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Integrating life cycle assessment and a farmer survey of management practices to study environmental impacts of peach production in Beijing, China

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Abstract:

While intensive peach production has expanded rapidly in recent years, few studies have explored the environmental impacts associated with specific regional systems or the optimal management strategies to minimize associated environmental risks. Here, data from a survey of 290 native farmers were used to conduct a life cycle assessment to quantify the acidification potential (AP), global warming potential (GWP), eutrophication potential (EP), and reactive nitrogen (Nr) losses in peach production in Pinggu District, Beijing. Total annual Nr losses, and GWP, AP, and EP values for peach production in Pinggu District were respectively 10.7 kg N t^{-1}, 857 kg CO_2-eq t^{-1}, 12.9 kg SO_2-eq t^{-1}, and 4.1 kg PO_4-eq t^{-1}. The principal driving factors were fertilizer production, transportation, and application, which accounted for 94%, 67%, 75%, and 94% of Nr losses, GWP, AP, and EP, respectively. In the high yield, high nitrogen-use efficiency (HH) group, relative values of Nr losses, GWP, AP, and EP were respectively 33%, 25%, 39%, and 32% lower than the overall averages for 290 orchards.

Further analyses indicate that improved farming practices such as decreasing application rates of fertilizers, increasing proportion of base fertilization rate, and proper fertilization frequency in the HH group were the main reasons for these orchards' better performance in peach yields and partial factor productivity of nitrogen fertilizer, and their reduced environmental impacts. These results highlight the need to optimize nutrient management in peach production in order simultaneously to realize both environmental sustainability and high productivity in the peach production system.

Keywords: Peach production; Life cycle assessment; Environmental emission mitigation; Nutrient management; Farming practice; Peri-urban agriculture

1. Introduction

Fruit intake is closely associated with positive health benefits. Intensive fruit production in China has rapidly expanded, with the planted orchard area and fruit yields, respectively increasing 1.5- and 5.6-fold between 1997 and 2016 (MAPC 2017). China now contributes 25% of the global fruit cultivation area and produces 31% of all fruit globally (FAO 2017). However, such fruit production requires high levels of chemical nitrogen (N) and phosphorus (P) fertilizer input in order to remain profitable (Zhang et al. 2013, 2018). For Chinese orchards growing pears and citrus fruits, nitrogen fertilizer use has been as high as 693 and 847 kg ha^{-1}, respectively (Wang et al. 2020; Yang et al. 2020). In prior reports from peach-producing areas in Northern China, average N, P_2O_5, and K_2O fertilizer applications were respectively up to 926, 499, and 731 kg ha^{-1} (Guo 2018). These high levels of fertilizer use have led to a range of adverse environmental effects, including soil acidification, reduced water quality, greater losses of reactive N (Nr) (Liu et al. 2020), and increased global warming potential (GWP) (Shi et al. 2009; Guo et al. 2010). Improving current understanding of the environmental impacts of different fruit production approaches in China and effectively mitigating such effects is urgently needed to improve current orchard management practices and guide the design of novel management strategies.

The ISO-standardized life cycle assessment (LCA) approach (ISO 2006a, b) was formulated to assess the total environmental effects of a given process or activity. It considers the inputs, materials, and energy usage involved in the different stages of the life cycle of a product of interest, and the quantification of the contributions of these life cycle steps to different categories of environmental impacts (Khoshnevisan et al. 2014). Previous studies have employed LCA approaches to quantify environmental effects associated with crop-specific or region-specific agricultural systems (Perrin et al. 2014). A majority of such analyses have focused on crop systems, including wheat (Chen et al. 2014; Yan et al. 2015) and maize (Zhao et al. 2016; Wang et al. 2007; Cui et al. 2013; Yan et al. 2015), revealing wheat production to be associated with a GWP of 3,000–3,707 kg CO_2-eq ha^{-1}, while maize production contributes a GWP of 2,300–3,629 kg CO_2-eq ha^{-1}, an AP of 38.1 kg SO_2-eq ha^{-1}, and an EP of 30.7 kg PO_4-eq ha^{-1}. Such LCA approaches have recently been utilized to quantify environmental burdens associated with fruit products while considering differing stages, system boundaries, and management approaches (Cerutti et al. 2011, 2014), with relatively high environmental risks found in peach (Cerutti et al. 2010; Ingrao et al. 2015; Guo et al. 2018), pear (Liu et al. 2010; Yan et al. 2015; Wang et al. 2020), citrus (Yang et al. 2020; Cerutti 2014; Alishah 2019), and apple production (Cerutti et al. 2013; Zhu et al. 2018). The environmental impacts can vary as a function of management practices even when assessing a single crop in a single area (Chen et al. 2014). It has also been found that appropriately optimized management strategies with improved fertilizer production efficiency can simultaneously increase crop yields while minimizing associated environmental impacts (Cui et al. 2013; Chen et al. 2014; Sha et al. 2021). As such, studying relationships among environmental impacts, orchard management practices, and yields should highlight new approaches to mitigating orchard-related environmental impacts, yet there have been few studies on this topic to date.

Beijing, the capital of China, is one of the largest megacities globally, with 22 million inhabitants and an area of 16,800 km^2 (Xu et al. 2017). The production of peach (*Amygdalus persica L.*) in the Pinggu District of Beijing began over 30 years ago, with the current planting area and annual production now totaling 14,667 ha and 200,000 tonnes, respectively (CASR 2019). Pinggu District was designated as an ecological conservation area under the Regulations of Beijing On Ecological Protection and Green Development of Ecological Conservation Areas (http://www.gov.cn/xinwen/2021-04/22/content_5601288.htm), underscoring the need to facilitate environmentally benign peach production in this area. However, reliable low-environmental-impact peach production remains challenging in China owing to the relatively low yields and high inputs of agricultural materials per unit area to maintain productive peach orchards (Guo et al. 2020). A detailed investigation of the factors in the orchard management cycle that drive the adverse environmental effects associated with peach production in Pinggu District provides the motivation for the present study. The objectives were (1) to evaluate the environmental impacts associated with peach production (including global warming potential [GWP], acidification potential [AP], eutrophication potential [EP], and reactive nitrogen losses [Nr]), and (2) to identify key contributing factors associated with these impacts via an LCA approach. Data were collected from 290 native farmers in the study area. Moreover, this study employed a grouping approach to better determine which management practices were suited to minimizing these environmental effects.

2. Materials and methods

2.1. Study area

This study was conducted in Pinggu District on the northeastern edge of Beijing (116°55′~117°24′E, 40°02′~40°22′N) (**Fig. 1a**). It lies within a mild, temperate continental monsoon climate zone with an annual average temperature of 11.5°C, and average annual precipitation of approximately 600 mm (450 mm from June-August). In this District, orchards, farmland (for cereal crops), and vegetable cultivation account for approximately 65%, 31%, and 4% of the total arable land, respectively (PSY 2020).

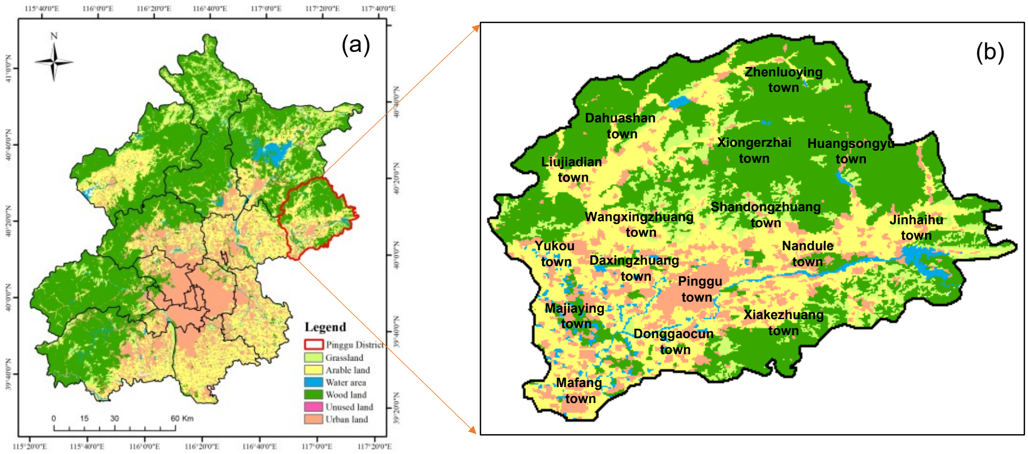

Figure 1. Maps showing the land-use of (a) Beijing city (the location of Pinggu District is outlined in red), and (b) Pinggu District, with names of municipal districts (or 'townships') included. The land-use data was downloaded from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn).

2.2. Life cycle assessment

LCA methods were used to assess four key environmental effects (Nr loss potential, GWP, acidification potential and eutrophication potential) associated with nutriment management in peach production as per ISO-14040 (2006a) and ISO-14040 (2006b).

