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The environmental impacts of different organic rice management in Italy considering different productive scenarios

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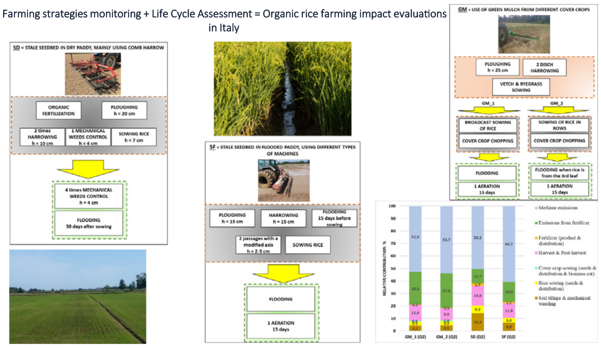
HIGHLIGHTS

- The environmental impact of organic rice cultivation was evaluated using LCA.
- Inventory data were collected in 10 farms for 3 years and for different cultivation practices.
- Yield is the main driver of the environmental impact.
- Shifting from the worst to the best management up to 40 % of impact reduction can be achieved.

GRAPHICAL ABSTRACT



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ABSTRACT

Rice cultivation has a key role in food security worldwide; on the other hand, it has a high potential impact on the environment and human health, mainly due to the extensive pesticides use and greenhouse gas emissions caused by flooded cultivation. In Italy, the rice sector based mainly on high-input monoculture. The transition toward organic agriculture can improve the environmental performance of rice farming according to the actual European sustainable food production strategy. Through LCA methodology, the study aims to evaluate the variability of the environmental impacts and the mitigation potential of four management strategies suitable for organic rice production in North Italy and two production potential levels observed during three-year monitoring on 10 farms in the study area. The LCA analysis includes the wide range of agronomic realities that characterise this farming system, assessing the variation in environmental performance by exploring eight plausible and possible scenarios for organic rice. Results suggest a considerable potential of organic rice production to mitigate its impact on natural resources, depending on the chosen agricultural practices. In particular, six LCA indicators showed a potential of reduction over 40 %, shifting from the worst-performing management to the better one.

Finally, the large variability of climate change impacts assessed, both in this study and in literature, is due to the corresponding existing large variability in terms of yield and available patterns of agricultural practices.

Today the farmers could reach acceptable yield values thanks to more efficient management than in the past. The acknowledgement for that performances relates to the development of the farmers' know-how and to the productive improvement connected to the long-term processes which characterise the organic systems (e.g. generation of soil fertility based on biological fertility and stable humus components; lowering of weeds pressure through the gradual introduction of other crops in rotation).

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1. Introduction

Food production addresses one of the most essential and basic human needs. That is even more true considering rice, a crop with a key role in food security in many countries worldwide (Seck et al., 2012). On the other hand, rice farming has a high potential impact on the environment and human health, due to the extensive pesticides use, in particular herbicides, that occurs when the economic growth and rising labour cost lead to a progressive giving up of hand weeding practice (Naylor, 1994). The rice crop is significantly affected by the crop-weed competition that, in the absence of agrochemicals, is considered the leading cause of yield variability and the main constraint of realising potential yield (Delmotte et al., 2011; Hazra et al., 2018). Rice was identified as one of the most important crops regarding the market value of sold and consumed agrochemicals (Woodburn, 1990), and rice sustainable farming management is still a crucial field of research (Yuan et al., 2021).

In Italy, the rice sector is mainly based on high-input monoculture, and the highest degradation of water quality due to pesticides and herbicides pollution is in the Northern rural areas (i.e. between the Piedmont and Lombardy regions) (ISPRA, 2018), where 94 % of the national rice area is placed (ISTAT, 2016). Thus about 49 % of the European rice cultivations are concentrated (FAO, 2018). In this context, the transition towards organic agriculture can improve the environmental performance of rice farming. Nowadays, that transition is also encouraged by the European sustainable food production strategy “Farm to Fork,” which is the core of the European Green Deal aiming to make food systems fair, healthy and environmentally friendly, encouraging the expansion of the organic agriculture sector (European Commission, 2020).

In general, organic farming is capable of reducing the environmental impact of agriculture by avoiding the use of synthetic compounds (e.g. fertilisers, pesticides) and by promoting practices (e.g. crop rotation, leguminous cultivation, organic fertilisers, green manure crops, and green mulching.) able to increase the soil carbon stock, and prevent the indirect environmental impacts due to the industrial production of inputs (Acuna et al., 2018). Organic agriculture produces biodiversity, with increases in abundance and species richness observed for birds, mammals, invertebrates and flora (Hole et al., 2005), shows higher economic values concerning some ecosystem services (Sandhu et al., 2008), and leads to a decrease of nitrate concentration into the water (Honisch et al., 2002). For rice, in particular, the organic system was observed to be able to increase the soil carbon storage capacity (Komatsuzaki and Syuaib, 2010) and organic matter content, facilitating the soil preparation (Mendoza, 2004) and promoting the ecological succession and temporal heterogeneity of the macrophyte communities into the soil (Martínez-Eixarch et al., 2017).

The Life Cycle Assessment (LCA) is an approach to quantify the environmental impacts of products and or services, and it is increasingly a key tool to support the transition towards more sustainable production patterns. Even if initially developed for industrial processes, LCA was more and more applied to agricultural systems over the years (Fusi et al., 2014, Fusi et al., 2017). Several LCA studies were carried out about conventional rice cultivation systems in developed (Bacenetti et al., 2020; Zoli et al., 2021) and in developing countries (e.g., Escobar et al., 2022). However, results from LCA reveal peculiar features of organic rice cultivation compared to other herbaceous organic crops. Aguilera et al., 2015 studied the global warming potential of 38 pairs of conventional and organic herbaceous cropping systems in Spain (functional unit: 1 kg product), showing the reduction of emission by 36–65 % organic management was assessed, except for rice. Unlike the other crops, organic rice showed an increase in emission by 8 %, compared to conventional rice. The authors highlighted that the rice cultivation in flooded fields differs from other crops because the greenhouse gases (GHG) balance mainly focuses on the methane emissions generated in water-saturated conditions for the anaerobic decomposition of organic matter. Organic rice involves incorporating the soil of organic manure and crop biomass, which, together with the lower yield, increases the methane emissions for a share that the carbon sequestration could not overcome and thus could not offset. Hokazono and Hayashi (2012), Hokazono et al. (2009), and Bacenetti et al. (2016), comparing organic and conventional rice, came to similar results, respectively, in Japan and North Italy, assessing an overall higher impact on organic management. Similarly, the study by (Blengini and Busto, 2009), carried out in North Italy, pointed out that although organic rice can decrease the impact per unit of cultivated area, this benefit declines when the product is a functional unit due to the yield decrease. Therefore, despite the above-mentioned ecological benefit and positive externalities related to organic rice and organic agriculture, the LCA environmental evaluations, considering the environmental impacts, suggest that organic rice farming needs to apply mitigation practices on par with the conventional system, choosing among different management options those with the lower impacts.

However, few studies address this issue, evaluating the variability of LCA outputs and assessing the mitigation potential among different management strategies available for organic rice growing. The comparative studies between organic and conventional rice show some limitations. Insufficient attention was on the existing range of practices and productive performances for organic rice. Often, organic farming seems to be considered a unique system, based on applying a universal management recipe extendible, with a slight approximation, from one monitored farm to all the organic farms of the study area. Most LCA carried out on organic rice assumes a limited variation and slight differences in agricultural practices between farms or between the growing seasons, so much that it is enough to consider few farms or one season to obtain data on management and yield (and thus environmental assessments), representative of the majority. Concerning the previously mentioned studies, Aguilera et al. (2015) considered three rice farms, characterised by shallow, productive performances (i.e. 2.48 t/ha d. m.), without providing details on crop management. Blengini and Busto (2009) considered the organic management adopted by only one rice farm and the resulting yield (i.e. 4.4 t/ha). Hokazono and Hayashi (2012) assessed the environmental impact based on the yield (3.37 t/ha) averaged on two different managements identified for organic rice. Bacenetti et al. (2016) considered the average yield reached during one growing season in 19 fields (i.e. 4.5 t/ha at commercial moisture 14 %) by only one rice farm, and the related management, based on mechanical weed control (i.e. four passages of harrow) and large organic matter input (i.e. incorporation into the soil of both compost and cover crop biomass).

However, Bell et al. (2008) pointed out that organic agriculture is more than a process of recipe adoption: the universal practices and standard protocols are unsuitable for managing the complexity of organic cropping systems, affected by cumulative effects of long-term dynamics. Concerning rice, Orlando et al. (2020), monitoring 50 organic rice fields belonging to 10 farms during a three-year study in North Italy, reported the adoption by the farmers of knowledge-intensive adaptive management strategies. The authors identified three main functional principles underlying these strategies: weed control, involving mechanical action to exploit phytotoxic effects (Vitalini et al., 2020a; Vitalini et al., 2020b). Each identified strategy was not a universal recipe but involved a wide range of operative variants, maintaining the same functional principle but shaping the agronomic practices to the case-specific needs (i.e. season-specific and site-specific). Furthermore, a wide range of productive performance occurred (i.e. grain yield at commercial moisture 14 %: in middle-quartile 4 t/ha, in upper-quartile 6 t/ha). The organic rice yield was affected by many sources of variability, such as the history of the field (i.e. previous crop rotation) and the farmer's know-how. The farmer's experience and ability to identify the strategy fitting the site-specific cultivation conditions and promptly apply the related agronomic practices during the growing season were crucial in determining the productive performance. All this results in a wide range of management and production scenarios.

In this context, Bacenetti et al. (2016) study starts from the cropping system adopted by only one farm, it compares the current management practices (i.e. baseline scenario) with five alternative management practices scenarios. The authors assumed for the LCA the introduction of aeration during the cultivation period and replacing compost with other organic manures, analysing the related mitigation potential in environmental impact. The changes in fertiliser management reduced the environmental impacts from 13 % to 51 %, depending on the impact categories.

Regarding management strategy, practices, and productive performance, differences among different scenarios could explain discrepancies between the comparative studies, organic vs conventional, carried out on rice with LCA methodology.

