Sustainable Production and Consumption 27 (2021) 1021–1029

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Research article

Understanding farm-level differences in environmental impact and eco-efficiency: The case of rice production in Iran

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A R T I C L E I N F O

Article history:
Received 16 February 2021
Accepted 21 February 2021
Available online 23 February 2021

Editor: Prof. Adisa Azapagic

Keywords:
Eco-efficiency
Environmental performance
Life cycle assessment
Organic rice production
Sustainable agriculture
Yield

A B S T R A C T

Eco-efficiency, defined as the economic profit per unit of environmental impact, can largely differ between farms that produce the same crop. Understanding the underlying drivers of differences in eco-efficiency can help to identify effective options for increasing environmental product performance. Here, we analyzed differences in eco-efficiency between 200 paddy farms in Iran. With multiple linear regression modeling, we assessed the influences of farming system (conventional, limited input, organic) and yield, including potential interactions, on economic profit per unit of impact on ecosystems (terrestrial, freshwater, marine) and human health. Our results showed that the eco-efficiency of organic farming systems is (i) positively associated with yield, and (ii) systematically higher compared to conventional and limited input farming systems. We also found that the eco-efficiency of conventional and limited input systems is positively associated with yield for impacts on terrestrial ecosystems, but not for impacts on freshwater and marine ecosystems and human health. Our results reflect both higher economic profits and lower environmental impacts of organic paddy farms per unit of rice production compared to the other two production systems.

1. Introduction

Rice (*Oryza sativa* L.) plays a vital role in the food security of over half of the world population (Kumar and Ladha, 2011; Gutaker et al., 2019). Approximately 782 million tons of paddy rice were produced worldwide in 2018 (FAO 2018). At the same time, the production of paddy rice causes a variety of environmental impacts. Rice planting generates methane (CH_4) emissions causing global warming (IPCC 2006; Gaihre et al., 2014). Moreover, chemical fertilizers and pesticides are applied to increase paddy rice yield (Brentrup et al., 2004; Tang et al., 2020), leading to soil and water pollution in large areas of the world (Savci, 2012; Erisman et al., 2011), as well as potential risks to human health (Fu et al., 2008). Several life cycle assessment (LCA) studies quantified environmental impacts of paddy rice production from cradle to gate, including conventional as well as organic farming systems, and involving various countries such as Japan (Hokazono and Hayashi, 2012; Hatcho et al., 2012), Italy (Bacenetti et al., 2016; Blengini and Busto, 2009; Fusi et al., 2014), China (He et al., 2018; Zhang et al., 2010), Iran (Habibi et al., 2019; Mohammadi et al., 2015), and Thailand (Yodkhum et al., 2017). Some studies showed that the reduced use of fertilizers and pesticides in organic farming systems may result in lower toxicity and eutrophication impacts as well as reduced global warming impacts per unit of production (He et al., 2018; Yodkhum et al., 2017; Hokazono and Hayashi, 2015; Hokazono et al., 2009). In contrast, others found that organic rice farming does not necessarily lead to lower environmental impacts per unit of production compared to conventional farming, primarily due to lower yields in organic rice farm-

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[1] https://scholar.google.com/citations?user¼JQNGIlIAAAAJ&hl¼en

https://doi.org/10.1016/j.spc.2021.02.033
2352-5509/

ing (Hokazono and Hayashi, 2012; Hatcho et al., 2012; Blengini and Busto, 2009), but also due to high metal and methane emissions from organic manure (He et al., 2018). However, yields have been improving over time due to improved technologies and fertilizer management, leading to lower environmental impacts (Hokazono and Hayashi, 2012; He et al., 2018; Hokazono and Hayashi, 2015).

Beyond environmental impacts, the socioeconomic performance of crop production is considered important to move towards a more integrated life cycle sustainability evaluation (Pelletier, 2015). One of the indicators that can be used to integrate the economic and environmental dimensions in life cycle studies is eco-efficiency, here defined as the economic value added per unit of environmental impact (Huppes and Ishikawa, 2005). A limited number of studies looked at the eco-efficiency of paddy rice systems. Thanawong et al. (Thanawong et al., 2014) investigated the differences in eco-efficiency among 43 paddy farms in Bangladesh, with a focus different seasons and irrigation choices, and found wet-season rain-fed systems to be the most eco-efficient. Masuda (Masuda, 2016) showed that prolonged midseason drainage, aimed at reducing methane emissions, did not enhance the eco-efficiency of a Japanese rice farm, because the reduction of economic profit outweighed the reduction in environmental impact. Masuda (Masuda, 2019) further found evidence that increasing the size of rice farms improved the eco-efficiency of intensive rice production in Japan due to scaling efficiencies.