2.2.1. System boundary and functional units

Peach production was the focus of the present analysis, with the system boundary extending from inputs including mineral and fossil-fuel extraction to yields at the farm gate after fresh peach harvesting (**Fig. 2**). This peach production LCA was separated into the agricultural material input stage (AMS; consisting of fertilizer, paper bag, diesel fuel, and pesticide preparation and transportation) and the orchard management stage (OMS; consisting of weeding, pest management, fertilizer application, bagging, diesel fuel use, and the use of electricity for irrigation). We expressed environmental impacts in terms of both cultivation area (per ha) and peach yield (per metric tonne) because the different function units could lead to different results of impacts, and they are complementary, especially in the agricultural production systems (Van der Werf et al.

2007). Reliance on the sole impact/unit area ratio may lead to a preference for low input-low output systems, which probably decrease impacts at the regional level, but create a need for additional land use elsewhere, giving rise to additional impacts. On the other hand, reliance on the impact/unit production ratio only may lead to a preference for high input-high output systems, which can cause major pollution problems at the regional scale (Tamminga 2003). Besides, the previous studies in agricultural systems normally selected two functional units, and it is convenient to compare with other results of impacts in two functional units.

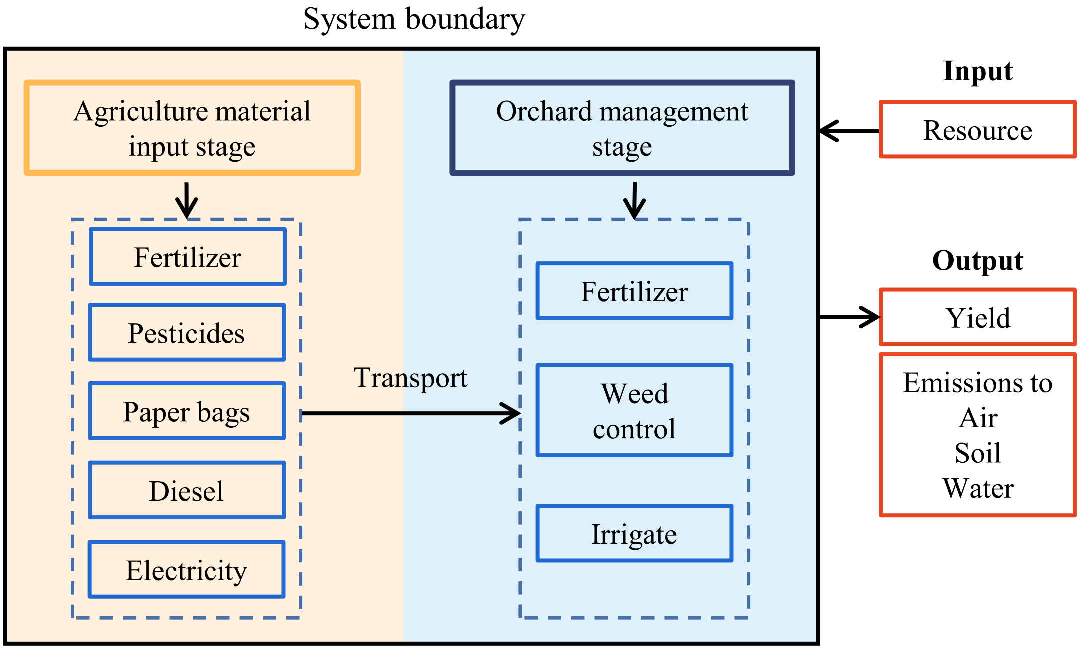

Fig. 2. LCA boundary of the peach production system

2.2.2. Impact categories

According to previous studies regarding orchards (Wang et al. 2020) and other crop production systems (Masuda 2016), fertilizers input is the dominant factor causing environmental pollutant emissions in the agricultural production stage. Moreover, Global warming, eutrophication, and acidification are most closely related to fertilizers input. Therefore, the four key impact categories associated with nutrient management practices assessed for this LCA study were: Nr loss potential, GWP (at a time-scale of 100-year), eutrophication potential (EP), and acidification potential (AP). Leaching of NO_3^-, NH_3 volatilization, and N_2O emissions were all included in Nr loss potential, while GWP was determined based on CO_2-equivalent factors from the Intergovernmental Panel on Climate Change (IPCC 2014). AP and EP were calculated using the EDIP97 method (Hauschild and Wenzel 1998). The primary reason we use the method EDIP97 is that there is little difference in the impacts of environmental acidification potential and eutrophication potential in the algorithm between this method and other methods (such as ReCipe 2016). Besides, we used the localized parameters instead of the built-in parameters of this method, and thus the results are closer to the actual agriculture production. Moreover, EDIP97 used in the previous study mainly focused on other agriculture products, such as pear and pepper production systems (Wang et al. 2020; Wang et al. 2018a). Hence, to compare the results of this study with other agricultural production systems easily, the EDIP97 method was chosen in this study.

2.2.3. Life cycle inventory analysis

Based on a questionnaire-based household survey methodology (Jia et al. 2013; Wu et al. 2014), and given the sizes of peach plantations, 5-6 villages were selected at random in 2020 from each of 6 townships (Dahuashan, Liujiadian, Nandule, Shandongzhuang, Wangxinzhuang, and Yukou, which are typical areas with peach production, **Fig. 1b**) in Pinggu District primarily responsible for peach production. Field investigators then collected data via survey from 5-10 farmers per village, with 290 fully completed surveys ultimately being collected. Survey questions were associated with peach cultivation and management, addressing topics such as production, the amounts and timing of synthetic and organic fertilizer application, annual electricity utilized for irrigation, diesel fuel consumed by soil management equipment, pesticide usage (including herbicides, insecticides, and fungicides), and paper bags used each year for fruit growth. This data is statistically summarized in **Table 1** with details for individual orchards presented in **Table S1**. The most common synthetic fertilizers employed in this region were urea and compound fertilizers, while sheep and chicken manure were the principal organic fertilizers employed. In this study, diesel fuel was only utilized for weeding and soil tillage.

Table 1. Summary of analyzed inputs and outputs for peach production farming in the Pinggu District of Beijing. Statistics are based on 290 farms.

	Mean	Range	SD
Input			
Chemical fertilizer (kg ha^{-1})			
N	651	0–3802	526
P_2O_5	654	0–3263	617
K_2O	612	0–1948	525
Organic fertilizer (kg ha^{-1})			
N	548	0–2808	594
P_2O_5	392	0–1996	448
K_2O	463	0–1948	468
Total fertilizer (kg ha^{-1})			
N	1200	67.5–4114	733
P_2O_5	1045	0–4262	679
K_2O	1075	0–3680	672
Pesticide (kg ha^{-1})	93.5	0–447	69.9
Electricity (kWh ha^{-1})	3646	0–13611	2100
Diesel (L ha^{-1})	173	0–1667	137
Paper bags (kg ha^{-1})	703	0–2150	412
Output			
Fruit yield (tonne ha^{-1}yr^{-1})	35.7	2.1–76.5	15.9

2.2.4. Emission parameters

We collected indicators associated with relevant fruit production impact categories from published literature based upon crops grown within the study region to evaluate the accuracy of the LCA analysis-derived environmental impacts. Relative pollutant emission quantities associated with fertilizers, pesticides, electricity, diesel, and paper bags for the AMS and OMS are summarized in **Tables S2 and S3**, respectively.

2.2.5. Environmental potential assessment

Environmental potentials were evaluated as follows.

$$EP_i = EP_{AMS-i} + EP_{OMS-i}$$

EP_i corresponds to the environmental potentials of i, which incorporates peach production Nr (kg N per unit), GWP (kg CO_2-eq per unit), AP (kg SO_2-eq per unit), and EP (kg PO_4-eq per unit) values. The EP_{AMS} and EP_{OMS} terms respectively correspond to the AMS and OMS environmental potentials, determined as follows,

$$EP_{AMS-i} = \sum (A_{AMSi-j} \times F_{AMSi-j})$$

$$EP_{OMS-i} = \sum (A_{OMSi-j} \times F_{OMSi-j})$$

where A_{AMSj} and A_{OMSj} respectively correspond to rates of application of substance *j* during AMS and OMS, while F_{AMSj} and F_{OMSj} respectively correspond to the emission factor (**Table S3**) for substance *j* in the AMS and OMS. N (kg), P_2O_5 (kg), K_2O (kg), pesticides (kg), diesel fuel (L), electricity (kWh) and paper bags (kg) were included as *j* items in this analysis. Conversion coefficients for calculating GWP, AP, and EP based on emissions of pollutants during the orchard management stage have been provided in **Table S4** (IPCC 2014, Hauschild and Wenzel 1998, Guo 2019).

2.3. Grouping of farmers based upon yields and the efficiency of nitrogen fertilizer utilization

Associations between environmental impacts and management practices were assessed using a grouping approach (Ye et al. 2011). First, a general analysis of peach production-related environmental impacts was conducted using the survey data collected from the 290 participating farmers, after which the association between their management practices and these environmental impacts was evaluated. Data from surveyed farmers were separated into the following four groups based on their peach yield and average partial factor productivity of nitrogen fertilizer (PFP-N) (which is a characteristic parameter that represents nitrogen-use efficiency (NUE), with higher PFP-N values indicating a better NUE): a low yield and low PFP-N (LL, 123 farmers) group which has both lower yield and PFP-N than the average values (35.6 t ha^{-1} and 45.4 kg kg^{-1}, respectively); a low yield and high PFP-N (LH, 28 farmers) group which has lower yield and higher PFP-N than the average values; a high yield and low PFP-N (HL, 75 farmers) group which has a higher yield and lower PFP-N than the average values; and a high yield and high PFP-N (HH, 64 farmers) group which has a higher yield and higher PFP-N than the average values (**Fig. 3**). PFP-N was defined as the yield (kg ha^{-1}) divided by the N application rate (kg ha^{-1}), and served as the primary N fertilizer efficiency index when evaluating the relationship between orchard management strategies, peach yields, and potential environmental effects.

