Environmental Impacts, Human Health, and Energy Consumption of Nitrogen Management for Maize Production in Subtropical Region

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Abstract

Over-application of fertilizers could not improve crop yield and agronomic efficiency, but result in increasing nitrogen (N) surplus and adverse effects on the ecosystem sustainability. Although some previous studies have addressed one or a few environmental aspects in crop production, an integrated assessment for the effects of N fertilizer on multiple environmental impacts, and the optional steps of normalization and weighting is required. A consecutive 2-yr plot-based field experiment was conducted with five N fertilizer levels (0, 90, 180, 270, and 360 kg N ha-1) in maize production at three sites in Southwest China, to evaluate the environmental performance and sustainability through joint use of life cycle assessment (LCA) and energy consumption analysis. Results demonstrated that the optimal N rate (180 kg N ha-1) showed greater potential for maintaining high yield (achieved 86% of the yield potential) and reducing the global warming (-31%), acidification (-47%), eutrophication (-44%) compared to farmers' practice, and energy depletion potentials, by reducing pollutants emission during the production and transportation of N fertilizer and Nr losses at farm stage. Optimal N treatment indirectly reduced the land use, life-cycle human toxicity, aquatic eco-toxicity, and terrestrial eco-toxicity potentials by improving grain yield and agronomic efficiency. In addition, the optimal N treatment reduced the energy consumption by enhancing the energy use efficiency (EUE) (+74%) and reducing non-renewable energy form (-45%) than the farmer's practice. This study will provide comprehensive information for both scientists and farmers involved in maize production and N management in subtropical region.

Highlights

1. Maize production system has low yield and high environmental impacts in subtropical region.
2. The optimal nitrogen application rates were determined in this region.
3. Optimal N rate maintained high yield and reduced the negative environmental impacts.
4. Environmental factors are important in driving agronomic efficiency and environmental impacts in subtropical region.

1. Introduction

There are increasing concerns about the effects of agricultural practices on crop production, environmental pollution, and ecosystem sustainability (Chen et al., 2014; Daniel et al., 2019). Excessive fertilizers could not improve crop yield and agronomic efficiency, but result in increasing N surplus and environmental risks, such as greenhouse gases emissions (Eric et al. 2020), soil acidification (Hao et al. 2020), and eutrophication of groundwater (Huang et al. 2017). There is an urgent need to optimize N fertilizer management, including N rate, to improve N use efficiency (NUE), reduce environmental risks, and thus meet the dual challenges of crop productivity and ecosystem sustainability.

Over the last decade, N management and NUE studies have been undertaken for the major cropping production systems. Previous studies showed that the optimal N rates were still high in maize production regions of China (Guo et al. 2020; Zheng et al. 2017). Several studies (Wang et al. 2019; Zheng et al. 2017) indicated a great potential to increased grain yield and NUE, and reduce environmental impacts through reducing reactive nitrogen (Nr) losses (Huang et al., 2021). However, previous studies are limited in scope as they focused on only a single aspect of the environmental risks, such as the global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP) (Cui et al. 2018; Chen et al. 2014). Therefore, due to the increasing public awareness and government concern of environmental damage, integrated measurement and assessment of the environmental impacts should be analyzed by considering the various impact indicators related to ecosystem quality and human health (Ahmed et al.

2017). Some previous studies have indicated that lower environmental impacts and higher eco-efficiency could be achieved by optimizing N fertilizer rates (increasing agronomic efficiency) for maize and wheat production in USA (Kim et al. 2014), Europe (Król-Badziak et al. 2020), Mediterranean environments (Todorović et al. 2018), and North China Plain (Yang et al. 2019). The information on how N fertilizer management affects the integrated potential environmental impacts and energy consumption is still unclear in subtropical regions.

Several studies have used life cycle assessment (LCA) to investigate the environmental impacts of the application of pesticide (Willkommen et al. 2021) and fertilizer (Hasler et al. 2015) in crop production systems. Normalization and weighting of LCA can facilitate the comparison of category indicator results (Blumetto et al. 2019; Esnouf et al. 2019). Only a few LCA studies in China integrated measurement and assessment of environmental impact categories, ecosystem quality, and human health, by using the weighting steps and normalization to evaluate the different environmental indicator results (Wang et al. 2015; Liang et al. 2018).

Southwest China is located in the subtropical region and accounts for 11% of maize in China, and 2.4% of the global maize production (FAO 2019; NBSC 2019). The over-application of N fertilizer in this area has caused serious environmental problems due to high precipitation, high temperature, and low soil pH. A consecutive 6 site-year field experiment with five N rates was conducted in this study to provide an integrated assessment of agronomic efficiency and environmental performances in maize production systems under various N application rates. The specific objective was to quantify (i) the agronomic impact (grain yield and NUE), (ii) the environmental impacts, and (iii) the energy consumption, and thus to evaluate the food security and overall environmental sustainability for maize production in Southwest China.

2. Materials And Methods

2.1. Site description

The field experiment was conducted from 2018-2019 with the same design at three experimental sites in Ya'an of Sichuan province, Qianxi of Guizhou province, and Fuling in Chongqing in China, respectively (Fig. 1). All three sites were located in the subtropical rain-fed maize production area in Southwest China, and have a subtropical humid monsoon climate. The mean air temperature and total precipitation over the maize season were showed in Fig. 2. The selected initial soil chemical and physical properties of the 0 to 30 cm soil depth at each experimental site were provided in Table S1.

2.2. Experimental design and management

This study was designed with five N rate treatments as N0 (control, CK), N90, N180, N270, N360 (farmer's practice rate), N rate were 0, 90, 180, 270, and 360 kg N ha^{-1} respectively. The field experiment was a randomized block design, with four replications. The size of each plot was 10 m long × 10 m wide. For the treatments that received N fertilizer, urea was spit-applied with 30% of N at pre-plant, 30% at six-leaf, and 40% at tasseling stage, respectively. Before sowing, calcium superphosphate (75 kg P_2O_5 ha^{-1}) and potassium chloride (75 kg K_2O ha^{-1}) as basal fertilizers. Details of fertilizer and pesticides application during maize growing seasons are showed in Table S2 and S3. The pre-plant basal fertilizers were band-applied at approximately 10 cm next to the plant row and 10-15 cm below the soil surface. The in-season application of urea was conducted by furrow.

The maize cultivars used in this study were Zhongyu 3, Zhongdan 808, and Hongdan 6, which have adapted to the experimental stations' climate and topography conditions in Southwest China. Seeding occurred in April with a planting density of 67500 plants ha^{-1} (length × width, 60 × 25 cm). Harvest occurred in late August or early September, depending on the site and year.

2.3. Sample analysis

At the harvest stage, maize in a 12-m^2 area were hand-harvested and threshed in each plot and grain were oven-dried at 75°C to constant weight. At both the tasseling and harvest stages, four uniform plants were collected within each plot by clipping plants at ground level. The samples were separated into grain, leaf, and straw and then oven-dried at 75°C to constant weight to determine the above-ground biomass. All samples were subsequently grounded to pass sieve (0.25 mm), digested using a mixture acid of H_2SO_4 and H_2O_2, and then determined for N concentration using the Kjeldahl procedure (Horowitz 1995). The above-ground N content of maize and agronomic efficiency (AE) of N use were calculated for the maize seasons in 2018 and 2019 using the following equations (Fang et al. 2006):

$N_{uptake} = N_{concentration} \times W_{biomass}$ (1)

AE (Agronomic efficiency, kg kg^{-1}) = $(Y_N - Y_{CK})$ / N rate (2)

where, N_{uptake} is the maize plant N content at harvest, $N_{concentration}$ is the N concentration of the above-ground biomass (grain, leaf, and straw), and $W_{biomass}$ is the weight of the above-ground biomass. Y_N and Y_{CK} are maize grain yield (kg ha^{-1}) in the N fertilization treatments and N0 (control, CK), respectively.

