 2014; Kanta Gaihre et al., 2014). In fact, besides soil and water pollution, energy and inputs (e.g., fertiliser, seeds, etc.) consumption, paddy fields (irrigated or flooded) are responsible for large methane emissions. According to the Fifth Assessment Report (IPCC, 2013), paddy rice cultivation (11%) is a major source of global CH_4 emissions and it is responsible for 9-11% of agricultural GHG emissions (about 0.52 $GtCO_2eq/yr$ mainly due to methane emissions). Thus, rice cultivation contributes to a great extent of the global warming phenomenon (Roy et al., 2007, 2009). Furthermore, in conventional rice production, the extensive application of plant protection products (mainly herbicides) in combination with wrong agricultural practices results in environmental concerns such as risks for human health and contamination of natural resources (Capri and Karpouzas, 2007).

To assess the environmental performances of agricultural activities, different methods have been developed. Among these, the Life Cycle Assessment (LCA) method is the most used. LCA is a standardised methodology designed for the holistic assessment of the environmental impacts and resources used associated to a product throughout its entire life cycle production process; by using LCA it is possible to analyse the potential environmental impacts of products (processes or services) throughout their whole life cycle (ISO, 2006).

Concerning the rice production system, some studies have been carried out in order to highlight its environmental impact (Leip and Bocchi, 2007; Hatcho et al., 2012; Blengini and Busto, 2009; Xu et al., 2013; Fusi et al., 2014); however, few of them are focused on organic rice production system (ORP) (Romani and Beltarre, 2007; Hokazono and Hayashi, 2012; Hokazono and Hayashi, 2015). With respect to the conventional rice production system (CRP), the organic one is characterised, on the one hand, by great yield variations and, on average, by yield reductions of about $^1/_3$ (Sinap, 2015) but, on the other hand, by fewer inputs used, the application of organic fertiliser instead of the mineral ones and the ban of chemicals for pest control. Therefore, without a comprehensive evaluation of all the operations carried out across the life cycle it is not possible to conclude which production systems, between ORP and CRP, shows the better environmental performance.

The aims of this study are: (i) to evaluate the environmental impact of ORP system in Northern Italy; (ii) to identify the environmental hotspots; (iii) to compare organic and traditional rice production systems; (iv) to propose possible mitigation strategies for ORP paying particular attention to the water management, organic fertilizers selection and crop residues valorisation.

2. Materials and methods

Life cycle assessment (LCA) has been used to estimate the environmental impacts of organic rice production system, following the ISO 14040/44 methodology (ISO, 2006) and the EPD guidelines developed for “Arable Crops” (Environdec, 2014).

2.1. Goal and scope definition

The goal of this study is to assess the environmental impact of organic rice production (ORP) in Northern Italy and, in particular, in Lombardy region. In more details, a representative farm for ORP was evaluated. In this farm, organic rice has carried out for several years and in 2014, 19 paddy fields were growth with a global agricultural area of 70.3 ha.

The environmental hotspots for ORP have been identified and different mitigation strategies have been proposed and analysed.

2.2. Description of Organic Rice Production (ORP) system

Rice is one of the most widespread cereals in Italy; in the eastern part of the Po Valley area (45°19′00″N, 8°25′00″E), it represents the main annual crop and an important revenues source for farmers. Although still now cultivated over a small area, interest about organic rice and its environmental performance is fast growing.

In temperate regions such as Italy, the rice (*Oryza sativa* spp. L.) is grown as a summer crop. In the northeast of Po Valley, the local climate is characterised by an average annual temperature of 12.7 °C and rainfall is mainly concentrated in autumn and spring (average annual precipitation is 745 mm). Thanks to the good water availability, in this climatic conditions, rice is mainly cultivated in flooded fields; the water has the main aim to keep the temperature and therefore prevent spikelet sterility in spring when cold air flows from the Alps.

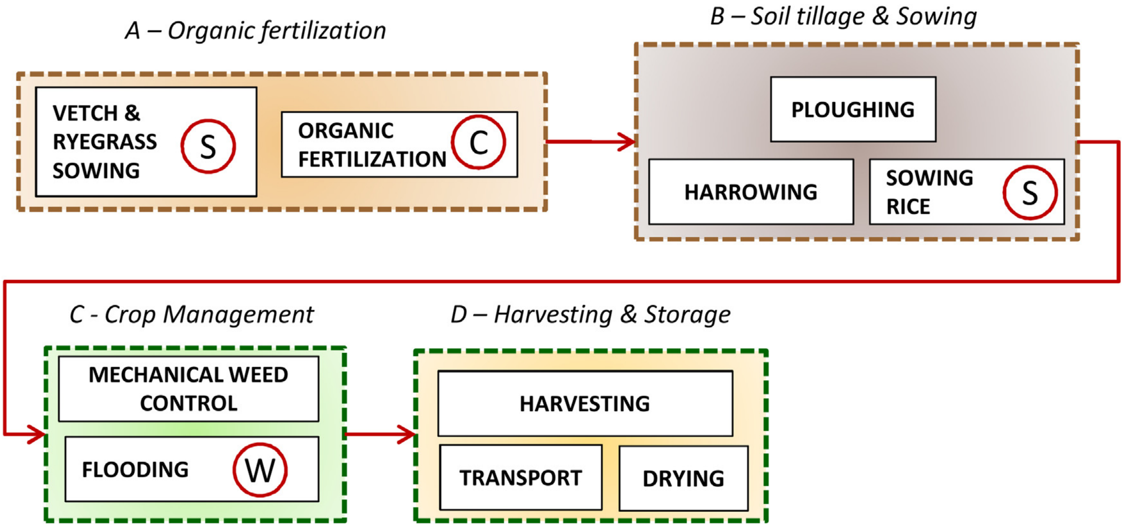

Fig. 1. Organic rice production (ORP) system (S = seeds, C = compost, W = water).

The cultivation practice for ORC is shown in Fig. 1.

The ORP system includes several operations carried out both on the field and at the farm; these operations have been gathered into 4 sections:

Section A: organic fertilisation. Before rice sowing, a mixture of vetch and ryegrass is sown (about 220 kg ha^{-1} of seed, 70% ryegrass and 30% vetch) and the biomass produced is incorporated into the soil in May when about 5 t ha^{-1} of dry mass is produced. Besides the green manure, an organic fertilisation is carried out with compost (22.5 t ha^{-1}).

