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The nitrogen and carbon footprints of vegetable production in the subtropical high elevation mountain region

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ABSTRACT

Mountain vegetable production has become a critical source of low heat-resistance vegetables in summer in subtropical regions, but evaluations based on life-cycle assessment (LCA) that are relevant to the environment and economics have not been reported. We conducted a survey to compare the cabbage yield and resource inputs for small-holder farms at a high (HEL, 900–1500 m) and low (LEL, 200–600 m) elevations in a subtropical region in Southwest China. We used LCA to quantify the nitrogen (N) and carbon (C) footprints, and used the yield and environmental impacts gap method to determine the potential to mitigate the environmental impacts of farming at HELs and LELs. The results show that the respective average reactive N (Nr) and greenhouse gas (GHG) emissions for the HEL and LEL were 137.0 kg N ha^{-1} and 6785 kg CO_2-eq ha^{-1}, and 126.7 kg N ha^{-1} and 6153 kg CO_2-eq ha^{-1}, respectively. The N and C footprints for the HEL were 17.3% and 16.2% lower, respectively, than those for the LEL due to the higher yield at the HEL. The average cabbage yield was 26.5% greater at the HEL (53.2 t ha^{-1}) than at the LEL (42.0 t ha^{-1}). The average total N application rate at the HEL was 455 kg N ha^{-1}, which was 6.0% greater than that at the LEL. There was great potential for yield increases and the mitigation of N and C footprints by farmers at both the HEL and LEL. Compared to the average of all surveyed farmers for HEL and LEL, those farmers whose yields and N fertilizer production efficiency were both higher than the average of all surveyed farmers (HH groups) reduced their N and C footprints by 44.7–49.4% and 44.4–51.2%, respectively, with 34.4–52.3% higher yield and 9.2–19.8% lower N application rate. This study indicates that high yield, low environmental cost, and high economic benefit can be achieved by advancing agronomic management based on the best farmers' practices for vegetable production in a subtropical high-elevation mountain region.

1. Introduction

Developing a sustainable vegetable production system is currently one of the main concerns for sustainable intensification of global agriculture. Greenhouse vegetable production in temperate regions solves the problem of vegetable supply being limited by low temperatures in winter, and mountain vegetable production in subtropical regions solves the problem of low heat-resistance vegetable production being limited by high temperatures in summer. China produces half of the world's vegetables, and mountain vegetable production has developed rapidly in China in recent decades. At present, mountain vegetable production accounts for 11.4% of the total vegetable production in China and 12.4% of the vegetable planting area in China (Qiu, 2017; China Statistical Yearbook, 2018). Furthermore, vegetable planting area will continually expand to higher elevations in mountainous regions as a result of global warming (Yao et al., 2017a; 2017b). Thus, the resource inputs and environmental impacts of mountain production need to be considered.

The nitrogen (N) and carbon (C) footprints represent the reactive N

Abbreviations: HEL, high-elevation level; LEL, low-elevation level; GHG, greenhouse gas; LCA, life cycle assessment; Nr_{NP}, the Nr emissions per profit USD during cabbage production; GHG_{NP}, GHG emissions per profit USD during cabbage production.

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(Nr) and greenhouse gas (GHG) emissions during the per unit weight production of vegetable products (Fan et al., 2018; Liang et al., 2019), and they are important factors for evaluating the sustainability of the agricultural production system. In recent decades, life cycle assessment (LCA), as a standardized ISO methodology, has been used widely to quantify the Nr loss and GHG emissions across all production stages (Romero-Gámez et al., 2014; Payen et al., 2015). In recent years, the environmental issues related to intensive vegetable production through the LCA method have received increased attention (Wang et al., 2018a; Zhou et al., 2019). Previous studies quantified the resource inputs and Nr and GHG emissions for a vegetable production system in a specific region for a specific crop, identified the major contributors, and compared the environmental impacts of different management practices, including optimizing fertilization rates, conventional open fields versus greenhouses (Martínez-Blanco et al., 2011), organic versus conventional farming (Venkat, 2012; He et al., 2016), and inorganic fertilizer only versus partially replacing inorganic fertilizer with organic fertilizer (Zhou et al., 2019). However, most of these studies focused on vegetable production in flat, low-elevation areas in temperate regions. Large differences in Nr and GHG emissions from vegetable production may exist between high-elevation (mountain) areas and low-elevation (conventional open field or greenhouse) areas in subtropical regions due to large variations of soil conditions, climate conditions, field management practices, etc. Several questions about these differences need to be answered. Does the higher price (compared to the price of low heat-tolerance vegetables produced in lower elevations) drive greater fertilizer inputs and consequent higher N and C footprints in the subtropical high-elevation region? What is the theory of vegetable yield in the subtropical high-elevation region, and how will it affect the N and C footprints? Empirical studies addressing these questions are lacking.

Mitigating N and C footprints is critical to achieve sustainable agricultural production (Gerber et al., 2016; Fan et al., 2017). Large variations in environmental impacts related to crop production exist among farmers in the same region due to large differences in inputs. For example, our previous study indicated that GHG emissions in the plastic-greenhouse pepper production system in the Yangtze River Basin, China, ranged from 5.3×10^3 to 8.0×10^3 kg CO_2-eq ha^{-1} (Wang et al., 2018a). Great mitigation of environmental impacts can be achieved through advanced nutrient management practices in cash crop production (Brentrup et al., 2004; Wang et al., 2018b). For example, the high yield and high N fertilizer use efficiency (HH) group, with the best nutrient management practice, substantially improved yield by 35.0% and minimized the environmental impact by 37.3% in an open-field pepper production system in China (Wang et al., 2018b). Potential for yield increase and mitigation of environmental impacts for vegetable production among farmers in high-elevation mountainous areas may exist due to large variations in inputs. However, the extent of these potentials for vegetable production in the subtropical high-elevation mountainous regions remains poorly studied.

Southwest China is the largest region of mountain vegetable production in China, accounting for 49.3% of the country's mountain vegetable planting area and 40.3% of its mountain vegetable production (Qiu, 2017; Zhang et al., 2017; China Statistical Yearbook., 2018). Due to its great elevation differences and diverse ecosystems, it is also a region with typical vegetable production in both flat plains with low elevation and mountainous areas with high elevation. Cabbage is the major low heat-resistance vegetable grown in this region. Here, we used farm survey data and a farmer grouping method to conduct a life cycle assessment (LCA) to: 1) identify the resource inputs and N and C footprints for cabbage production in the high-elevation mountainous region of Southwest China; 2) compare the differences in resource input, yield, net profit, and N and C footprints of the cabbage production between high- and low-elevation levels; and 3) analyze the potentials for yield increase and mitigation of N and C footprints of farmers. We sought to provide a means to achieve sustainable vegetable production by leveraging locally available technologies and climate resources in the subtropical high-elevation mountain region.

2. Materials and methods

2.1. Study area and vegetable crop

The survey was conducted from November 2018 to January 2019 in Wuling Mountain in Wulong County, Chongqing, China (29°02′–29°40′ N, 107°14′– 108°05′ E), which is characterized by extremely hot summers (Fig. 1). The climate is humid subtropical monsoon. The elevation of vegetable field ranges from 175 to 1800 m. Cabbage (*Brassica oleracea* var. *capitata* L.) is the major vegetable crop in this region and accounts for 29.3% of the entire vegetable planting area, with an average planting area of 0.2 ha per farmer.

2.2. Environmental impact assessment

2.2.1. Inventory analysis

First, we divided the surveyed cabbage farmers on Wuling Mountain into two elevation levels (Qiu, 2017; Zhang et al., 2017): a high-elevation level (HEL, 900–1500 m), with a cabbage growth period from April to July, average monthly rainfall of 129.5 mm, and average monthly air temperature of 18.3 °C, and a low-elevation level (LEL, 200–600 m), with a growth period from March to June, average monthly rainfall of 123.6 mm, and average monthly air temperature of 20.5 °C. Second, 50 farmers from two rural towns in each elevation level were randomly selected. The survey also involved two dealers from each elevation level who were engaged in selling seed, fertilizers, pesticides, and plastic film or purchasing vegetables from the surveyed farmers. Face-to-face interviews of farmers were conducted to collect information about their field management practices in cabbage production. The survey of dealers focused on the market price of cabbage and each resource.

2.2.2. System boundary

This study focused on cabbage production (from seeding to harvest), which was divided into the agricultural materials stage (MS) and the arable farming stage (FS). The agricultural materials stage considered the production and transport of each input (inorganic and organic fertilizers, pesticides, diesel fuel, and plastic film); however, the impact of seed was not considered because it was applied in small quantities. The arable FS included the application of fertilizers and pesticides to the farmland, and the use of diesel by agricultural machinery. This study focused on the Nr and GHG emissions associated with the field management. The functional units for analysis were "per hectare", "per tonne", and "per unit of net profit made by cabbage production", as these could clarify environmental performance well.