2.4. Life cycle assessment (LCA) method

2.4.1. Goal and scope

In this study, the objective of the LCA was to comprehensive assessment environmental impacts of N fertilization in maize production in Southwest China. One Mg of maize grains was selected as the basis (functional unit) for the analysis. The system boundary was defined as from the cradle to the farm gate, which included two subsystems as 1) the agricultural materials system (MS) and 2) the farming system (FS). The MS referred to the raw material extraction, processing and production of fertilizers and pesticides, as well as the transportation to farm in this study. The FS included soil preparation, sowing, and applications of fertilizer and pesticides. The production processes of machines and irrigation were not considered in this study due to the rare machine use and the rain-fed production system in Southwest China. The life cycle inventory per Mg maize production under different N treatments is shown in Table 1.

Table 1

Life cycle inventory per Mg maize production as affected by N rate treatments.

	N0	N90	N180	N270	N360
CO (g)	94.6	93.0	110	156	193
CO_2 (kg)	103	162	202	291	365
CH_4 (g)	3.66	4.85	5.96	8.54	10.7
SO_x (g)	533	654	797	1138	1422
NH_3 (kg)	1.93	3.14	3.57	4.36	5.03
NO_3 (kg)	8.96	9.94	10.4	11.4	12.3
N_2O (g)	603	650	668	702	733
NO_x (g)	610	730	887	1266	1581
P_{tot} (g)	135	36.4	25.2	24.9	23.9
COD (g)	1719	1750	2075	2930	3639
Pesticide to air (g)	64	39.0	27.0	26.7	25.6
Pesticide to water (g)	14.4	3.94	2.71	2.73	2.64
Pesticide to soil (g)	620	168	116	115	110
As (mg)	2.89	0.703	0.475	0.469	0.448
Cu (mg)	3.39	0.825	0.558	0.551	0.527
Zn (mg)	27.4	6.67	4.51	4.46	4.26
Cd (mg)	0.721	0.175	0.119	0.117	0.112
Pb (mg)	10.5	2.55	1.72	1.70	1.63

Values represent the mean of year 2018 and 2019.

2.4.2. Life cycle inventory (LCI) analysis

For this study, the life cycle inventory compiled all consumed resources and their corresponding emissions related to the functional unit (ISO 2006a). In the MS, the LCI (Table S5) concerning the production of fertilizers, pesticide, fuel, and electricity were taken from Yue (2013), Wang et al. (2018), and Liang (2009), which were widely used for local products. In the FS, the emission factors for Nr loss were derived from the peer-reviewed publications, which were restricted to studies from Southwest China, using the meta-analysis method. The N losses of direct N_2O emissions, NH_3 volatilization, and N leaching from urea were calculated using the emission factors (Table S4). The indirect N_2O emission was considered 1.00% of the volatilized NH3-N and 0.75% of the leached NO_3-N (IPCC 2006). The NO_x emission was calculated 10% of the total N_2O (Wang et al. 2017; Brentrup et al. 2004), and the phosphorus loss was considered as 1% of total phosphorus fertilizer inputs (Gaynor et al. 1995). The pesticide emissions to soil, water, and air were considered as 43%, 1%, and 10% of the applied pesticide mass, respectively (Van Calker et al. 2004). Using heavy metals' input-output balance calculated the losses of them (Zn, As, Cd, Cu, Pb) (Wang et al. 2017). The inputs of heavy metals were mainly from seeds and fertilizers, and the related data were derived from Liang (2009).

2.4.3. Life cycle impact assessment

The impact assessment can further process and interpret the LCI data (Table S5), which involves characterization, weighting, and normalization. For this study, eight category indicators were considered, 1) renewable land resource use (LU), 2) energy depletion potential (ED), 3) global warming potential (GWP), 4) acidification potential (AP), 5) eutrophication potential (EP), 6) human toxicity potential (HTP), 7) aquatic ecotoxicity potential (AEP), and 8) terrestrial ecotoxicity potential (TEP). Characterization results were analyzed by using the factors relevant to the use and emission of each type of resource (Liang et al. 2018). The various potential environmental impacts (PEI) were calculated according to the ISO standard (ISO 2006 a, b) using the following equation:

$$\mathrm{PEI}_{(j)} = \sum_{i=1}^{n} E_{F(j)i} \times Rate_{(j)i} \quad (3)$$

Where, $\mathrm{PEI}_{(j)}$ represents the potentials for *j* environmental impact category; $E_{F(j)i}$ represents the characterization factor of per unit i resource (fertilizers and pesticides, etc) use or emission potential in relevant to *j* environmental impact category; $\mathrm{Rate}_{(j)i}$ represents the rate of i resource (fertilizers and pesticides, etc) use or emission potential.

Normalization and weighting analysis can provide further interpretation of potential environmental impacts. Normalization was considered by dividing each category indicator based on the reference values (Brentrup et al. 2004; Liang et al. 2018). Normalization values of per-capita environmental impact in China (including LU, ED, GWP, AP, and EP) for 2010, and those of the per-capita eco-toxicity impact in the world (including HTP, AEP, and TEP) were used due to a lack of eco-toxicity references in China, as shown in Table S6. All impact categories were aggregated to one composite environmental indicator (EI) by weighting analysis, which was determined by using the following equation:

$$\mathrm{EI} = \sum W_j \times R_j \quad (4)$$

where W_j represents the weighting factors of *j* impact category (Wang et al. 2007); and Rj represents the normalization value of *j* impact category.

2.4.4. Interpretation of results

Interpretation of results was conducted to evaluate how and to what extent optimizing N rate could affect the impact category indicators, and to identify the agricultural material inputs and management process that substantially contributed to each impact category indicator. We also assessed the impact of N fertilization on human health using the analysis of Disability Adjusted Life Years (DALYs), which were defined as the potential cumulative number of years loss connected to grain production. They were calculated using the equation,

$\mathrm{DALY}_i = \mathrm{D}_{Fi} \times \mathrm{Rate}_i$ (5)

Where, DALY_i represents the DALY derived from *i* pollution emission; D_{Fi} represents the endpoint human health damage factors from ReCiPe 2008 (Huijbregts et al. 2017; Goedkoop et al. 2009); Rate_i represents the rate of *i* pollution.

2.5. Energy use efficiency of maize production

The energy budget of maize production system includes the input energy consumed in various operation processes for agricultural inputs, and the output energy produced in terms of grain yield and other above-ground straw biomass

(Lal et al. 2019). For this study, the input energy consumption was calculated by multiplying the input amounts of fertilizers, pesticide, seeds, human labor, and field operations (Table S2, S3) with their respective energy conversion coefficients (Table S7). Indirect energy included energy embodied in pesticides, fertilizers, and seeds, while direct energy referred to human labor in the maize production. Renewable energy consists of seeds and human labor, while non-renewable energy included the fertilizers, pesticides. The net energy (NE), energy use efficiency (EUE), and energy productivity of the system were calculated using the equation (Chaudhary et al. 2017):

NE = Output energy - input energy (6)

EUE = Output energy / input energy (7)

Energy productivity = Maize economic yield / input energy (8)

2.6. Statistical analysis

All the study data were processed using Excel 2019. A one-way ANOVA was used to test the interactive and main effects of sub-regions or years on grain yield, fertilizers rate, and environmental indexs using SAS 9.3 statistical software. Where treatment effects were significant, means were compared by least significant difference (LSD) tests at $p < 0.05$.