Section B: soil tillage and sowing. Primary tillage is performed with a plough (30 cm deep), in order to incorporate into the soil the biomass produced by ryegrass and vetch as well as the compost. Besides the primary tillage, soil tillage includes also an intervention with a rotary harrow (secondary tillage). The sowing is performed in non-flooded fields using a precision seeder (220 kg ha^{-1} of rice seed). With respect to CRP, the seed rate is higher (about +10%) because of higher mortality rate mainly due to weeds competitions and mechanical weed control. Sowing is carried out at 5–6 cm depth.

Section C: crop management. Two main operations characterise this section that, compared to CRP, is simplified because no interventions with chemicals (herbicides and pesticides) and chemical fertilisers are performed. The weed control is carried out four times by means of a spring tine harrow and performed until rice emergence. After mechanical weed control, the rice fields are flooded and no aerations (drainage) are scheduled. The flooding ends only at the beginning of September (approximately 2 weeks before the harvest).

Section D: harvesting and storage operations. This includes harvesting, transport and drying. After the waxy-ripeness, when the moisture content of rice grain decreases below 30%, the crop is harvested using a combine harvester. The rice paddy is loaded into two farm trailers coupled with tractors, and transported to the farm (at 2.45 km distance). At the farm, the paddy rice moisture is brought to the commercial value (14%) through the use of a dryer fed with natural gas. Rice straw is left in the soil and incorporated into the soil the following year.

2.3. Functional unit

The functional unit (FU) is defined as a quantified performance of a product system to be used as a reference unit in a LCA (ISO, 2006). With regards to the agricultural production systems, different functional units can be selected; the most frequently chosen are:

(i) the mass of product (grain, fruit, biomass, milk, etc.) (Andresson, 2000; Brentrup et al., 2004; González-García et al., 2012; Bacenetti et al., 2015a; Bacenetti and Fusi, 2015; Noya et al., 2015,Ingrao et al., 2014);

(ii) the cultivated area (e.g., 1 ha) (Blengini and Busto, 2009; Nemececk et al., 2011; Negri et al., 2014);

(iii) the energetic value of the product (Bacenetti et al., 2014; Bacenetti et al., 2015c; Pierobon et al., 2015; Renzulli et al., 2015);

(iv) the energy produced (e.g., biogas to electricity) (Bacenetti et al., 2013; Lijó et al., 2014a; Lijó et al., 2014b; Lijó et al., 2015).

In this study, consistently with other LCA analysis focused on cereal grain production, 1 ton of rice grain (at commercial moisture of 14%) has been chosen as FU.

2.4. System boundaries

A cradle-to-farm gate perspective has been adopted. The following activities were included in the analysis: raw materials extraction (e.g., fossil fuels), manufacture of the agricultural inputs (e.g., seed, fertilisers and agricultural machines), use of the agricultural inputs (fertilisers emissions, diesel fuel emissions, and tire abrasion emissions), maintenance and final disposal of machines.

The system boundaries are reported in Fig. 2. For each of the 4 sections described in sub-chapter 2.3, the lifecycle of each agricultural process has been included within the system boundaries. In more details, the following processes were considered: raw materials extraction (e.g., minerals, fossil fuels, and metals), manufacture (e.g., seeds, tractors and agricultural implements), use (diesel fuel and lubricant consumption and related emissions, tire abrasion), maintenance and final disposal of machines, and supply of inputs to the farm (e.g., compost).

As regard to the emissions related to ORP system, three different emission sources were considered: emissions associated

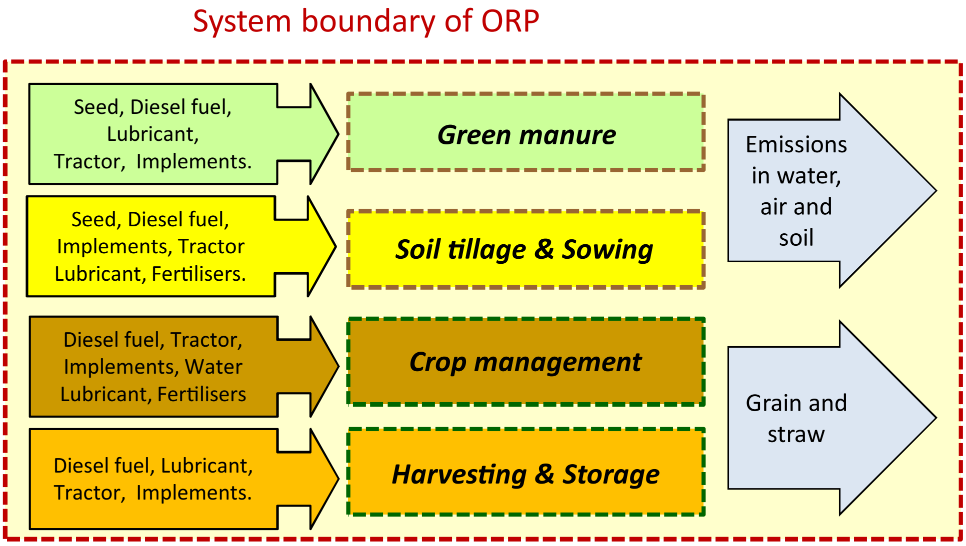

Fig. 2. System boundary for ORP system.

Table 1
Crop cultivation practice for ORP system.

Section	Month	Field Operation	Operative machine	Tractor		Fuel Consumption	Input		Time	Data source
				kW	kg	kg ha^{-1}	Product	Amount	h/ha	
(A) Green manure	October	Sowing	Seeder	90	5050	7.2	Seeds	140 kg ha^{-1} ryegrass 60 kg ha^{-1} vetch	0.90	Farm surveys and farmer interviews (average data for eleven paddy fields)
(B) Soil Tillage & Seeding	April	Organic fertilization	Manure spreader	120	7200	34.9	Compost	22.5 t ha$^{-1(b)}$	5.05	
	April	Ploughing	Plough	135	7600	27.7			1.10	
	April	Harrowing	Rotary harrow	90	5050	18.6			1.70	
	May	Sowing	Seeder	90	5050	6.4	Seeds	220 kg ha^{-1} rice	0.86	
(C) Crop management	May – June	Mechanical weed control	Harrow tines$^{(c)}$	90	5050	2.9			0.20	
	June – September	Water management	–	–	–	–	Water	40000 m^3 ha^{-1}	–	
(D) Harvesting & Storage	September	Harvest	Combine harvester	335	15500	36.1		5.3 t ha^{-1} (27% of moisture)	0.80	
	September	Transport	Trailer	90	5050	15.1			0.80	
	September	Transport	Trailer	90	5050	15.1			0.80	
	September	Drying	Dryer	–	–	–	–	–	–	Farmer interviews

(a) 5 interventions, (b) Moisture = 50%; Nitrogen content = 30 kg t^{-1} of dry matter, (c) Five interventions.

with fertilisers application, emissions due to flooding (mainly methane) and emissions related to fuels combustion.