2.2.3. Environmental cost assessment

2.2.3.1. Nr emissions and N footprint. Nr emissions were quantified from the perspective of LCA according to ISO guidelines (ISO-14040, 2006a, 2006b). The Nr emissions (kg N ha^{-1}) consisted of emissions from the MS and FS components. They were estimated as follows:

$$\text{Nremissions} = \text{MS} - Nr + FS - Nr \quad (1)$$

$$MS - Nr = \sum_{i=1}^{m} PM_{iN_r} \times Rate_{iN_r} \quad (2)$$

$$FS - Nr = N_2O + NH_3 + \text{NO} + NO_3^{-1} \quad (3)$$

where MS-Nr represents the Nr emissions from the production and transportation of all inputs (inorganic fertilizers, organic fertilizer, pesticides, plastic film, and diesel consumption by machinery). FS-Mr denotes the Nr emissions from the application of organic and inor-

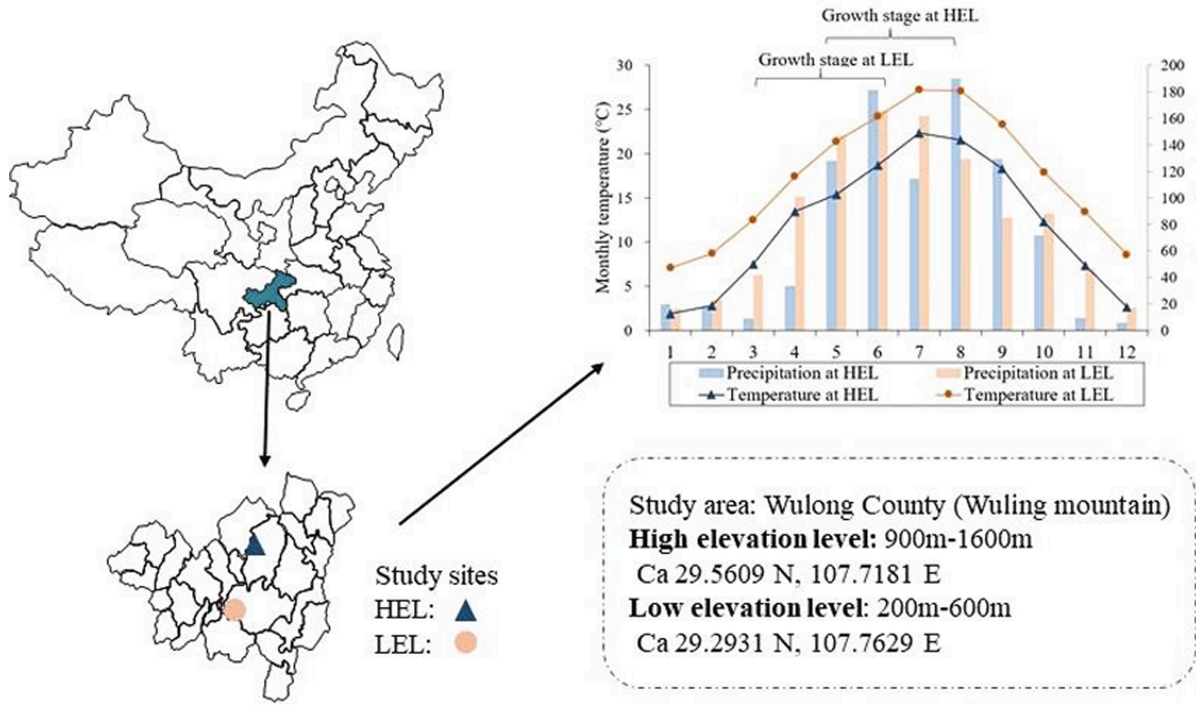

Fig. 1. Locations of the HEL and LEL study sites. The top-left map shows the location of Chongqing in China and the bottom-left map is Wulong County. Monthly temperature and precipitation of the high- and low-elevation study sites are shown in the top-right. HEL, the high-elevation level (900–1500 m); LEL, the low-elevation level (200–600 m).

ganic fertilizer, which include nitrous oxide (N_2O) emissions, ammonia (NH_3) volatilization, nitric oxide (NO) emissions, and N leaching (Leach et al., 2012; Liang et al., 2018). PM_{iNr} represents the Nr emission factor of the *i*-th input (fertilizers, pesticides, plastic film, and diesel consumption by machinery) produced and transported; these are recorded in Table S1. $Rate_{iNr}$ represents the application rate of the *i*-th input category during cabbage production. N_2O is the direct cumulative amount of N_2O emissions from soil to which inorganic and organic N fertilizer had been applied·NH_3 represents the ammonia (NH_3) volatilization loss from inorganic and organic N fertilizer following application. NO is the NO emissions from inorganic and organic N fertilizer application and NO_3^{-1} represents the amount of N leaching from inorganic and organic N fertilizer following application. Each Nr loss was calculated by multiplying the application rate of inorganic and organic N fertilizer by the corresponding emission factor. The emission factors of N_2O emissions, N leaching, and NH_3 volatilization were chosen based on the local conditions and the latest indicators from published studies considering similar vegetable production systems (Table S2). We used the same emission factors for N_2O emissions and NH_3 volatilization from organic manure and inorganic fertilizer (Zhang et al., 2016; Wang et al., 2018c).

The N footprint was defined as the Nr emissions per tonne of product, and was calculated as:

$$\text{NFootprint} = \text{Nremission}/\text{Y} \tag{4}$$

where Nr emission represents the Nr emissions per ha, and Y represents the cabbage fresh yield (t ha^{-1}).

2.2.3.2. Greenhouse gas (GHG) emissions and carbon (C) footprint. The GHG emissions, including emissions of CO_2, CH_4, and N_2O throughout the entire life cycle of vegetable production, were estimated according to the IPCC (2013), and were divided into two components: the GHG emissions 1) from the MS stage and 2) during the FS stage, which were determined by the following equations:

$$\text{GHGemission} = MS-GHG + FS-GHG \tag{5}$$

$$FS-\text{GHG} = \sum_{i=1}^{m} PM_{iGHG} \times Rate_{iGHG} \tag{6}$$

$$\text{FS}-\text{GHG} = (N_2O + NH_3 \times 0.01 + NO_3^{-1} \times 0.025) \times 265 \times 44/28 \tag{7}$$

where MS-GHG represents the GHG emissions from the production and transportation of all inputs (inorganic fertilizers, organic fertilizer, pesticides, plastic film, and diesel consumption by machinery). FS-GHG represents the GHG emissions during the application of all inputs, including direct N_2O emissions and indirect pathways (NH_3 and NO_3^{-1} lost as N_2O-N). PM_{iGHG} represents the GHG emission factor of the *i*-th input produced and transported; these are recorded in Table S1. $Rate_{iGHG}$ represents the application rate of the *i*-th input category (e.g., fertilizer, pesticides, plastic film, and diesel) during cabbage production. N_2O represents the direct N_2O emissions from inorganic and organic N fertilizer following application, NH_3 represents the Nr lost by NH_3 volatilization from inorganic and organic N fertilizer following application, and NO_3^{-1} represents the N leaching from inorganic and organic N fertilizer following application. The fraction 44/28 is the molecular weight ratio of N_2O to N_2O-N, and 0.01 and 0.025 are the coefficients for NH_3 and NO_3^{-1} lost as N_2O-N, respectively (Perrin et al., 2014).

The C footprint was defined as the GHG emissions per tonne of product, and calculated by the following equation:

$$Cfootprint = GHGemission/Y \tag{8}$$

where *GHG emission* represents the GHG emissions per ha and *Y* represents the fresh yield of cabbage (t ha^{-1}).

2.3. Profitability assessment

The net profit was determined as the difference between the total production income and the total agricultural costs. Total production income was calculated using cabbage fresh yield and the market price. Agricultural costs were calculated by the summation of all resource inputs, including labor and seeds (Table S3). Net profit was estimated as follows:

$$Netprofit = Y^{*}P_{cabbage} - \sum_{i=1}^{m} rate_i{}^{*}P_i \quad (9)$$

where Y represents the fresh yield of cabbage, $P_{cabbage}$ represents the market price of cabbage, and *i* represents each input category, including fertilizers, pesticides, diesel fuel, seeds, and labor. $Rate_i$ represents the application rate of the *i*-th input category, and P_i represents the price of the *i*-th input category (recorded in Table S3).