3. Result

3.1. Grain yield, above-ground N uptake and agronomic efficiency

In both years, grain yield at all sites significantly increased with N rates up to 180 kg N ha^{-1} (N180 treatment). Increasing N rates over the N180 failed to further increase grain yield (Fig. 3). Grain yield was generally not different between N 180 and N 360 at all site-years, except at Ya'an site in 2018, where N360 resulted in greater grain yield than N180. The mean above-ground N uptake at all site-years was from on average of 42.1 kg ha^{-1} in N0 to 166 kg ha^{-1} in N360. The above-ground N uptake increased with N rates from N0 to the N180 treatment. Increasing N rates over the N180 did not increase above-ground N uptake further (Fig. 3). The AE decreased with increasing N rate, from an average value of 23 kg kg^{-1} in N90 to 13 kg kg^{-1} in N360. Across all site-years, the average AE at all site-years was 21.3 and 23.5 kg kg^{-1} for the N90 and N180 treatment, respectively, which were much higher than that for the N270 and N360 treatment.

3.2. Environmental impacts and non-renewable resource consumption

N fertilizer application directly or indirectly affected environmental impacts and non-renewable resource consumption. In 2019, as shown in Fig. 4, the GWP, AP, EP, and ED at all sites increased with the N rate from N0 to N180 treatment, and then increased substantially from N180 to N360 treatment. In 2018, the N180 treatment showed the lowest GWP (Fig. 4a) and ED (Fig. 4g) in Ya'an, and the N0 treatment showed the highest values. AP and EP in N0 treatment has low values at all site-years, except at Ya'an site in 2018. AP and EP in N90 treatment were higher than N180 treatment at Ya'an site in 2018. In both years, the GWP significantly increased with increasing N rate, from an average value of 292 kg CO_2-eq Mg^{-1} in N0 treatment to 593 kg CO_2-eq Mg^{-1} in N360 treatment (Fig. 4), except for Ya'an site. The GWP in N180 treatment was 20% and 31% lower than that in N270 treatment and N360 treatment, respectively. The AP significantly increased with N rates, with values being 32% and 47% lower in N 180 than in N270 treatment and N360 treatment, respectively. The N0 treatment had the lowest EP (0.15 kg PO_4-eq Mg^{-1}), whereas the N270 and N360 (1.7

and 2.1 kg PO_4-eq Mg^{-1}) treatments had the highest ones (Fig. 4). The ED increased with N rates, with values being 29% and 43% lower in N180 than in N270 and N360, respectively.

The HTP and AEP were dominated by pesticide emissions to air and water. In contrast, the TEP was dominated by both the pesticides inputs to soil and heavy metal contaminants derived from fertilizers input. In both years, LU, HTP, AEP and TEP were influenced indirectly by N fertilizer and decreased significantly with the increasing N rate from N0 treatment to N180 treatment, then stabilized at N180 treatment and higher N rate treatments (Fig. 5). All impact category indicators decreased with the increasing grain yield. All impact category indicators were not significantly different between the N180, N270, and N360 treatments. Overall, the N180 treatment showed the highest potential to reduce environmental costs and had the most desired environmental performances (Fig. 4, 5).

3.3. Human health impacts

In both years, 15 environmental pollutants were compiled and expressed as the potential cumulative number of years loss based on per Mg grain production, to evaluate N fertilizer application's effects on human health (Table 2). The N360 treatment showed the highest impact on human health, being 4.86×10^{-1} DALY.Mg^{-1}. The N180 treatment showed the lowest human health burden (3.87×10^{-1} DALY.Mg^{-1}), 12% and 20% lower than the N270 and N360 treatments, respectively (Table 2). Among the environmental pollutants, N_2O emission had the most significant contribution (62%-73%) to human health damage, which was mainly associated with the N fertilizer production and electricity consumption. The NO_x and SO_2 showed a comparable level of damage to human health, with a contribution of 14% and 11%, respectively. Cadmium was the most significant heavy metal with a contribution of 4% to human health damage. These four environmental pollutants contributed over 96% to the total human health burden. Among the 5 N rates, the N180 treatment had the lowest human health burden (Table 2).

Table 2
Human health impacts per Mg of maize production as affected by N rate treatments.

Pollutant	Damage category	Damage factor (DALY.kg^{-1} emission)	N0	N90	N180	N270	N360
CO	Photochemical oxidant formation	$1.78×10^{-9}$	$1.68×10^{-7}$	$1.66×10^{-7}$	$1.96×10^{-7}$	$2.77×10^{-7}$	$3.44×10^{-7}$
CO_2	Climate change	$1.40×10^{-6}$	$1.44×10^{-4}$	$2.27×10^{-4}$	$2.83×10^{-4}$	$4.07×10^{-4}$	$5.11×10^{-4}$
CH_4	Climate change	$3.50×10^{-5}$	$1.28×10^{-4}$	$1.70×10^{-4}$	$2.09×10^{-4}$	$2.99×10^{-4}$	$3.75×10^{-4}$
SO_2	Particulate matter formation	$5.20×10^{-5}$	$2.77×10^{-2}$	$4.40×10^{-2}$	$4.14×10^{-2}$	$5.92×10^{-2}$	$7.40×10^{-2}$
NH_3	Particulate matter formation	$8.32×10^{-5}$	$1.61×10^{-4}$	$2.61×10^{-2}$	$2.97×10^{-2}$	$3.63×10^{-2}$	$4.18×10^{-2}$
N_2O	Climate change	$4.17×10^{-4}$	$2.51×10^{-1}$	$2.91×10^{-1}$	$2.78×10^{-1}$	$2.93×10^{-1}$	$3.05×10^{-1}$
NO_x	Particulate matter formation	$5.72×10^{-5}$	$3.49×10^{-2}$	$4.18×10^{-2}$	$5.07×10^{-2}$	$7.24×10^{-2}$	$9.04×10^{-2}$
Pesticide to air	Human toxicity	$4.34×10^{-6}$	$6.26×10^{-4}$	$1.69×10^{-4}$	$1.17×10^{-4}$	$1.16×10^{-4}$	$1.11×10^{-4}$
Pesticide to water	Human toxicity	$7.76×10^{-6}$	$1.12×10^{-5}$	$3.03×10^{-5}$	$2.10×10^{-5}$	$2.10×10^{-5}$	$2.02×10^{-5}$
Pesticide to soil	Human toxicity	$1.58×10^{-6}$	$9.80×10^{-4}$	$2.65×10^{-4}$	$1.83×10^{-4}$	$1.81×10^{-4}$	$1.74×10^{-4}$
As	Human toxicity	$1.04×10^{-2}$	$3.01×10^{-2}$	$7.31×10^{-3}$	$4.94×10^{-3}$	$4.88×10^{-3}$	$4.66×10^{-3}$
Cu	Human toxicity	$7.33×10^{-6}$	$2.49×10^{-5}$	$6.05×10^{-6}$	$4.09×10^{-6}$	$4.04×10^{-6}$	$3.86×10^{-6}$
Zn	Human toxicity	$3.09×10^{-4}$	$8.48×10^{-3}$	$2.06×10^{-3}$	$1.39×10^{-3}$	$1.38×10^{-3}$	$1.32×10^{-3}$
Cd	Human toxicity	$6.66×10^{-2}$	$4.80×10^{-2}$	$5.17×10^{-2}$	$7.93×10^{-3}$	$7.79×10^{-3}$	$7.46×10^{-3}$
Pb	Human toxicity	$4.20×10^{-4}$	$4.41×10^{-3}$	$1.07×10^{-3}$	$7.23×10^{-4}$	$7.14×10^{-4}$	$6.85×10^{-4}$
Sum (DALY.Mg^{-1})			$4.07×10^{-1}$	$4.20×10^{-1}$	$3.87×10^{-1}$	$4.41×10^{-1}$	$4.86×10^{-1}$

Values represent the mean of year 2018 and 2019.