The fields under study were previously dedicated to rice cultivation, therefore, carbon sequestration into the soil was not included, following the recommendations of PCR "arable crops" (Environdec, 2014).

2.4.1. Alternative scenarios

Five alternative scenarios (AS) have been considered, besides the Baseline (BS) described in the previous sub-chapters. In more detail:

Alternative scenario 1 (AS1): in this scenario, during the flooding (the first at mid June and the second at the end of June) two aerations are performed by draining the field. Such practice, allowing the oxygenation of the soil (thanks to the contact with the atmosphere air), reduces the anaerobic decomposition of the organic matter into the soil and, consequently, the methane emissions (for details on methane emissions calculation see. Sub-chapter 2.5). Nevertheless, beside the reduction of methane emissions, also a decrease of grain yield (-10%) has been taken into account considering a higher competition of weeds, mainly the terrestrial ones such as barnyard grass (*Echinochloa crus-galli* L.).

Alternative scenario 2 (AS2): in this scenario, the compost has been substituted with cattle manure as organic fertiliser.

Alternative scenario 3 (AS3): in this scenario, the compost has been replaced by cattle slurry as organic fertiliser.

Alternative scenario 4 (AS4): dried poultry manure was used in this scenario in place of compost.

Alternative scenario 5 (AS5): in this scenario, the straw is assumed to be collected and sold. Following the EPD recommendation for "Arable crops" (Environdec, 2014) and previous studies (Fusi et al., 2014), an economic allocation has been performed between grain and straw. To balance the higher removal of nutrients from the soil due to straw collection, an increase of compost rate application has been considered.

2.5. Inventory data collection

Data concerning field operations and agricultural inputs were obtained directly from the producer involved in this study. The farm, located in the district of Pavia, includes 19 different fields and it can be considered representative of the Italian organic cultivation practice because organic rice is produced by several years over more than 70 ha.

The cultivation practice of the ORP system was identified by means of interviews with the farmer and of surveys in 19 paddy fields. In more details, the information concerning field operations and rice grain drying (e.g., the working times, the characteristics of tractors and agricultural equipment such as mass, age, power, length and width and life span), the amount of production factors applied (e.g., fertiliser, water, etc.) were collected through a survey form.

2.5.1. Inputs

The diesel fuel consumption was directly measured during surveys on the paddy rice fields. For the operations involved in the alternative scenarios, the diesel fuel consumption was estimated considering the power requirements by the operative machines and their effective field capacity according to Fiala and Bacenetti (2012).

Regarding the green manure, considering experimental field tests previously carried out in the same area (Romani and Beltrarre, 2007), a biomass production of 5.1 t ha^{-1} of dry matter and a nitrogen input of 133 kg ha^{-1} were considered.

The amount of tractors and agricultural equipment needed for each field operation was calculated considering the annual working times and the physical[1] and the economical[2] life span.

Table 1 reports the main average inputs data for the ORP system under study (baseline scenario), as well as the characteristics for tractors and agricultural equipment used.

Background data for the production of seeds (rice, ryegrass and vetch), diesel fuel, compost, tractors and agricultural machines (equipment and combine harvester) were obtained from the Ecoinvent database Database v.3 (Althaus et al., 2007; Frischknecht

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[1] Physical life span (PLS, h) was considered equal to 12000 h for tractors, 2000 h for plough, harrows, seeders and compost spreader, 2500 h for the self-propelled harvester and 3000 h for farm trailers (Bodria et al., 2006).

[2] Economical life span (ELS, years) is 12 years for tractors and farm trailers, 10 years for self-propelled harvester and compost spreader; 8 years for plough, harrows and seeders.

Table 2
Ecoinvent unit processes used for the inventory.

PROCESS and INPUT	ECOINVENT PROCESS
Organic fertilization	Compost, at plant[a] Solid manure loading and spreading, by hydraulic loader and spreader/CH U[b–c] Transport, lorry 16-32t, EURO5/RER U
Tillage operation	Tillage, ploughing/CH U[b] Tillage, harrowing, by rotary harrow/CH U[b]
Sowing	Sowing/CH U[b]
Seed	Grass seed organic, at regional storehouse/CH U[d] Pea seed organic, at regional storehouse/CH U[e] Rice seed organic, at regional storehouse/CH U
Mechanical weed control	Tillage, harrowing, by spring tine harrow/CH U[b]
Water	Water, lake
Harvest	Combine harvesting/CH U[b]
Transport of rice grain	Transport, tractor and trailer/CH U[b]
Drying	Grain drying, low temperature/CH U
Diesel fuel	Diesel, at regional storage/RER U
Lubricant oil	Lubricating oil, at plant/RER U
Tractors	Tractor, production/CH/I U
Operative machine	Agricultural machinery, general, production/CH/I U
Organic fertilization in AS 3	Slurry spreading, by vacuum tanker/CH[b]
Organic fertilization in AS 4	Poultry manure, dried, at regional storehouse/CH
Transport of poultry manure	Transport, lorry 7.5-16t, EURO5/RER U
Bailing in AS 5	Baling/CH U[b]

[a] Modified according Blengini (2011), [b] Field operations were modified considering site specific parameters (working time, fuel and lubricant oil consumptions, annual use and lifespan of tractors and operative machines), [c] Also in AS 2 for manure spreading, [d] For ryegrass, [e] Modified considering for the vetch a yield of 2.51 t ha^{-1}, (instead of of 3.04 t ha^{-1} considered for pea).

et al., 2007; Jungbluth et al., 2007; Nemecek and Käggi, 2007; Spielmann et al., 2007). Table 2 reports the different Ecoinvent processes considered in the analysis.

Where a different organic fertiliser is applied instead of compost (AS2, AS3, AS4), the rates were computed considering the nitrogen content. In more details, the following amount were applied: 67.5 t ha^{-1} of cattle manure in AS2, 88.8 t ha^{-1} of cattle slurry in AS3 and 9.1 t ha^{-1} of dried poultry manure in AS4.

Table 3 highlights the main differences about BS and AS for what concerns in particular the organic fertilization while, as regard to AS5, Table 4 reports the information for the economic allocation.

2.5.2. Outputs

2.5.2.1. Grain and straw production. For the different 19 paddy fields, the grain yield was measured by means of the farm weighbridge (Table 5). In the analysis average values (5.3 t ha^{-1} of rice grain at 27% of moisture corresponding to 4.5 t ha^{-1} at commercial moisture) were considered.