Environmental impacts of the economic benefits were defined as Nr and C emissions per profit USD made by cabbage production, which were determined using the following equations:

$$Nr_{NP} = Nremission/netprofit \quad (10)$$

$$GHG_{NP} = GHGemission/netprofit \quad (11)$$

where Nr_{NP} and GHG_{NP} represent the Nr and GHG emissions per profit USD made by the cabbage production. Nr and GHG emissions are expressed on a per ha basis.

2.4. Grouping of farmers by yield and N fertilizer use efficiency

1) Based on 50 farmers in each elevation level, we quantified the differences in resource input and N and C footprints between the two elevation levels.
2) The 50 farmers were subdivided into three groups at each elevation level according to average yield and average N-fertilizer production efficiency (PFP-N) to quantify the potential for increase in yield and for the mitigation of environmental impacts (Wang et al., 2018a; Cui et al., 2014): 1) a high yield and low PFP-N group (HL; yield was above the average yield and PFP-N was below the average PFP-N within the same elevation level), 2) a high yield and high PFP-N group (HH; both the yield and PFP-N were higher than the average within the same elevation level), and 3) a group (AV) including all surveyed farmers within the same elevation level. The numbers of farmers in the HL and HH groups were 23 and 14 for HEL and 17 and 13 for LEL, respectively.

The PFP-N was determined using the following equation:

$$PFP - N = Y/N \quad (12)$$

where *Y* represents the fresh yield of cabbage (t ha^{-1}) and *N* represents the total N fertilizer application rate (kg N ha^{-1}).

2.5. Statistical analysis

To quantify the resource input and environmental impact at HEL and LEL, Excel 2016 (Microsoft, Redmond, WA, USA) was used to calculate the resource input, N footprint, C footprint, economic benefit, and errors (i.e., 95% confidence intervals [CIs], standard deviation, and standard errors). One-way analysis of variance (ANOVA) was conducted to evaluate the treatment effects statistically, and group means were compared by least significant difference (LSD) at the 5% level of probability using SigmaPlot 12.0 (Systat Software, San Jose, CA, USA).

3. Results

3.1. Cabbage yield, fertilizer application rate, and profitability

Among the 50 farmers surveyed at the HEL, the average cabbage yield was 53.2 (CI: 49.0–57.5) t ha^{-1}, which was 26.5% greater than that for the LEL of 42.0 (CI: 37.5–46.5) t ha^{-1} (Fig. 2). The average total fertilizer N and P application rates at the HEL were 455 (CI: 428–482) kg N ha^{-1} and 216 (CI: 192–239) kg P_2O_5 ha^{-1}, which were 6.0% and 11.3% greater than those at the LEL, respectively. By contrast, the average total K rate at the HEL (177; CI: 157–198) kg K_2O ha^{-1} was 21.8% lower than that at the LEL. When considering only the nutrients from organic fertilizer, the average organic N, P, and K rates for the HEL were 9.9 (CI: 7.9–11.9) kg N ha^{-1}, 5.9 (CI: 4.2–7.5) kg P_2O_5 ha^{-1}, and 7.0 (CI: 5.3–8.7) kg K_2O ha^{-1}, which were 70.7%, 68.1%, and 71.4% lower than those of the LEL, respectively (Fig. 2). Considering profitability, with the greater yield and total N and P fertilizer use at the HEL, the average income [6567 (CI: 6042–7092) USD ha^{-1}] and cost [1538 (CI: 1485–1591) USD ha^{-1}] for the HEL were 36.7% and 3.8% greater, respectively, than for the LEL, and the corresponding net profit [5029 (CI: 4497–5560) USD ha^{-1}] for the HEL was 51.3% greater (Fig. 3).

3.2. Nr emissions, N footprint, and Nr emissions per profit USD (Nr_{NP})

When expressed per hectare of cabbage-planted area, the average Nr emissions for the HEL and LEL were 137.0 (CI: 128.9–145.1) kg N ha^{-1} and 126.7 (CI: 115.7–137.7) kg N ha^{-1}, respectively (i.e., the Nr emissions for the HEL were 8.1% greater than for the LEL; Fig. 4). This difference was mainly attributed to the greater N fertilizer application rate at the HEL. When expressed per tonne of cabbage yield, the average N footprint for the HEL [2.82 (2.57–3.06) kg N t^{-1}] was 17.2% lower than for the LEL [3.40 (3.04–3.77) kg N t^{-1}], mainly due to the higher yield at the HEL (Fig. 4). When expressed per profit USD made from cabbage production, the Nr_{NP} for the HEL [0.032 (0.029–0.036) kg N USD^{-1}] was 38.8% lower than for the LEL [0.053 (0.044–0.061) kg N USD^{-1}] (Fig. 4). The greater yield and net profit were the main reasons for the lower N footprint and Nr_{NP} at the HEL. The contributions of N_2O, NH_3, NO, and NO_3-N to the total Nr emissions were comparable between the HEL and LEL. NO_3-N leaching was the major contributor to the total Nr emissions, accounting for 64.8% (Fig. 5). NH_3 volatilization (26.9%) was a secondary contributor, as were N_2O, MS-Nr, and NO, despite their small percentages (2.1, 2.5, and 3.8%, respectively) (Fig. 5).

3.3. GHG emissions, C footprint, and GHG emissions per profit USD (GHG_{NP})

When expressed per hectare of cabbage-planted area, the average GHG emissions for the HEL and LEL were 6785 (CI: 6394–7176) kg CO_2-eq ha^{-1} and 6153 (CI: 5647–6660) kg CO_2-eq ha^{-1}, respectively (i.e.,

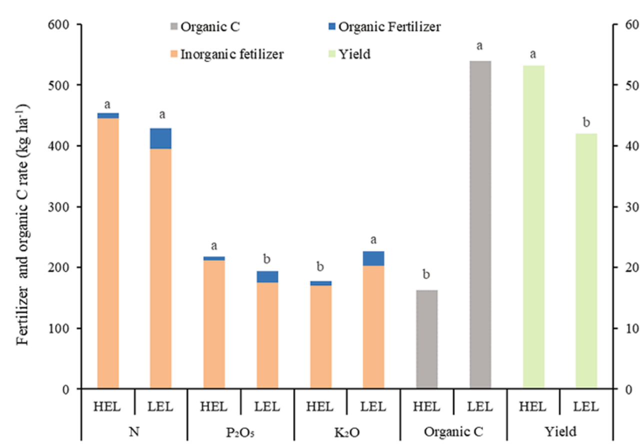

Fig. 2. Surveyed fertilizer application rates (organic and inorganic), organic C input, and cabbage yield in the high- and low-elevation areas of a subtropical region. The organic C was from organic fertilizer. For each parameter, different lowercase letters represent significant differences according to the least significant difference test ($p < 0.05$). HEL, high-elevation level (900–1500 m); LEL, low-elevation level (200–600 m).

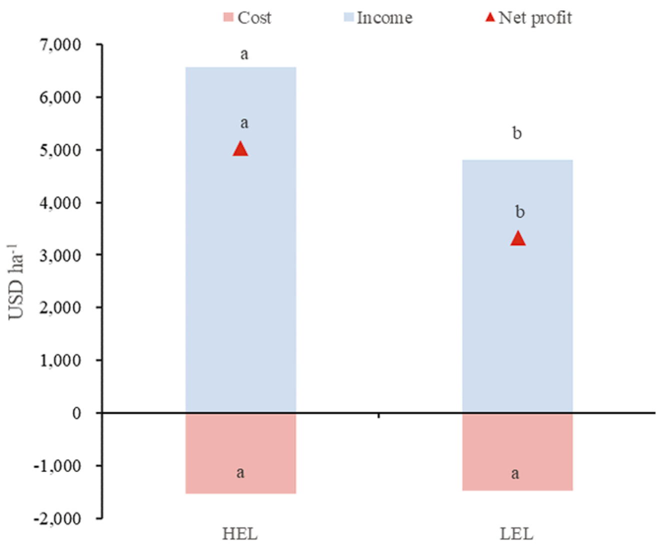

Fig. 3. The cost, income, and net profit for cabbage production at the HEL and LEL. Different lowercase letters represent significant differences according to the least significant difference test ($p < 0.05$). HEL, high-elevation level (900–1500 m); LEL, low-elevation level (200–600 m).