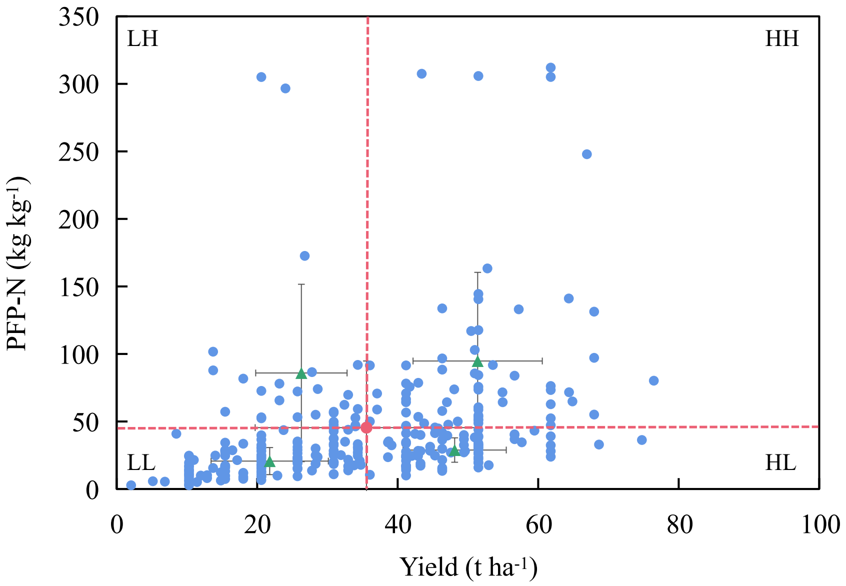

Fig. 3. Associations between partial factor productivity of nitrogen fertilizer (PFP-N) and peach yields in Pinggu District as determined from data from 290 farmers surveyed from 2019-2020. (LL, n=123; LH, n=28; HL, n=75; HH, n=64; the red dot shows average values of peach yield and PFP-N across all farmers while the green triangles and bars show the corresponding average values and standard deviations for the four groups.)

2.4. Statistical analysis

One-way analysis of variance (ANOVA) was applied to detect significant differences in inputs (fertilizer, pesticide, electricity, diesel, and paper bags), outputs (yield) and environmental impacts (Nr loss, GWP, AP, and EP) of peach production among the four farmer groups. All statistical analyses were conducted using SPSS11.5 (SPSS Inc., Chicago, IL, USA), and significance was set at $p < 0.05$. A random forest (RF) model was used to analyse impact factors on PFP-N and yield of peach. This is an ensemble approach to regression in which the classification algorithm builds a large number of decision trees with the output as the mean prediction of the individual trees (Breiman 2001; Liaw and Wiener 2002). The RF classifier consists of tree classifiers and each classifier is generated using a randomly selected subset of the variables that are independent of the input variable sampling, and each tree votes for the most popular projective units to classify the input variables (Breiman 2001). The RF classifier has been shown to be more successful than other classifiers in assembling the ensemble (Dietterich 2002). The detail of the model is described in **Text S1** in the Supplement.

3. Results and Discussion

3.1. Peach production inputs, yields, and environmental impacts

The major inputs and outputs associated with peach production in this analysis are summarized in **Table 1**. The mean peach yield (range) for the 290 farmers surveyed in Pinggu District was 35.7 tonne ha^{-1} (2.1–76.5 tonne ha^{-1}), with mean N, P_2O_5, and K_2O fertilizer application rates of 1200 kg ha^{-1} (67.5–4114 kg ha^{-1}), 1045 kg ha^{-1} (0–4264 kg ha^{-1}), and 1075 kg ha^{-1} (0–3680 kg ha^{-1}), with 60, 62 and 59% synthetic N, P and K fertilizers, respectively. The mean PFP-N was 45.5 kg kg^{-1} (2.8–312 kg kg^{-1}), while the mean amount of electricity consumed for irrigation purposes and the mean amount of diesel fuel consumed in the context of mechanized soil tillage were 3646 kWh ha^{-1} (0–13611 kWh ha^{-1}) and 173 L ha^{-1} (0–1667 L ha^{-1}), respectively. Pesticide use and bagging were necessary to produce high-quality peaches, and the amounts of pesticides and paper bags utilized by surveyed farmers ranged from 0–447 and 0–2150 kg ha^{-1}, respectively.

Mean respective Nr losses, and GWP, AP, and EP values calculated in terms of planting area were 293 kg N ha^{-1}, 23488 kg CO_2-eq ha^{-1}, 351 kg SO_2-eq ha^{-1}, and 113 kg PO_4-eq ha^{-1} (**Table 2**), with corresponding values of 10.7 kg N t^{-1}, 857 kg CO_2-eq t^{-1}, 12.9 kg SO_2-eq t^{-1}, and 4.1 kg PO_4-eq t^{-1}, respectively, when expressed in terms of yield (**Table 2**). These results suggest that peach production in Pinggu District entails a high degree of environmental risk. Factors that can govern crop yields and environmental impacts include fertilizer input, soil conditions, and weather (Wang et al. 2018a). As shown in **Table S5**, the potential environmental impacts identified in this study were 1.5–2.8 times those associated with pear and peach production in Northern China (Wang et al. 2020, Guo et al. 2018), citrus orchard management in southwestern China (Yang 2020), apple cultivation in Shaanxi and Shandong provinces (Zhu et al. 2018), and Chinese orange and banana orchards (Yan et al. 2016). The GWP of peach production in Pinggu District was 4.1 times greater than the peach production system in the Mediterranean (Vinyes et al. 2017). Similarly, higher values of AP and EP were also found in peach production in Pinggu District when compared with previous studies conducted in other countries, including Iran (Alishah 2019), Spain (Nicolo 2018, Ribal 2017, Beltran-Esteve 2017), and Italy (Nicolo 2018) in the orange production system (**Table S5**). This is primarily attributable to the higher rates of fertilizer application identified in the present analysis (**Table 1**); such application, and most notably N fertilizer application, accounting for 73%–96% of agriculture-related environmental impacts (Wang et al. 2020), mainly as a consequence of NH_3 emission and of NO_3^--N runoff and leaching after the application of N fertilizers (Wang et al. 2018b).

Fertilizer transportation and production are the two important critical factors governing GWP (Wang 2018), and, relative to lower peach production GWP values in Northern China reported by Guo et al. (2018), we identified rates of N and P fertilization in Pinggu District that were 1.3 and 2 times higher. Farmers in Pinggu District are heavily motivated to achieve a high yield by economic incentives, spurring them to apply large quantities of fertilizers (Li, 2013). By surveying 6863 Chinese fruit yields, Zhang et al. (2013) found that the excess N fertilizer applied for an average 36.7 tonne ha^{-1} fruit yield was 550 kg N ha^{-1} on average. This is consistent with the present result and highlights the extent to which excess N fertilizer was applied in peach production in Pinggu District. Overall, these findings emphasize the substantial environmental risk associated with both the planting area and fruit yield of peach production in this region, suggesting that pronounced efforts must be made to curtail these impacts by developing a thorough understanding of the impacts of different nutrient management practices.

Table 2. Mean environmental impacts (including reactive N losses and global warming, acidification, and eutrophication potentials) during the AMS and OMS stages of peach growth expressed in terms of both planting area and peach yields

		Agricultural material stage			Orchard management stage			Total
		Fertilizer	Pesticide	Paper bags	Fertilizer	Diesel	Electricity	
Per ha of the peach production								
Reactive N losses	kg N ha^{-1}	8.93	0.439	0	272	4.51	7.18	293
Global warming potential	kg CO_2-eq ha^{-1}	11374	1786	1245	5757	592	2734	23488
Acidification	kg SO_2-eq ha^{-1}	30.9	0.982	4.02	252	10.4	52.9	351
Eutrophication	kg PO_4-eq ha^{-1}	3.78	0.181	1.62	104	3.06	0.0158	113
Per ton of the peach production								
Reactive N losses	kg N t^{-1}	0.325	0.016	0	9.90	0.149	0.289	10.7
Global warming potential	kg CO_2-eq t^{-1}	414	63.9	40.6	209	19.5	110	857
Acidification	kg SO_2-eq t^{-1}	1.12	0.035	0.131	9.16	0.343	2.13	12.9
Eutrophication	kg PO_4-eq t^{-1}	0.138	0.006	0.053	3.67	0.001	0.123	3.99

3.2. Environmental impacts in different peach farmer groups

We grouped surveyed farmers into the LL, LH, HL, and HH groups (**Fig. 3**) based upon these PFP-N values (see Section 2.3). Significant differences in Nr, GWP, AP, and EP values were found among the four groups, whether expressed on the basis of planting area or peach yields (**Figs. 4 and 5**). When expressed relative to planting area, the average Nr losses in the HH group was 44%, 62%, and 33% lower than corresponding values in the LL, HL, and overall average values, respectively. Similarly, the HH group exhibited GWP values that were reduced by 34%, 52%, and 25%, AP values that were reduced by 38%, 56%, and 39%, and EP values that were reduced by 77%, 61%, and 33%, respectively, as compared to the LL, HL, and overall average values. These lower potential impact values in the HH group are primarily attributable to the reduced fertilizer input in this group (**Table 3**), with farmers in the HH group having used 46%, 63%, and 35% less fertilizer than farmers in the LL group, HL group, and the overall average values. Relative to the LH group, the Nr, GWP, AP, and EP values in the HH group were 31%-41% higher (**Fig. 4**), given that the HH group utilized 41% more N fertilizer relative to the LH group (**Table 3**).