When two aerations are scheduled (AS1), a yield reduction, due to weeds competition, of about 10% was highlighted by the farmer.[3] Production of straw was computed considering a Harvest Index (HI, ratio among the grain dry mass and the global above ground dry biomass) equal to 0.45 (Boschetti et al., 2006).

2.5.2.2. Emissions from fertiliser application. Emissions due to the fertiliser applications were evaluated considering soil type, climatic conditions and spreading technique.

Nitrogen emissions (nitrate, ammonia, and nitrous oxide) were computed following the IPCC Guidelines (2006). Phosphate emissions, calculated following Prahsun (2006) and Nemecek and Käggi (2007); in more details, two different phosphorus emissions into water were considered:

- leaching to the ground water: assessed using a factor of 0.07 kg P ha^{1} year^{-1}; and
- run-off to surface water: evaluated considering 0.175 kg P ha^{-1} year^{-1} as emission factor.

Due to a lack of data on the fraction of the eroded soil, phosphate emissions through erosion to surface waters have not be included.

2.5.2.3. Emissions from organic matter decomposition. Methane emissions from anaerobic decomposition were computed following the IPCC methodology (IPCC, 2006). More specifically, the default methane emission factor (1.30 kg CH4·ha^{-1}·day^{-1}) was corrected with the scaling factors for water regime before and during cultivation, the number of aeration periods, and the application of organic matter. In more detail, the following aspects were considered:

i) no aerations in BS, AS2, AS3, AS4 and AS5, two aerations in AS1,
ii) a non-flooded preseason longer than 180 days,
iii) a period among straw incorporation and beginning of the cultivation lower than 30 days.

The methane emission in the different scenario (see. Table 3) ranges from a minimum of 119.73 kg ha^{-1} in AS1, where two aerations are scheduled, to a maximum of 445.79 kg ha^{-1} in AS3, in which cattle slutty substitutes the compost.

2.6. Sensitivity analysis

To test the robustness of the results and investigate the effect of key assumptions, the following parameters have been considered within the sensitivity analysis:

i) emission of methane: minimum and maximum emission factors defined by IPCC (2006) have been considered, first by

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[3] Based on previous experience.

Table 3
Main LCI differences among BS and the alternative scenario (AS).

Scenario [a]	Organic fertiliser						Additional info	Methane emission (kg ha^{-1})
	Type	Amount	Main Inputs & Outputs	Nitrogen content	Spreading	Transport Distance[h]		
BS	Compost	22.5 t ha^{-1}	6 kg t^{-1} of diesel fuel[b]; 140 kWh t^{-1} of electricity[b]	15.0 kg t^{-1} of fresh matter [b]	manure spreader (coupled with a tractor of 100 kW; diesel cons. 11.09 kg ha^{-1})[f]	60 km	–	232.71
AS1	Compost	22.5 t ha^{-1}					−10% of grain yield	119.73
AS2	Cattle manure	67.5 t ha^{-1}	–	5.0 kg t^{-1} of fresh matter [d]	manure spreader (coupled with a tractor of 100 kW; diesel cons. 5.04 kg ha^{-1})[f]	5 km	–	397.65
AS3	Cattle slurry	88.8 t ha^{-1}	–	3.8 kg t^{-1} of fresh matter [e]	slurry tank (coupled with a tractor of 120 kW, diesel cons. 47.18 kg ha^{-1})[f]	5 km	–	445.79
AS4	Dried poultry manure	9.1 t ha^{-1}	153 kWh t^{-1} of heat from natural gas[c]; 110 kWh t^{-1} of electricity[c]; 0.106 kg t^{-1} of NH_4 emission[c]	37.2 kg t^{-1} of fresh matter [c]	fertiliser spreader (coupled with a tractor of 90 kW; diesel cons. 4.94 kg ha^{-1})[f]	45 km	–	238.35
AS5	Compost	25.4 t ha^{-1}	6 kg t^{-1} of diesel fuel[b]; 140 kWh t^{-1} of electricity[b]	15.0 kg t^{-1} of fresh matter [b]	fertiliser spreader (coupled with a tractor of 100 kW; diesel cons. 12.74 kg ha^{-1})[f]	60 km	Windrower (coupled with a tractor of 90 kW; diesel cons. 5.16 kg ha^{-1}) and baler (coupled with a tractor of 120 kW, diesel cons. 11.54 kg ha^{-1}) [e]. 4.3 t ha^{-1} of straw are collected; 12.7 kg of nitrogen per ton of straw – dry matter [g]	212.44

[a] green manure is considered in all the scenarios; [b] Blengini, 2008; [c] Fabbri et al., 2008; Fabbri et al., 2009; Nicholson et al., 2004; [d] Bacenetti et al., 2016; [e] Lijó et al., 2015; [f] Fiala and Bacenetti, 2012; [g] Fusi et al., 2014; [h] transport distance has been calculated based on the biggest and nearest supplier.

assuming all minimum (0.8 kg CH_4 ha^{-1} day^{-1}) and then all maximum values (2.2 kg CH_4 ha^{-1} day^{-1});

ii) emission of N_2O, NO_3 and NH_3 from fertilizer application: minimum and maximum emission factors defined by IPCC (2006) have been considered, first by assuming all minimum and then all maximum values; rice yield: minimum and maximum values recorded in the 19 paddy fields were considered, first assuming the minimum (3.40 t ha^{-1} at commercial moisture) and then the maximum (5.79 t ha^{-1} at commercial moisture) yield.

The sensitivity analysis was performed on the BS scenario.

2.7. Life Cycle Impact Assessment (LCIA)

The environmental impacts have been estimated using the midpoint ILCD method (Wolf et al., 2012 – http://eplca.jrc.ec.europa.eu/?page_id=86). The following impact categories were considered: climate change (CC, expressed as kg CO_2 eq.), ozone depletion (OD, expressed as kg CFC-11 eq.), particulate matter (PM, expressed as kg PM2.5 eq), human toxicity (HT, expressed as CTUh), Photochemical ozone formation (POF, expressed as kg NMVOC eq.), terrestrial acidification (TA, expressed as molc H+ eq.), terrestrial eutrophication (TE, expressed as molc N eq.), freshwater eutrophication (FE kg P eq.), marine eutrophication (ME, expressed as kg N eq.), freshwater ecotoxicity (FEx, expressed as CTUe), and mineral and fossil resource depletion (MFRD, expressed as kg Sb eq.). These impact categories were selected because they have been recognized as the most representatives for agricultural systems (Guinée et al., 2002; Renzulli et al., 2015).

Table 4
Parameters for economic allocation.

Product	Yield t ha^{-1}	Price € ha^{-1}	Allocation Factor %
Grain	4.50[a]	815[c]	93.9
Straw	4.31[b]	55[c]	6.1

[a] At commercial moisture (14%); [b] at 20% of moisture; [c] Enterisi, 2014.