GHG emissions for the HEL were 10.3% greater than for the LEL; Fig. 4), mainly because of the greater N and P fertilizer input at the HEL. When expressed per tonne of cabbage yield, the C footprint for the HEL [140 (127–152) kg CO_2-eq t^{-1}] was 16.2% lower than for the LEL [167 (149–184) kg CO_2-eq t^{-1}] (Fig. 4). When expressed per profit USD of cabbage production, the GHG_{NP} for the HEL [1.60 (1.41–1.78) kg CO_2-eq USD^{-1}] was 38.3% lower than for the LEL [2.59 (2.14–3.03) kg CO_2-eq USD^{-1}] (Fig. 4). The lower C footprint and GHG_{NP} for the HEL was mainly caused by the greater yield and net profit. Fertilizer dominated the C footprint, contributing 95.9–96.1% of the total C footprint; MS- and FS-fertilizer accounted for 57.4–58.2% and 37.6–38.7%, respectively. Other materials accounted for only 3.9–4.1% (Fig. 5).

3.4. Fertilizer application rate, and yield among different groups

Compared to the average (AV) within the same elevation level, the cabbage yields in the HH group for the HEL (71.5 t ha^{-1}) and LEL (64.0 t ha^{-1}) were 34.4% and 52.3% greater, respectively (Table 1). The corresponding total N application rate of the HH group for the HEL and LEL was 19.8% and 9.2% lower, respectively (Table 1). Compared with the AV group, within the same elevation level, the inorganic N fertilizer application rate for the HEL and LEL was 20.7% and 20.8% lower, respectively. By contrast, the organic N fertilizer application rate of the HH group was 35.3% and 127.1% greater, respectively, than the values of the corresponding AV groups (Table 1). As a result, the PFP-N of the HH group at the HEL and LEL was greater by 62.4% and 72.5% than the corresponding PFP-N of the AV group, respectively.

3.5. Environmental impacts among different groups

When expressed on the basis of hectares of cabbage-planted area, at the HEL, the Nr emissions for the HH group were 20.1% and 20.8% lower than those of the AV and HL groups, respectively (Fig. 6). At the LEL, the Nr emissions of the HH group were 13.0% and 17.2% lower than those of the AV and HL groups, respectively (Fig. 6). The Nr emissions gap between the HH group and the AV group was substantially greater for the HEL (27.6 kg N ha^{-1}) than for the LEL (16.5 kg N ha^{-1}). The GHG emissions were similar to the Nr emissions: the GHG emissions of the HH group were 15.5–19.7% and 17.5–20.3% smaller than those of the AV and HL groups, respectively (Fig. 6). The GHG emissions gap between the HH and the AV groups was also greater for the HEL (1335 kg CO_2-eq ha^{-1}) than for the LEL (954 kg CO_2-eq ha^{-1}) (Fig. 6). The lower environmental impacts on an area basis for the HH group were due to the lower N fertilizer application rate (Table 1). When expressed per tonne of cabbage yield, the HH group had an N footprint that was 44.7–49.4% and 17.9–25.8% lower than those of the AV and HL groups, respectively, within the same elevation level (Fig. 6). The C footprint of the HH group was also lower than those of the AV and HL groups by 44.4–51.2% and 18.0–25.3%, respectively, within the same elevation level. The N footprint gap between the HH and the AV groups was 1.26 kg N t^{-1} for the HEL and 1.68 kg N t^{-1} for the LEL, and the corresponding C footprint gap was 62 kg CO_2-eq t^{-1} for the HEL and 85 kg CO_2-eq t^{-1} for the LEL (Fig. 6). The higher yield and lower N fertilizer input for the HH group were the main reasons for lower environmental impacts on a product basis, which also resulted in higher net profit and lower environmental impacts on a profit basis. When expressed on the basis of profit USD of cabbage production, compared to the AV and HL groups within the same elevation level, the Nr_{NP} of the HH group was 54.8–65.6% and 24.6–32.5% lower and the GHG_{NP} was 54.5–66.9% and 24.6–31.9% lower, respectively (Fig. 6).

4. Discussion

4.1. Comparison of N and C footprints at the two elevation levels

The environmental impact of cabbage production differed greatly between the HEL (900–1500 m) and LEL (200–600 m). At the HEL, the Nr and GHG emissions for cabbage production on an area basis were 137 kg N ha^{-1} and 6,785 kg CO_2-eq ha^{-1}, which were 8.1% and 10.3% greater, respectively, than those at the LEL and also greater than previously reported Nr (43 kg N ha^{-1}, Fig. S1) and GHG (4060–4854 kg CO_2-eq ha^{-1}, Fig. S1) emissions for open-field vegetables under the same system boundary (from planting to the farm gate). First, the difference in N application rate was the main reason for the variation in the N and C footprints between the two elevation levels. For example, the corresponding average N input at the HEL was 455 kg ha^{-1}, which was higher than that at the LEL (429 kg ha^{-1}) and higher than in a previous study (Fig. S1). The higher N and P runoff loss of the sloped arable land in the mountainous area may have reduced the fertilizer N and P use efficiency (Preltl et al., 2017; Zhong et al., 2018). Yao et al. (2017a; 2017b) reported that the total N and P loss at slope gradients of 20° was 18.1% and 10.8% greater than that at slope gradients of 5°, respectively. Second, the emission factors varied due to the differences in fertilizer type (urea, thiamine, and ammonium nitrate), soil moisture, and temperature conditions in the vegetable fields (Dobbie et al., 1999; Lin et al., 2010). However, the Nr and GHG emissions in this study were lower than those for greenhouse vegetable production (19820–46485 kg CO_2-eq ha^{-1}) reported previously (Liang et al., 2019; Khoshnevisan et al., 2014; He et al., 2016; Zarei et al., 2019). Besides the substantially greater N fertilizer inputs (816–2786 kg ha^{-1}) in greenhouse production, the extra use of structural materials (plastic film, metal, and electricity) in greenhouse cultivation compared with the open-field cultivation pattern in this study could also have contributed to the higher Nr and GHG emissions for vegetable production under greenhouse conditions. Fertilizer was the major contributor to the GHG emissions of cabbage, accounting for 95.9–96.1% of the total GHG emissions, which was higher than that of greenhouse vegetable production (84.9–89.4%) (He et al., 2016). This could have resulted from the low application rate of plastic film and structural materials in open-field cabbage production. In this study, the N and C footprints were significantly lower by 17.3% and 16.2%, respectively, at the HEL than at the LEL, mainly due to a higher yield at the HEL. The average yield (53.2 t ha^{-1}) for the HEL was 26.5% higher than that for the LEL (42.0 t ha^{-1}). The higher yield at the HEL can be explained by several factors. Temperature and precipitation are crucial to crop yield and environmental impact (Maggio et al., 2005; Bai et al., 2019). There was no significant difference in monthly precipitation between the HEL and LEL during the crop growth stage, but there