3.4. Aggregative environmental performance

The China per-capita environmental impact values in the year 2010, and the global per-capita eco-toxicity impact values in 2000 were used as references to analyze the aggregative environmental performance of N fertilization in maize production (Fig. 6). The N180 treatment showed the lowest or relatively lower impact values and the N0 treatments showed the highest values of LU, AEP, TEP, and HTP (Fig. 6a). The GWP, AP, EP, and ED increased slightly with N rate from N0 to N180 treatment, and substantially with N rate from N180 to N360 treatment. These results indicated that the LU and AEP were the most important indicators for environmental impacts, followed by the EP, AP, and AP. On the contrary, the values for ED, GWP, HTP, and TEP were quite low, with all of them being less than 0.4 person equivalent Mg^{-1} grain. Compared to the N360, the N180 treatment reduced the AP impact by 46%, from 0.43 to 0.23 person equivalent Mg^{-1} grain; and reduced the EP by 45%, from 0.55 to 0.30 person equivalent Mg^{-1} grain; and also reduced the ED by 42% and GWP by 31%. Overall, the normalization results in response to N rate showed the same trend as the characterization results (Fig. 4, 5, 6).

The results indicated that the environmental indicator decreased firstly then increased with the increasing N rate (Fig. 6b). Across the five treatments, the aggregated environmental indicator was dominated by AP (11%), EP (13%), and AEP (67%) (Fig. 6b). The higher the N rate, the greater the AP, EP, and AEP contributed to the aggregated environment indicator. Among the five N treatments, the N180 had the lowest environment indicator (0.26 EcoX Mg^{-1}), which was 34% and 16% less than the N0 (0.40 EcoX Mg^{-1}) and N360 treatment (0.32 EcoX Mg^{-1}), respectively. For the N0 treatment, the aggregated environment indicator was dominated by AEP (87%) and TEP (8.8%) (Fig. 6b). As for N360 treatment, the highest share for the environmental impact was also dominated by AEP (52%), followed by EP (21%), and AP (19%).

3.5. Energy use efficiency

In this study, we calculated the energy budget of maize production by assessing the energy flow, accounting for the input energy consumed in various operation processes for agricultural inputs, and the output energy produced in terms of grain yield and other above-ground straw biomass. The output energy and net energy (NE) significantly increased with increasing N rates until the N180 treatment. However, increasing N rates over the N180 treatment failed to further increase NE (Table 3; Table S8). Among the five N treatments, the N180 had the highest NE (106 GJ ha^{-1}), which was 78.5% and 14.8% higher than the N0 (59.4 GJ ha^{-1}) and N360 treatments (92.3 GJ ha^{-1}), respectively. As shown in Table 3 and Table S8, EUE and energy production efficiency decreased slightly with the increment in N rates over 90 kg N ha^{-1}, while decreased substantially from N0 to N90 treatment. The same trend was found for indirect and non-renewable energy (Table 4, Table S9).

Table 3
The 2-yr mean value of the output energy, net energy, energy use efficiency and energy production efficiency for maize production system as affected by N rate treatments in the subtropical region of China.

Treatment	Input energy (GJ ha^{-1})	Output energy (GJ ha^{-1})	Net energy (GJ ha^{-1})	Energy use efficiency	Energy productivity(Mg GJ^{-1})
N0	4.4 ± 0.17	63.7 ± 34.4	59.4 ± 23.1	14.5 ± 7.6	0.94 ± 0.5
N90	12.6 ± 0.13	93.9 ± 24.3	81.3 ± 24.3	7.4 ± 1.9	0.48 ± 0.1
N180	20.9 ± 0.12	127 ± 19.4	106 ± 19.2	6.1 ± 0.9	0.40 ± 0.1
N270	29.2 ± 0.17	128 ± 20.0	99.5 ± 20.0	4.4 ± 0.7	0.28 ± 0.04
N360	37.5 ± 0.15	133 ± 14.1	95.3 ± 14.1	3.5 ± 0.4	0.23 ± 0.02

Table 4
The 2-yr mean value of the renewable (E_r), non-renewable (E_n), direct (E_d) and indirect (E_i) energy forms for maize production system as affected by N rate treatments in the subtropical region of China.

Treatment	E_d (GJ ha^{-1})	E_i (GJ ha^{-1})	E_r (GJ ha^{-1})	E_n (GJ ha^{-1})
N0	0.877	3.48	1.26	3.48
N90	0.877	11.8	1.26	11.7
N180	0.877	20.0	1.26	20.0
N270	0.877	28.4	1.26	28.3
N360	0.877	36.6	1.26	36.6

4. Discussion

4.1. Effects of N rate on maize production

It is widely acknowledged that the N fertilizer plays a vital role in increasing crop yields, while yield response decreased with increasing N rates. In this study, excessive use of N fertilizer (>180 kg N ha^{-1}) did not show any benefits on grain yield, above-ground N uptake or AE. Similarly, previous studies have showed a linear-plateau relationship between the application of N fertilizer and maize grain yield (Cui et al. 2010). The mean yield with 180-360 kg N ha^{-1} achieved 86%-90% of the yield potential of maize yield in Southwest China (Liu et al. 2017). The N180 treatment can maintain the same high grain yield as that with high N fertilizer (≥ 270 kg N ha^{-1}), which was attributed to more N uptake by maize plant and accumulation after the post-silking stage (Fig. S1) (Srivastava et al. 2018). Thus, the N application rates currently used by the farmers' practice in maize production (>280 kg N ha^{-1}; PDNDRCC 2019) could be reduced by approximately 36% to 180 kg N ha^{-1}. The optimal N rate of 180 kg N ha^{-1} in this study was 13-21% lower than that in some previous studies (206-227 kg N ha^{-1}) in the studied region (Li et al. 2020). Higher N surplus and N losses were found in N270 treatment and N360 treatment (Fig. S3), and would lead to high accumulation of soil residual N (Gao et al. 2016), and subsequent loss via NH_3 volatilization, N leaching, and greenhouse-gas emissions such as N_2O (Wang et al. 2020; Sebilo et al. 2013).

4.2. Environmental consequences and energy consumption

To our knowledge, this study is the first to integrally assess the environmental impacts, human health impacts and sustainability for N fertilization in maize production in Southwest China. Eight impact category indicators were assessed in order to evaluate the multi-indicator environmental impacts of five different N rates by employing the LCA approach, which provided more scientific support for decision-making of N management in maize production (Brentrup et al. 2004). Although comparisons between different LCA studies in different regions are not straightforward (Wang et al. 2015; Leach et al. 2012), there were many interesting results from this study. The maize production in Southwest China involves several environmental hotspots, such as LU, GWP, EP, and ATP, which are significantly different from previous research for other crop production systems in China (Wang et al. 2017), India (Mohanty et al., 2017), USA (Kim et al. 2014). The particular challenges for China's agricultural systems are greater than those in other countries with larger land, water endowments, and smaller populations. The LU for maize production in this study was lower than that in the USA and Denmark (Liang et al. 2018). In contrast, the GWP, AP, and EP of maize production in this study was higher than those in other regions of the world (Grassini et al. 2012).

Intensive farmland is favorable for the field works by agricultural machineries, low inputs and high yield in developed countries. However, high N inputs and low grain yield from extensive farmland in Southwest China.