3. Results

3.1. Baseline scenario

Table 6 reports the environmental impact for the ORP system, while Fig. 3 shows the relative contribution to the impacts of all the inputs and outputs included in the ORP system.

As can be seen in Fig. 3, the CC category is dominated by the emissions of methane produced by the flooded fields (41%) and by the production of compost (49%). The latter greatly contributes to

Table 5
Rice grain yield in the 19 paddy fields investigated in this study.

Paddy rice field	Area (ha)	Grain yield[a] (t ha^{-1})
1	3.65	5.54
2	5.55	5.76
3	2.65	4.96
4	1.65	3.4
5	2.45	3.55
6	5.45	5.59
7	4.3	5.44
8	3.45	4.92
9	3.75	5.79
10	4.25	5.77
11	5.66	5.48
12	1.88	4.05
13	2.27	4.88
14	3.8	5.67
15	4.09	5.86
16	3.01	5.78
17	4.72	3.99
18	4.98	5.69
19	2.74	5.71

[a]Average moisture = 27%.

Table 6
Environmental impacts of BS. (All impacts expressed per 1 t of paddy rice at commercial moisture).

Impact Category	Unit	Score
CC	kg CO_2 eq.	3269.75
OD	kg CFC-11 eq.	$8.08\,10^{-5}$
HT	CTUh	$2.75\,10^{-5}$
PM	kg PM2.5 eq	2.38
POF	kg NMVOC eq.	8.76
TA	molc H+ eq.	100.95
TE	molc N eq.	453.38
FE	kg P eq.	0.14
ME	kg N eq.	38.69
FEx	CTUe	899.47
MFRD	kg Sb eq.	$8.94\,10^{-3}$

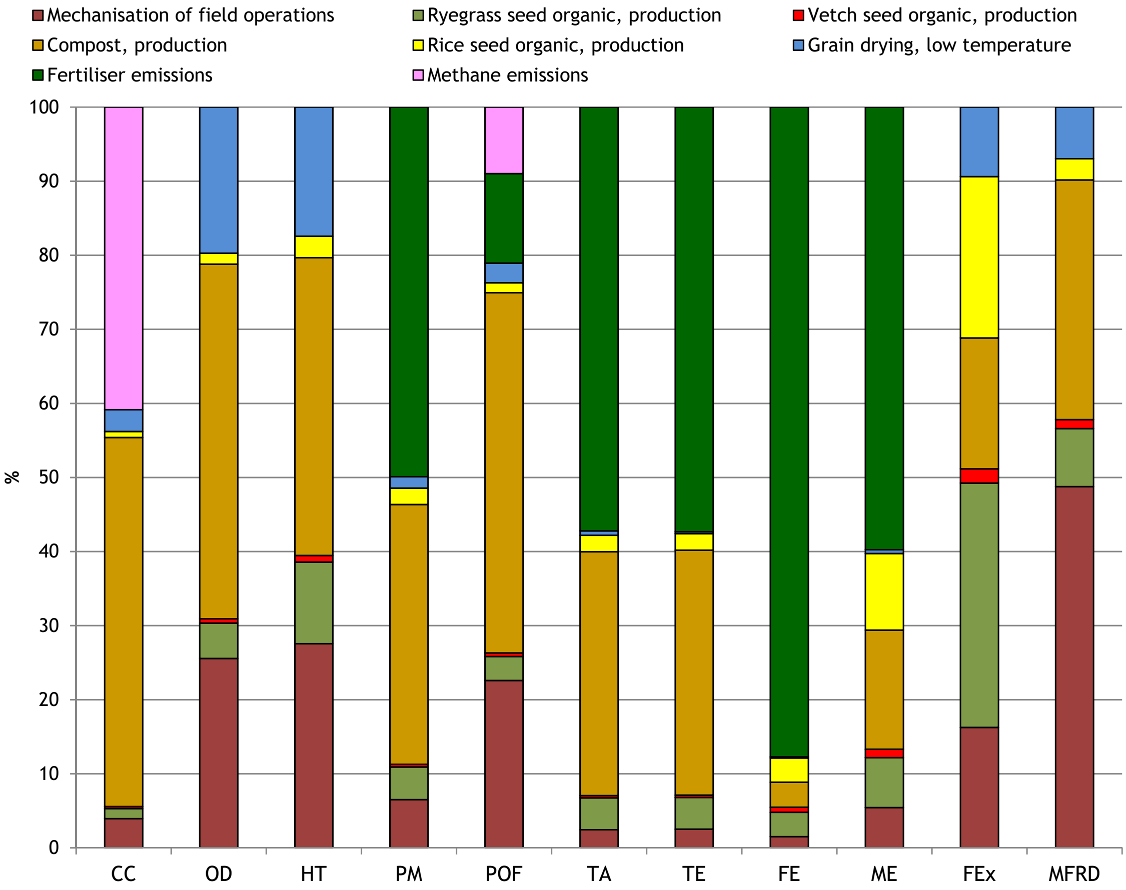

Fig. 3. Hotspots identification in baseline scenario (BS).

many other impact categories, in particular OD (48%), PM (36%), HT (40%), POF (49%), TA (33%), TE (33%) and MFRD (32%).The large impact of compost is mostly due to the consumption of electricity and thermal energy required for its production. The emissions associated with the fertiliser application account for 57% of TA, 57% of TE, 60% to ME and 88% to FE. The mechanisation of field operations[4] contributes almost 49% to MFRD, 28% to HT, 26% to OD, 23% to POF, 23% to FEx, 5% to ME, less than 4% to CC and it is almost negligible in the remaining impact categories. The diesel fuel production and the emissions associated to its combustion are the major contributors to the impact derived from mechanisation. The grain drying stage affects OD and HT by 19% and 17% respectively, while it contributes less than 10% to FEx and MFRD. The production of rice seeds appears to be critical for the FEx category (22%) while it is not significant in all the other categories analysed.

As mentioned in Sub-chapter 2.6, to test the robustness of the results, a sensitivity analysis has been undertaken and the results are presented in Table 7.

The variation of the methane emissions factors affects two impact categories, namely CC and POF: while the overall effect on the POF is small (+5% and −3% with maximum and minimum methane emission factor, respectively), CC ranges widely (+24% and −14% with maximum and minimum methane emission factor, respectively). Although the variation between the maximum and minimum emission factors is large, no environmental effects are detected for all the evaluated impact categories except for CC and POF where, however, the effect is proportionally lower.