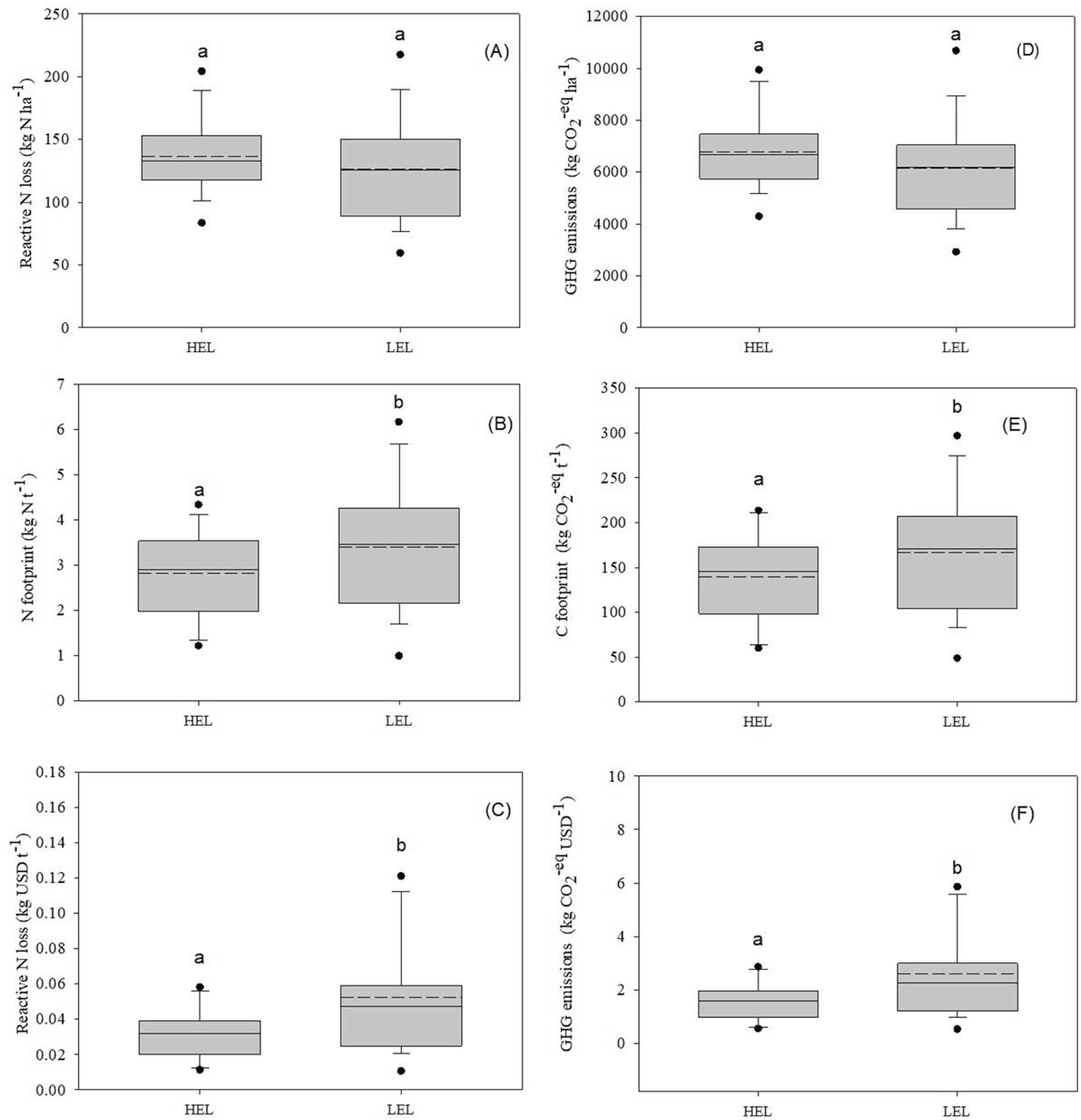

Fig. 4. The reactive N loss (a–c) and GHG emissions (d–f) per ha, tonne, and profit USD, respectively, of cabbage production at a HEL and LEL. HEL, high-elevation level (900–1500 m); LEL, low-elevation level (200–600 m). Different lowercase letters represent significant differences according to the least significant difference test ($p < 0.05$).

was a significant difference in monthly temperature. The optimal temperature for cabbage growth is relatively low (10–25 °C) (Tanyi et al., 2018; Sun, 2010), and the air temperature decreases with increasing elevation. Cabbage prefers lower temperatures, especially at the heading stage (15– 20 °C) (Fang et al., 2008). With the relatively lower mean monthly temperature during the growth stage (18.1 °C) at the HEL (Fig. 2), this resulted in higher production at the HEL than at the LEL. In addition, the higher N and P fertilizer application rates at the HEL may explain the higher yield. However, the cabbage yield at the HEL was lower than that of the temperate region (57.1–67.1 t ha^{-1}) (National Cost and Benefit Data of Agricultural Products, 2018). This may be a result of the better conditions for agriculture in the temperate plain region, including larger-scale farming, better irrigation systems, and a better road network. A large potential for yield increase exists for farmers in both the HEL and LEL.

Compared with the N and C footprints for vegetable production in other regions with low elevation, the N footprint for the HEL was higher than the average N footprint (0.047 kg N t^{-1}) for tomato production under recommended practices in North China (Liang et al., 2018), and the C footprint for the HEL was lower than the C footprint (178 kg CO_2-eq t^{-1} vegetable) for pepper production in East China (Wang et al., 2020). These differences could be attributed to variation in PFP-N among the different studies. For example, the PFP-N at the HEL (117 kg yield per kg N) in this study was lower by 49% than that (231 kg yield per kg N) in tomato production under the recommended practices in North China (Liang et al., 2018), which caused the larger N footprint at the HEL. Additionally, the PFP-N at the HEL in this study was 53% greater than that of the pepper production (76 kg yield per kg N) in East China (Wang et al., 2020), which caused the lower C footprint at the HEL. Similarly, the Nr and GHG emissions per unit of net profit for the

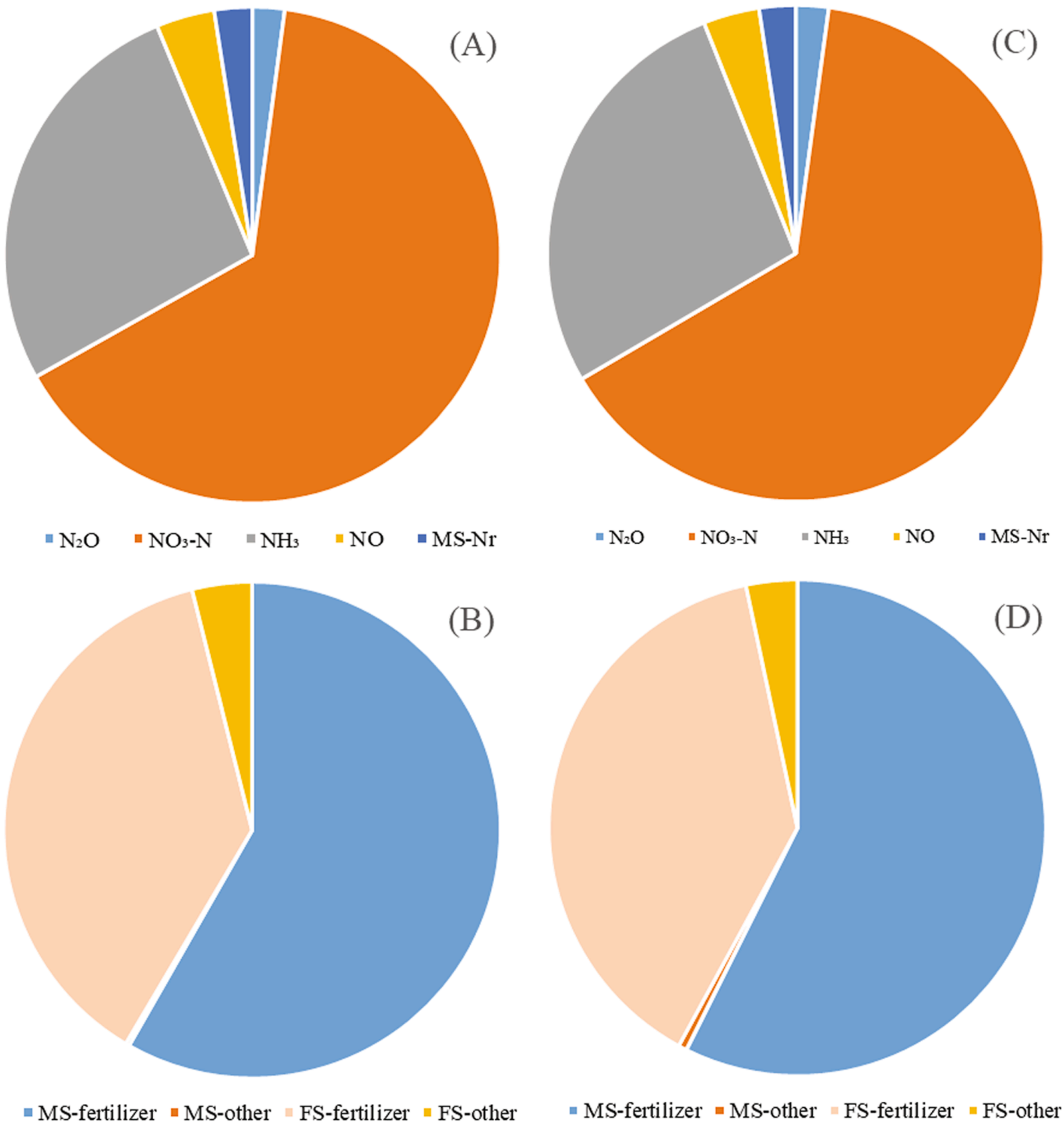

Fig. 5. Contributions of different variables to the N (A, C) and C (B, D) footprints at the HEL and LEL, respectively. MS-Nr, Nr emissions during material stage; N_2O, NO_3-N, NH_3, and NO, the Nr lost by N_2O emission, N leaching and runoff, NH_3 volatilization, and NO emission from inorganic and organic N fertilizer following application, respectively; MS-fertilizer, the GHG emissions from N, P, and K fertilizer during the material stage; MS-other, the GHG emissions from other materials during the material stage; FS-fertilizer and FS-other, the GHG emissions from fertilizer and other materials during the farm stage, respectively. HEL, the high-elevation level (900–1500 m); and LEL, the low-elevation level (200–600 m).

HEL were 38.8% and 38.3% lower, respectively, than those for the LEL, due to higher net profit caused by higher cabbage yield. As a consequence, these results revealed that cabbage production at the HEL not only has an economic competitive advantage, but also has an advantage of low N and C footprints on a product and profit basis.