So far, studies on the environmental impacts or eco-efficiency of paddy rice production typically focused on a limited number of farms, a limited number of inputs (e.g. nitrogen or irrigation only), or a limited number of environmental impacts on midpoint level (e.g. global warming, toxicity and eutrophication). To our knowledge, studies that comprehensively and systematically explain the variability in environmental impacts and eco-efficiency between individual paddy farming systems and farms are lacking up to now. The goal of our study was to systematically analyze the combined influence of two key farm characteristics, i.e. farming system (conventional, limited input, organic) and yield, on the environmental impacts and eco-efficiency related to ecosystems and human health. The analysis is based on data gathered for 200 individual paddy farms in northern Iran, reflecting farm-level variability in environmental impacts on endpoint level i.e., biodiversity and human health, estimated based on underlying mechanisms and midpoint impact categories.

2. Materials and methods

2.1. Paddy rice farms

Mazandaran, a northern Iranian province located at the south coast of the Caspian Sea (Fig. S1), is the most important producer of paddy rice in Iran. The province yielded 42% of Iran's total rice production in 2019, totaling a production of 1420,000 tons of rice from 204,000 hectares (ha) of cultivated paddy fields (Ministry of Jihad-e-Agriculture of Iran 2019). Our analysis covers paddy rice production of three farming systems in the Mazandaran province: conventional farming, organic farming, and farming with limited external inputs. Conventional farming refers to intensive farming via the application of pesticides and synthetic chemical fertilizers, while organic farming avoids pesticides and synthetic fertilizers. Shifting from conventional to organic agriculture happens gradually. Accordingly, limited input farming systems rely on inputs of synthetic fertilizers and pesticides below the amounts commonly used in conventional systems. We obtained farm-specific life cycle inventory data from Saber et al., (2020), gathered via questionnaires distributed among paddy farmers in North Iran in 2019. These data contain information on diesel fuel, electricity, fertilizers, biocides, seeds, nylon, farm yard manure, oil, machinery, and steel. We also retrieved economic data (i.e., yield and production costs per farm) via the same questionnaires. The sample size was 200 paddy farms, including 137 conventional system farms, 47 limited input system farms, and 16 organic systems farms. An overview of the environmental and economic foreground data obtained from the farms is given in Table 1. The specific information of each of the 200 farms is provided as supplementary information (see SIa, Excel file).

2.2. Eco-efficiency analysis

Eco-efficiency is a ratio that expresses how much economic profit is made per unit of impact, which is the reverse of the amount of impact per dollar made, as expressed in LCA (Thanawong et al., 2014; Ichimura et al., 2009; Georgopoulou et al., 2014; Sabiha et al., 2017). We calculated the eco-efficiency for each of four impact categories (i.e., terrestrial, freshwater and marine ecosystems and human health) and each paddy farm as (Soheili-Fard et al., 2018):

$$\text{Eco} - \text{efficiency} = \frac{Net\ economic\ profit}{Environmental\ impact} \quad (1)$$

The higher the eco-efficiency, the higher the net profit relative to the environmental burden/impact (Konstantas et al., 2020). The eco-efficiency indicator can, for instance, be used to determine cost-effective methods to decrease environmental impacts (Martínez-Blanco et al., 2015).

2.3. Economic profits

We determined the net economic profit (in US $/ton of rice) for each of the 200 paddy farms by subtracting the production costs from the production revenue for the year 2019. Farm-specific costs involved all variable and fixed costs over the entire product life cycle (Korpi and Ala-Risku, 2008). Fixed costs included depreciation, maintenance and repair of machineries, rent of land, and agricultural insurance, while variable costs refer to labor and material inputs. Production revenues were specific to each farm management system in 2019. The sale price of organic paddy rice was 133,000 Rial (Iranian monetary unit) per kg paddy produced, while the sale price for per kg paddy produced at the other two systems was 90,000 Rial. We converted sale prices to US dollar based on conversion rate of 113,000 Rial per dollar in 2019. All economic indices such as total production revenue, total fixed and variable costs, sales price, and net profit are outlined in Table S1.

2.4. Environmental impacts

2.4.1. Inventory data

We quantified the environmental impacts per functional unit of 1 ton of rice produced up to the farm-gate. The system boundaries included seed bed preparation, tillage, transplanting, biocides and fertilizer application, weeding, and harvesting. The environmental information collected via the questionnaires refers to the use of agricultural machineries for preparing plant beds and harvesting (Table S2), lubricating oil, diesel fuel, electricity, water use, applied chemical fertilizers and biocides, total amount of rice seed, nylon and steel rebar for nursing place, accompanied by all farm expenditure on applied inputs (see SIa for foreground data). We retrieved background data on emissions equivalent for diesel fuel burning based upon per unit of energy consumption from the EcoInvent database 3.2 (Wernet et al., 2016) and we estimated chemical fertilizer and farm yard manure emissions from the usage of various inputs following the IPCC (IPCC 2006) (Table S3). Further, we calculated CH_4 emissions from rice cultivation at farm level, accounting

Table 1
Environmental and economic data, and their respective ranges across the sampled farms ($n = 200$).