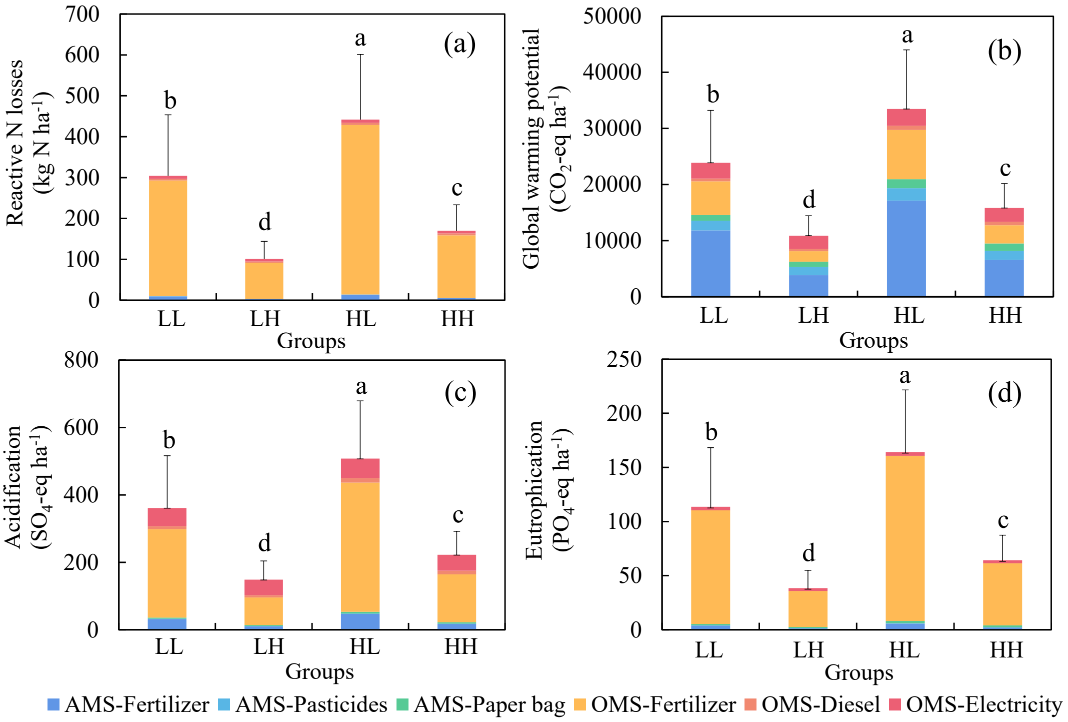

Fig. 4. (a) Reactive N losses, (b) GWP, (c) AP, and (d) EP per ha of peach production

in the LL, LH, HL, and HH farmer groups that are defined in Fig. 3. AMS: agricultural materials production stage; OMS: orchard management stage. The error bars are the standard errors of means, and values without same letters on the bars denote significant differences between the groups ($p < 0.05$).

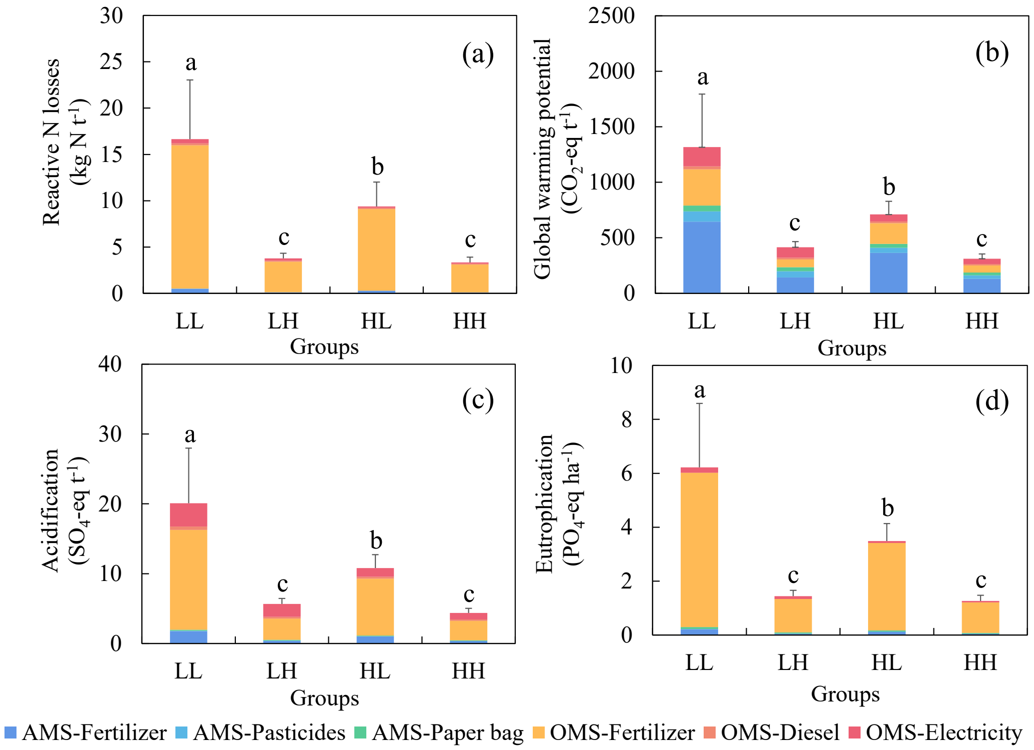

Fig. 5. (a) Reactive N losses, (b) GWP, (c) AP, and (d) EP per tonne of peach production in the LL, LH, HL, and HH farmer groups that are defined in Fig. 3. AMS: agricultural materials production stage; OMS: orchard management stage. The error bars are the standard errors of means, and values without same letters on the bars denote significant differences between the groups ($p < 0.05$).

Table 3. Life cycle inventory data and primary management practices in the LL, LH, HL, and HH farmer groups that are defined in Fig. 2. Data are means ± standard deviation (mean values without same letters in the same row denote significant differences between the groups ($p < 0.05$)).

Item	Farmer group			
	LL	LH	HL	HH
Input				
Chemical fertilizer (kg ha^{-1})	Mean	Mean	Mean	Mean
N	720 ± 531^{a}	306 ± 206^{b}	861 ± 642^{a}	425 ± 236^{b}
P_2O_5	730 ± 630^{a}	340 ± 330^{b}	774 ± 765^{a}	504 ± 391^{b}
K_2O	668 ± 510^{a}	324 ± 228^{b}	720 ± 674^{a}	505 ± 367^{b}
Organic fertilizer (kg ha^{-1})				
N	533 ± 592^{b}	96.3 ± 150^{c}	989 ± 598^{a}	259 ± 320^{c}
P_2O_5	364 ± 445^{b}	92.1 ± 145^{c}	712 ± 469^{a}	201 ± 266^{c}
K_2O	441 ± 457^{b}	174 ± 269^{c}	780 ± 453^{a}	257 ± 359^{c}
Total fertilizer (kg ha^{-1})				
N	1253 ± 639^{b}	402 ± 191^{d}	1850 ± 669^{a}	683 ± 270^{c}
P_2O_5	1094 ± 671^{b}	432 ± 316^{d}	1486 ± 679^{a}	705 ± 369^{c}
K_2O	1110 ± 613^{b}	498 ± 339^{c}	1500 ± 713^{a}	763 ± 484^{c}
Pesticide (kg ha^{-1})	90.4 ± 66.5^{b}	73.5 ± 36.8^{b}	115 ± 91.4^{a}	83.5 ± 51.2^{b}
Electricity (kWh ha^{-1})	3742 ± 2173^{ab}	3102 ± 1910^{b}	4060 ± 2345^{a}	3213 ± 1586^{b}
Diesel (L ha^{-1})	156 ± 120^{b}	129 ± 135^{b}	215 ± 156^{a}	173 ± 134^{ab}
Paper bags (kg ha^{-1})	572 ± 407^{b}	547 ± 401^{b}	910 ± 374^{a}	783 ± 350^{a}
Output				
Yield (t ha^{-1}year^{-1})	21.8 ± 8.3^{d}	26.3 ± 6.5^{c}	48.1 ± 7.3^{b}	51.4 ± 9.2^{a}

On a peach yield basis, the HH group exhibited the lowest environmental impacts of these four groups of farmers (**Fig. 5**). Relative to the average values for all surveyed farmers, the HH group exhibited mean Nr, GWP, AP, and EP values that were reduced by 60%, 55%, 57%, and 59%, respectively. Relative to the LL, LH, and HL groups, the HH group exhibited Nr values that were reduced by 80%, 12%, and 65%, GWP values that were reduced by 76%, 25%, and 56%, AP values that were reduced by 78%, 23%, and 59%, and EP values that were reduced by 80%, 12%, and 64%, respectively. These differences were largely attributable to higher yields and reduced fertilizer input, thereby significantly improving N fertilizer use efficiency in the HH group. The PFP-N in the HH groups was 359%, 10%, and 229% higher than that in the LL, LH, and HL groups, respectively (**Fig. 3**).