4.2. Potential for mitigation of N and C footprints

The results of this study indicate great potential for mitigation of the N and C footprints of cabbage production in subtropical high- and low-elevation mountain regions. The HH group significantly reduced N and C footprints by 44.7–49.4% and 44.4–51.2%, respectively, for both the HEL and LEL compared to AV (Fig. 6). These results were attributed to the following factors. On one hand, the N fertilizer application rate in the HH group was 9.2–19.8% lower than that of the AV group, with the result that the Nr and GHG emissions of HH on an area basis were lower by 13.0–20.1% and 15.5–19.7%, respectively. These results are comparable with those of previous studies at a LEL. On the other hand, the yield of the HH group was 34.4–52.3% greater than that of the AV group. This higher yield can be attributed to the advanced nutrient management based on the best practices of the local farmers in the HH group (Fig. 7). With regard to yield-related production factors, organic C input and plant density were the limiting factors for higher yield at the HEL (Fig. 7 D, E), and organic C input could also significantly improve cabbage yield at LEL (Fig. 7 I). This indicates that the yield gap can be closed through greater organic fertilizer application and optimized plant

Table 1
Surveyed fertilizer inputs of cabbage production among the different groups at a HEL and LEL. To analyze the effects of farm management on the environmental effects of cabbage production, the data on yield vs. PFP-N were divided into three groups: mean yield and mean PFP-N (AV), high yield and low PFP-N (HL), and high yield and high PFP-N (HH). HEL, cabbage grown at a high elevation (900–1500 m); LEL, cabbage grown at a low elevation (200–600 m).

		Yield	Total fertilizer application rate (kg ha^{-1})			Inorganic fertilizer application rate (kg ha^{-1})			Organic fertilizer application rate (kg ha^{-1})			
		t ha^{-1}	N	P_2O_5	K_2O	N	P_2O_5	K_2O	C	N	P_2O_5	K_2O
H-C	AV	53.2 ± 16.5	454.6 ± 104.5	215.6 ± 91.8	177.3 ± 78.8	444.7 ± 101.6	212.0 ± 91.9	170.3 ± 77.5	162.8 ± 129.5	9.9 ± 8.0	5.9 ± 6.5	7.0 ± 6.7
	HL	68.0 ± 11.1	460.3 ± 144.1	261.3 ± 106.1	178.6 ± 86.7	445.0 ± 140.6	256.0 ± 107.4	167.7 ± 84.4	255.2 ± 85.7	15.3 ± 5.7	10.3 ± 6.9	10.9 ± 6.7
	HH	71.5 ± 12.3	364.7 ± 46.4	206.8 ± 61.5	157.1 ± 76.2	352.0 ± 44.9	201.1 ± 61.4	149.6 ± 75.2	220.3 ± 73.0	12.7 ± 4.6	5.7 ± 4.0	7.6 ± 6.3
L-C	AV	42.0 ± 17.4	429.0 ± 148.1	193.7 ± 89.9	226.8 ± 186.8	395.3 ± 132.7	175.3 ± 75.8	202.3 ± 169.4	540.0 ± 799.8	33.7 ± 50	18.4 ± 32.7	24.5 ± 37.8
	HL	63.8 ± 9.1	466.4 ± 186.8	259.5 ± 99.1	357.1 ± 257.4	386.2 ± 160.4	220.6 ± 96.6	301.4 ± 243.8	1282.8 ± 774.1	80.2 ± 48.4	38.9 ± 35.2	55.7 ± 38.8
	HH	64.0 ± 10.0	389.7 ± 132.3	254.4 ± 105.3	301.7 ± 211.3	313.0 ± 95.7	217.2 ± 109.3	249 ± 183.1	1226.2 ± 793.3	76.6 ± 49.6	37.2 ± 33.4	52.8 ± 37

density, which could result in greater economic and environmental benefits. Meanwhile, the higher quality of vegetables produced at the HEL (Nie et al., 2011) increased the price for the vegetables. Furthermore, due to the higher yield and profit in the HH group, Nr_{NP} and GHG_{NP} were 54.8–65.6% and 54.5–66.9% lower, respectively, compared with the AV group at the same elevation level.

In this study, the HH group showed a substantially lower N fertilizer input and an environmental impact advantage. However, further opportunity remains for optimization in the HH group based on the cabbage farmers' practices. First, optimizing the N fertilizer rate is the most cost-effective measure to reduce the N and C footprints (Lu et al., 2011; Zhang et al., 2016). The application rate of inorganic N (313– 352 kg N ha^{-1}) in the HH group was higher than the recommended fertilization rate (263 kg N ha^{-1}) for the region surveyed (Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2018). This indicates that there is a potential to decrease the amount of fertilizer N use in the HH group. Therefore, optimizing the N fertilizer rate based on the nutrient demands of cabbage in this region is needed to reduce the N and C footprints. Second, many studies have shown that partially substituting inorganic fertilizer with organic fertilizer could synchronize the crop N demand with the soil N supply, thus increasing yield and decreasing N and C footprints (Zhou and Butterbach-Bahl, 2014; Zhang et al., 2016; Yang et al., 2019). Limited organic fertilizer application, far below the recommended organic fertilizer rate (Guidelines on fertilization of major spring crops in 2018, Issued by the Ministry of Agriculture and Rural Affairs of the P.R.C.), compared to that of vegetable production in the temperate low-elevation region (Zhou et al., 2019; Gu et al., 2015) was used in the region surveyed, especially at the HEL. The poor road network condition and consequent high transportation costs have limited the application of organic fertilizer in this region. Therefore, in the subtropical mountain region, yield increase and N and C footprint mitigation benefits can be achieved through improvement of the road transportation system and greater organic fertilizer inputs. Third, no enhanced efficiency fertilizer was found to be used within the two regions surveyed, even in the HH group. Hence, substituting traditional fertilizer with enhanced efficiency fertilizer, especially slow-release fertilizer or fertilizer with a nitrification inhibitor, could further mitigate the environmental impacts. In addition, the use of enhanced efficiency fertilizer can decrease the frequency of fertilizer application and labor costs, improving the economic benefit of cabbage production.

Mountain vegetable production in subtropical regions has become a critical strategy for supplying low heat-resistance vegetables in summer. This study is the first to evaluate the resource inputs and environmental impacts of vegetable production in a subtropical high-elevation mountain region. The study indicates that cabbage production at the HEL attained greater yield and net profit with lower N and C footprints. Meanwhile, advancing the agronomic management based on the best farmers' practices in the high- or low-elevation mountain regions could significantly reduce the N and C footprints while also increasing yield, which is consistent with previous studies (Cui et al., 2014; Wang et al., 2020). This will enable policymakers and farmers to optimize vegetable distribution and management and thus improve economic benefit and reduce environmental impact.

5. Conclusion

There were significant differences in resource inputs and environmental impacts for cabbage production between the HELs and LELs in the subtropical mountain region. Compared to those at the LEL, the Nr and GHG emissions at the HEL were 8.1% and 10.3% greater due to higher fertilizer input; however, the N and C footprints at the HEL were lower than those at the LEL due to higher yield at the HEL. There is great potential for yield increases and mitigation of the N and C footprints for vegetable production in the mountain area. Advancing agronomic management based on the best practices of the farmers would offer substantial yield improvement and environmental and economic