	Conventional ($n = 137$)					Limited external input ($n = 47$)					Organic ($n = 16$)				
	Min	1st quartile	Median	3rd quartile	Max	Min	1st quartile	Median	3rd quartile	Max	Min	1st quartile	Median	3rd quartile	Max
Foreground environmental data (unit/hectare/year)															
Seed (kg)	25	38	45	50	83	25	39	40	53	65	35	39	45	50	60
Nylon (kg)	4.4	7.5	8.2	9.1	14	5	7	8	9	13.4	6	7.3	8	9	9.8
Nitrogen (kg N)	70	200	230	280	357	55	80	100	120	210	0	0	0	0	0
Phosphate (kg P_2O_5)	0	116	180	220	325	0	80	100	110	195	0	0	0	0	0
Potassium (kg K_2O)	0	50	70	100	200	0	15	50	75	100	0	0	0	0	0
Manure (kg)	0	0	0	800	1005	0	200	350	650	900	300	473	625	745	800
Pesticide (kg)*	8.0	13.0	14.8	17.4	20.3	6.2	8.0	8.7	9.9	15.4	0	0	0	0	0
Oil (kg)	1.1	1.6	1.8	2.3	4.1	0.8	1.1	1.2	1.4	1.7	0.8	1.1	1.2	1.3	1.5
Electricity (kWh)	0	85	200	394	720	0	187	231	311	470	81	154	191	259	289
Diesel fuel (kg)	17.2	258	335	421	688	162	194	237	267	363	77	132	146	160	190
CH_4 field emissions (kg/ hectare /year)															
CH_4	135	135.6	135.6	135.6	151	135	138.9	141.4	146.1	150.2	140	143.5	145.8	147.6	148
Yield (ton/hectare/year)															
Yield	3.50	4.32	4.66	4.80	5.69	3.00	3.90	4.10	4.25	5.21	1.98	3.11	3.35	3.49	3.95
Economic data ranges ($/ton paddy produced)															
Fixed cost	30	400	460	548	660	345	407	480	407	680	390	400	463	490	700
Variable cost	980	1230	1380	1484	1700	870	1065	1200	1320	1490	500	657.5	794	888	1000
Total life cost	1440	1700	1820	1971	2267	1380	1544	1672	1790	2090	988	1091	1229	1371	1700
Total revenue	2787	3442	3710	3823	4531	2389	3106	3265	3384	4149	2330	3663	3942	4116	4649
Net profit	230	365	400	430	514	299	355	395	424	471	608	729	797	862	906

*Specification of the active ingredients are given in the supplementary information (SIa).

for differences in manure application between the farms, according to IPCC (Ogle et al., 2019) (Table S4).

We also estimated On-Farm diesel fuel emissions (Wernet et al., 2016) and residue burning emissions to air (Wikström and Adolfsson, 2004) (Table S5) and heavy metal emissions from farm yard manure (FYM) and chemical fertilizers to soil (Durlinger et al., 2015) (Table S6) and assumed that 100% of the biocides were emitted to agricultural soil. Note that we did not include changes in soil organic carbon in our assessment due to lack of empirical data for different rice production systems in Iran. The production of rice may, however, increase soil organic carbon erosion exacerbating climate change among other impacts (Lal, 2020).

2.4.2. Life cycle impact assessment (LCIA)

We used the ReCiPe2016 endpoint method for the life cycle impact assessment. The environmental impacts in the ReCiPe2016 endpoint method are specified into three main damage categories: ecosystems quality, human health and resource scarcity (Huijbregts et al., 2017). Here, we focused on damage to ecosystem quality, subdividing the impacts into terrestrial, freshwater, and marine ecosystems, as well as human health damage. We included three distinct sets of damage factors (individualist, hierarchist, and egalitarian), as reported in ReCiPe2016. The individualistic perspective provides impact factors with relatively strong scientific evidence and a 20 year time horizon. The hierarchist perspective represents impacts with broad scientific consensus over a time horizon of 100 years. The egalitarian perspective is taking into account all quantifiable impact pathways over the longest time horizon (1000 years to infinite) (Huijbregts et al., 2017).

We calculated new ecosystem damage factors for three pesticides (i.e., fipronil, trifloxystrobin, and bensulfuron methyl ester), as they were lacking in ReCiPe2016 while applied at some of the 200 farms included. To this end, we gathered fate and effect data for these three pesticides and calculated impact factors with USES-LCA (Van Zelm et al., 2009). Ecosystem impact factors are provided in Table S7.

2.5. Statistical analysis

For each damage category (damage to terrestrial, freshwater, and marine ecosystems and damage to human health) and each perspective (hierarchist, egalitarian and individualist), we analyzed how environmental impact or eco-efficiency are related to farming system and yield by fitting a multiple linear regression model. Because relationships with yield may differ among farming systems, we included an interaction between farming system and yield. We established a similar regression model also for net profit. In addition, we assessed the relative contributions of the underlying midpoint impact categories (e.g. global warming, land use, etc.) to the farm-specific endpoint impacts. We performed all the statistical analyses in R (Team RC 2017), version 4.0.0, including the package 'visreg' (Breheny and Burchett, 2017) to visualize the regression models.