When the minimum and maximum emission factors for N_2O, NO_3, NH_3 are taken into consideration half of the evaluated impact categories are not influenced but the results for the remaining 6 are deeply affected. In more details, HT, TA, TE and ME are more than double when the maximum values are considered.

As expected, considering that the mass-based selected FU, the overall effect of yield variation on the environmental impacts is significant, from −22% up to +87%. Among the 11 environmental effects evaluated, TA, TE, FE and ME are the most affected by yield variation while CC is the less influenced. This result can be explained by the direct correlation between CH_4 emissions and the production of grain and straw: when the grain yield is higher (or

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[4] Mechanisation of field operations includes: the production of diesel fuel required by tractors and its associated emissions, the production and maintenance of tractors and agricultural machineries.

Table 7
Sensitivity analysis: Environmental impact variations expressed as percentage (data refer to BS).

Impact category	Rice yield		CH_4 emission factor		N_2O, NO_3, NH_3 emission factor	
	Max	Min	Max	Min	Max	Min
CC	−21%	+19%	+24%	−14%	0%	0%
OD	−18%	+79%	0%	0%	0%	0%
PM	−22%	+86%	0%	0%	0%	0%
HT	−19%	+80%	0%	0%	+109%	−54%
POF	−22%	+86%	+5%	−3%	+95%	−21%
TA	−22%	+72%	0%	0%	+120%	−58%
TE	−22%	+87%	0%	0%	+121%	−58%
FE	−22%	+87%	0%	0%	0%	0%
ME	−22%	+87%	0%	0%	+153%	−60%
FEx	−22%	+87%	0%	0%	0%	0%
MFRD	−20%	+83%	0%	0%	0%	0%

lower) also the straw production increases (or decreases) and, consequently, the methane emissions due to its incorporation into the soil grow (or drop).

3.2. Comparison among the BS and alternative scenarios

Fig. 4 shows the comparison among the five alternative scenarios (AS) evaluated.

AS1 represents the worst environmental option across all the categories considered, except CC. The higher environmental burden in 10 out of 11 impact categories is mainly due to the decrease of the yield (-10%) caused by the introduction of two aerations. The latter, on the other hand, determines a reduction of the emissions of methane, hence a better performance in CC (-9%) with respect to BS.

In AS2, where cattle manure substitutes the compost, respect to BS, the environmental burden of ORP is reduced for all the 11 evaluated impact categories; this reduction ranges from −3.4% in FE to −50.8% in OD. Similar results are achieved in AS3 where compost is replaced by cattle slurry. However, respect to AS2, the environmental benefits arising from the use of slurry (AS3) are lower. This is due to the higher impact associated with slurry transportation and application, with respect to cow manure: greater amount of slurry are required to obtain the same fertilising effect as manure. Moreover, the higher results in CC (2312 kg $CO_2eq\,t^{-1}$ in AS2 and 2596 kg $CO_2eq\,t^{-1}$ in AS3) are due to the increase of methane emissions related to the application of slurry.

In AS4, where dried poultry manure is used in place of compost, the environmental load of ORP is reduced, with respect to BS, across all the 11 impact categories. Respect to BS, the main benefits

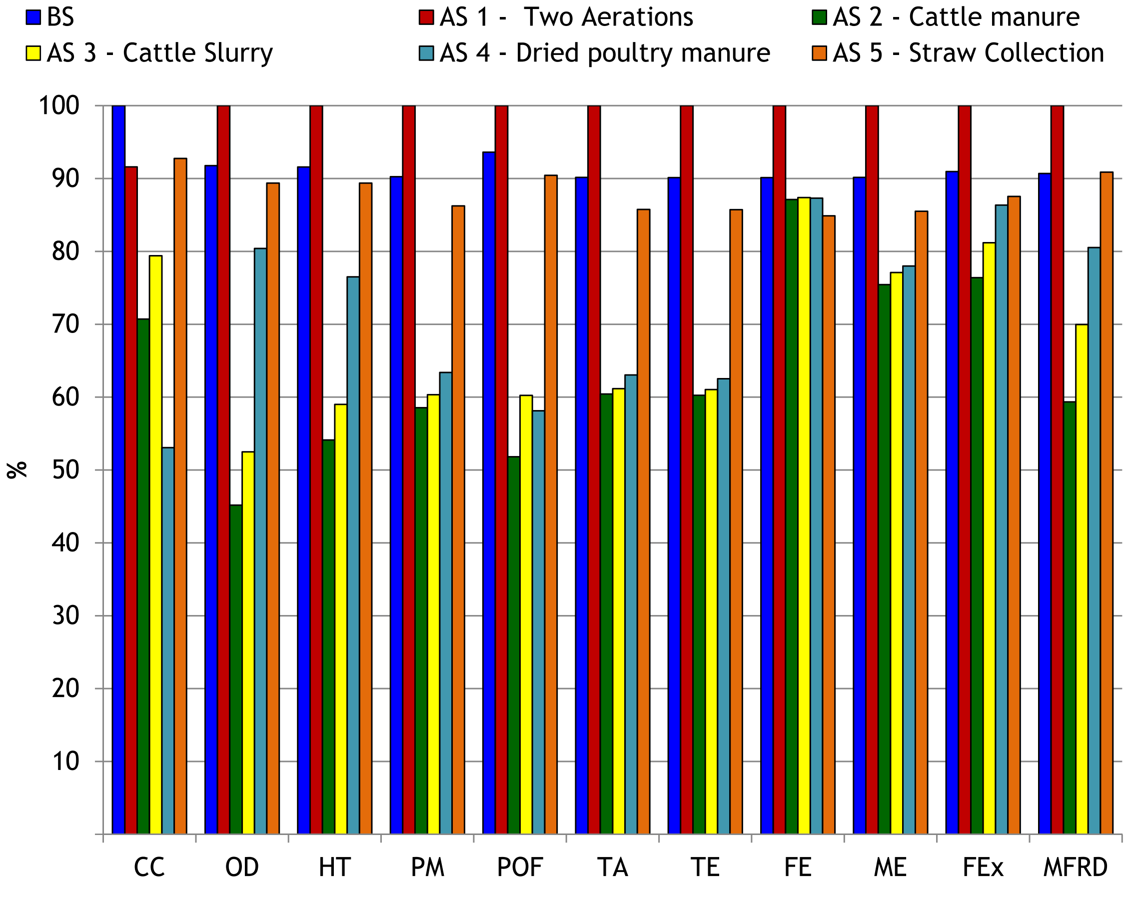

Fig. 4. Comparison among the BS and the different alternative scenarios (AS).

are achieved in CC (-46.9%) while the lowest in OD, ME, and MFRD (-12% approximately), FEx (-5.0%) and FE (-3.1%). The reduction of such impacts is mainly due to lower application rates, lower demand of heat and electricity for the production of the dried poultry manure compared to compost and, finally, to lower methane emissions occurring during the manufacturing and application of the dried poultry manure. Respect to AS2 and AS3, where the cattle manure and slurry replace the compost, in AS4 a smaller reduction of OD, HT, FE, FEx and MFRD is obtained, mainly because of the emissions of ammonia occurring during the drying process and the energy consumption required for drying the poultry manure. On the other hand, AS4 outperforms all the scenarios in CC due to low methane emissions associated with poultry manure application and to the shorter distance travelled by the fertilizer (see Table 3).