He et al. (2018) found for organic rice cropping systems in China lower impacts (functional unit: 1 kg product) concerning non-renewable energy depletion, water depletion, acidification potential, eutrophication potential, aquatic toxicity potential and human toxicity potential, and recommended the organic rice farming as sustainable agricultural practices, in comparison with conventional. These results are based on data collected from 98 farms, thus considering a wide range of farm realities and management systems practised for 5, 10 and 15 years, with the related average yield (i.e. 5.3, 6.0 and 6.1 t/ha, respectively). Conversely, Hokazono and Hayashi (2012) found that organic rice has worst environmental performance than conventional rice for the following impact categories: non-renewable energy depletion, acidification potential, eutrophication potential; and similarly, Bacenetti et al. (2016) for the following impact categories: mineral and fossil resource depletion (i.e. similar to non-renewable energy depletion category), terrestrial acidification (i.e. similar to acidification potential category), freshwater and marine eutrophication (i.e. components of the eutrophication potential), and human toxicity potential.

In contrast with the current literature, Yodkhum et al. (2017) showed that the GHG emissions of organic paddy rice were considerably lower than conventional, considering data collected from sixteen farms in Thailand and information retrieved from different local sources (Don-Chiang Organic Agricultural Cooperative, Mae-teang district, Chiang Mai province, Office of Agricultural Economics, Ministry of Agriculture and Cooperatives). The authors explained the highest environmental performance found for organic rice with the lower use of organic fertilisers, the lower diesel fuel consumption and the different water regime during the cultivation period (i.e. rain-fed and deep water, instead of continuous flooding) compared to the conventional system and other organic systems considered by previous studies.

In this context, the present study aims to evaluate the variability of the environmental impacts and the mitigation potential of four management strategies suitable for organic rice production in North Italy through LCA. The study compares four alternative patterns of agricultural practices and two production potential levels observed during three-year monitoring on 10 farms in the study area (Orlando et al., 2020). The study wants to make the LCA analysis inclusive of the wide range of agronomic realities that characterise this farming system, assessing the variation in environmental performance by exploring eight plausible and possible scenarios for organic rice.

2. Materials and methods

2.1. Study area and data collection

The study area was the North Italian rice cultivation district, where during three growing seasons (i.e. 2016, 2017, 2018), the research considered a total number of 50 rice paddy fields. The fields belonged to ten organic farms in the two crucial Italian rice provinces: Vercelli and Pavia province (in the Piedmont and Lombardy regions, respectively), covering 67 % of the national production (ISTAT, 2016).

The monitoring involved ten farmers identified as local pioneers of organic rice farming during the participatory research by Orlando et al. (2020). The farmers are representative of the local reality of the organic sector, thanks to key information such as i) the farms were controlled by agronomists and specialized technicians in the rice sector with a deep knowledge of the territory, who as responsible for company inspections, in addition to those carried out by the certification body, they verify the standards of real organic cultivation; ii) they are local pioneers of organic rice cultivation, with a pre-existing relationship of trust with the research group (e.g. ex-student); iii) farmers are part of the Organic Rice Network cited in Orlando et al., 2020. The latter study aimed to fill the knowledge gap about the management strategies and productive performance reachable by growing rice with an organic system, and the present work started from the author's conclusions to define the scenarios described in the following Sections 2.3 and 2.4.

A wide range of cultivation conditions characterised the 50 fields (see Appendix A):

- 62 % and 38 % were in Pavia and Vercelli provinces, respectively (fewer fields in Piedmont where the organic rice sector is a younger reality);
- 44 % characterised by silty-loam soil and 12 % by silt soil (mainly associated with fields in Vercelli province, whose soils are characterised by a higher percentage of silt), while 40 % was characterised by sandy-loam and 4 % by loamy-sand soil (mainly associated with fields in Pavia province, whose soils are characterised by a higher percentage of sand);
- 30 % were monitored in the 2016 growing season, 44 % in 2017 and 26 % in 2018;
- 46 % was managed by farmers with eight or more years of experience in organic farming (most farmers of Pavia province), while 54 % of farmers started to grow organic rice between 2014 and 2015 (most farmers of Vercelli province).

For all the fields, information concerning the agricultural practices, agronomic inputs, and the resulting grain yield (ton/ha at 14 % of commercial moisture) were collected through face-to-face farmer interviews and field surveys, in the beginning, during and at the end of the crop cycle.

Background data for the production of seeds (rice, ryegrass and vetch), fuel, organic manure, tractors and agricultural machines were from the Ecoinvent database Database v.3.7 (Althaus et al., 2007; Frischknecht et al., 2007; Jungbluth et al., 2007; Nemecek and Käggi, 2007; Spielmann et al., 2007). The fuel consumption and intervention time were measured directly during field surveys through a stopwatch and a graded portable fuel tank for a sample of ten fields. This sub-sample of fields was representative of some agronomic interventions underlying the management strategies that were taken into account (see Section 2.4). The data were used to validate the fuel consumption values assessed with the support of the Ecoinvent database Database v.3.7 for the less common machinery used in the organic rice field (e.g. minimum tillage machinery). The production of straw was considered a harvest index of 0.45 (Boschetti et al., 2006).

2.2. Life Cycle Assessment

The Life Cycle Assessment (LCA) aim to evaluate the environmental impacts of the organic rice cropping system, considering eight scenarios, given by four management strategies combined with two production levels, as shown in Table 1. The scenarios are better detailed in Sections 2.3 and 2.4.

The LCA was performed following the ISO 14040/44 standards (ISO, 2006) and the Environmental Product Declarations (EPD) guidelines defined for “Arable Crops” (Environdec, 2014).

The selected functional unit (FU) was 1 ton of rice grain, at commercial moisture (14 %). Concerning the system boundaries, the study performed a “from cradle to farm gate” assessment, considering the following processes: the extraction of the raw materials (e.g. minerals, fossil fuels and metals), the production of agricultural inputs (e.g. seeds, fertilisers, tractors,

Table 1

Environmental impact (EI) categories computed in eight scenarios for organic rice cultivation, given by four management strategies (GM_1 = green mulching with broadcast rice sowing; GM_2 = green mulching with dry period; SD = stale seedbed in dry paddy; SF = stale seedbed in flooded paddy), each one combined with two production levels (Q2 = middle yield, 3.91 t/ha; Q3 = upper yield, 5.65 t/ha).

EI category and abbreviation		Scenarios		
	Unit	n.	Management strategy	Production levels
Climate change (CC)	kg CO_2 eq.	1	GM_1	Q2
Ozone depletion (OD)	kg CFC-11 eq.	2	GM_1	Q3
Human toxicity (HTc)	CTUh			
Particulate matter (PM)	kg $PM_{2.5}$ eq.	3	GM_2	Q2
Photochemical ozone formation (POF)	kg NMVOC eq.	4	GM_2	Q3
Terrestrial acidification (TA)	molc H^+ eq.			
Terrestrial eutrophication (TE)	molc N eq.	5	SD	Q2
Freshwater eutrophication (FE)	kg P eq.	6	SD	Q3
Marine eutrophication (ME)	kg N eq.			
Freshwater ecotoxicity (FEx)	CTUe	7	SF	Q2
Mineral and fossil resource depletion (MFRD)	kg Sb eq.	8	SF	Q3

machines, lubricant), the supply of inputs to the farm (e.g. transport), the use of agricultural inputs (e.g. fertiliser application, diesel fuel and lubricant consumptions, tire abrasion, and the related pollutant emissions), the maintenance and final disposal of machines, the grain and straw production, the emissions of N and P compounds due to fertilisers applications, field flooding (methane), and fuels combustion.

The inventory data were collected by means of surveys at the farms and interviews with the farmer. Primary data were used with regard to yield and the consumption of seed, fertilisers, pesticide, and fuels. According to Lovarelli and Bacenetti (2017), regarding the mechanization of field operations the modelling considered the mass of the different machines, their life span and annual working time as well as their effective field capacity (ha/h).

Secondary data were used with regard to the emissions from fertiliser application and from organic matter decomposition. Nitrogen emissions were evaluated as: (i) ammonia volatilization: using emission factors suggested by EMEP/CORINAIR (EMEP/EEA, 2019); (ii) N_2O and NO direct emissions: using emission factors calculated by Bouwman et al. (2002); (iii) N_2O indirect emissions: using emission factors suggested by IPCC (2019); and (iv) nitrate emissions (leaching and runoff): using emission factors suggested by IPCC (2019). Phosphate emissions in water were calculate following Prahsun (2006). The methane emissions were estimated using the emission factors and the methodology proposed by the IPCC (2019). Pesticide emissions were estimated according to the Product Category Rules for Arable Crops (Environdec, 2014).

The impact assessment was carried out using the characterisation factors provided by the midpoint ILCD method (Wolf et al., 2012) and considering the impact categories described in Table 1.

2.3. Scenarios: production levels

The organic rice yield data published by Orlando et al. (2020) was considered since the vast number of monitored fields (i.e. 50), with heterogeneous features, supply a representative framework concerning the possible production trend drawn by organic rice farming in the study area. The yield dataset showed normal distribution and high variability, with mean values of 3.91 t/ha and 5.65 t/ha, respectively, in the middle (Q2) and upper (Q3) quartiles. Therefore, LCA analysis considered two plausible and probable production levels. i) the currently more common situation in the study area (i.e. middle yield level Q2) and ii) an improvement scenario in which the yield increases in the short-term, mainly thanks to the crop rotation adoption and the development of the farmer's know-how and her/his adaptive management (with resulting decrease of yield losses due to weed incidence).

Table 2

Patterns of agricultural practices concerning the “stale seedbed in dry paddy” (SD) and the “stale seedbed in flooded paddy” (SF) strategies, both based on mechanical weed control.