3. Results

3.1. Economic profits

We found that net profit ($ profit per ton of paddy produced) increases with yield for all three production systems (Fig. 1). Further, we found that the net profit is systematically higher for organic production systems compared to limited external input and conventional paddy production systems, due to the higher sale price per unit of paddy rice produced ($R^2 = 0.87$; Table S8).

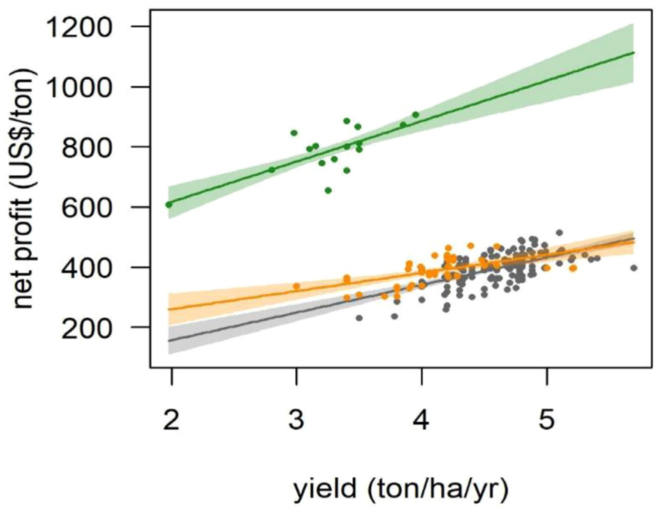

Fig. 1. Net profit ($/t paddy produced) in relation to yield (ton/ha/year) for each farming systems (conventional = gray, limited input = orange, and organic = green). The shaded areas around the lines indicate the 90% confidence intervals.

3.2. Environmental impacts

Following the hierarchist perspective, impacts on terrestrial ecosystems per ton of rice produced decrease with increasing yield for all farming systems (R^2 = 0.76; Fig. 2; Table S9). This negative trend is strongest for organic farming systems, which show the lowest impacts of the three farming systems for yields larger than three tons per hectare per year (Fig. 2a). Impacts on aquatic ecosystems and human health increase with enhancing yields for conventional and limited input farming systems. In contrast, for organic farming systems, impacts remain constant (freshwater and marine ecosystems) or decrease (human health) with increasing yields (R^2 = 0.49–0.68; Table S9). We also found that conventional farming systems have systematically larger impacts compared to the two other farming systems (Fig. 2b-d). Trends were similar for both the egalitarian and individualist perspectives (Figures S2 and S3). The environmental impacts and yields for each farm are also reported in the SI (see SIb, Excel file).

3.3. Eco-efficiency

According to the hierarchist perspective, the eco-efficiency of organic farming systems is positively related to yield and is sys-