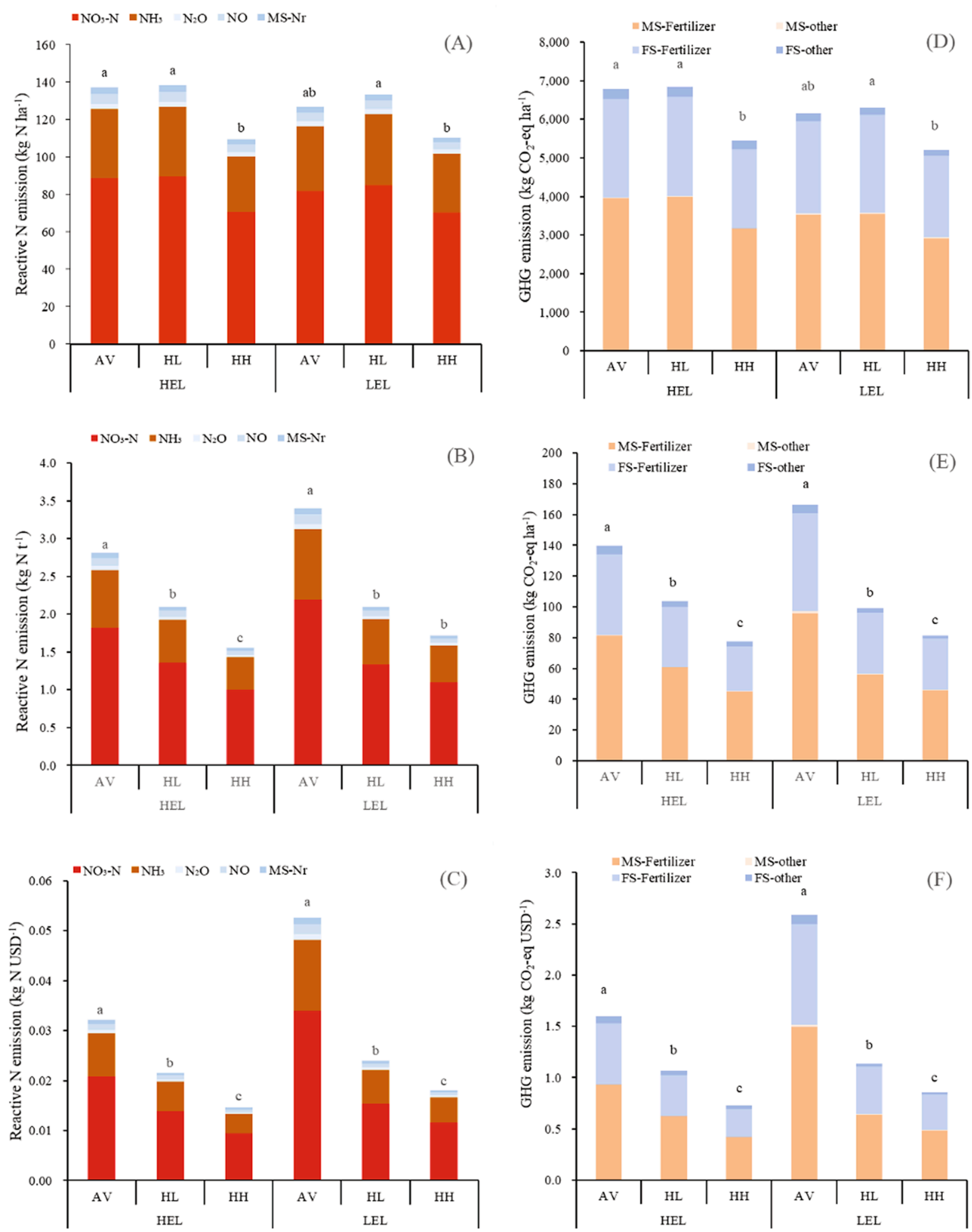

Fig. 6. Reactive N loss (A–C) and GHG emissions (D–F) on per ha, tonne, and profit USD bases for cabbage production at high and low elevations. To analyze the effects of farm management on the environmental effects of cabbage production, the data on yield vs. PFP-N were divided into three groups: the mean yield and PFP-N (AV), high yield and low PFP-N (HL), and high yield and high PFP-N (HH). HEL, high elevation level (900–1500 m); LEL, low elevation level (200–600 m). Different lowercase letters represent significant differences according to the least significant test ($p < 0.05$).

benefits of vegetable production.

CRediT authorship contribution statement

Tao Liang: Investigation, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Dunxiu Liao:** Investigation,

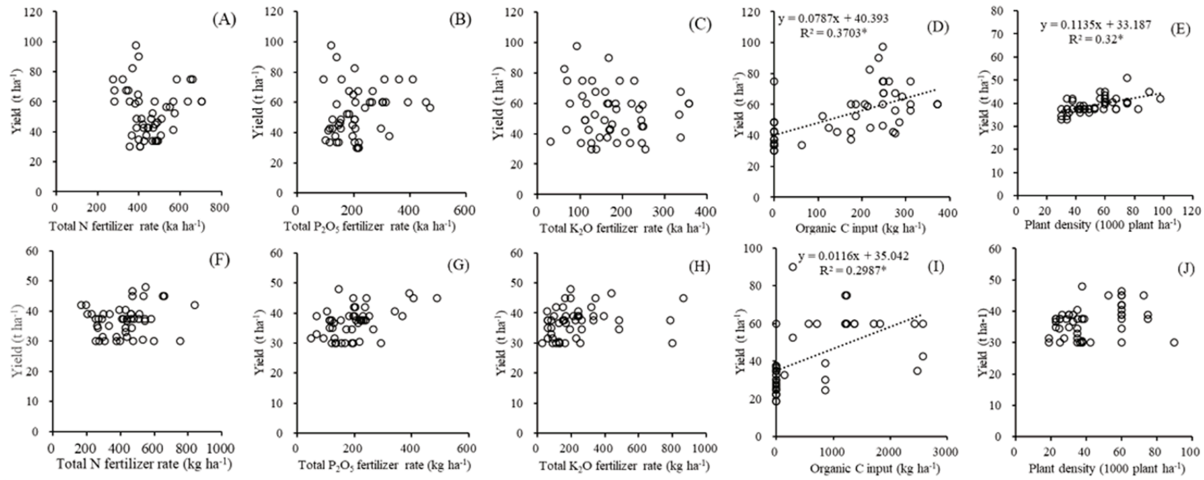

Fig. 7. Relationships between cabbage yield and yield-related production factors (total N fertilizer, total P_2O_5 fertilizer, total K_2O fertilizer, organic C, and plant density) for the HEL (A–E) and LEL (F–J). The lines represent trend lines. * Significant at $p < 0.05$. HEL, high-elevation level (900–1500 m); LEL, low-elevation level (200–600 m).

Supervision. **Shuai Wang:** Investigation, Supervision. **Bai Yang:** Writing - review & editing. **Jingkun Zhao:** Writing - review & editing. **Changfeng Zhu:** Writing - review & editing. **Zhang Tao:** Investigation, Supervision. **Xiaojun Shi:** . **Xinping Chen:** Investigation, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Xiaozhong Wang:** Investigation, Methodology, Data curation, Writing - original draft, Writing - review & editing.

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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.107298.

References

Bai, Y.P., Deng, X.Z., Jiang, S.J., Zhao, Z., Miao, Y., 2019. Relationship between climate change and low-carbon agricultural production: a case study in Hebei Province. China. Ecol. Indic. 105, 717–726. https://doi.org/10.1016/j.ecolind.2018.04.003.

Brentrup, F., Küsters, J., Lammel, J., Barraclough, P., Kuhlmann, H., 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology II. The application to N fertilizer use in winter wheat production systems. Eur. J. Agron. 20, 265–279. https://doi.org/10.1016/S1161-0301(03)00024-8.

China Statistical Yearbook, 2018. http://www.stats.gov.cn/tjsj/ndsj/2018/indexch.htm (accessed on 17 October 2019).

Cui, Z.L., Wang, G., Yue, S.C., Wu, L., Zhang, W.F., Zhang, F.S., Chen, X.P., 2014. Closing the N-use efficiency gap to achieve food and environmental security. Environ. Sci. Technol. 48, 5780–5787. https://doi.org/10.1021/es5007127.

Dobbie, K.E., McTaggart, I.P., Smith, K.A., 1999. Nitrous oxide emissions from intensive agricultural systems: variations between crops and seasons, key driving variables, and mean emission factors. J. Geophys. Res. 104, 26891–26899. https://doi.org/10.1029/1999JD900378.

Fan, C.H., 2017. Biochar reduces yield-scaled emissions of reactive nitrogen gases from vegetable soils across China. Biogeosciences 14, 2851–2863. https://doi.org/10.5194/bg-14-2851-2017.

Fan, C.H., Li, B., Xiong, Z.Q., 2018. Nitrification inhibitors mitigated reactive gaseous nitrogen intensity in intensive vegetable soils from China. Sci. Total Environ. 612, 480–489. https://doi.org/10.1016/j.scitotenv.2017.08.159.

Fang, Z., Peitian, Sun., Liu, Y., 2008. Cabbage cultivation technique. Jindun Press, Beijing, China, pp, 15-17.

Gerber, J.S., Carlson, K.M., Makowski, D., Mueller, N.D., Garcia de Cortazar-Atauri, I., Havlík, P., Herrero, M., Launay, M., O'Connell, C.S., Smith, P., West, P.C., 2016. Spatially explicit estimates of N_2O emissions from croplands suggest climate mitigation opportunities from improved fertilizer management. Glob. Change Biol. 22, 3383–3394. https://doi.org/10.1111/gcb.13341.

Gu, B.J., Ju, X.T., Chang, J., Ge, Y., Vitousek, P.M., 2015. Integrated reactive nitrogen budgets and future trends in China. P. Natl. Acad. Sci. USA 112, 8792–8797. https://doi.org/10.1073/PNAS.1510211112.

Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2018. Guidelines on fertilization of major spring crops in 2018. http://www.moa.gov.cn/ztzl/nyhfjlzxd/201803/t20180330_6139380.htm (accessed on 17 October 2019).