Section	Field operation	Period	Fuel	Other input	
			kg/ha	product	kg/ha
SD strategy					
Tillage	Levelling	Every 3 years	54.5		
	Field banks	Every 3 years	8.6		
	Ploughing (20 cm)	End April	45.5		
	Harrowing (15 cm)	Early May	9.9		
Organic manure	Spreading	End April	34.9	Pelleted organic manure	450
Mechanical weeding	Comb harrowing	n. 3 in pre-sowing	7.2		
	n. 7 interventions	10–15 May			
	(5 cm)	n. 4 in post-sowing	9.6		
		16–30 May			
Sowing	Row-sowing (6 cm)	15 May	5.3	Rice seeds	240
Harvesting & Storage	Harvest	October	38.4		
	Transport		30.2		
	Drying		–		
Days of flooding	67				
SF strategy					
Tillage	Levelling	Every 3 years	54.5		
	Field banks	Every 3 years	8.6		
	Ploughing (15 cm)	End April	40		
	Harrowing (15 cm)	Early May	9.9		
Organic manure	Spreading	Every 3 years	34.9	Hoof and horn fertiliser	500
Mechanical weeding	Modified smoothing 2 interventions (3 cm)	Pre-sowing	3.3		
		12–17 May	3.3		
Sowing	Broadcast-sowing	20 May	0.9	Rice seeds	240
Harvesting & storage	Harvest	October	38.4		
	Transport		30.2		
	Drying		–		
Days of flooding	101				

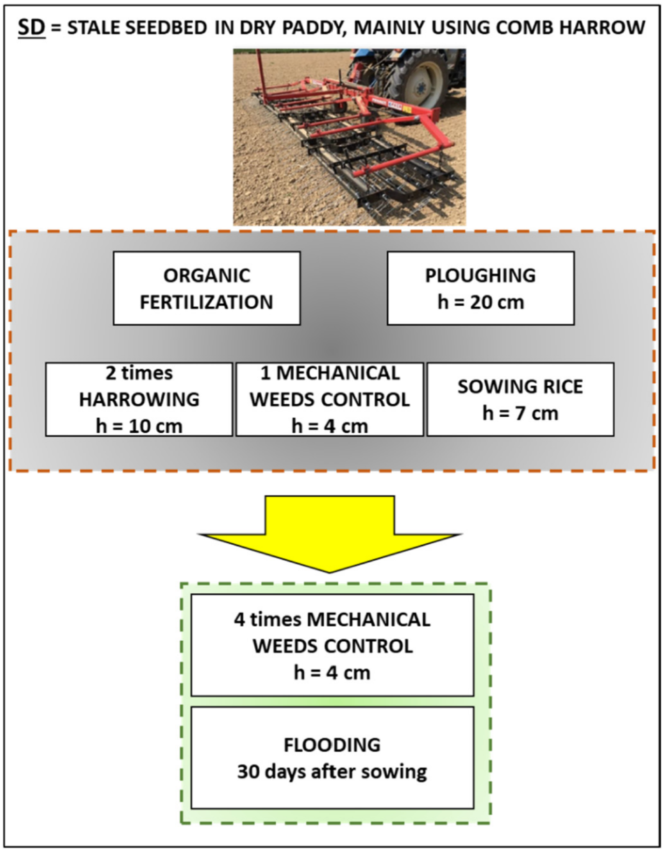

Fig. 1. Stale seedbed in dry paddy (SD) management strategy.

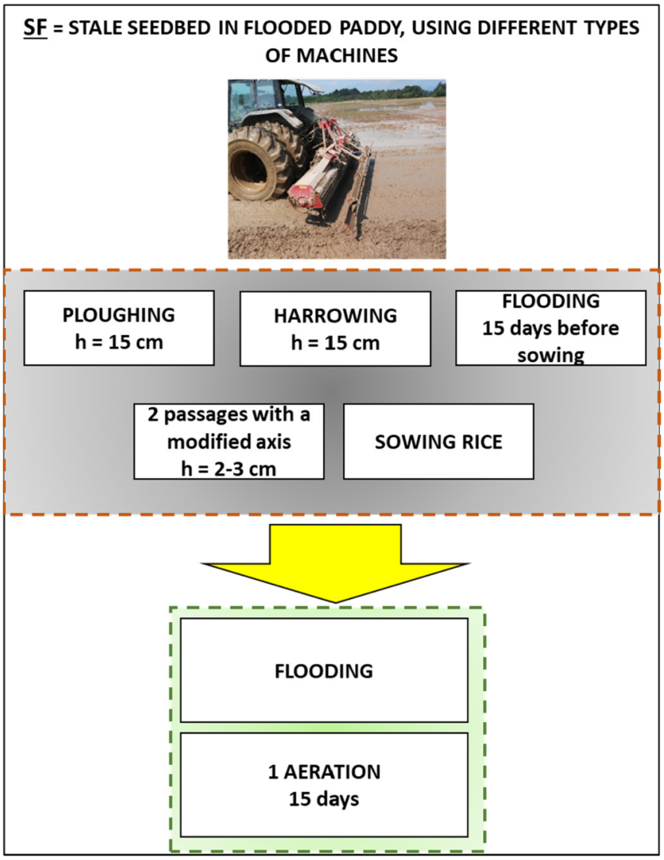

Fig. 2. Stale seedbed in flooded paddy (SF) management strategy.

2.4. Scenarios: management strategies

The most promising management strategies resulting from the field monitoring were based: i) on mechanical weeding, with stale seedbed and superficial tillage, performed in dry paddy field (i.e. strategy named: stale seedbed in dry paddy; SD) or flooded paddy field (i.e. strategy named: stale seedbed in flooded paddy; SF); ii) on weeds control performed through green mulching from a cover crop, and the flooding of the resulting biomass close to the sowing (strategy named: green mulching with broadcast rice sowing; GM_1) or after a post-sowing dry period (i.e. strategy named: green mulching with dry period; GM_2). The LCA considered the four crop management options. The agricultural practices, agronomic input and flooding days data are in Tables 2 (SD and SF) and 3 (GM_1, GM_2), described below and showed in Figs. 1, 2 and 3.

2.4.1. "Stale seedbed in dry paddy" (SD)

The strategy based on the weeds' mechanical control and the well-known technique of the stale seedbed in the dry field (Ferrero, 2003). After the harrowing follows a superficial passage with a comb harrow, carried out pre-and post-sowing. The number of passages with comb harrow varies depending on the weed incidence until seven steps. The rice sowing is in-row on dry land. The sowing depth (5 cm) and the post-sowing dry period (on average 23 days) are adopted to comb harrow operability and avoid rice seedlings damage. The strategy is feasible in intermittent water access (i.e. constrained by the water supply calendar established by the local authority), but it is not so suitable for soil with a firm texture. Fig. 1 resumes the SD strategy.

2.4.2. "Stale seedbed in flooded paddy" (SF)

Contrary to the SD strategy, after the harrowing, the rice paddy field is flooded for an average of 14 days before sowing. So, weed eradication occurs in water through minimum tillage (i.e. two interspersed passages). The farmers used innovative machinery for this operation and realised modifying existing ones (i.e. adding tines to a bar generally used for field levelling). After that, the broadcast sowing of rice occurs in water. The weed control is performed mechanically and by the "puddling" effect (Bhagat et al., 1996, physical obstacle and anaerobic conditions provided by mud). Fig. 2 resumes the SF strategy. This strategy requires flexible access to the irrigation water supply, and it is not so suitable for loose soil with fast drainage.

The agricultural practices, agronomic input and flooding days data related to the green mulching strategy are named GM_1 and GM_2 which are described below and reassumed in Table 3 GM_1, GM_2 and Figs. 3 and 4

2.4.3. "Green mulching with broadcast rice sowing" (GM_1)

A cover crop mixture (i.e. graminaceous, such as *Lolium multiflorum* Lam., and leguminous, such as *Vicia sativa* L.) sown before rice, and the weed control based on complex dynamics that involve the cover crop competition, the green mulching effect, the allopathic relationships between weeds and the sowed species (Vitalini et al., 2020a; Vitalini et al., 2020b), and the toxic effects of the organic acids developed as a consequence of the cover crop biomass fermentation. The broadcast sowing of rice is on dry land and the standing cover crop. Immediately after, chopping the cover crop and the field flooding, activating the fermentation processes. This flooding lasts on average five days and follows a dry period (on average 12 days). Timely water management is a crucial element for the success of this strategy. Then, flexible access to the water supply is required.

2.4.4. "Green mulching with dry period" (GM_2)

This strategy is a variant of the GM_1 system, developed by the farmers to minimise the negative impact of the organic acids on rice germination.

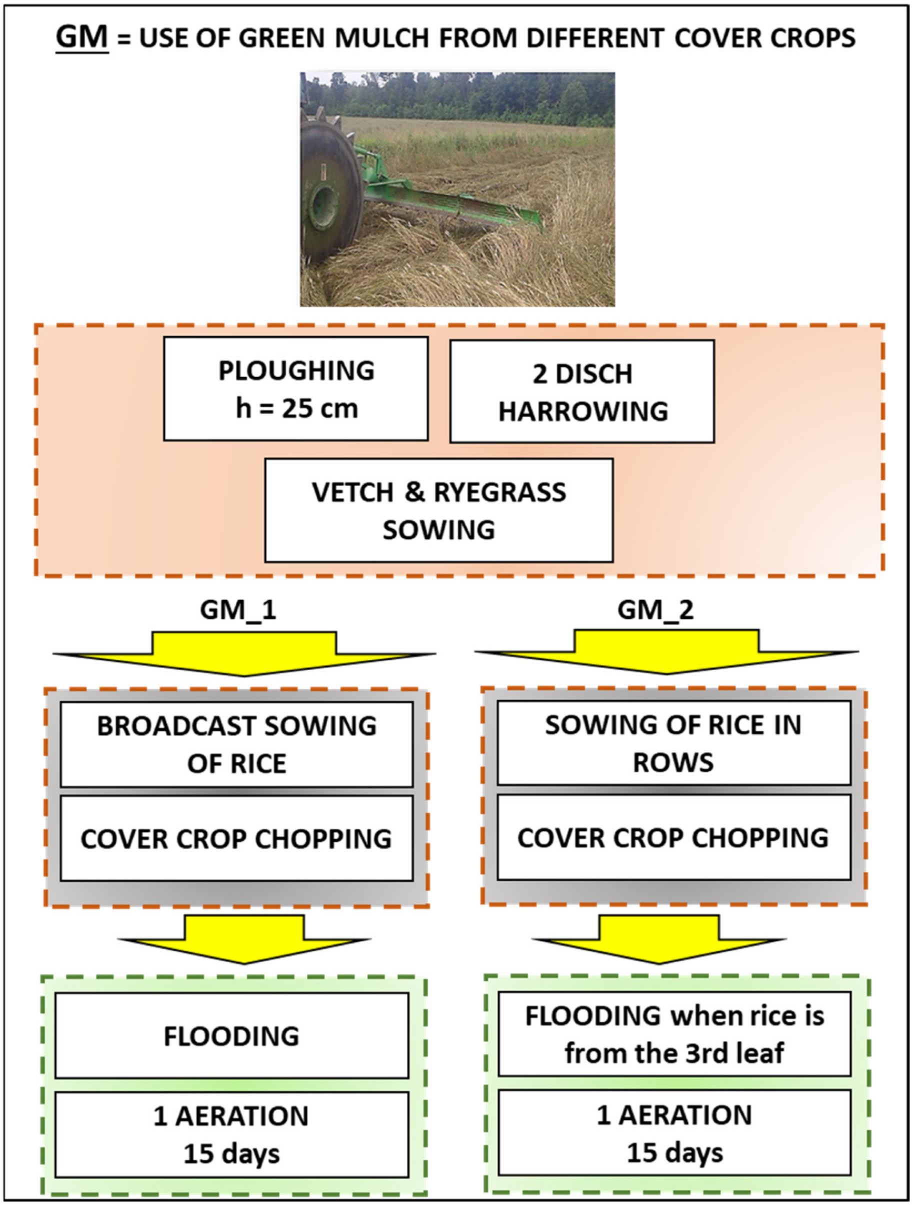

Fig. 3. The green mulching strategy underlining the two options: green mulching with broadcast rice sowing, GM_1 and green mulching with dry period, GM_2).