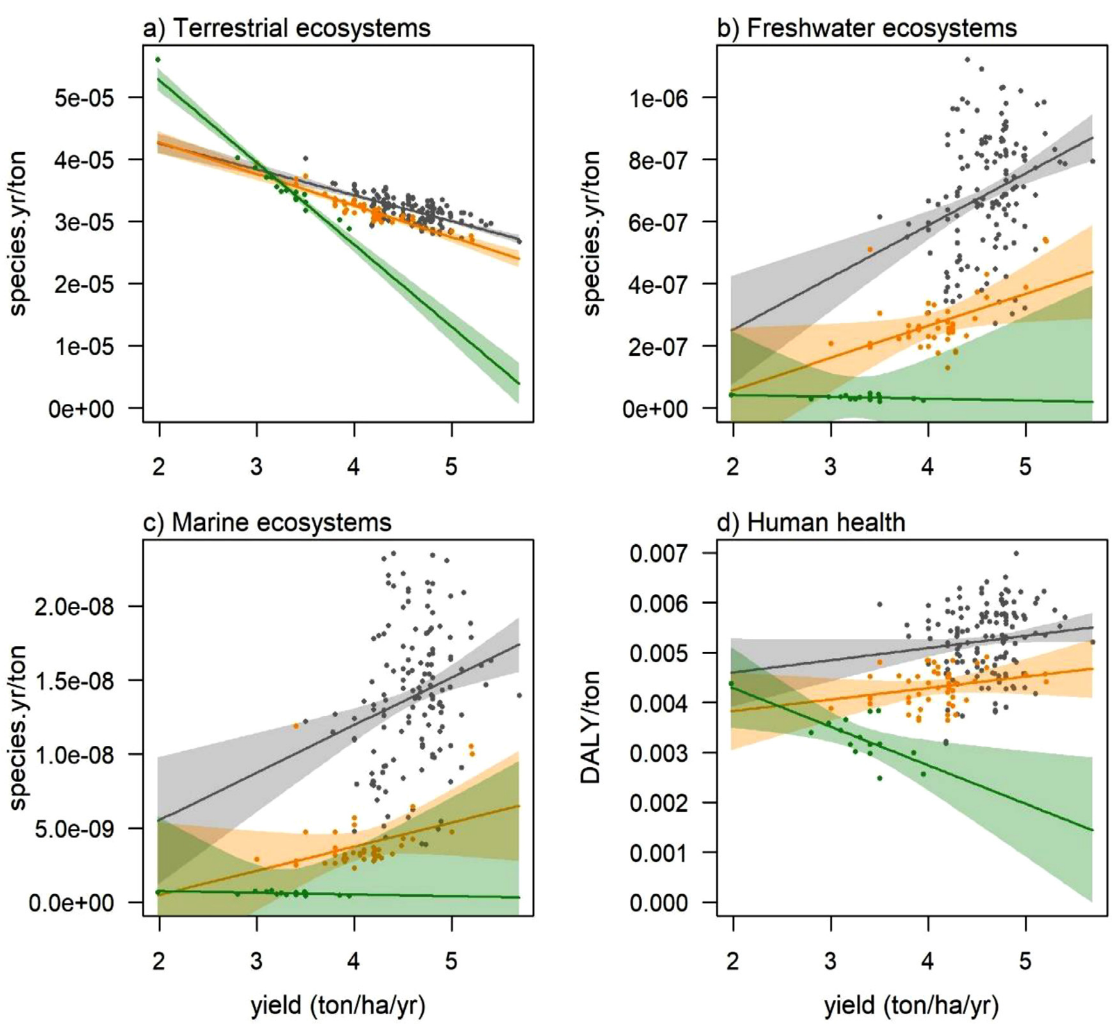

Fig. 2. Environmental impacts per ton of paddy rice production in relation to the yield per farming system (conventional = gray, limited input = orange, and organic = green) based on hierarchist viewpoint for (a) terrestrial ecosystems, (b) freshwater ecosystems, (c) marine ecosystems, and (d) human health impacts. The shaded areas around the lines indicate the 90% confidence intervals. Underlying coefficients are given in the SI (see Table S9).