In AS5 the straw is assumed to be sold instead of incorporated into the soil. With respect to BS, this alternative straw management system determines a slightly lower environmental impact (from −2.4% up to −14.9%) with respect to BS in all the evaluated impact categories. This is due both to the allocation of the impacts between the rice and straw (based on economic values) and to the lower methane emissions produced (due to the reduced amount of organic material incorporated into the soil). In MFRD, the impact of AS5 is similar (-0.2%) to BS: the fuel consumption for baling and transporting the straw offsets the environmental benefits arising from the allocation of the impacts between the straw and the grain.

3.3. Comparison with traditional rice production

Fig. 5 reports, for the same geographic area, the comparison between ORP (BS) and traditional rice cultivation (TRP). The main differences between the two rice cultivation practices involve:

i) fertilization: in both the production systems organic fertilization with compost is performed but green manure is carried out only in ORP,
ii) weed management: in TRP it is performed using herbicides (2 herbicides applications are performed) in ORP, where chemical herbicides are not admitted, mechanical weed control (5 interventions with harrow tines) is carried out,;
iii) drainage of the flooded field: 1 aeration is performed in TRP, none in the ORP baseline scenario;
iv) grain yield: higher production is achieved in TRP (8.02 t ha^{-1} – 27% moisture content – corresponding to 6.81 t ha^{-1} at the commercial moisture).

Detailed information about the inventory of TRP is reported as supplementary material.

ORP shows higher environmental impact for 9 of the 10 evaluated impact categories, it performs better than TRP only for FEx, the impact category almost completely affected by pesticide emissions. Although with reduced differences between ORP and TRP, similar results are obtained also when considering 1 ha as FU (see Table S2 in supplementary materials). This highlights that the different yield (higher in TRP) enlarges the differences between the two production systems but is not the only reason for the lower impact of TRP. In fact, in ORP, the higher amount of organic matter introduced into the soil with the green manure involves higher methane emissions (affecting CC and POF) while the mechanical weed control if, on the one handavoids the use of agro-chemicals (with related benefit for FEx) on the other hand implies higher diesel fuel consumption (affecting almost all the evaluated impact categories).

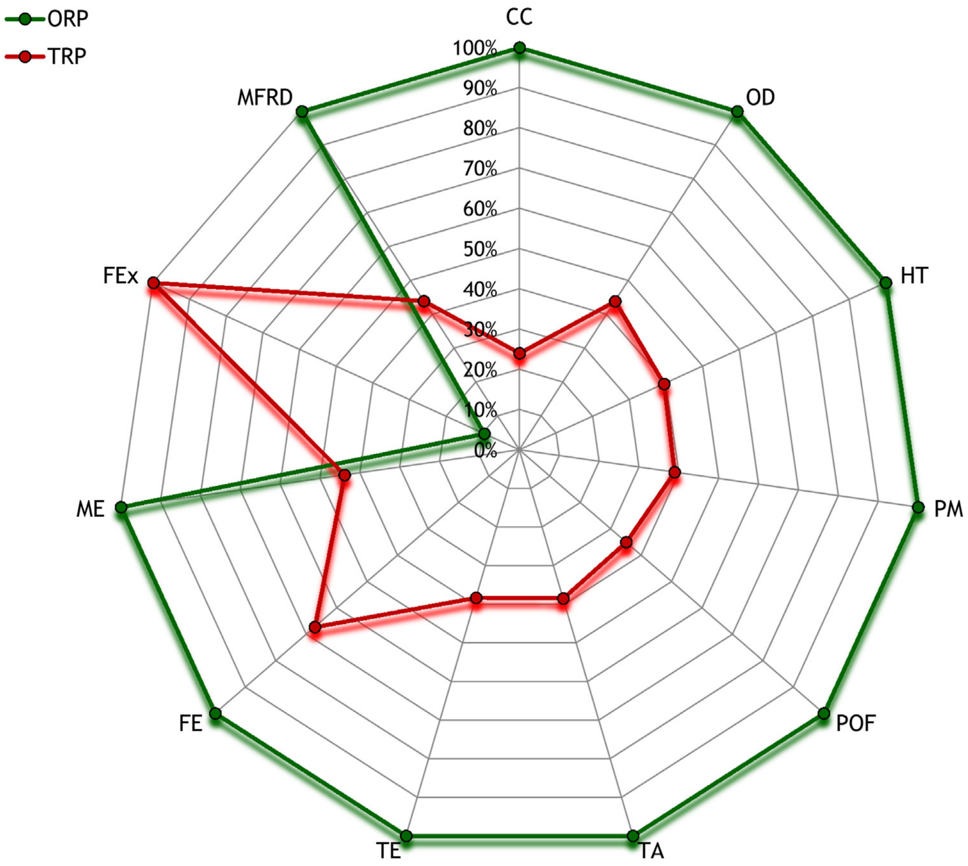

Fig. 5. Relative comparison between ORP (green) and TRP (red).

4. Discussion

The environmental impact of organic rice cultivation is mainly due to fertiliser application. Compost production is an energy-intensive process while its application, as well as green manure, involve the emission of N and P compounds into soil, air and water together with methane release in air. Besides the application of fertilisers, also the consumption of diesel fuel, associated with the mechanization of field operations, plays a key role. The major contributors identified in this study are consistent with that was found in other studies on paddy rice cultivation (e.g. Blengini and Busto, 2009; Yoshikawa et al., 2010; Fusi et a., 2014). Although several life cycle assessment studies of rice have been carried out, direct comparison with the results in the current study is not easy owing to different functional units, types of systems (there is a lack of studies on organic rice), assumptions and life cycle impacts assessment methodologies used. Most studies are based in Asia, i.e. Japan (Harada et al., 2007; Hokazono and Hayashi, 2012; Roy et al., 2009; Yoshikawa et al., 2012), Bangladesh (Roy et al., 2007), Thailand (Kasmaprapruet et al., 2009; Yossapol and Nadsataporn, 2008) and China (Wang et al., 2012). The majority of the available studies included within the system boundaries the milling stage (i.e. Yossapol and Nadsataporn, 2008; Blengini and Busto, 2009; Kasmaprapruet et al., 2009; Yoshikawa et al., 2012) and one of them analysed the whole life cycle up to consumption (Roy et al., 2007). The greatest variation among the studies is found in the number of impacts considered and the methodologies used to estimate them. The latter includes ReCiPe (Goedkoop et al., 2009); IPCC (2001), ecological footprint, CML (Guinée et al., 2002) and SEMC (2000) methods. This and the other differences, including the selected functional unit and the exclusion of capital goods from the evaluation, have led to very different results among the studies, making it difficult to compare them. Table 8 summarises the main methodological differences among the different studies.