The main differences are the following: i) the rice is sown in-row, on dry land and the standing cover crop; ii) instead of flooding, a post-sowing dry period follows (on average 30 days), at the end of which the cover crop chopped, and the field flooded. This flooding lasted on average eight days and was followed by a dry period (on average 12 days). The postponing of these operations later in the season, compared to the GM_1 strategy, shifts the fermentation period when rice is at the leaf development stage (3°–4° leaves unfolded) instead of at the germination stage, and in the farmer's opinion, this could be able to reduce the adverse effects of organic acids on rice.

Among the four management strategies, some operations are in common: the field levelling and bank maintenance, and, even if carried out in different periods or at different depths, the ploughing and harrowing. On the other hand, the organic manuring differs i) the SD system is high-intensive in mechanical operations and often applied in soil characterised by higher sand percentage and faster mineralisation rate. Therefore, it is good practice to integrate the soil fertility with an annual input of organic manure; ii) in the GM_1 and GM_2 systems, combining leguminous species as a cover crop and minimum tillage conservative practices, the organic manuring is planned every three years and the same occurs in SF systems: since usually the farmer, that chooses the SF strategy, decides to apply it year in, and year out, alternating with the GM_1 or GM_2 systems. Fig. 3 resumes the GM strategy.

Finally, the irrigation schedules (i.e. cycles of flooding and dry periods) are in Fig. 4: all the strategies have in common a dry period in July, even if with different duration, and involved a non-irrigated pre-harvest period starting from about 20th August. On the other hand, the SD and GM_2 systems are characterised by a long dry period compared to the other strategies.

3. Results

3.1. Comparison between the management strategies

Table 4 reports organic rice production's environmental impacts based on 11 impact categories, considering eight different scenarios, combining four management strategies and two production levels. The

Table 3
Patterns of agricultural practices concerning the "green mulching with broadcast rice sowing" (GM_1) and the "green mulching with dry period" (GM_2) strategies, both based on weed control through the use of cover crops and their biomass.

Section	Field operation	Period	Fuel	Other input	
			kg/ha	product	kg/ha
GM_1 strategy					
Tillage	Levelling	Every 3 years	54.5		
	Field banks	Every 3 years	8.6		
	Ploughing (25 cm)	End August	51.4		
Cover crop	Row-sowing (3 cm) combined with harrowing (15 cm)	Early September	0.9	Vetch	25
				Italian ryegrass	25
	Biomass chopping	15th May	9.0		
Organic manure	Spreading	every 3 years	34.9	Hoof and horn fertiliser	500
Sowing	Broadcast-sowing	14 May	0.9	Rice seeds	240
Harvesting & storage	Harvest	October	38.4		
	Transport		30.2		
	Drying		–		
Days of flooding	79				
GM_2 strategy					
Tillage	Levelling	every 3 years	54.5		
	Field banks	every 3 years	8.6		
	Ploughing (25 cm)	end August	51.4		
	Harrowing (15 cm)	early September	9.9		
Cover crop	Broadcast-sowing	early September	7.4	Vetch	25
				Italian ryegrass	25
	Biomass chopping	12th May	9.0		
Organic manure	Spreading	every 3 years	34.9	Hoof and horn fertiliser	500
Sowing	Row-sowing (3 cm)	18 April	4.5	Rice seeds	240
Harvesting & storage	Harvest	October	38.4		
	Transport		30.2		
	Drying		–		
Days of flooding	52				

contribution analysis for the Climate Change impact category is shown in Fig. 5.

Fig. 6 shows the SD system the better environmental performance concerning the impact categories: CC, PM, ME, TA (Fig. 6a–d) and TE (Appendix B), while the worst one in terms of MFRD (Fig. 6f).

Fig. 5 shows for SD management the lower percentage contribution to CC due to methane emissions (i.e. 50.2 % vs a range of 52.6–60.7 % assessed for the other systems) and emissions from fertilisers (i.e. 11.7 % vs a range of 16.0–27.6 % of the others), but the more significant contribution due to mechanical operations (i.e. 14 % vs a range of 4.2–6.8 % of the others) and depth sowing (i.e. 6.2 % vs a range of 3.3–3.6 % of the others). The lower environmental impacts are due to the incorporation of stabilised organic matter into the soil through organic fertilisers, instead of the green biomass used by the "green mulching" systems (GM_1 and GM_2), and to the shorter period of flooding (total 67 days), compared to SF (101 days) or GM_1 (79 days) systems, thanks to the post-sowing dry period. That reduces the impact on natural resources, minimising the negative phenomena associated with the anaerobic decomposition of organic matter in the rice paddy field. On the other hand, the SD system involves mechanical weed control, based on many passages of shallow tillage and depth sowing, leading to more consumed fuel.

The SF system follows second in place the SD strategy in the best environmental performances (Table 4) for what concern the categories: CC, PM, ME, TA (Fig. 6a–d) and TE (Appendix B), with lower impacts than GM_1 and GM_2 systems. The MFRD values, even if higher than the "green mulching" strategies, are much lower than SD (Fig. 6f), thanks to

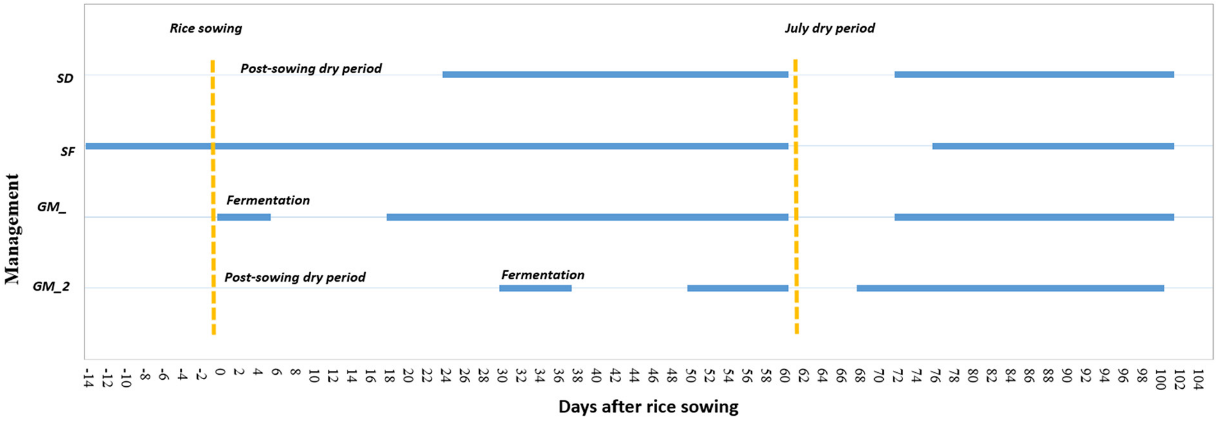

Fig. 4. Irrigation schedule describing the cycles of flooding for the management scenarios, characterised by a rice row-sowing and post-sowing dry period (i.e. SD and GM_2) or rice broadcast-sowing and subsequent flooding (i.e. SF and GM_1).

Table 4

Environmental impact (EI) categories referred to 1 t of paddy rice at commercial moisture, evaluated in eight scenarios for organic rice cultivation. Legend: Δ = variation, Q3-Q2; GM_1 = green mulching with broadcast rice sowing; GM_2 = green mulching with dry period; SD = stale seedbed in dry paddy; SF = stale seedbed in flooded paddy; Q2 = middle yield; Q3 = upper yield.

Impact category	*Unit*	GM_1			GM_2			SD			SF		
		Q2	Q3	Δ	Q2	Q3	Δ	Q2	Q3	Δ	Q2	Q3	Δ
CC	kg CO_2 eq	1365	1038	− 24 %	1296	975	− 25 %	780	623	− 20 %	1050	832	− 21 %
OD	mg CFC-11 eq.	38.7	32.3	− 17 %	32	25.6	− 20 %	38.5	30	− 22 %	31.3	25.1	− 20 %
HTc	CTUh	1.59×10^{-5}	1.33×10^{-5}	− 16 %	1.31×10^{-5}	1.05×10^{-5}	− 20 %	1.63×10^{-5}	1.27×10^{-5}	− 22 %	1.28×10^{-5}	1.03×10^{-5}	− 20 %
PM	kg PM2.5 eq.	1.18	0.89	− 25 %	1.17	0.88	− 25 %	0.44	0.38	− 14 %	0.62	0.5	− 19 %
POF	kg NMVOC eq.	2.94	2.18	− 26 %	2.82	2.07	− 27 %	2.7	1.99	− 26 %	2.38	1.75	− 26 %
TA	molc H+ eq.	50.14	37.95	− 24 %	49.97	37.79	− 24 %	15.34	13.83	− 10 %	24.62	20.21	− 18 %
TE	Molc N eq.	224.2	169.4	− 24 %	223.9	169.1	− 24 %	68.2	61.4	− 10 %	109.9	90.1	− 18 %
FE	kg P eq.	0.16	0.12	− 25 %	0.149	0.109	− 27 %	0.15	0.11	− 27 %	0.147	0.108	− 27 %
ME	kg N eq.	22.65	17.09	− 25 %	22.62	17.07	− 25 %	7.36	6.49	− 12 %	11.47	9.31	− 19 %
FEx	CTUe	1449	1169	− 19 %	1245	967	− 22 %	1483	1134	− 24 %	1232	958	− 22 %
MFRD	g Sb eq,	6.18	4.59	− 26 %	5.78	4.2	− 27 %	13.89	9.82	− 29 %	7.47	5.36	− 28 %

the few mechanical passages and the broadcast sowing. Fig. 5 shows SF management has the highest percentage contribution to CC due to methane emissions (i.e. 60.7 % vs a range of 50.2–53.7 % of the others), resulting from the more extended flooding period that starts two weeks before sowing. Moreover, contrary to the SD system, moderate fuel consumption makes the mechanical operations responsible for 6.8 % of the GHG emissions in the SF strategy. In SF management, the moderate use of fuel and organic fertiliser balances the environmental impact due to the prolonged period of flooding. This strategy can obtain an adequate weed control, thanks to the combination of the mechanical action with targeted water management and the "puddling" effect, and at the same time involves a low fuel consumption, close to "green mulching" systems but avoiding their environmental complications due to the fermentation of green biomass.