The substantial variability observed for peach yields, PFP-N, and environmental costs (**Figs. 3, 4 and 5**) suggest that associated environmental impacts can be minimized by learning optimal farming practices (Wang et al. 2018a; Guo et al. 2018; Cui et al. 2018). Farmers in the HH group achieved better peach yields with a reduced fertilizer input, thereby incurring less severe environmental costs. Therefore, factor analysis among the four groups was performed to identify management practices that good farmers could use to improve the PFP-N and reduce the environmental potentials.

To identify the dominant factor for mitigating the environmental potentials, the contributions of individual inputs in the AMS and OMS to the four environmental potentials were calculated, as shown in **Fig 6**. Fertilizer production and application was the main factor contributing to Nr losses, contributing an average of 94% (91%–96%) across these four groups. Fertilizer was also the primary contributor to GWP in the AMS (35%–51%) and OMS (17%–26%), followed by electricity and diesel consumption in the OMS (11%–25%), and pesticide consumption in the AMS (7%–13%), as well as paper bag use in the AMS (4%–9%). Fertilizer contributed to 55%–75% of AP in the OMS and 7%–9% in the AMS, with electricity consumption in the OMS accounting for an additional 11%–31%. Paper bag use, pesticide application in the AMS, and diesel consumption in the OMS contributed only 6% (4%–7%) on average to AP across the four groups. Similar results were observed for EP, with pesticide and paper bag use accounting for < 3% of EP in the AMS. Fertilizer production, transportation, and application were the primary contributing factors associated with all four analyzed environmental impacts. Fewer fertilizer-related contributions were observed for the LH and HH groups relative to the other groups. Our results are similar to the finding of Wang et al. (2018) for pepper production that the reduction in environmental risks for the HH group were mainly explained by lower application rates of N and P fertilizer, higher application rates of K fertilizer, and higher yield.

A lack of knowledge or training may account for some of the poorer agronomic practices observed among smallholder farmers in this region, with fertilizer purchasing decisions primarily being price- and marketing-dependent (Huang et al. 2015; Qin et al. 2016). Farmers often believe that excess fertilizer application can minimize yield losses (Zhao et al. 2016a, b). Overall, our results suggest that peach production-related environmental impacts can be primarily mitigated while maintaining high yields by improving nutrient management strategies such that they align with those of farmers in the HH group. Training may therefore be an effective means of minimizing environmental damage associated with peach production in this region.

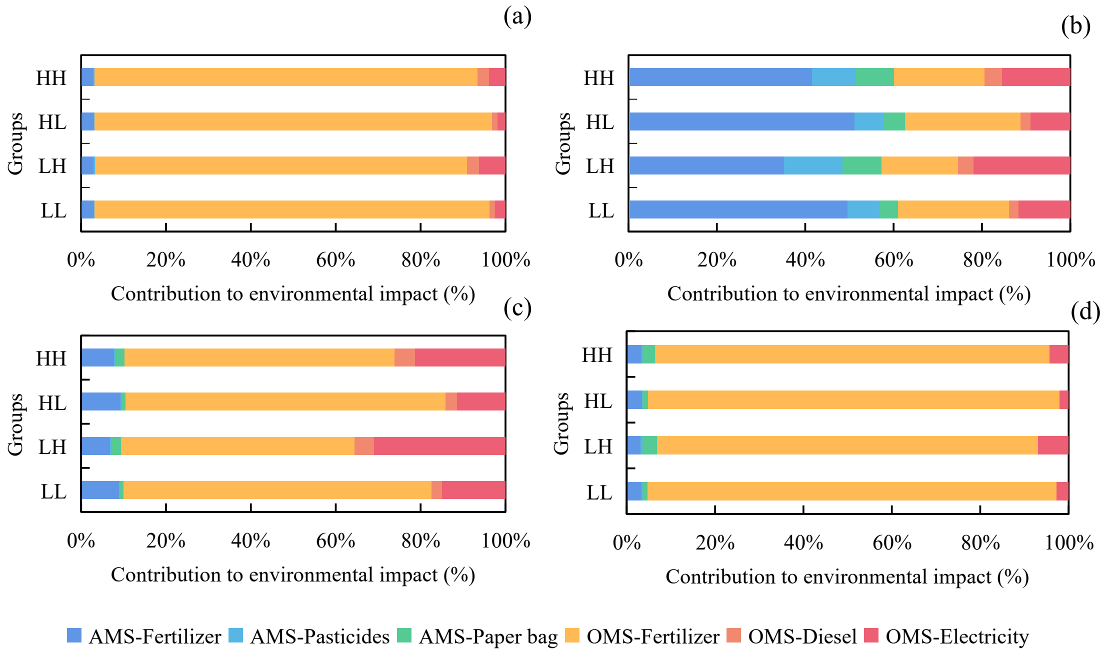

Fig. 6. Contributions to (a) reactive N losses, (b) GWP, (c) AP, and (d) EP in the LL,

LH, HL, and HH farmer groups that are defined in Fig. 2. AMS: agricultural materials production stage; OMS: orchard management stage.

3.3. Peach production-related farming practices in the four groups

From the RF model, P fertilizer application was the most important factor controlling the PFP-N of the peach orchards (**Fig. 7a**). In addition, K fertilizer application, fertilization frequency and pesticide application were also important controlling variables. By contrast, fertilization frequency, base fertilization rate proportion, pesticide application and K fertilizer application were important variables for the peach yield (**Fig. 7b**). In the HH group, the base fertilization rate proportion accounted for 61.2% of the total fertilizer applied, with this value being 9.6% and 44.7% higher than respective values in the LL and LH groups, respectively (**Fig. S1**). Besides, approximately 50% of orchards applied fertilizers 3–4 times per year, which is lower than corresponding value (69%) in HL group and higher than that (15%) in LH group (**Fig. S2**). Overall, the independent farmer practice variables selected from the RF models explained 25% of the total variance in both PFP-N and peach yield (**Fig. 7c and d**). These results indicate that relatively lower fertilizer application, higher proportion of base fertilization rate, and proper fertilization frequency are the three factors contributing most to achievement of high yield and high PFP-N of peach production in the HH group.

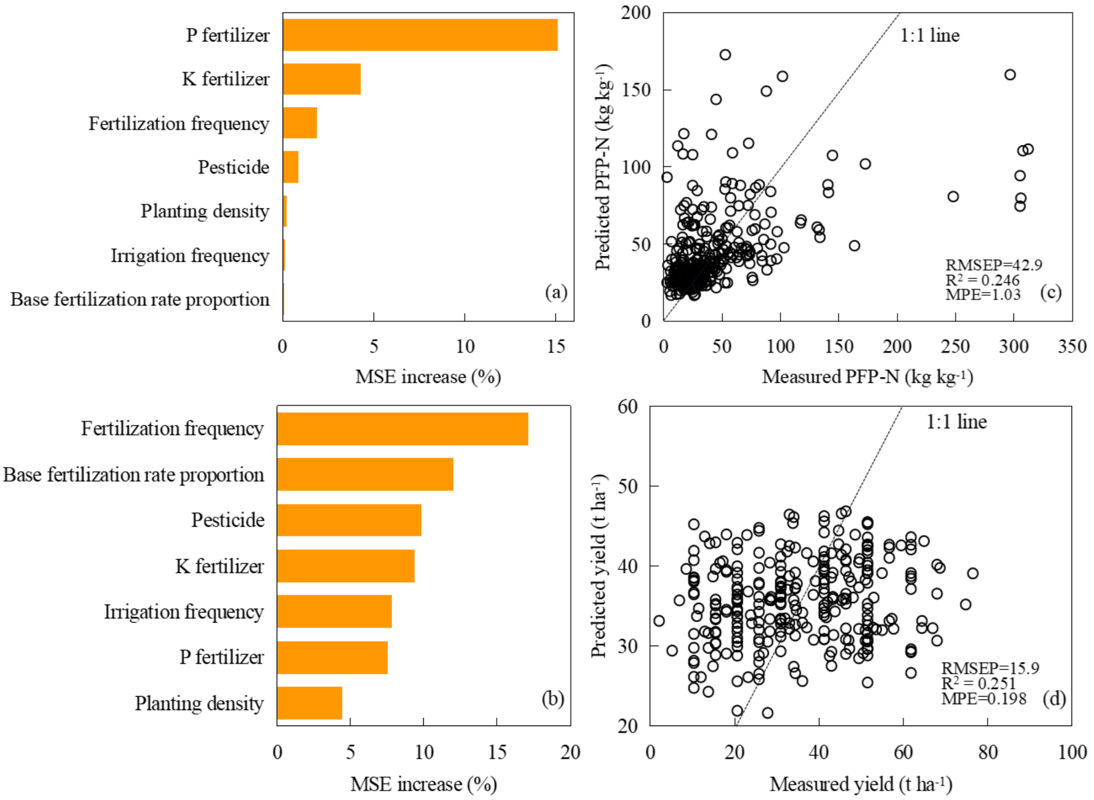

Fig. 7. Relative importance of independent variables for controlling (a) PFP-N and (b) yield as determined using random forests (RF) models and the performance of random forests models for detecting factors controlling change of (c) PFP-N and (d) yield.