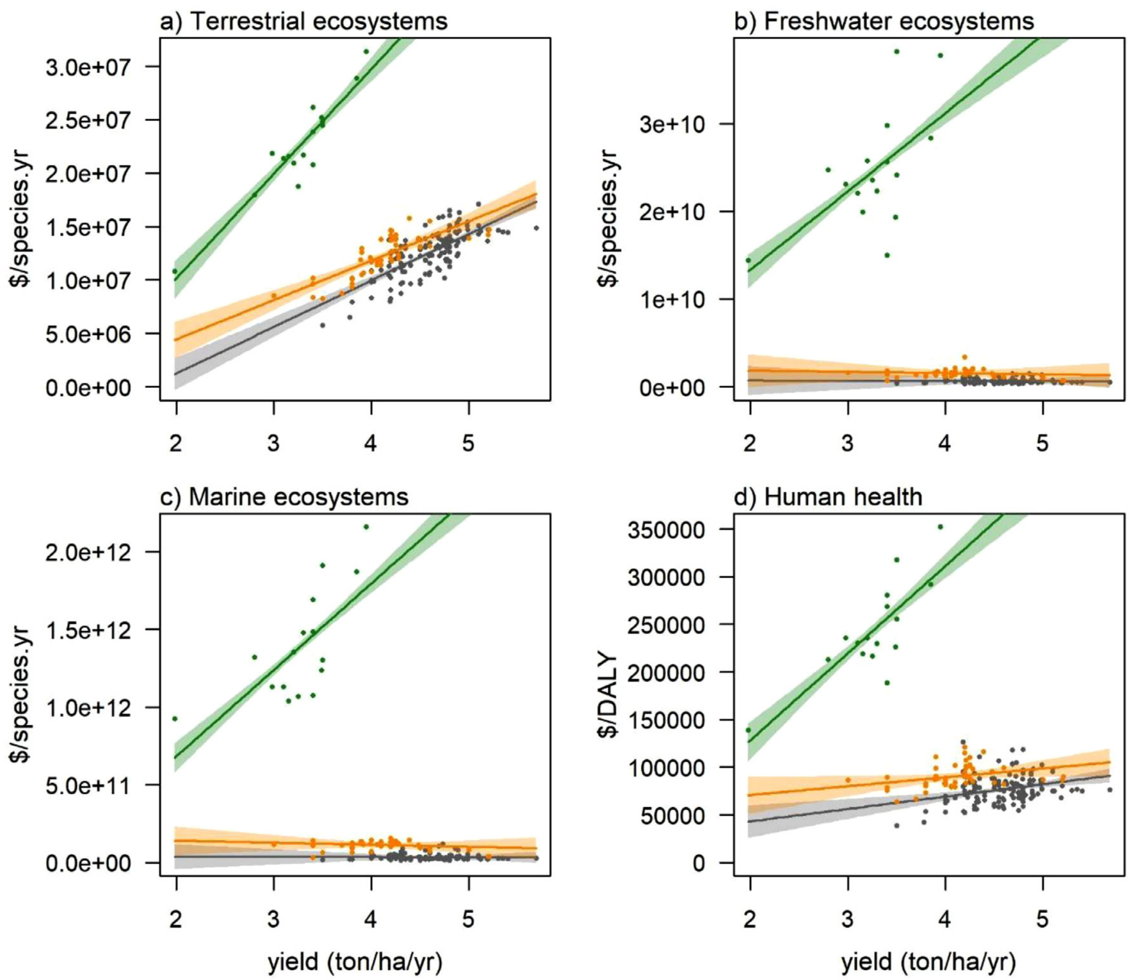

Fig. 3. Eco-efficiency of paddy rice production for damage to (a) terrestrial ecosystems, (b) freshwater ecosystems, (c) marine ecosystems ($ profit/species.year), and (d) human health ($ profit/DALY) as a function of yield (ton /ha/year) for each farming system (conventional = gray, limited input = orange, and organic = green). Results are for the hierarchist perspective. The areas around the lines indicate the 90% confidence intervals. Underlying coefficients are given in the SI (see Table S10).

tematically higher compared to conventional and limited input farming systems (R^2 = 0.86–0.96; Fig. 3; Table S10). This result was consistent across the four damage categories. For conventional and limited input farming systems, the eco-efficiency based on terrestrial ecosystems damage is positively related with yield, but the eco-efficiency based on the impacts on freshwater and marine ecosystems and human health do not significantly change with yield. We found the same trends for the egalitarian and individualist perspectives (Figures S4 and S5). The farm-specific eco-efficiency results for all systems and three perspectives are outlined in SIb, Excel file.

3.4. Relative impact contributions

According to the hierarchist perspective, land use has a dominant contribution to terrestrial ecosystems damage for all three farming systems, followed by global warming (Fig. 4). For damage to freshwater ecosystems, eutrophication plays an important role in all three farming systems, while ecotoxicity is particularly important in conventional farming systems. Toxicity was mainly caused by fipronil application in conventional farming systems, and contributed on average for 50% to freshwater ecosystem damage. Marine ecosystems damage is primarily related to toxic impact due to heavy metal emissions in the background system. This result was consistent across all three farming systems. Human health damage is mainly determined by global warming, fine particle matter formation, and non-carcinogenic toxicity for all three farming systems.

We found similar results for the individualist perspective, although global warming is less important for impacts on terrestrial ecosystem and human health due to the shorter time horizon compared to the hierarchist perspective (see SI, Fig. S6). For the egalitarian perspective, results were also similar with two notable exceptions. Non-carcinogenic toxicity becomes important for human health damage, particularly for conventional and limited input farming systems (see SI, Fig. S7). This reflects the longer time horizon taken into account in the egalitarian perspective compared to the hierarchist perspective, particularly influencing the importance of metal exposure levels. The second exception is the increased relative contribution of global warming to terrestrial ecosystems damage for all farming systems, also explained by the longer time horizon of impacts accounted for in the egalitarian perspective.

4. Discussion

4.1. Environmental impacts

Our findings showed that organic farming systems cause systematically lower environmental impacts per ton of rice produced compared to conventional and limited input farming sys-