Table 4 shows for the "green mulching" systems the worst environmental performance for what concerns the categories: CC, PM, ME, TA (Fig. 6a–d) and TE (Appendix B). However, for these categories, a noticeable potential for improvement is revealed, shifting from Q2 to Q3 level of production. SD and SF systems showed slight differences in the environmental performance between the two production scenarios (i.e. Q1 and Q2); GM_1 and GM_2 showed a more considerable difference and, thus, a wide variation range decreasing their environmental impacts at the yield increase. Moreover, GM_1 and GM_2 showed a lower impact on MFRD (Fig. 6e). The low fuel consumption is due to the "sod seeding" (GM_2) or broadcast sowing (GM_1) and the replacement of mechanical weeding with the green mulching practice. On the other hand, precisely this innovative and successful practice for weed control (Orlando et al., 2020) determined the lower environmental performance concerning the anaerobic fermentation of the flooded green mulching or the release of nitrogen compounds from the long-term decomposition of the leguminous biomass. No noticeable differences between GM_1 and GM_2 are in Fig. 5 regarding the percentage contribution of the GHG emissions sources to CC value. On the other hand, both systems showed higher percentages for the emissions from fertiliser (i.e. macro-nutrients from the cover crop biomass) than the SD and SF management (26.2–27.6 % vs a range of 11.7–16.0 % of the others). In absolute terms (Table 4), the two "green mulching" systems have, in most cases, similar environmental performances, except for the categories: HTc (Fig. 6f), OD and FedEx (Appendix B, figures bc and be), for which GM_2 showed lower impact than GM_1, probably concerning its more extended post-sowing dry period. Concerning these environmental categories (i.e. HTc, OD, FedEx),

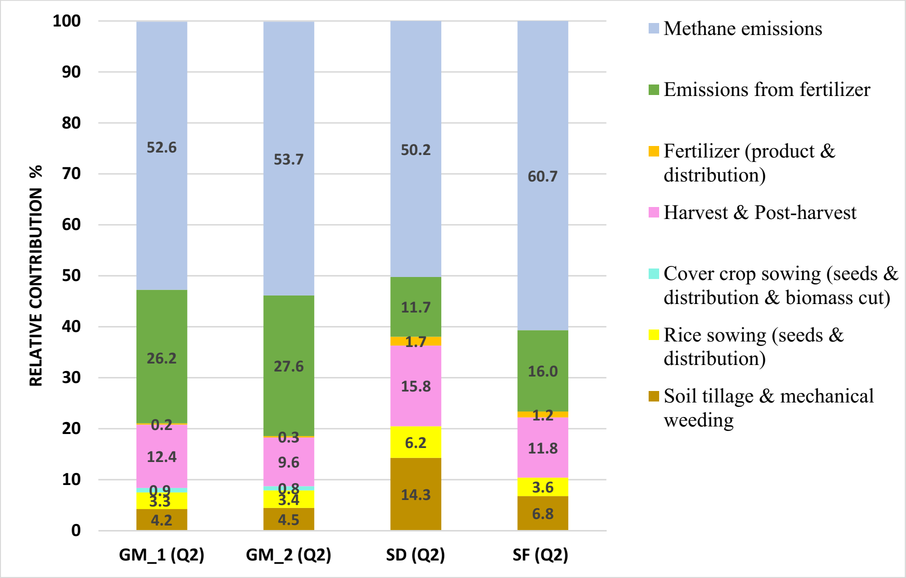

Fig. 5. Percentage contribution of different sources of GHG emissions to climate change total value assessed for each management strategy (GM_1 = green mulching with broadcast rice sowing; GM_2 = green mulching with dry period; SD = stale seedbed in dry paddy; SF = stale seedbed in flooded paddy).

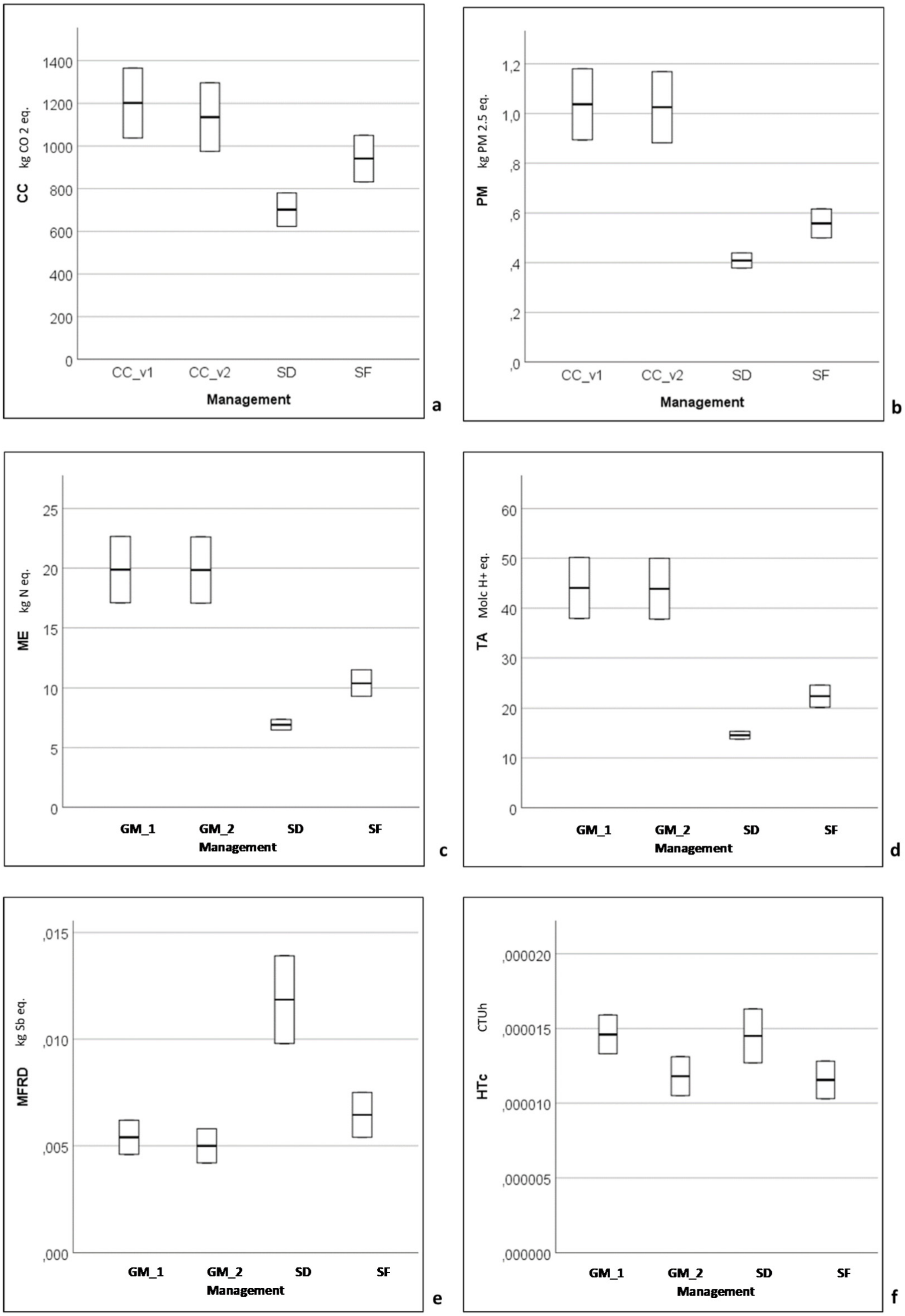

Fig. 6. Represents the environmental impact categories CC, PM, ME, TA, MFRD, HTc, the minimum, maximum, and mean value (the bottom, top and middle line of each box, respectively), evaluated for the four management strategies (i.e. GM_1, GM_2, SD, SF).

GM_2 and SF systems moved within a similar values range, performing better than GM_1 and SD strategies.

Finally, the results (Table 4) show, for organic rice, environmental impact values within a wide range of variations, depending on the farmer's choices regarding the water management, the weed control strategy, and the nutrients and organic matter replenishment plans. Moreover, the results suggest different environmental impacts, shifting from Q2 to Q3 productive level, with different sensitivities depending on the management strategy: the four systems showed different improvement potential for some important impact categories.

The management based on the mechanical weed control and external fertiliser input (i.e. SD) results globally in the best environmental

Table 5

Percentage variation of the environmental impact (EI) categories between the management strategies (i.e. maximum vs minimum value across the analysed managements) for each productive level (Q2 = middle yield, Q3 = upper yield).

EI	% Variation	
	Q2	Q3
CC	−43	−40
OD	−19	−22
HTc	−21	−23
PM	−63	−58
POF	−19	−19
TA	−69	−64
TE	−70	−64
FE	−8	−10
ME	−68	−62
FEx	−17	−18
MFRD	−58	−57

performance. At the same time, the GM_1 and GM_2 systems showed the worst performance for most categories, even if they were based on good agricultural practices, such as the use of resources internal to the farm for the maintenance of soil fertility and the low soil disturbance through minimum tillage and the cover during the winter period. However, extensive literature established the multiple environmental benefits due of the use of winter cover crops (Dabney et al., 2001), leguminous plants (Stagnari et al., 2017) and green mulch (Thakur and Kumar, 2020). These practices are among the topics addressed by the European Innovation Partnership (EIP-AGRI; https://ec.europa.eu/) in order to foster competitive and sustainable farming, and the local police support them for agriculture in many countries and by FAO in the strategies of conservation agriculture (FAO, 2011) or integrated soil fertility management (FAO, 2018). This discrepancy with the LCA outputs highlights the need to integrate the comparison between the organic rice managements with other evaluations and use non-LCA indicators to obtain an all-encompassing assessment of the environmental performance of each farming system.