This study indicated that the N180 treatment significantly reduced the environmental impacts in terms of GWP, AP, EP, and ED in comparison to the N360 treatment while achieving a comparable high yield (8.2 Mg ha^{-1} on average). Similar to the results of Brentrup et al. (2004) and Yan et al. (2016), a low N application rate (N90) decreased crop yield production whereas an excessive rate (N360) increased environmental risks (Fig. 3, 7). The N180 treatment clearly showed the most favorable results, with the lowest aggregative environmental value while maintaining high grain yield, which indicated that increased yield and reduced environment impacts were win-win (Fig. 3, 7). On the one hand, the N180 treatment could meet the crop demand, reduce N surplus, and then reduce a series of environmental impacts scaled by unit area (compared to 270-360 kg N ha^{-1}). On the other hand, the N180 treatment also resulted in lower environmental impacts scaled by unit yield (compared to environmental impacts per unit area of 0-180 kg N ha^{-1}). Overall, the results indicated that among the five N rates, the optimal N rate of 180 kg N ha^{-1} showed greater potential for enhancing yield and reducing environmental impacts.

The energy use efficiency (energy ratio) ranged between 3.5-4.4 for N application rates from 270 to 360 kg N ha^{-1}, indicating an inefficiency for energy use in the maize production in Southwest China, compared to USA (5.3), Germany (5.5), and Northeast China (4.5) (Grassini et al. 2012; Felten et al. 2013). Increasing N rate over the N180 failed to further increase maize and output energy. The NE can be increased by improving the crop yield and/or decreasing energy inputs consumption (Table 3, 4, S8, S9). The output energy was significantly higher than net energy (Table 3), which can be concluded that in maize production, energy is being lost. Therefore, there are inevitable environmental costs associated with energy loss. To ensure optimum energy use, productivity should increase with the existing level of energy inputs, and input energy should reduce without affecting the productivity.

4.3. Contributing factors to environmental impacts

In this study, nitrogen fertilizer and pesticides were the most important two original factors for the environmental impacts, as seen in previous studies (Grassini et al. 2013). Grain yield was also an important factor for the environmental impacts, as all the environmental impacts were assessed based on per Mg maize production. The lack of farmers' knowledge and information in crop, fertilizer management might be a major contributor to the high N surplus in Southwest China (Chen et al. 2014). As a result, high N inputs and low grain yield from extensive farming in Southwest China. Although the grain yield increased at high N rate (farmers' practice, 360kg N ha^{-1}) due to the greater N uptake, the N surplus also increased. Meanwhile, the low yield of maize production at the low N application (90 kg N ha^{-1}) resulted in high environmental impacts per Mg production. Therefore, the "4R" principles to N management should be highly recommended for maize production in this region (Li et al. 2017).

Similar to previous studies, pollutant emissions of fertilizer production, transportation and application were major contributors to various environmental impacts (Grassini et al. 2013). On the one hand, the increment of N fertilizer could increase pollutant emissions (CO_2 emission contributing to GWP, SO_2, and NO_x associated with AP and NH_4 and NH_3 emissions associated with EP) and energy consumption during N fertilizer production and transportation (Liang 2009). On the other hand, at the farming stage, high N surplus (Fig. S3) increased exponentially with increasing N rate, leading to substantial nitrate accumulation in soil (Wang et al. 2020; Sebilo et al. 2013). The on-farm NH_3 volatilization increased linearly, while N_2O emissions and N leaching increased exponentially with N surplus in southwest China (Fig. S3) (Cui et al. 2018). The N losses to the ecosystem through N_2O, NH_3, and NO_3^- leachates cause environmental problems (e.g. GWP, AP, EP, AEP, and TEP) and the threat to human health (HTP). From the perspective of human health damage expressed as DALY per Mg maize production, the five main pollutants came from the application of N fertilizer at farming stage (NH_3 and N_2O) and the production process of N fertilizer and electricity at agricultural materials stage (such as: SO_2, CO_2, and NO_x). Reasonable fertilizer application strategy is therefore needed to reduce the pollutant emissions during N fertilizer production and application processes. In this study, the N 180 treatment reduced 20-31% of GWP, 32-47% of 45% of AP, and 10-20% of the human health damage compared to the N 270-360 treatment. Therefore, reducing Nr losses associated with excessive N fertilizer application is the key measure to mitigate the negative environmental and health impacts (Bodirskyet et al. 2014; Willkommen et al. 2021; Drzeżdżon et al. 2018).

Environmental factors are important in driving N losses and low yield in tropical/subtropical environments (Fig. S2) (Alam et al. 2017). On the one hand, the meteorological factors can influence N losses through its direct impact on N_2O direct, NH_3 volatilization, and N leaching and indirect impact on maize yield (Han et al., 2020). The high precipitation and temperature in maize season (Fig. 2), and the low Growing Degree-Days (GDD) (Yin et al. 2017) in Southwest China, could lead to high N losses to the ecosystem through N_2O, NH_3 and NO_3^- leachates, by reducing nutrient availability and solar radiation (Fig. 2; Fig. S2) (Sebilo et al. 2013). Among these, high precipitation was a key driving factor for N leaching over the whole maize growing season (Yao et al. 2021). Excessive fertilizer N input can result in high accumulation of soil residual nitrate, which can further move to the deeper soil layers due to the nitrate's high mobility and the downward water fluxes with high precipitation (Wang et al. 2020; Sebilo et al. 2013). The experimental soil pH was low (pH, 5.3-5.8) (Table S1), could decrease denitrification but increase the risk of N loss through leaching (Wang et al. 2020). Such risk could likely be even more serious for the experimental area as water holding capacity of soils was low (i.e. Luvic Xerosols, Ail-perudic Cambosols and Typic Purpli-Udic Cambosols) (Table S1).

4.4. Potential limitations of this study

In this experimental area, although optimized N application showed great potential to reduce the environmental impacts, there are still some effects of stress on maize production because of regional climate, soil characteristics, and N management practices remain (Snyder et al. 2009; Chien et al. 2009). At the arable farming process, it is hard to advance the accuracy and completeness of the LCA results in Southwest China, due to the complexity and variety of ecological conditions, with high temperature, high and uneven precipitation, and variation in soil properties (Fig. 2; Table S1). In this study, the environmental impacts were not direct measurements under the actual field experiments, but based on estimations through site-specific equations for Southwest China. The LCA results were highly dependent on the accuracy of the system boundary and LCI. Measurements in factor-controlled field experiments over multiple site-years are needed to better assess environmental pollutants in maize production in Southwest China. We should consider previous studies from Southwest China for important parameters that are missing (Wang et al. 2017). Further studies should analyse the long-term trend of environmental pollutants with optimised N management in maize production system under various ecological conditions in Southwest China. Despite these limitations, this study provides meaningful findings about the agronomic, environmental and ecosystem sustainability in maize production system.

5. Conclusion

An assessment of a 6 site-year field study has integrally evaluated the productivity, agronomic efficiency, and the environmental impacts of N fertilization in maize production system in the subtropical region. The results indicated that, nitrogen fertilizer application at the optimal rate of 180 kg N ha^{-1} yr^{-1} achieving a high grain yield, and meanwhile reduced the negative environmental impacts through increasing agronomic efficiency and reduction of N losses, compared to farmers' N practice. Low N input in the optimized N management reduces pollutants emission and energy consumption during the production and transportation of N fertilizer, on-field Nr losses at farming stage. There was a decrease in life-cycle pollutants emission that mitigated the overall human health damage. Optimized N achieved the highest net energy with low input energy among all N treatments, reduced the losses of non-renewable resource. High N application and environmental factors are important in driving environmental impacts in subtropical region. The evidence could be used in decision-making for future sustainable agricultural policies in the sub-tropical regions with environmental factors similar to that occur in Southwest China. Further studies may be required to identify maize production and the long-term trend of environmental pollutants at the optimal N rate application under various cropping systems and agro-climatic regions, especially in high temperature or high precipitation regions.