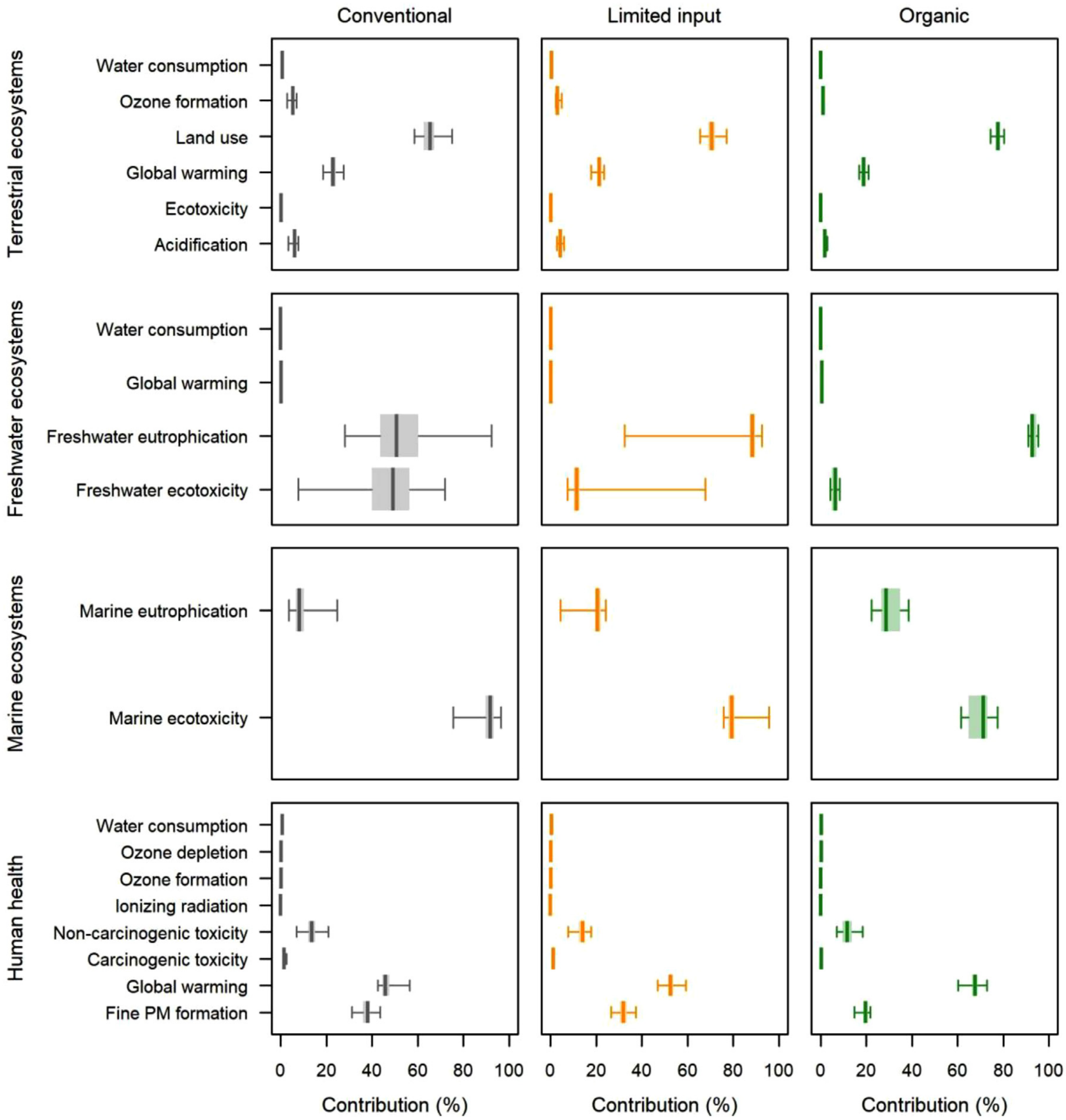

Fig. 4. Relative contribution of each impact category to damage to terrestrial ecosystems, freshwater ecosystems, marine ecosystems, and human health according to the hierarchist viewpoint. The center of the box is equal to the median value across the farm-specific outcomes, the box represents the interquartile range (from 25th to 75th percentile) and the whiskers represent the minimum and maximum. Contributions per farm are given in SIc, Excel file.

tems. These findings are in line with the results from Hokazono and Hayashi (Habibi et al., 2019), and Yodkhum et al. (Zhang et al., 2010), yet against the results of Blengini and Busto (Blengini and Busto, 2009). Blengini and Busto (Blengini and Busto, 2009) carried out an LCA study on 1 kg of milled packed rice from the paddy field to the supermarket comparing alternative rice farming methods. Their results showed that the reduction in environmental impacts from the avoided use of fertilizers and chemicals by organic farming was fully counterbalanced by the lower grain yield compared to conventional farming. Several studies showed that yields in organic rice cultivations can be highly variable and have been increasing with improved technologies for organic fertilizer or manure application and scale expansion (Hokazono and Hayashi, 2012; He et al., 2018; Hokazono and Hayashi, 2015; Bacenetti et al., 2020). Our study suggests that organic farming can lead to a good income in combination with improved yields compard to earlier studies. We showed that the sources of environmental impacts in paddy rice systems are mainly land use, fertilizer use, pesticide use and CH_4 rice field emissions.

For terrestrial ecosystems, lower damage per ton rice produced by organic farming systems with yields larger than 3 tons/ha/year can be explained by the fact that land use impacts per unit of area, a dominant contributor to ecosystem damage, are lower for organic farming systems in comparison with conventional systems (Huijbregts et al., 2017). The dominance of land use impacts also explains why terrestrial ecosystem impacts systematically decrease with yields in all farming systems, as less land will be needed to produce the same amount of paddy. A decrease in environmental footprints with increasing yields is also reported for other crops, including durum wheat and tomato production (Heidari et al., 2017; Pishgar-Komleh et al., 2017).

Organic farming systems also cause smaller freshwater ecosystem damage per unit of rice production compared to conventional and limited input farming systems, reflecting a reduction in pesticide use, notably fipronil and diazinon, and synthetic fertilizers, as also shown by other researchers (He et al., 2018; Batáry et al., 2012; Meng et al., 2017). The combination of biological control with chemical methods in the fight against pests and fungi can decrease the usage of agrochemicals. As an example, the use of the parasitoid wasp *Trichogramma brassicae* for the control of striped rice stem-borer *Chilo suppressalis* in paddy farms is an important method of integrated pest management (Afifah et al., 2019). However, freshwater ecosystem damage per ton rice produced does not decrease with yield for conventional and limited input farming systems. Relatively large amounts of fertilizers and pesticides are required by these farming systems, overcompensating the gain in yields. An eco-agricultural strategy and practice for rice production by improving education and socioeconomic conditions of farmers may help to reduce the impacts of pollution due to nutrients and pesticides (Chen et al., 2015).