4. Discussion

The assessed environmental performance of organic rice production took into account two productive levels recorded for the study area by Orlando et al. (2020), 3.91 t/ha (Q2) and 5.65 t/ha (Q3), and thus a range of yield variability consistent with the data shown in literature by similar studies (e.g. 3.83 t/ha, Hokazono and Hayashi, 2012; 4.4 t/ha, Blengini and Busto, 2009; 4.5 t/ha, Bacenetti et al., 2016; 5.3 t/ha and 6.0 t/ha, He et al., 2018). Table 5 shows the relative variation of the environmental impacts among the management strategies for each production level.

The results suggest considerable potential for organic rice production to mitigate its impact on natural resources, depending on the chosen agricultural practices. In particular, six LCA indicators showed a potential of reduction over 40 %, shifting from the worst-performing management to the better one, with the following Q2–Q3 average values: TE and TA — 67 %, ME — 65 %, PM — 61 %, MFRD — 58 %, and CC — 42 %. The remaining ones (i.e. HTc, OD, POF, FEx, FE) showed a potential mitigation potential, with values ranging between −8 % and −22 %. Similarly, Bacenetti et al. (2016), considering different options in terms of water and soil fertility management, found a potential to decrease the environmental impacts, compared to a baseline scenario, over −40 % for most of the LCA-indicators (i.e. TE, TA, PM, MFRD, CC, OD, HT, POF).

Focusing on the impact category “climate change” (CC), the values assessed across the scenarios were characterised by a wide range of variability, ranging from 623 to 1365 kg CO_2 eq. (i.e. minimum-maximum values, Table 4). Comparing this range with the values shown in literature by similar studies (i.e. LCA of organic rice system “from cradle to gate”), Yodkhum et al. (2017) found a value close to our minimum (i.e. 580 kg CO_2 eq.), while Hokazono and Hayashi (2012) found, in correspondence to the highest yield (i.e. 3.8 t/ha), a value close to our maximum (i.e. 1500 kg CO_2 eq.). Concerning the latter study, the CC value assessed by the authors is still 10 % higher than ours, but the rice system that they have considered involved continuous flooding for a total of 180 days, vs our range of 52–101 days, and this leads to a higher potential for methane emissions.

Blengini and Busto (2009) assessed for organic rice produced in the same study area of our research (i.e. Vercelli province, in Piedmont Region) a level of GHG emissions 20 % more than the conventional systems, namely of 3480 kg CO_2 eq., a value about 2.5 times higher than our maximum. However, the authors performed the study in 2009 when the organic rice cultivation covered only 3 % of the total cultivated area of the province: it was exceptional management in its early days, rarely adopted by the farmers. Moreover, as the same authors highlighted, it resulted in a general lack of data for organic rice farming. Therefore, it is probably that the improvement in soil and water management during the last 10 years has reduced the GHG emissions due to organic rice production significantly.

Another study carried out by Bacenetti et al. (2016), in the same study area of our research (i.e. Pavia province, in Lombardy Region), assessed for a baseline scenario of organic rice cultivation a level of GHG emission much higher than our maximum and close to that found by Blengini and Busto (2009) (i.e. 3270 kg CO_2 eq.). However, the authors evaluated the potential of mitigation for the CC LCA indicator as equal to −47 %, reachable thanks to improvements in crop management. The resulting value, corresponding to 1736 kg CO_2 eq., falls roughly within the same order of magnitude as our maximum. However, in the authors' best management scenario, the values assessed for the CC impact category were 27 % higher than our maximum. Nevertheless, in all the scenarios considered by Bacenetti et al. (2016):

The green manure originated from the cover crop mixture (i.e. vetch and ryegrass) is combined each year with the further distribution of organic fertiliser; in our study, instead, when leguminous species are grown during the winter, the use of an organic fertiliser product is planned only one time every three years (i.e. GM_1, GM_2).

The cover crop biomass method is combined with mechanical weeding in several passages of comb harrow; in our study, instead, the two practices are alternative; the systems based on mechanical weeding (i.e. SD, SF) exclude the cover crop cultivation.

The overall no flooding period seems not to be considered so large such in our study where instead, all the strategies involve aeration during July, and some of them (i.e. SD, GM_2 and GM_1) a post sowing dry period with different extensions (Fig. 4), since the aeration periods play a role in the mechanical weeding, in the management of some pests (e.g. *Lissorhoptrus oryzophilus* Kuschel 1952) and aquatic weeds (e.g. *Heteranthera reniformis* Ruiz & Pav., *Heteranthera rotundifolia* (Kunth) Griseb., *Alisma plantago-aquatica* L., *Alisma lanceolatum* With., *Ammannia coccinea* Rottb., *Ammannia robusta* Heer & Regel).

Finally, the large variability of climate change impacts assessed for organic rice farming, both in this study and in literature, is due to the corresponding large variability in terms of yield and available patterns of agricultural practices. For example, considering the CC impact category, the practice patterns affect the contribution of the primary GHG emissions sources, influencing the underlying processes: e.g. the duration of the soil aeration period and the amount of the flooded organic matter impact the anaerobic decomposition of organic matter and consequently the methane emissions that alone cover 50–61 % of the total CC values (Fig. 5), as well as, the quantity of green biomass or organic fertiliser and their N and P contents determine the N and P compounds release into soil, air and water (i.e. 12–28 % of CC, Fig. 5), and the fuel consumption associated with the mechanisation of field operations affect the CO_2 emissions (4–14 % of the CC, Fig. 5).

Even if this study focuses on the comparison among different cultivation practices of organic rice system it cannot be neglected that most of the rice produced is grown following the conventional cultivation practice. This latter differs from the organic one mainly with regard to the fertilisation, to the pest and disease management and, often, for the productive performances. In conventional cultivation, fertilisation is usually carried out using chemical fertilisers (whose production is an energy-intensive process), pests and diseases are managed using synthetic pesticides and the grain yield are usually lower (up to 50 % of yield reduction) (Bacenetti et al., 2016). These differences have a direct effect on the environmental performances:

- when the yield reduction respect to the conventional rice is high (>30 %) and a mass-based FU is selected, the organic rice systems show higher environmental impact except than for the impact categories affected by the emissions of pesticide active ingredients (e.g., freshwater ecotoxicity);
- when an area-based functional unit is selected the impact of organic rice is lower respect to the conventional system;
- for the impact categories affected by energy and fossil fuels consumption, in organic rice the use of organic fertilisers and crop rotation to manage soil fertility have a positive effect and reduce the relative contribution of fertilizing on the total impact.

5. Conclusion

The large variability of environmental performance emerged confirm the organic rice farming variability of management strategies, with a mitigation potential related which shift from the worst to the best scenario, from −67 % to −8 %, depending on the LCA impact category considered. The LCA-indicators that showed the higher reduction potential, and thus the larger range of variability, were the follows: TE (−67 %), TA (−67 %), ME (−65 %), PM (−61 %), MFRD (−58 %), and CC (−42 %). These results agree with the wide variability of the environmental impacts assessed for organic rice by similar studies and point out the need to consider the different agronomic options available for organic systems in the comparative studies with the conventional system to avoid significant misinterpretations of the outcomes. Concerning this, for example, the maximum value of the climate change impact category, assessed in the worst scenario for organic rice (i.e. lower yield level and higher impacting management strategy; 1500 kg CO_2 eq), resulted in being regardless lower than half of the values evaluated by other authors in comparative studies (i.e. conventional vs organic farming systems) carried out in the same study area (e.g. 3270 kg CO_2 eq in Pavia province, Bacenetti et al., 2016; 3480 kg CO_2 eq in Vercelli province, Blengini and Busto, 2009). The discrepancy is mainly due to the different management patterns considered by the different researchers. Indeed, the environmental performances in the present study are a consequence of an improvement path followed by organic farmers. The results showed that today, the farmers could reach acceptable yield values thanks to more efficient management than in the past (e.g. more extended soil aeration, less input in green or organic manure). The acknowledgement of that performances relates to the development of the farmers' know-how (Orlando et al., 2020) and to the productive improvement connected to the long-term processes which characterise the organic systems (e.g. generation of soil fertility based on biological fertility and stable humus components; lowering of weeds pressure through the gradual introduction of other crops in rotation).

The study points out the need to review the outcomes of comparative studies, conventional vs organic systems, in the light of these new results, including in the impact assessment of the organic farming variability recognised from different points of view (e.g. yield, management and practices efficiency). Moreover, the different management strategies adopted for organic rice cultivation in the present study, the SD system (i.e. based on the mechanical weed control and the use of external fertiliser products), showed the best environmental performance, with significant lower impacts for 5 out 11 LCA-indicators (i.e. CC, PM, ME, TA, TE), the SF system showed overall intermediate performance.

In contrast, the “green mulching-based” managements (i.e. GM_1 and GM_2) showed the worst performance, with significantly higher impacts for 5 out of 11 LCA-indicators lowest impacts only for the MFRD impact category. However, concerning this, the “green mulching” systems showed a more considerable impact decrease potential, in correspondence of yield improvements, and involves the “good practices” (i.e. use of cover crop and leguminous species, use of input internal to the farm) that are supported by the public authorities and by the policies for the sustainability.

The LCA approach was adopted because it is largely used to assess the environmental impact of the agriculture process (Saber et al., 2021; Soussana, 2014; Yodkhum et al., 2018). However, Notarnicola et al., 2017 underlined that LCA is focused on the impacts of process and neglects the environmental benefits and, externalities i.e. biodiversity and habitats conservation, and further ecosystems services also related to agricultural process and activities. From an LCA viewpoint, organic agriculture is not an obvious answer to environmental problems because LCA express impacts per unit of a product by default, which should be a precise measure of what the system delivers but cannot consider, for example, indirect effects. However, organic agriculture generally emits fewer pollutants per unit of land occupied than conventional agriculture (an area-based approach); it may have higher impacts per unit of product due to its lower yields per unit area (van der Werf et al., 2020).