In addition to farming practices, education level of farmers may be an indirect influencing factor. For example, 36% of laboring family members in the HH group had a junior high school or higher educational level, as opposed to 19%, 26%, and 23% in the LL, LH, and HL groups, respectively (**Fig. S3**). Better educated farmers in the HH group than farmers in other groups can render them better equipped to acquire, update, and apply new information and technologies (Li et al. 2019). Based on a fixed-effect panel model of over 20,000 rural households in China between 1995 and 2016, Ren et al. (2021) found that the low ratio of fixed inputs such as machinery and knowledge to total inputs is the determining factor of over-fertilization in smallholder farms (Ren et al. 2021). Knowledge-based training and cooperation based upon region - or crop - specific studies can effectively improve the adoption of novel agronomic technologies by farmers (Zhang et al. 2016). Policymakers can thus leverage this information to identify effective approaches to advancing farm management practices with the goal of minimizing adverse environmental impacts.

3.4. Recommendations and outlook for sustainable peach production

In recent years, fruit quality expectations in China have risen substantially as living standards and economic prosperity continue to increase. Rising expectations have changed Chinese fruit production from extensive (more area but low yield and quality) to intensive management for higher yield and quality on potentially less area (Zhou et al. 2017). Peach yields are an essential consideration for farmers' earnings. The present study reveals that it is possible for farming practices such as lower application rates of fertilizers and proper fertilization frequency to increase NPF-N and peach yields (**Fig. 3 and Table 3**). Consumer preference surveys indicate that the quality of the fresh peaches is also important (Byrne 2005; Crisosto 2002). Fruit quality is a rather nebulous concept that incorporates nutritive value, aesthetic properties, sensory properties including smell, taste, and texture, and safety considerations and mechanical properties including firmness, density, volume, mass, and sphericity (Crisosto and Costa 2008). In addition to environmental factors and cultivar-specific factors (Frecon et al. 2002; Liverani et al. 2002), the quality of peaches is primarily influenced by production-related practices in orchards such as crop-load management (Berman and DeJong 1996), irrigation (Bryla et al. 2005), fertilization (Jia et al. 1999), pruning, and canopy structuring (Farina et al. 2005; Kumar et al. 2010). It is thus crucial that the link between fruit quality and environmental costs be defined to establish approaches that maximize quality while minimizing associated environmental harm. Studies on this topic can yield evidence-based strategies amenable to optimal environmental and agricultural management strategies.

While China accounts for 21% of the global fruit production area, its per capita water resources are only a quarter of the overall global levels (Zhao et al. 2014). Several industries in Beijing have been constrained by water shortages (Wen and Zu 2013), making it essential that optimal irrigation strategies be developed to minimize water waste via drip irrigation directly to the root area of plants, thereby promoting watersaving agricultural practices. Owing to limited overlap between agricultural machinery and agronomy in China, many management practices, including pruning and fertilizer application, are still conducted manually (Wang et al. 2017). As the rural workforce continues to age, this will adversely impact chemical and fertilizer efficiency, profitability, and other factors in the fruit industry (Yuan and Chen 2019). To ensure that peach production in Pinggu District remains sustainable, it is thus important that research and beneficial technologies be promoted. Moreover, environmental mitigation strategies should be further evaluated to develop an intensive, mechanized peach industry that remains sustainable through optimal orchard management. Additional research regarding the environmental costs associated with modernized peach production strategies is warranted to achieve this goal.

Although the present study combined the LCA method and farmer surveys to quantify the environmental impact of peach production, some uncertainties also existed. For example, emission factors of pollutants (e.g., NH_3 and N_2O) used in this study were obtained from previous publications rather than special for Pinggu District. This may lead to uncertainties in emissions of pollutants in this study because emission factors may differ regionally due to differences in climate, soil environment, and fertilization methods. Besides, LCA has been a helpful tool for quantifying various environmental impacts of agricultural production throughout their life spans. However, the LCA based on inventory analysis inevitably has truncation error, which means the accounting may be incomplete (Suh 2004). Last but not least, this study mainly focused on the environmental impact of peach planting and production but did not consider subsequent storage, transportation, sales, and other links. In order to fully evaluate the environmental cost of peach from production to consumer disposal, the system boundary should be further extended to the whole life cycle of peach.

4. Conclusions

This study highlights the significant environmental risks associated with peach production in Pinggu District of Beijing, underscoring the importance of exploring approaches to mitigate such environmental impacts. For the total cultivation area, the total annual Nr losses, GWP, AP, and EP calculated for the 290 farmers in this region surveyed were 293 kg N ha^{-1}, 23,488 kg CO_2-eq ha^{-1}, 351 kg SO_2-eq ha^{-1}, and 113 kg PO_4-eq ha^{-1}, respectively. On a peach yield basis, these respective values were 10.7 kg N t^{-1}, 857 kg CO_2-eq t^{-1}, 12.9 kg SO_2-eq t^{-1} and 4.1 kg PO_4-eq t^{-1}. Overall, these yield-based values tended to be higher than those associated with the production of vegetable or cereal crops. The primary factors contributing to these environmental potentials were the production, transportation, and application of fertilizers (94% of the Nr losses, 67% of the GWP, 75% of the AP, and 94% of the EP).

The scales of environmental impact potentials varied significantly among the four groups of farmers defined in this study as a function of fertilizer PFP-N and peach yields. Relative to the overall averages of these two quantities for these 290 native farmers, the mean Nr, GWP, AP, and EP values on a per-yield basis in the high PFP-N, high yield (HH) group were respectively reduced by 33%, 25%, 39%, and 32%. The differences were largely attributable to the reduced rates of fertilization, higher proportion of base fertilization rate, and suitable frequency of fertilization in the HH group. These results highlight the need to further optimize nutrient management and other peach farming practices (proper planting density, trickling irrigation, proper use of chemical pesticides) to simultaneously improve productivity and environmental sustainability.

Author contribution statement

Ziyue Li: Conceptualization, Methodology, Investigation, Validation, Formal analysis, Writing – original draft, Visualization, **Yongliang Chen**: Methodology, Investigation, Formal analysis, Writing – review & editing, **Wen Xu**: Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition, **Mathew R. Heal**: Writing – review & editing, **Fanlei Meng**: Writing – review & editing, **Qishao**: Writing – review & editing, **Aohan Tang**: Writing – review & editing, **Jiechen Wu**: Writing – review & editing, **Xuejun**

Liu: Writing – review & editing, **Zhenling Cui**: Resources, Supervision, Project administration, Writing – review & editing.

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Availability of data and materials

The concerned data and materials are available from the principal investigator and corresponding author

Declarations

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Consent to participate The authors provided consent to participate in this study.

Consent for publication All the co-authors consent to the publication of this work.

Competing interests The authors declare no competing interests.

References:

Alishah A, Motevali A, Tabatabaeekoloor R, Hashemi SJ (2019) Multiyear life energy and life cycle assessment of orange production in Iran. Environ Sci Pollut Res 26:32432–32445. https://doi.org/10.1007/s11356-019-06344-y.

Beltran-Esteve M, Reig-Martinez E, Estruch-Guitart V (2017) Assessing eco-efficiency: A metafrontier directional distance function approach using life cycle analysis. Environ. Impact Assess Rev 63:116–127. https://doi.org/10.1016/j.eiar.2017.01.001.

Berman ME, DeJong TM (1996) Water stress and crop load effects on fruit fresh and dry weights in peach (Prunus persica). Tree Physiol 16:859–864. https://doi.org/10.1093/treephys/16.10.859.

Breiman L (2001) Random forests. Mach Learn 45:5–32. https://doi.org/10.1023/A:1010933404324.

Bryla DR, Dickson E, Shenk R, Johnson RS, Crisosto CH, Trout TJ (2005). Influence of irrigation method and scheduling on patterns of soil and tree water status and its relation to yield and fruit quality in peach. Hortscience 40:2118–2124. https://doi.org/10.21273/HORTSCI.40.7.2118.

Byrne DH (2005) Trends in stone fruit cultivar development. Horttechnology 15:494–500. https://doi.org/10.21273/HORTTECH.15.3.0494.