Abbreviations

AE, agronomic efficiency;	LCI, Life cycle inventory;
AEP, aquatic ecotoxicity potential;	LU, land resource use;
AP, acidification potential;	MS, materials system;
ED, depletion potential;	N, nitrogen;
EI, environmental indicator;	NE, net energy;
EP, eutrophication potential;	NH_3, ammonia;
EUE, energy use efficiency;	N_2O, Nitrous oxide;
FS, farming system;	Nr, Reactive nitrogen;
GWP, global warming potential;	NUE, N use efficiency;
HTP, human toxicity potential;	TEP, terrestrial ecotoxicity potential;
LCA, Life cycle assessment;	

Declarations

Availability of data and materials All data generated or analyzed during this study are included in this published article and its supplementary information files.

Authors' contributions

Zhi Yao, Investigation, Methodology, Data curation, Writing - original draft, Writing - review & editing.

Wushuai Zhang and Xingbang Wang, Investigation, Methodology, Data curation, Writing - review & editing.

Ming Lu, Wei Zhang, and Dunyi Liu, Methodology, Writing - review & editing. Xiaopeng Gao and Yuanxue Chen, Writing - review & editing, Supervision.

Xinping Chen, Writing - review & editing, Conceptualization, Supervision, Funding acquisition.

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Compliance with ethical standards

Ethical approval Not applicable

Consent to participate Not applicable

Consent to publish Not applicable

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Figures

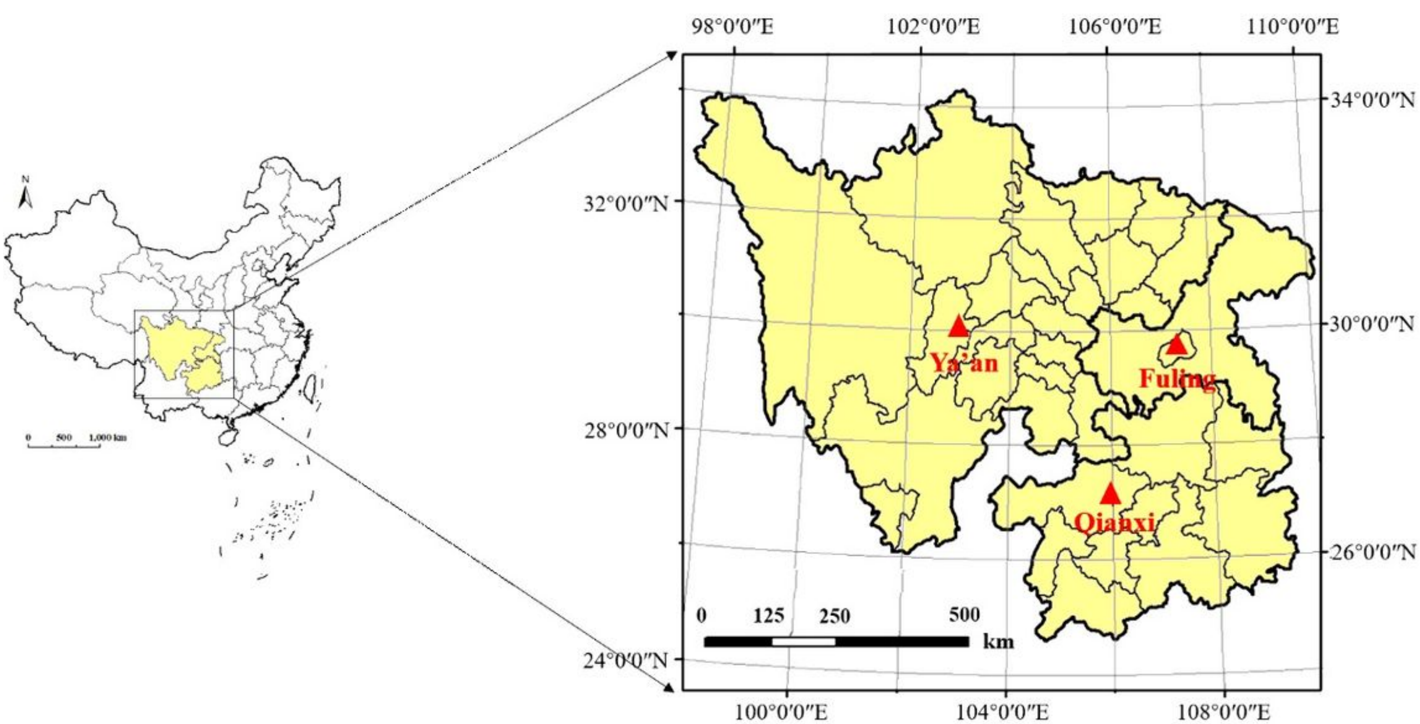

Figure 1

Location of the field experimental sites. The experiments were conducted from 2018-2019 at the experimental stations of Ya’an (29°58¢ N, 102°58¢ E, 627.6 m a. s. l.) in Sichuan province, Qianxi (27°00¢ N, 106°12¢ E, 1215 m a. s. l.) in Guizhou province and Fuling (29°45¢ N, 107°25¢ E, 274 m a. s. l.) in Chongqing city. All three sites are located at the subtropical rain-fed maize production area in Southwest China, and has a subtropical humid monsoon climate.