The only LCA studies on organic rice are those by Blengini and Busto (2009) and Hokazono and Hayashi (2012, 2015). Although, for the reason outlined before, a direct comparison of the results with the ones obtained in this study is not possible, similarities can be found in particular regarding the hotspot identification. Blengini and Busto (2009) carried out an LCA study on the rice production system in Italy from the paddy field to the supermarket. They compared the results of conventional and organic rice production concluding, similarly to our study, that the benefits arising from the avoided use of fertilisers and chemicals are heavily reduced or, for some indicators, cancelled due to the lower grain yield. Hokazono and Hayashi (2012) assessed the rice production processes in Japan from tilling to husking through three farming systems: organic, environmentally friendly, and conventional. As in our study, the contribution analysis identified direct field emissions, field operations, and compost production as the main drivers of the environmental impact. Consistently with Blengini and Busto (2009), also Hokazono and Hayashi (2012) found that environmental impacts of organic rice cultivation were, on average, higher than those of conventional rice cultivation. The study undertaken by Hokazono and Hayashi (2015) aimed to compare crop rotation systems used in organic farming (organic rotation systems) with those of both conventional farming (conventional rotation systems) and continuous rice cropping systems in Japan. In this case, the authors concluded that organic rotation systems have the potential of being recommended as sustainable agricultural practices, in comparison with conventional rotation systems and continuous (organic and conventional) rice production systems.

Therefore, the comparison between organic and traditional rice production systems carried out in this study is in agreement with the results found by other authors (Blengini and Busto; 2009 and 2012) and shows how the usually lower yield achieved in the organic systems deeply affect the environmental results when a mass based functional unit is selected. This aspect was highlighted not only for rice: Audsley et al. (1997) and Williams et al. (2016), for organic wheat, reported that the lower burdens per hectare corresponded to higher burdens per unit mass of product.

The proposed scenarios AS1, AS2, AS3, AS4 and AS5 represent alternative viable strategies for reducing the environmental impacts of organic rice. When the substitution of compost is considered (AS2, AS3 and AS4), great environmental benefits are obtained in the impact categories where the production of compost represents a hotspots (CC, OD, HT, POF and MFRD). Being the use of fertilisers a key element in rice cultivation, another author (Yoshikawa et al., 2012) investigated two alternative fertilising practices: chemical fertiliser application and green manure. The results showed that the utilisation of green manure reduces the impact due to energy consumption and eutrophication, though increases CC (due to higher methane emissions from soil).

CC can also be reduced by introducing an additional aeration period in the rice cultivation cycle (AS1). This alternative scenario, however, determines an aggravation of 7 impact categories due to the lower yield resulting from the introduction of two aerations. Slightly better performance can also be achieved from the collection of the straw (AS5), where the decrease of environmental load ranges from 0.2% to 14.9%.

The use of cattle manure instead of compost allows achieving the best environmental performance in nine out 11 categories. The only exceptions are CC, for which the use of dried poultry manure represents the best option, and FE, for which the collection of the straw is slightly better than AS2.

5. Conclusions

Rice cultivation involves different agricultural activities that produce several impacts on the environment. Organic productions

Table 8
Available LCA studies on rice and their main characteristics in term modelling choices.

Study	Country	System boundaries	FU	LCIA method
Haranda et al. (2007)	Japan	From cradle to farm gate	60 m^2 of land	Carbon footprint
Roy et al. (2007)	Bangladesh	From farm gate to consumption	1 ton of rice	Material and energy use and CO^2 emissions
Yossapol and Nadsataporn (2008)	Thailand	From cradle to milling plant gate	1 ton of rice	NS
Blengini and Busto (2009)	Italy	From cradle to milling plant gate	1 kg of milled packed rice	IPCC 2011, SEMC 2000
Kasmaprapruet et al. (2009)	Thailand	From cradle to milling plant gate	1 kg of milled rice	EDIP 97
Ferng (2011)	Taiwan	From cradle to farm gate	1 ha	Ecological footprint
Yoshikawa et al. (2012)	Japan	From cradle to grave	1 kg of rice	Carbon footprint
Xu et al. (2013)	China	From cradle to farm gate	1 ton of rice	GWP100
Fusi et al. (2014)	Italy	From cradle to farm gate	1 ton of rice	Recipe
	Japan	From cradle to farm gate	1 MJ of energy yield	GWP100, CML2001

systems are expected to be a viable solution to this issue; nevertheless, few evaluations have been carried out with the specific purpose to assess the environmental performance of organic rice.

This work has studied the environmental performance of organic rice cultivation with the aim of identifying hotspots and opportunities for improving its environmental performance. 19 paddy fields over a global agricultural area of about 70 ha were considered and analysed.

Different scenarios, representing alternative viable agricultural options, have also been proposed and investigated.

The results of the study suggest that, consistently with other studies, the major hotspots of rice cultivation were the fertilisation, the mechanisation of field operations and the emissions of methane associated with the flooded field and of nitrogen and phosphorous compounds from fertiliser application.

Among the strategies proposed to improve the environmental performance of organic rice, the substitution of organic compost with cattle manure appears to bring the greatest benefits in 9 out of 11 impact categories. Such benefits range from approximately 13% up to 51%, depending on the impact categories considered. The introduction of aerations during the cultivation period can reduce only climate change (about −9%) but increase all the other environmental effects.

The results of the current study represent a starting point for the implementation of mitigation strategies in rice production areas where rice is cultivated in flooded fields and where different organic fertilisers are available. Future LCA studies should also take into account the comparison among different rice varieties, irrigation management (e.g., rice cultivation in drained fields) as well as changing climatic conditions, so to give a broader environmental assessment of organic rice production.

Author contributions

JB and AF wrote the paper; JB and MN collected the inventory data; JB elaborated the inventory data; all the authors conceived the study.

Any opinions, findings, conclusions or recommendations expressed are those of the author(s) and do not necessarily reflect the views of the Departments involved in this study.

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