CASR (China Agriculture Statistical Report) (2019) Available online: http://www.stats.gov.cn/tjsj/ndsj/2020/indexch.htm. Accessed 10 August 2021

Cerutti A, Beccaro G, Bruun S, Bosco S, Donno D, Notarnicola B, Bounous G (2013) Life cycle assessment application in the fruit sector: State of the art and recommendations for environmental declarations of fruit products. J Clean Prod 73:125–135. http://dx.doi.org/10.1016/j.jclepro.2013.09.017.

Cerutti A, Bruun S, Beccaro G, Bounous G (2011) A review of studies applying environmental impact assessment methods on fruit production systems. J Environ Manag 92:2277–2286. https://doi.org/10.1016/j.jenvman.2011.04.018.

Cerutti AK, Bagliani M, Beccaro GL, Bounous G (2010) Application of ecological footprint analysis on nectarine production: methodological issues and results from a case study in Italy. J Clean Prod 18:771–776. https://doi.org/10.1016/j.jclepro.2010.01.009.

Cerutti AK, Bruun S, Donno D, Beccaro GL, Bounous G (2013) Environmental sustainability of traditional foods: the case of ancient apple cultivars in Northern

Italy by multifunctional LCA. J Clean Prod 52:245–252. https://doi.org/10.1016/j.jclepro.2013.03.029.

Chen XP, Cui ZL, Fan MS, Vitousek P, Zhao M, Ma WQ, Wang ZL, Zhang WJ, Yan XY, Yang JC, Deng XP, Gao Q, Zhang Q, Guo SW, Ren JJ, Li SQ, Ye YL, Wang ZH, Huang JL, Tang QY, Sun YX, Peng XL, Zhang JW, He MG, Zhu YJ, Xue JQ, Wang GL, Wu L, An N, Wu LQ, Ma L, Zhang WF, Zhang FS (2014) Producing more grain with lower environmental costs. Nature 514:486–489. https://doi.org/10.1038/nature13609.

Chen XP, Cui ZL, Vitousek PM, Cassman KG, Matson PA, Bai JS, Meng QF, Hou P, Yue SC, Romheld V, Zhang FS (2011) Integrated soil-crop system management for food security. Proc Natl Acad Sci USA 108:6399–6404. https://doi.org/10.1073/pnas.1101419108.

Crisosto CH (2002) How do we increase peach consumption? Acta Hortic 59:601–605. https://doi.org/10.17660/ActaHortic.2002.592.82.

Crisosto CH, Costa G (2008) Preharvest factors affecting peach quality. In: Layne, D.R., Bassi, D. (Eds.), The Peach: Botany, Production and Uses. CAB Int 09:536–549.

Cui ZL, Yue SC, Wang GL, Meng QF, Wu L, Yang ZP, Zhang Q, Li SQ, Zhang FS, Chen XP (2013) In-season root-zone N management for mitigating greenhouse gas emission and reactive N losses in intensive wheat production. Environ Sci Technol 47:6015–6022. https://doi.org/10.1021/es4003026.

Cui ZL, Zhang HY, Chen XP, Zhang CC, Ma WQ, Huang CD, Zhang WF, Mi GH, Miao YX, Li XL, Gao Q, Yang JC, Wang ZH, Ye YL, Guo SW, Lu JW, Huang JL, Lv SH, Sun YX, Liu YY, Peng XL, Ren J, Li SQ, Deng XP, Shi XJ, Zhang Q, Yang ZP, Tang L, Wei CZ, Jia LL, Zhang JW, He MR, Tong YA, Tang QY, Zhong XH, Liu ZH, Cao N, Kou CL, Ying H, Yin YL, Jiao XQ, Zhang QS, Fan MS, Jiang RF, Zhang FS, Dou ZX, (2018) Pursuing sustainable productivity with millions of smallholder farmers. Nature 555:363. https://doi.org/10.1038/nature25785.

Dietterich TG (2002) Machine learning for sequential data: a review. Joint IAPR International Workshops on Statistical Techniques in Pattern Recognition (SPR) and Structural and Syntactic Pattern Recognition (SSPR).

https://doi.org/10.1007/3-540-70659-3_2.

FAO (Food and Agriculture Organization of the United Nations) (2017) FAOSTAT. Database-Resources. Food and Agriculture Organization of the United Nations. Available online: http://www.fao.org/faostat/zh/#home. Accessed 10 August 2021

FAO (Food and Agriculture Organization of the United Nations) (2016) FAOSTAT Database; Food and Agriculture Organization of the United Nations: Rome, Italy. Available online: http://www.fao.org/faostat/zh/#home. Accessed 10 August 2021

Farina V, Lo Bianco R, Inglese P (2005) Vertical distribution of crop load and fruit quality within vase- and Y-shaped canopies of "Elegant Lady" peach. Hortscience 40:587–591. https://doi.org/10.21273/HORTSCI.40.3.587.

Guo C Y (2019) Study on fertilization inputs and nitrogen optimization of peach orchard in typical areas of China. Southwest university, China.

Guo C Y, Wang X, Li Y, He X, Zhang W, Wang J (2018) Carbon Footprint Analyses and Potential Carbon Emission Reduction in China's Major Peach Orchards. Sustainability 10:1–17. https://doi.org/10.3390/su10082908.

Guo JH, Liu XJ, Zhang Y, Shen JL, Han WX, Zhang WF, Christie PK, Goulding WT, Vitousek PM, Zhang FS (2010) Significant acidification in major Chinese croplands. Science 327:1008–1010. https://doi.org/10.1126/science.1182570.

Hauschild M, Wenzel H (1998) Environmental Assessment of Products. Scientific Background, Vol. 2. Chapman and Hall, London.

Hayo MG, Van der Werf, John T, Kathy L (2006) Environmental impacts of farm scenarios according to five assessment methods. Agric Ecosyst Environ 118:327–338. https://doi.org/10.1016/j.agee.2006.06.005.

Huang JK, Huang ZR, Jia XP, Hu RF, Xiang C (2015) Long-term reduction of nitrogen fertilizer use through knowledge training in rice production in China. Agric Syst 135:105–111. https://doi.org/10.1016/j.agsy.2015.01.004.

Ingrao C, Matarazzo A, Tricase C, Clasadonte MT, Huisingh D (2015) Life cycle assessment for highlighting environmental hotspots in Sicilian peach production systems. J Clean Prod 92:109–120. https://doi.org/10.1016/j.jclepro.2014.12.053.

IPCC (2014) Climate Change 2014: Impacts, Adaptation and Vulnerability: Regional

Aspects. Cambridge University Press.

ISO-14040 (2006a) Environmental management life cycle assessment principles and framework.

ISO-14040 (2006b) Environmental management life cycle assessment requirements and guidelines.

Jia H, Hirano K, Okamoto G (2008) Effects of fertilizer levels on tree growth and fruit quality of “Hakuho” peaches (Prunus persica). Engei Gakkai Zasshi 68:487–493. https://doi.org/10.2503/jjshs.68.487.

Jia XP, Huang JK, Xiang C, Hou LK, Zhang FS, Chen XP, Cui ZL and H Bergmann (2013) Farmer's adoption of improved nitrogen management strategies in maize production in China: an experimental knowledge training. J Integr Agric 12:364–373. https://doi.org/10.1016/S2095-3119(13)60237-3.

Khoshnevisan B, Rafiee S, Omid M, Mousazadeh H, Clark S (2014) Environmental impact assessment of tomato and cucumber cultivation in greenhouses using life cycle assessment and adaptive neuro-fuzzy inference system. J Clean Prod 73:183–192. https://doi.org/10.1016/j.jclepro.2013.09.057.

Kumar M, Rawat V, Rawat JMS, Tomar YK (2010) Effect of pruning intensity on peach yield and fruit quality. Sci Hortic 125:218–221. https://doi.org/10.1016/j.scienta.2010.03.027.

Li SH (2013) Peach. China Agriculture Press: Beijing, China (in Chinese)

Li YJ, Yang M, Zhang ZZ, Li WL, Zhang XD (2019) An ecological research on potential for zero-growth of chemical fertilizer use in citrus production in China. Ekoloji 28:1049–1059.

Liaw A, Wiener M (2002) Classification and regression by randomForest. R News 2:18–22.

Liu XJ, Xu W, Du EZ, Tang AH, Zhang Y, Zhang YY, Wen Z, Hao TX, Pan YP, Zhang L, Gu BJ, Zhao Y, Shen JL, Zhou F, Gao ZL, Feng ZZ, Chang YH, Goulding K, Collett JL, Vitousek PM, Zhang FS (2020) Environmental impacts of nitrogen emissions in China and the roles of policies in emission reduction. Phil Trans Roy Soc A 378:20190324. https://doi.org/10.1098/rsta.2019.0324.

MAPC (Ministry of Agriculture of the People's Republic of China) (2017) China Agriculture Statistical Report 2016; China Agricultural Press: Beijing, China 65–68.

Masuda K (2016) Measuring eco-efficiency of wheat production in Japan: a combined application of life cycle assessment and data envelopment analysis. J Clean Prod 126: 373-381. https://doi.org/10.1016/j.jclepro.2016.03.090.