Finally, the “good practices” penalisation by the LCA outcomes points out the need to integrate this tool, suitable for the assessment of the impact, with others, suitable for the evaluation of the environmental benefits and ecosystem services (Pavan and Ometto, 2018), in order to obtain a reliable, systemic and integrated assessment of the sustainability of farming systems and its management systems.

CRediT authorship contribution statement

Valentina Vaglia: Methodology, Investigation, Writing – original draft, Writing – review & editing. **Jacopo Bacenetti:** Methodology, Writing – original draft, Writing – review & editing. **Francesca Orlando:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Sumer Alali:** Investigation. **Ezio Bosso:** Investigation. **Stefano Bocchi:** Conceptualization, Supervision, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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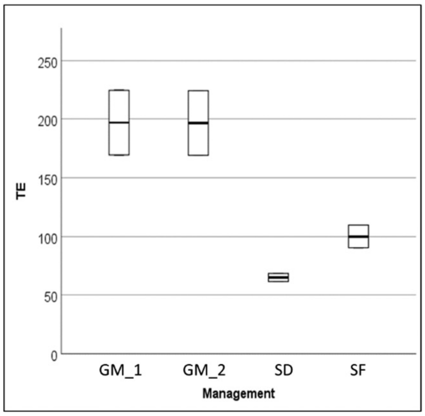
Appendix A

That annex shows in a table the features of the monitored organic rice fields: the experience in organic agriculture of belonging farmer, the Province (P = Pavia, V = Vercelli), the soil texture (SA-LO = sandy-loam; SI-LO = silty-loam; LO-SA = loamy-sand; SI = silt) and the growing season of data collection.

ID field	Testing organic since	Province	Soil texture	Growing season
1	1976	P	SA-LO	2016
2	1976	P	SA-LO	2016
3	1976	P	SA-LO	2017
4	1976	P	SA-LO	2017
5	1976	P	SA-LO	2018
6	1976	P	SA-LO	2018
7	2006	P	SI-LO	2016
8	2006	P	SI-LO	2016
9	2006	P	SI-LO	2016
10	2006	P	SI-LO	2017
11	2006	P	SI-LO	2017
12	2006	P	SI-LO	2017
13	2006	P	SI-LO	2018
14	2006	P	SI-LO	2018
15	2006	P	SI-LO	2018
16	2008	P	SA-LO	2016
17	2008	P	SA-LO	2017
18	2008	P	SA-LO	2018
19	2008	P	SA-LO	2016
20	2008	P	SA-LO	2016
21	2008	P	SA-LO	2017
22	2008	P	SA-LO	2017
23	2008	P	SA-LO	2018
24	2016	P	SA-LO	2017
25	2016	P	SA-LO	2017
26	2016	P	SA-LO	2017
27	2016	P	SA-LO	2017
28	2016	P	SA-LO	2018
29	2016	P	SA-LO	2018
30	2016	P	LO-SA	2016
31	2016	P	LO-SA	2017
32	2015	V	SI	2016
33	2015	V	SI	2016
34	2015	V	SI	2017
35	2015	V	SI	2017
36	2015	V	SI	2017
37	2015	V	SI	2018
38	2015	V	SI-LO	2016
39	2015	V	SI-LO	2016
40	2015	V	SI-LO	2016
41	2015	V	SI-LO	2017
42	2015	V	SI-LO	2017
43	2015	V	SI-LO	2017
44	2015	V	SI-LO	2018
45	2015	V	SI-LO	2018
46	2015	V	SI-LO	2017
47	2015	V	SI-LO	2017
48	2015	V	SI-LO	2018
49	2016	V	SI-LO	2016
50	2016	V	SI-LO	2017

Appendix B

That annex shows figures a, c, d, and e for the environmental impact categories TE, FE, OD, POF, FEx, the minimum, maximum and mean value (the bottom, top and middle line of each box, respectively), evaluated for the four management strategies (i.e. GM_1, GM_2, SD, SF).



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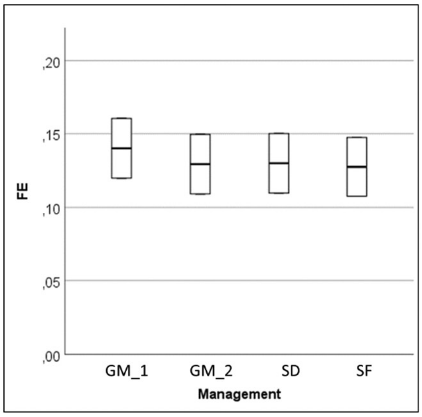

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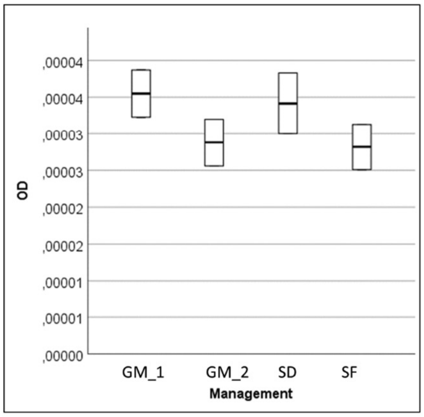

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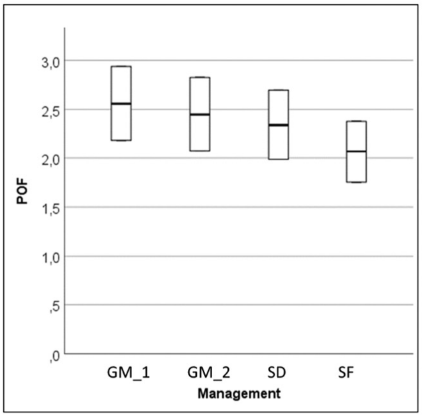

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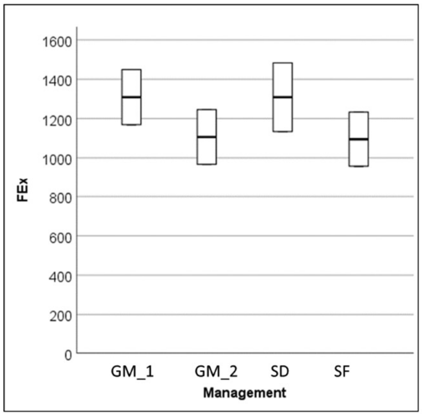

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References

Acuna, M.A., Niggli, U., Love, N., Moeskops, B., Padel, S., Schmutz, U., Lehejček, J., Beck, A., Müller, A., Ulmer, K., Chable, V., Levidow, L., Mulvany, P., 2018. Scientific Evidence on How Organic food and Farming Contribute to Sustainable Food Security.Available at last access 20/04/2021 https://orgprints.org/id/eprint/35006/1/dePorras-etal-2018-tporganics-briefing-evidence-of-the-performance-of-organic-farming.pdf.

Aguilera, E., Guzmán, G., Alonso, A., 2015. Greenhouse gas emissions from conventional and organic cropping systems in Spain. I. Herbaceous crops. Agron. Sustain. Dev. 35 (2), 713–724. https://doi.org/10.1007/s13593-014-0267-9.

Althaus, H.J., Chudacoff, M., Hischier, R., Jungbluth, N., Osses, M., Primas, A., 2007. Life cycle inventories of chemicals. Ecoinvent Report No. 8, v2.0 EMPA. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Bacenetti, J., Fusi, A., Negri, M., Bocchi, S., Fiala, M., 2016. Organic production systems: sustainability assessment of rice in Italy. Agric. Ecosyst. Environ. 225, 33–44. https://doi.org/10.1016/j.agee.2016.03.046.

Bacenetti, J., Paleari, L., Tartarini, S., Vesely, F.M., Foi, M., Movedi, E., Confalonieri, R., 2020. May smart technologies reduce the environmental impact of nitrogen fertilization? A case study for paddy rice. Sci. Total Environ. 715, 136956.

Bell, M.M., Lyon, A., Gratton, C., Jackson, R.D., 2008. Commentary: the productivity of variability: an agroecological hypothesis. Int. J. Agric. Sustain. 6 (4), 233–235. https://doi.org/10.3763/ijas.2008.c5004.

Bhagat, R.M., Bhuiyan, S.I., Moody, K., 1996. Water, tillage and weed interactions in lowland tropical rice: a review. Agric. Water Manag. 31 (3), 165–184. https://doi.org/10.1016/0378-3774(96)01242-5.

Blengini, G.A., Busto, M., 2009. The life cycle of rice: LCA of alternative agri-food chain management systems in Vercelli (Italy). J. Environ. Manag. 90 (3), 1512–1522. https://doi.org/10.1016/j.jenvman.2008.10.006.

Boschetti, M., Bocchi, S., Stroppiana, D., Brivio, A.P., 2006. Estimation of parameters describing morpho-physiological features of mediterranean rice varieties for modelling purposes. Ital. J. Agrometeorol. 3, 40–49.

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Modeling global annual N2O and NO emissions from fertilized fields. Global Biogeochemical Cycles 16 (4), 28-1.

Dabney, S.M., Delgado, J.A., Reeves, D.W., 2001. Using winter cover crops to improve soil and water quality. Commun. Soil Sci. Plant Anal. 32 (7–8), 1221–1250. https://doi.org/10.1081/CSS-100104110.

Delmotte, S., Tittonell, P., Mouret, J.C., Hammond, R., Lopez-Ridaura, S., 2011. On farm assessment of rice yield variability and productivity gaps between organic and conventional cropping systems under Mediterranean climate. Eur. J. Agron. 35 (4), 223–236. https://doi.org/10.1016/j.eja.2011.06.006.

EMEP/EEA, 2019. Air Pollutant Emission Inventory Guidebook 2019 - 3.D. Crop Production and Agricultural Soils 2019, pp. 24–29.

Environdec, 2014. Available at EPD "ArableCrops" , pp. 1–23 Last access 20/04/2021 http://environdec.com/en/PCR/Detail/?Pcr=8804#.VaPW7F_tlBc.

Escobar, N., Bautista, I., Peña, N., Fenollosa, M.L., Osca, J.M., Sanjuán, N., 2022. Life cycle thinking for the environmental and financial assessment of rice management systems in the Senegal River valley. J. Environ. Manag. 310, 114722.