Finally, if yields are higher than 3 ton/ha/year in organic farming systems, lower human health impacts per ton of rice produced were observed compared to conventional and limited input farming systems. This systematic difference is mainly caused by less fertilizer use, and resulting lower fine particulate formation by ammonia emissions and global warming by nitrous oxide emissions, in organic farming systems. Apart from these differences between environmental impacts, we also found that CH_4 field emissions were relevant for human health impacts via global warming in all three farming systems. Our CH_4 field emission calculations are, however, tentative. We followed the Tier 1 emission factor approach from the IPCC (Ogle et al., 2019) with mostly generic emission scaling factors, except for a farm-specific manure application scaling factor. Field measurements of CH_4 emissions at the farm level could substantially improve our environmental impact calculations. Regardless of these uncertainties, several other studies also showed the importance of methane field emissions in greenhouse gas footprint calculations of rice (Fusi et al., 2014; Yodkhum et al., 2017). Reducing CH_4 emissions in all three rice farming systems can be achieved, for instance, via alternate wetting and drying irrigation practice through intentional, periodic introduction of aerobic soil conditions (Runkle et al., 2019).

4.2. Eco-efficiency

We found that the eco-efficiency of paddy rice production, based on farm-specific net profit and environmental impacts, was systematically larger for organic farming systems compared to limited input and conventional farming systems. This finding was consistent across four damage categories representative of ecosystem quality and human health and reflects not only the lower environmental damages per ton of rice produced, but also the systematically higher net economic profit of organic rice. We also found a strong positive relationship between eco-efficiency and yield for organic farming systems, which can be explained by a positive correlation between net profit and yield, as well as a negative to neutral correlation between environmental impact and yield (Fig. 1, Fig. 2). The eco-efficiency of limited input and conventional farming systems did not change with yield for freshwater and marine ecosystems and for human health impacts, reflecting that both environmental impact and economic profit are positively related to yield in these systems. Improving yield can be obtained by introducing more inputs of fertilizer and pesticides. This was also found by Masuda (Masuda, 2019) who recommended to increase eco-efficiency by improved resource efficiency. Higher yields result in less land needed per unit of rice produced, causing the steepest increase in eco-efficiency over yield for terrestrial ecosystems. More efficient use of land and inputs is also associated to expanding farm size, as shown and recommended by Masuda (Masuda, 2019). The implementation of economies of scale, reduced outsourcing of farm work, and savings in chemical fertilizers and pesticides will lead to improved eco-efficiency.

Yield improvements in organic farming systems may be achieved by using certified seeds and new paddy rice cultivars and varieties, transplanting strong seedlings, applying crop rotation, and implementing targeted nutrient management (Nhamo et al., 2014; Wang et al., 2017; Das et al., 2014; Senthilkumar et al., 2018). Moreover, bio-fertilizers and compost could be used to enhance chemical and physical properties of the soil that ultimately increase crop yields (Sarwar et al., 2007). Application of bio-fertilizers can also keep the soil from N and minimize N_2O emissions by preventing other forms of N, involving ammonia and nitrate, from loss.

Judged from a production perspective, in our study organic rice farming outcompetes limited input and conventional farming systems from both an economical and environmental point of view, and accordingly from an eco-efficiency point of view. However, the competitiveness of organic farming systems strongly relies on demands for organic rice along with increased yields. The small shares of organic rice on the market can be attributed to limited demand for organic food due to higher prices for consumers. Including environmental externalities in market prices of rice, as proposed by several authors (Balmford et al., 2018; Preety et al., 2001; Shao et al., 2019), could be a strong incentive to move towards organic farming systems for rice production.

5. Conclusion

Based on detailed farm-level data on paddy rice production in Iran, we found that organic farming systems have a systematically higher eco-efficiency compared to limited-input and conventional farming systems. We further found that the eco-efficiency of organic farming systems is positively correlated with yield. Higher yields in limited-input and conventional farming systems only result in a higher eco-efficiency when considering impacts on terrestrial ecosystems, but not in terms of impacts on freshwater and marine ecosystems and human health. This implies that the economic profit of higher yields in low-input and conventional systems is counterbalanced by higher environmental impacts by using more external inputs, such as fertilizers and pesticides. Moving towards an organic farming system is considered highly beneficial both for the economic profit of rice farmers and for reducing damage towards human health and ecosystems. Improved education of farmers and including environmental externalities in market prices of rice could help to increase the market share of organic rice farming.

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.

Acknowledgments

We gratefully acknowledge the financial support provided by the Department of Agronomy and Plant Breeding, Sari Agricultural Sciences and the Natural Resources University of Iran.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.02.033.

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