He, X., Qiao, Y., Liu, Y., Dendler, L., Yin, C., 2016. Environmental impact assessment of organic and conventional tomato production in urban greenhouses of Beijing city. China. J. Clean. Prod 134, 251–258. https://doi.org/10.1016/j.jclepro.2015.12.004.

IPCC (Intergovernmental Panel on Climate Change), 2013. Impacts, adaptation vulnerability (accessed June 2015). http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-TS_FGDall.pdf.

ISO-14040, 2006a. Environmental management life cycle assessment principles and framework. http://refhub.elsevier.com/S0959-6526(20)30205-5/sref20.

ISO-14040, 2006b. Environmental management life cycle assessment requirements and guidelines. http://refhub.elsevier.com/S0959-6526(20)30205-5/sref21.

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.

Leach, A.M., Galloway, J.N., Bleeker, A., Erisman, J.W., Kohn, R., Kitzes, J., 2012. A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment. Environ. Dev 1, 40–66. https://doi.org/10.1016/j.envdev.2011.12.005.

Lin, S., Iqbal, J., Hu, R.G., Feng, M.L., 2010. N_2O emissions from different land uses in mid-subtropical China. Agric. Ecosyst. Environ. 136, 40–48. https://doi.org/10.1016/j.agee.2009.11.005.

Liang, L., Bradley, G.R., Wu, W.L., Lal, R., Wang, L.Y., Wang, Y.C., 2019. A multi-indicator assessment of peri-urban agricultural production in Beijing. China. Ecol. Indic. 97, 350–362. https://doi.org/10.1016/j.ecolind.2018.10.040.

Liang, L., Ridoutt, B.G., Lal, R., Wang, D.P., Wu, W.L., Peng, P., Hang, S., Wang, L.Y., Zhao, G.S., 2018. Nitrogen footprint and nitrogen use efficiency of greenhouse tomato production in North China. J. Clean. Prod 208, 285–296. https://doi.org/10.1016/j.jclepro.2018.10.149.

Lu, K., 2011. Optimized Management of Nitrogen Fertilizer and Strategies for Reducing Nitrogen Leaching Loss in Greenhouse Vegetable Field in Taihu Region. PhD, Nanjing Agricultural University thesis, Nanjing. (In Chinese).

Maggio, A., Pascale, S.D., Ruggiero, C., Barbieri, G., 2005. Physiological response of field-grown cabbage to salinity and drought stress. Eur. J. Agron. 23, 57–67. https://doi.org/10.1016/j.eja.2004.09.004.

Martínez-Blanco, J., Muñoz, P., Antón, A., Rieradevall, J., 2011. Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. J. Clean. Prod 19, 985–997. https://doi.org/10.1016/j.jclepro.2010.11.018.
Nie, Q., Zhu, F., Qiu, Q., 2011. Effects of different elevation on mosses, yield and quality of radish. J. Changjiang Vegetables 13, 7–8 (In Chinese).
Payen, S., Basset-Mens, C., Perret, S., 2015. LCA of local and imported tomato: an energy and water trade-off. J. Clean. Prod 87, 139–148. https://doi.org/10.1016/j.jclepro.2014.10.007.
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. Ass 19, 1247–1263. https://doi.org/10.1007/s11367-014-0724-3.
Preltl, G., Romeo, M., Bacchi, M., Monti, M., 2017. Soil loss measure from Mediterranean arable cropping systems: effects of rotation and linage system on C-factor. Soil. Till. Res. 170 (7), 85–93. https://doi.org/10.1016/j.still.2017.03.006.
Qiu, Z.M., 2017. Development status and technical demand of mountain vegetable industry in China. China Vegetables 7, 9–12 (In Chinese).
Romero-Gámez, M., Audsley, E., Suárez-Rey, E.M., 2014. Life cycle assessment of cultivating lettuce and escarole in Spain. J. Clean. Prod. 73, 193–203. https://doi.org/10.1016/j.jclepro.2013.10.053.
Sun, D., 2010. Cabbage cultivation and pest control. Tianjin Science & Technology Translation & Publishing Corp, Tianjin, China, pp. 6-25.
Tanyi, C.B., Ngosong, C., Ntonifor, N.N., 2018. Effects of climate variability on insect pests of cabbage: adapting alternative planting dates and cropping pattern as control measures. Chem. Biol. Technol. Agric. 5, 25. https://doi.org/10.1186/s40538-018-0140-1.
Venkat, K., 2012. Comparison of twelve organic and conventional farming systems: a life cycle greenhouse gas emissions perspective. J. Sustain. Agr 36, 620–649. https://doi.org/10.1080/10440046.2012.672378.
Wang, X.Z., Liu, B., Wu, G., Sun, Y.X., Guo, X.S., Jin, Z.H., Xu, W.N., Zhao, Y.Z., Zhang, F.S., Zou, C.Q., Chen, X.Q., 2018a. Environmental costs and mitigation potential in plastic-greenhouse pepper production system in China: a life cycle assessment. Agr. Systs. 167, 186–194. https://doi.org/10.1016/j.agsy.2018.09.013.
Wang, X.Z., Zou, C.Q., Zhang, Y.Q., Shi, X.J., Liu, J.Z., Fan, S.S., Liu, Y.M., Du, Y.F., Zhao, Q.Y., Tan, Y.G., Wu, C.L., Chen, X.P., 2018b. 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, X.Z., Zou, C.Q., Gao, X.P., Guan, X.L., Zhang, W.S., Zhang, Y.Q., Shi, X.J., Chen, X.P., 2018c. Nitrous oxide emissions in Chinese vegetable systems: a meta-analysis. Environ. Pollut. 239, 375–383. https://doi.org/10.1016/j.envpol.2018.03.090.
Wang, X.Z., Liu, B., Wu, G., Sun, Y.X., Guo, X.S., Jin, G.Q., Jin, Z.H., Zou, C.Q., Dave, C., Chen, X.P., 2020. Cutting carbon footprints of vegetable production with integrated soil-crop system management: a case study of greenhouse pepper production. J. Clean. Prod. 254, 120158 https://doi.org/10.1016/j.jclepro.2020.120158.
Yang, T., Li, F.B., Zhou, X.Y., Xu, C.C., Feng, J., Fang, F.P., 2019. Impact of nitrogen fertilizer, greenhouse and crop species on yield-scaled nitrous oxide emission from vegetable crops: a meta-analysis. Ecol. Ind. 105, 717–726. https://doi.org/10.1016/j.ecolind.2019.02.001.
Yao, N., Yu, B., Cai, F., Wang, T.W., Zhu, H.R., 2017. Characteristic of soil nitrogen and phosphorus loss in Danjiangkou Reservoir area. Bull. Soil Water Conserv. 37(1):097-103. (In Chinese) https://doi.org/10.13961/j.cnki.stbctb.2017.01.018.
Yao, Z.Y., Zhang, L.J., Tang, S.H., Li, X.X., Hao, T.T., 2017b. The basic characteristics and spatial patterns of global cultivated land change since the 1980s. J. Geogr. Sci. 27, 771–785. https://doi.org/10.1007/s11442-017-1405-5.
Zarei, M.J., Kazemi, N., Marzban, A., 2019. Life cycle environmental impacts of cucumber and tomato production in open-field and greenhouse. J. Saudi Soc. Agric. Sci. 18, 249–255. https://doi.org/10.1016/j.jssas.2017.07.001.
Zhang, M., Li, B., Xiong, Z.Q., 2016. Effects of organic fertilizer on net global warming potential under an intensively managed vegetable field in southeastern China: a three-year field study. Atmos. Environ. 145, 92–103. https://doi.org/10.1016/j.atmosenv.2016.09.024.
Zhang, Y.M., Liu, X.B., Tang, W.C., Zhong, J.G., 2017. Development status and prospect of high mountain vegetables in Chongqing. China Vegetables 10, 19–22 (In Chinese).
Zhong, X., Zhang, L., Yue, X.R., Nian, F.Z., Jia, G.J., Yue, X.R., 2018. Soil N and P Loss in slope Farmland of Dianchi Watershed. J. Soil Water Conserv. 32, 42–46 (In Chinese).
Zhou, J., Li, B., Xia, L.L., Fan, C.H., Xiong, Z.Q., 2019. Organic-substitute strategies reduced carbon and reactive nitrogen footprints and gained net ecosystem economic benefit for intensive vegetable production. J. Clean. Prod 225, 984–994. https://doi.org/10.1016/j.jclepro.2019.03.191.
Zhou, M.H., Butterbach-Bahl, K., 2014. Assessment of nitrate leaching loss on a yield-scaled basis from maize and wheat cropping systems. Plant Soil 374, 977–991. https://doi.org/10.1007/s11104-013-1876-9.