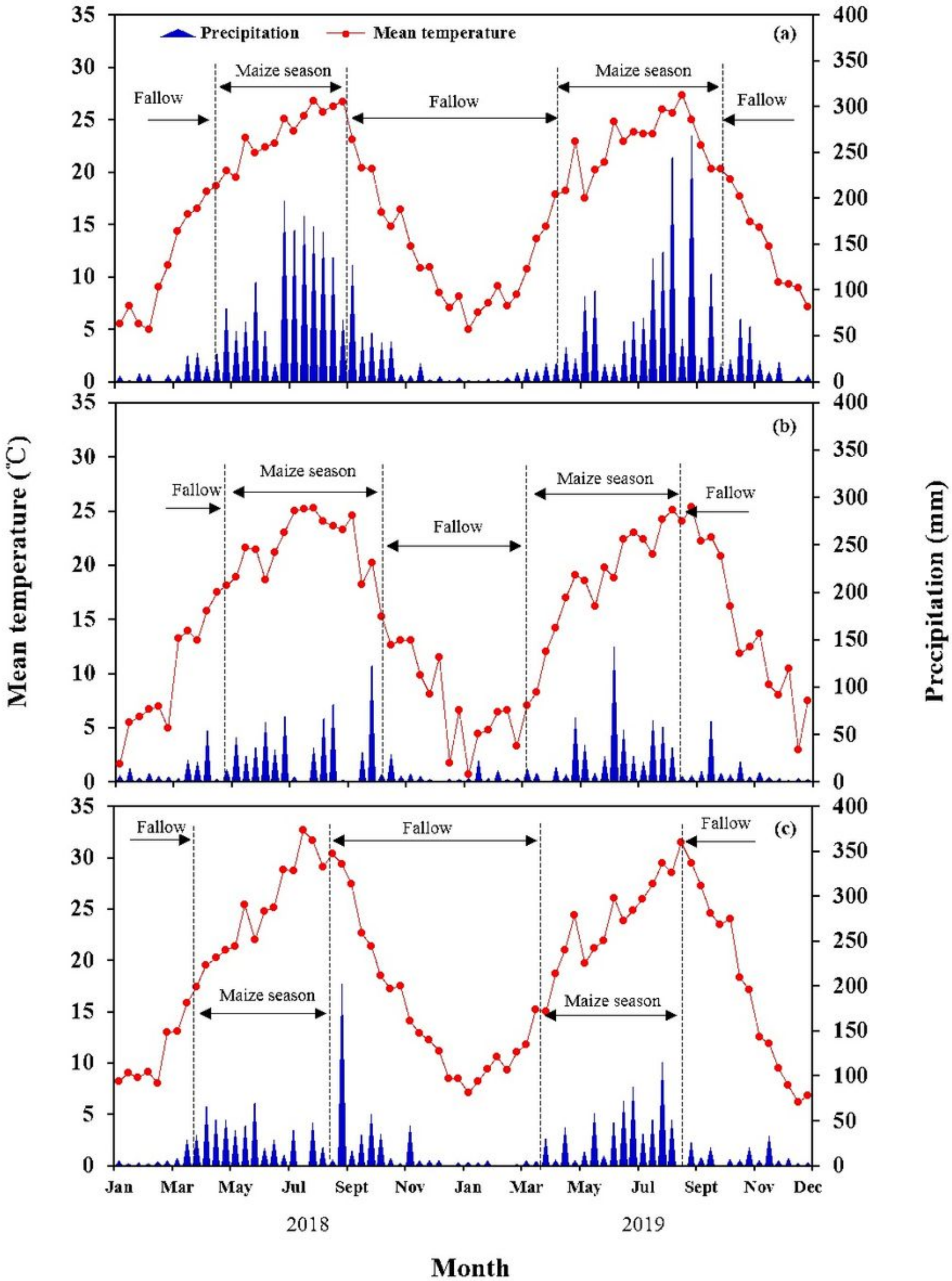

Figure 2

Precipitation and mean temperature at the trial sites in 2018 and 2019. The blue bars and red points represent total precipitation and mean temperature of each ten days, respectively. In Ya’an (a), the maize growing seasons were April 18 to September 15 in 2018, and April 3 to September 6 in 2019, and the precipitation over the maize season were 1812 mm in 2018 and 1479 mm in 2019. In Qianxi (b), the maize season were April 5 to September 18 in 2018 and March 27 to September 9 in 2019, and the precipitation over the maize season were 933 mm in 2018 and 891 mm in

2019. In Fuling (c), the maize growing seasons were March 26 to August 12 in 2018 and March 28 to August 8 in 2019, and the precipitation over the maize season were 797 mm in 2018 and 758 mm in 2019.

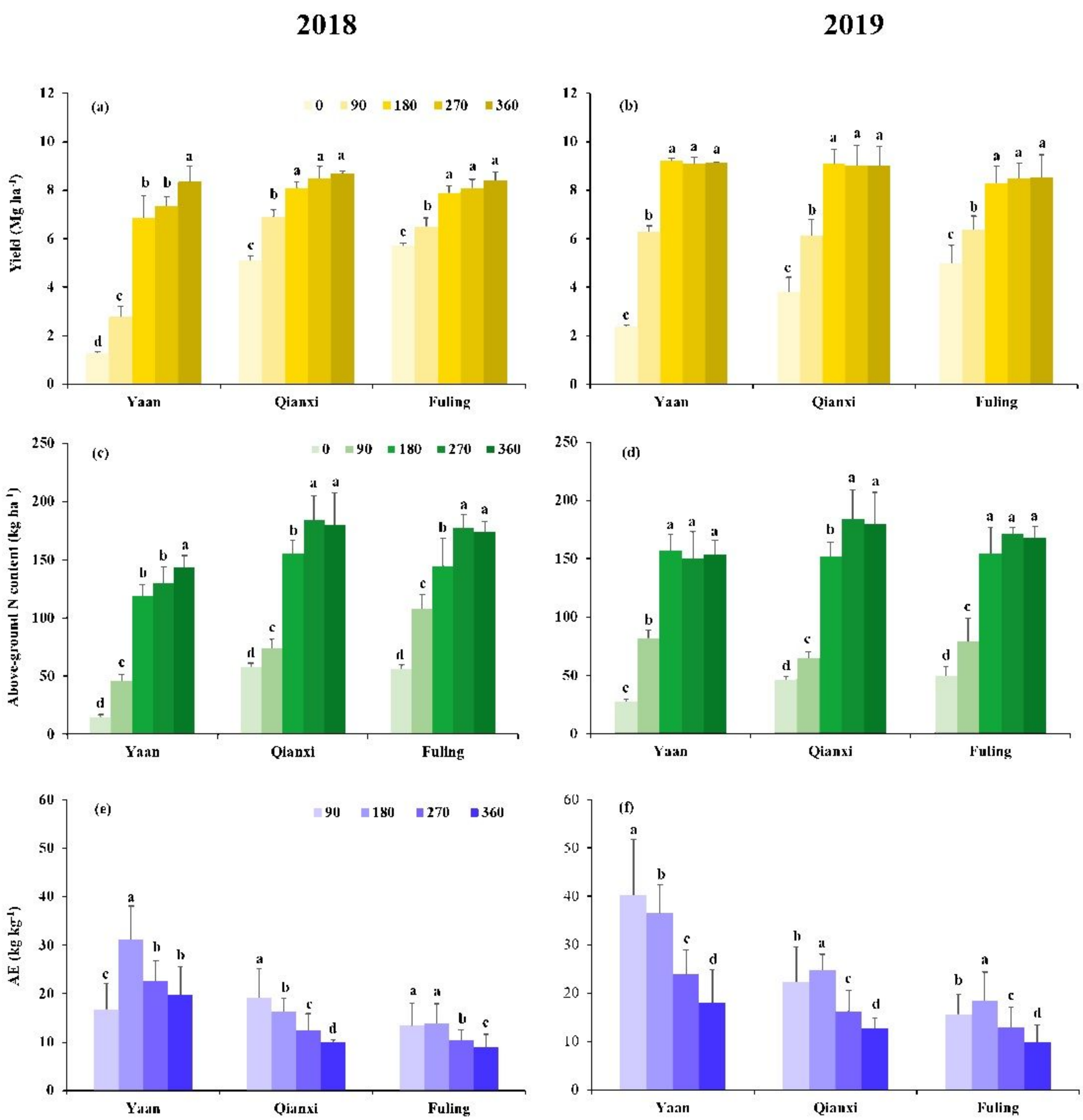

Figure 3

Maize grain yield (a, b), above-ground N content (c, d) and fertilizer N agronomic efficiency (AE, e, f) in 2018 and 2019. N0 (control, CK), N90 (90 kg N ha^{-1}), N180 (180 kg N ha^{-1}), N270 (270 kg N ha^{-1}), and N360 (360 kg N ha^{-1}, farmer's practice rate). Maize grain yield was reported by applying a moisture factor of 15.5%. Means followed by the same lowercase letter are not significantly different among N treatments at $p < 0.05$ according to LSD. Vertical bars represent ± S.E. of the mean.