Menzel CM, Lagadec MD (2014) Increasing the productivity of avocado orchards using high-density plantings: a review. Sci Hortic 177:21–36. https://doi.org/10.1016/j.scienta.2014.07.013.

Nicolo BF, De Salvo MC, Ramirez-Sanz C, Estruch V, Sanjuan N, Falcone G, Strano A (2018) Life cycle assessment applied to different citrus farming systems in Spain and Italy. Agroecol. Sustain. Food Syst 42:1092–1105. https://doi.org/10.1080/21683565.2018.1490942.

Perrin A, Basset-Mens C, Gabrielle B (2014) Life cycle assessment of vegetable products: a review focusing on cropping systems diversity and the estimation of field emissions. Int J Life Cycle Assess 19:1247–1263. https://doi.org/10.1007/s11367-014-0724-3.

PSY (Pinggu Statistical Yearbook) (2020) Available online: http://www-bjpg-gov-cn.vpn.cau.edu.cn:8118/pgqrmzf/zwxx0/sjxz/index.html Accessed 30 November 2020.

Ren CC, Jin SQ, Wu YY, Zhang B, Kanter D, Wu B, Xi XC, Zhang X, Chen DL, Xu JM, Gu BJ (2021) Fertilizer overuse in Chinese smallholders due to lack of fixed inputs. J Environ Manage 293:112913. https://doi.org/10.1016/j.jenvman.2021.112913.

Ribal J, Ramirez-Sanz C, Estruch V, Clemente G, Sanjuan N (2017) Organic versus conventional citrus. Impact assessment and variability analysis in the Comunitat Valenciana (Spain). Int J Life Cycle Assess 22:571–586. https://doi.org/10.1007/s11367-016-1048-2.

Sha ZP, Liu HJ, Wang JX, Liu XJ, Misselbrook T (2021) Improved soil-crop system management aids in NH3 emission mitigation in China. Environ Pollut

289:117844. https://doi.org/10.1016/j.envpol.2021.117844.

Shi WM, Yao J, Yan Feng (2009) Vegetable cultivation under greenhouse conditions leads to rapid accumulation of nutrients, acidification and salinity of soils and groundwater contamination in South-Eastern China. Nutr Cycl Agroecosyst 83:73–84. https://doi.org/10.1007/s10705-008-9201-3.

Stephen C, Enda C, Karli V (2017) Systematic review of greenhouse gas emissions for different fresh food categories. J Clean Prod 140:766–783. https://doi.org/10.1016/j.jclepro.2016.04.082.

Suh S (2004) Functions, commodities and environmental impacts in an ecological-economic model. Ecol Econ 48: 451-467. https://doi.org/10.1016/j.ecolecon.2003.10.013.

Tamminga S (2003) Pollution due to nutrient losses and its control in European animal production. Livestock Production Sci 84:101–111. https://doi.org/10.1016/j.livprodsci.2003.09.008.

Van der Werf HMG, Tzilivakis J, Lewis K, Basset-Mens C (2007) Environmental impacts of farm scenarios according to five assessment methods. Agric. Ecosyst. Environ 118:327-338. https://doi.org/10.1016/j.agee.2006.06.005.

Vinyes E, Asin L, Alegre S, Munoz P, Boschmonart J, Gasol CM (2017) Life cycle assessment of apple and peach production, distribution and consumption in Mediterranean fruit sector. J Clean Prod 149:313–320. https://doi.org/10.1016/j.jclepro.2017.02.102.

Wang J, Zhang L, He X, Zhang YQ, Wan Y, Duan SY, Xu CY, Mao XY, Chen XP, Shi XJ (2020) Environmental mitigation potential by improved nutrient managements in pear (Pyrus pyrifolia L.) orchards based on life cycle assessment: A case study in the North China Plain. J Clean Prod 262:121–273. https://doi.org/10.1016/j.jclepro.2020.121273.

Wang MR, Ma L, Strokal M, Ma WQ, Liu XJ, Kroeze C (2018b) Hotspots for nitrogen and phosphorus losses from food production in China: A county-scale analysis. Environ Sci Technol 52:5782-5791. https://doi.org/10.1021/acs.est.7b06138.

Wang MX (2007) Life cycle assessment of the winter wheat-summer maize production system on the North China Plain. Int J Sust Dev World 14:400–407. https://doi.org/10.1080/13504500709469740.

Wang X, Zou C, Zhang Y (2018a) Environmental impacts of pepper (Capsicum annuum L) production affected by nutrient management: A case study in southwest China. J Clean Prod 171:934–943. https://doi.org/10.1016/j.jclepro.2017.09.258.

Wang Z, Song YZ, Liu H (2017) China’s fruit tree pruning machinery research status and development trends. J Agric Mech 3:126–130.

Wen K, Zhu EJ (2013) Annual report on Beijing-Tianjin-Hebei metropolitan region development. Beijing, China: Social Sciences Academic Press.

Wu L, Chen XP, Cui ZL, Zhang WF, Zhang FS (2014) Establishing a regional nitrogen management approach to mitigate greenhouse gas emission intensity from intensive smallholder maize production. Plos One 9:98481. https://doi.org/10.1371/journal.pone.0098481.

Xu W, Song W, Zhang YY, Liu XJ, Zhang L, Zhao YH, Liu DY, Tang AH, Yang DW, Wang DD, Wen Z, Pan YP, Fowler D, Collett JL, Erisman JW, Goulding K, Li Y, Zhang FS (2017) Air quality improvement in a megacity: implications from 2015 Beijing Parade Blue pollution control actions. Atmos Chem Phys 17:31–46. https://doi.org/10.5194/acp-17-31-2017.

Yan M, Cheng K, Yue Q, Yan Y, Rees R M, Pan G (2016) Farm and product carbon footprints of china's fruit production—life cycle inventory of representative orchards of five major fruits. Environ Sci Pollut Res 23:4681-4691. https://doi.org/10.1007/s11356-015-5670-5.

Yang M, Cheng K, Luo T, Yan Y, Pan G (2015) Carbon footprint of grain crop production in China - based on farm survey data. J Clean Prod 104:130–138. https://doi.org/10.1016/j.jclepro.2015.05.058.

Yang M, Long Q, Li W (2020) Mapping the environmental cost of a typical citrus-producing county in China: hotspot and optimization. Sustainability 12:1827. https://doi.org/10.3390/su12051827.

Ye YL, Wang GL, Huang YF, Zhu YJ, Meng QF, Chen XP, Zhang FS, Cui ZL (2011) Understanding physiological processes associated with yield-trait relationships in modern wheat varieties. Field Crop. Res 124:316–322. https://doi.org/10.1016/j.fcr.2011.06.023.

Yuan B, Chen C (2019) Evolution of a development model for fruit industry against background of rising labor cost: intensive or extensive adjustment?. Sustainability 11:38–64. https://doi.org/10.3390/su11143864.

Zhang WF, Cao GX, Li XL, Zhang HY, Wang C, Liu QQ, Chen CP, Cui ZL, Shen JB, Jiang RF, Mi GH, Miao YX, Zhang FS, Dou ZX (2016) Closing yield gaps in China by empowering smallholder farmers. Nature 537:671–674. https://doi.org/10.1038/nature19368.

Zhang WF, Dou ZX, He P, Ju XT, Powlson D, Chadwick D, Norse D, Lu YL, Zhang, Y, Wu L, Chen XP, Cassman KG, Zhang FS (2013) New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. Proc Natl Acad Sci USA 110:8375–8380. https://doi.org/10.1073/pnas.1210447110.

Zhang Y, Lei H, Zhao W, Shen Y, Xiao D (2018) Comparison of the water budget for the typical cropland and pear orchard ecosystems in the North China Plain. Agric Water Manag 198:53–64. https://doi.org/10.1016/j.agwat.2017.12.027.

Zhao LS, Sun CZ, Zheng DF (2014) Water resource utilization efficiency and its spatial spillover effects measure in China. Acta Geogr Sin 69:121–133. https://doi.org/10.11821/dlxb201401012.

Zhao PF, Cao GX, Zhao Y, Zhang HY, Chen XP, Li XL, Cui ZL (2016) Training and organization programs increase maize yield and nitrogen-use efficiency in smallholder agriculture in China. Agron J 108:1944–1950. https://doi.org/10.2134/agronj2016.03.0130.

Zhao RG, He P, Xie JG, Johnston AM, Xu XP, Qiu SJ, Zhao SC (2016) Ecological intensification management of maize in northeast China: agronomic and environmental response. Agric Ecosys Environ 224:123–130. https://doi.org/10.1016/j.agee.2016.03.038.

Zhou HM, Zhang FC, Kjelgren R, Li-Feng WU, Gong DZ, Zhao N (2017) Peach yield and fruit quality is maintained under mild deficit irrigation in semi-arid China. J Integr Agric 16:1173–1183. https://doi.org/10.1016/S2095-3119(16)61571-X.

Zhu Z, Jia ZJ, Peng L, Chen Q, He L, Jiang Y, Ge S (2018) Life cycle assessment of conventional and organic apple production systems in China. J Clean Prod 201:156–168. https://doi.org/10.1016/j.jclepro.2018.08.032.