European Commission, 2020. Farm to fork strategy.Available atFora Fair, Healthy and Environmentally-friendly Food System Last access 20/04/2021 https://ec.europa.eu/food/sites/food/files/safety/docs/f2f_action-plan_2020_strategy-info_en.pdf.

FAO, 2018. Promoting Conservation Agriculture in Timor-Leste. http://www.fao.org/3/i8858en/I8858EN.pdf.

FAO, 2011. Prepared by WOCAT coordinated by the FAO for UN A TerrAfrica partnership pubblication.Available atSustainable Land Management in Practice Part 2, Best Practices SLM for sub-Saharan Africa last access 20/04/2021. http://www.fao.org/3/i1861e/i1861e05.pdf.

Ferrero, A., 2003. Weedy rice, biological features and control. In: Labrada, R. (Ed.), Weed Management for Developing Countries: Addendum 1. FAO PlantProduction and Protection Paper 120 Add. 1. FAO, Rome , pp. 89–107. http://www.fao.org/docrep/006/y5031e/y5031e00.htm#Contents.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., Humbert, S., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2007. 2007 Implementation of Life Cycle Impact Assessment Methods.

Fusi, A., Bacenetti, J., González-García, S., Vercesi, A., Bocchi, S., Fiala, M., 2014. Environmental profile of paddy rice cultivation with different straw management. Sci. Total Environ. 494, 119–128.

Fusi, A., González-García, S., Moreira, M.T., Fiala, M., Bacenetti, J., 2017. Rice fertilised with urban sewage sludge and possible mitigation strategies: an environmental assessment. J. Clean. Prod. 140, 914–923.

Hazra, K.K., Swain, D.K., Bohra, A., Singh, S.S., Kumar, N., Nath, C.P., 2018. Organic rice: potential production strategies, challenges and prospects. Org. Agric. 8 (1), 39–56. https://doi.org/10.1007/s13165-016-0172-4.

He, X., Qiao, Y., Liang, L., Knudsen, M.T., Martin, F., 2018. Environmental life cycle assessment of long-term organic rice production in subtropical China. J. Clean. Prod. 176, 880–888. https://doi.org/10.1016/j.jclepro.2017.12.045.

Hokazono, S., Hayashi, K., 2012. Variability in environmental impacts during conversion from conventional to organic farming: a comparison among three rice production systems in Japan. J. Clean. Prod. 28, 101–112. https://doi.org/10.1016/j.jclepro.2011.12.005.

Hokazono, S., Hayashi, K., Sato, M., 2009. Potentialities of organic and sustainable rice production in Japan from a life cycle perspective. Agron. Res. 7, 257–262. https://agronomy.emu.ee/wp-content/uploads/2009/10/p7sI18.pdf.

Hole, D.G., Perkins, A.J., Wilson, J.D., Alexander, I.H., Grice, P.V., Evans, A.D., 2005. Does organic farming benefit biodiversity? Biol. Conserv. 122 (1), 113–130. https://doi.org/10.1016/j.biocon.2004.07.018.

Honisch, M., Hellmeier, C., Weiss, K., 2002. Response of surface and subsurface water quality to land use changes. Geoderma 105 (3–4), 277–298. https://doi.org/10.1016/S0016-7061(01)00108-2.

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

ISO 14044, 2006. Environmental Management - Life Cycle Assessment - Requirements and Guidelines. International Organization for Standardization.

ISPRA, 2018. ISPRA Rapporto nazionale pesticidi nelle acque: Dati 2015-2016. In: ISPRA (Ed.), Rapporti 282/2018. ISBN: 978-88-448-0848-8 last access 20/04/2021 https://www.isprambiente.gov.it/files2018/pubblicazioni/rapporti/Rapporto_282_2018.pdf.

ISTAT, 2016. Data About Rice Production in Italy. . http://agri.istat.it. (Accessed 20 April 2021).

Jungbluth, N., Chudacoff, M., Dauriat, A., Dinkel, F., Doka, G., Faist Emmenegger, M., Gnansounou, E., Kljun, N., Schleiss, K., Spielmann, M., Stettler, C., Sutter, J., 2007. Life cycle inventories of bioenergy. Ecoinvent Report No. 17. Swiss Centre for Life Cycle Inventories, Dübendorf.

Komatsuzaki, M., Syuaib, M.F., 2010. Comparison of the farming system and carbon sequestration between conventional and organic rice production in West JavaIndonesia. Sustainability 2 (3), 833–843. https://doi.org/10.3390/su2030833.

Lovarelli, D., Bacenetti, J., 2017. Bridging the gap between reliable data collection and the environmental impact for mechanised field operations. Biosyst. Eng. 160, 109–123.

Martínez-Eixarch, M., Curcó, A., Ibáñez, C., 2017. Effects of agri-environmental and organic rice farming on yield and macrophyte community in Mediterranean paddy fields. Paddy Water Environ. 15 (3), 457–468. https://doi.org/10.1007/s10333-016-0563-x.

Naylor, R., 1994. Herbicide use in Asian rice production. World Dev. 22 (1), 55–70.

Nemecek, T., Käggi, T., 2007. Life Cycle Inventories of Agricultural Production Systems. Final Report Ecoinvent v2.0 No.15a. Agroscope FAL Reckenholz and FAT Taenikon. Swiss Centre for Life Cycle Inventories, Zurich and Dübendorf, Switzerland.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. J. Clean. Prod. 140, 399–409. https://doi.org/10.1016/j.jclepro.2016.06.071.

Orlando, F., Alali, S., Vaglia, V., Pagliarino, E., Bacenetti, J., Bocchi, S., 2020. Participatory approach for developing knowledge on organic rice farming: management strategies and productive performance. Agric. Syst. 178, 102739. https://doi.org/10.1016/j.agsy.2019.102739.

Pavan, A.L.R., Ometto, A.R., 2018. Ecosystem services in life cycle assessment: a novel conceptual framework for soil. Sci. Total Environ. 643, 1337–1347. https://doi.org/10.1016/j.scitotenv.2018.06.191.

Prahsun, V., 2006. Erfassung der PO4-Austrage fur die Okobilanzierung SALCA Phosphor. Agroscope Reckenholz _Tanikon.

Saber, Z., van Zelm, R., Pirdashti, H., Schipper, A.M., Esmaeili, M., Motevali, A., Huijbregts, M.A., 2021. Understanding farm-level differences in environmental impact and eco-efficiency: the case of rice production in Iran. Sustain. Prod. Consum. 27, 1021–1029.

Sandhu, H.S., Wratten, S.D., Cullen, R., Case, B., 2008. The future of farming: the value of ecosystem services in conventional and organic arable landAn experimental approach. Ecol. Econom. 64 (4), 835–848. https://doi.org/10.1016/j.ecolecon.2007.05.007.

Seck, P.A., Diagne, A., Mohanty, S., Wopereis, M.C.S., 2012. Crops that feed the world 7: Rice. Food Security 4, 7–24. https://doi.org/10.1007/s12571-012-0168-1.

Soussana, J.F., 2014. Research priorities for sustainable agri-food systems and life cycle assessment. J. Clean. Prod. 73, 19 e 23. https://doi.org/10.1016/j.jclepro.2014.02.061.

Spielmann, M., Bauer, C., Dones, R., 2007. Transport services. Ecoinvent Report No. 14. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Stagnari, F., Maggio, A., Galieni, A., Pisante, M., 2017. Multiple benefits of legumes for agriculture sustainability: an overview. Chem. Biol. Technol. Agric. 4 (1), 2. https://doi.org/10.1186/s40538-016-0085-1.

Mendoza, Teodoro C., 2004. Evaluating the benefits of organic farming in rice agroecosystems in the Philippines. J. Sustain. Agric. 24 (2), 93–115. https://doi.org/10.1300/J064v24n02_09.

Thakur, M., Kumar, R., 2020. Mulching: boosting crop productivity and improving soil environment in herbal plants. J. Appl. Res. Med. Aromat. Plants 100287. https://doi.org/10.1016/j.jarmap.2020.100287.

van der Werf, H.M.G., Knudsen, M.T., Cederberg, C., 2020. Towards better representation of organic agriculture in life cycle assessment. Nat. Sustain. 3, 419–425. https://doi.org/10.1038/s41893-020-0489-6.

Vitalini, S., Orlando, F., Vaglia, V., Bocchi, S., Iriti, M., 2020a. Potential role of Lolium multiflorum lam. in the management of rice weeds. Plants 9 (3), 324. https://doi.org/10.3390/plants9030324.

Vitalini, S., Orlando, F., Palmioli, A., Alali, Sumer, Airoldi, Cristina, Noni, Ivano De, Valentina Vaglia Bocchi, S., Iriti, M., 2020. Correction to: different phytotoxic effect of Lolium multiflorum Lam. leaves against Echinochloa oryzoides (Ard.) Fritsch and Oryza sativa L. Environ Sci Pollut Res 27, 35870. https://doi.org/10.1007/s11356-020-10140-4.

Wolf, M.A., Pant, R., Chomkhamsri, K., Sala, S., Pennington, D., 2012. International Reference Life Cycle Data System (ILCD) Handbook: Towards more sustainable production and consumption for a resource-efficient Europe. European Commission, Joint Research Centre (JRC) Reference Report EUR 24982 EN, Luxembourg Publications 2012 https://doi.org/10.2788/85727.

Woodburn, A.T., 1990. The current rice agrochemicals market. Pest Management in Rice. Springer, Dordrecht, pp. 15–30 https://doi.org/10.1007/978-94-009-0775-1_2.

Yodkhum, S., Gheewala, S.H., Sampattagul, S., 2017. Life cycle GHG evaluation of organic rice production in northern Thailand. J. Environ. Manag. 196, 217–223. https://doi.org/10.1016/j.jenvman.2017.03.004.

Yodkhum, S., Sampattagul, S., Gheewala, S.H., 2018. Energy and environmental impact analysis of rice cultivation and straw management in northern Thailand. Environ. Sci. Pollut. Res. 25 (18), 17654–17664.

Yuan, S., Linquist, B.A., Wilson, L.T., et al., 2021. Sustainable intensification for a larger global rice bowl. Nat. Commun. 12, 7163. https://doi.org/10.1038/s41467-021-27424-z.

Zoli, M., Paleari, L., Confalonieri, R., Bacenetti, J., 2021. Setting-up of different water managements as mitigation strategy of the environmental impact of paddy rice. Sci. Total Environ. 799, 149365.