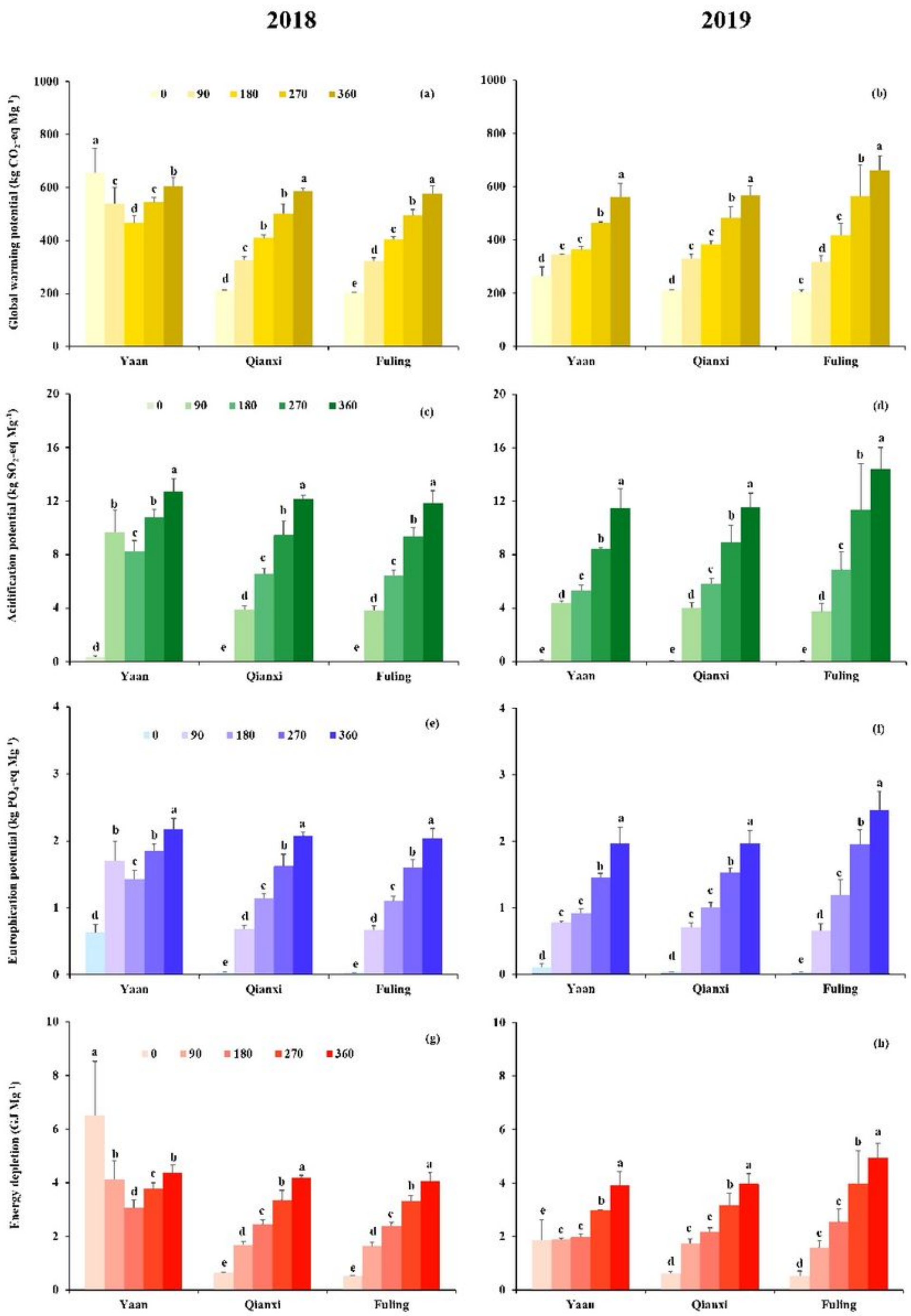

Figure 4

Average life-cycle global warming potential (a, b), acidification potential (c, d), eutrophication potential (e, f) and non-renewable energy depletion potential (g, h) per Mg grain production as affected by N rate treatments in year 2018-2019. N0 (control, CK), N90 (90 kg N ha^{-1}), N180 (180 kg N ha^{-1}), N270 (270 kg N ha^{-1}), and N360 (360 kg N ha^{-1}, farmer's practice rate). Means followed by the same lowercase letter are not significantly different among N treatments at $p < 0.05$ according to LSD. Vertical bars represent ± S.E. of the mean.

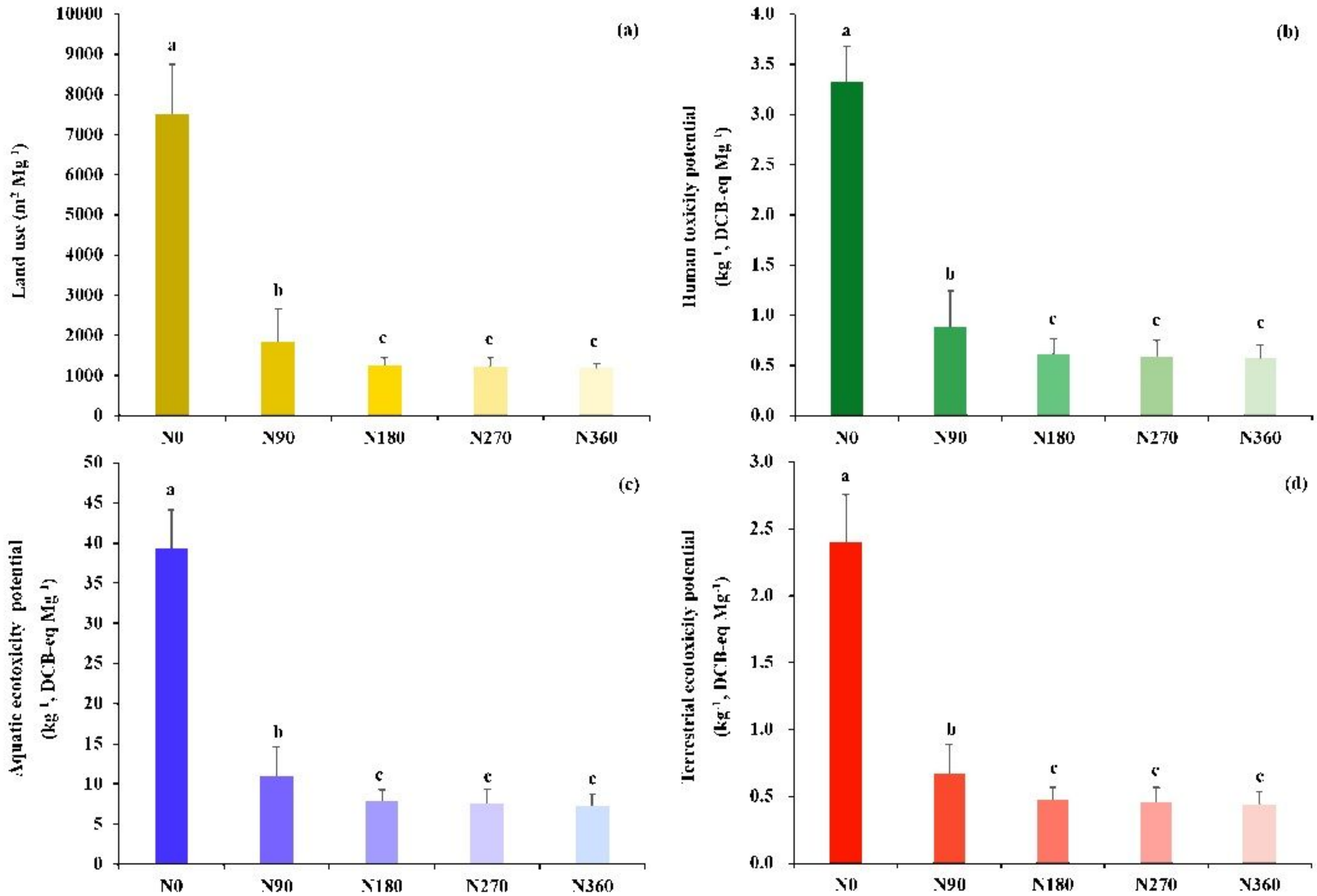

Figure 5

The 2-yr mean life-cycle land use (a), human toxicity potential (b), aquatic ecotoxicity potential (c) and terrestrial ecotoxicity potential (d) per Mg grain production as affected by N rate treatments. N0 (control, CK), N90 (90 kg N ha^{-1}), N180 (180 kg N ha^{-1}), N270 (270 kg N ha^{-1}), and N360 (360 kg N ha^{-1}, farmer's practice rate). Means followed by the same lowercase letter are not significantly different among N treatments at $p < 0.05$ according to LSD. Vertical bars represent ± S.E. of the mean.

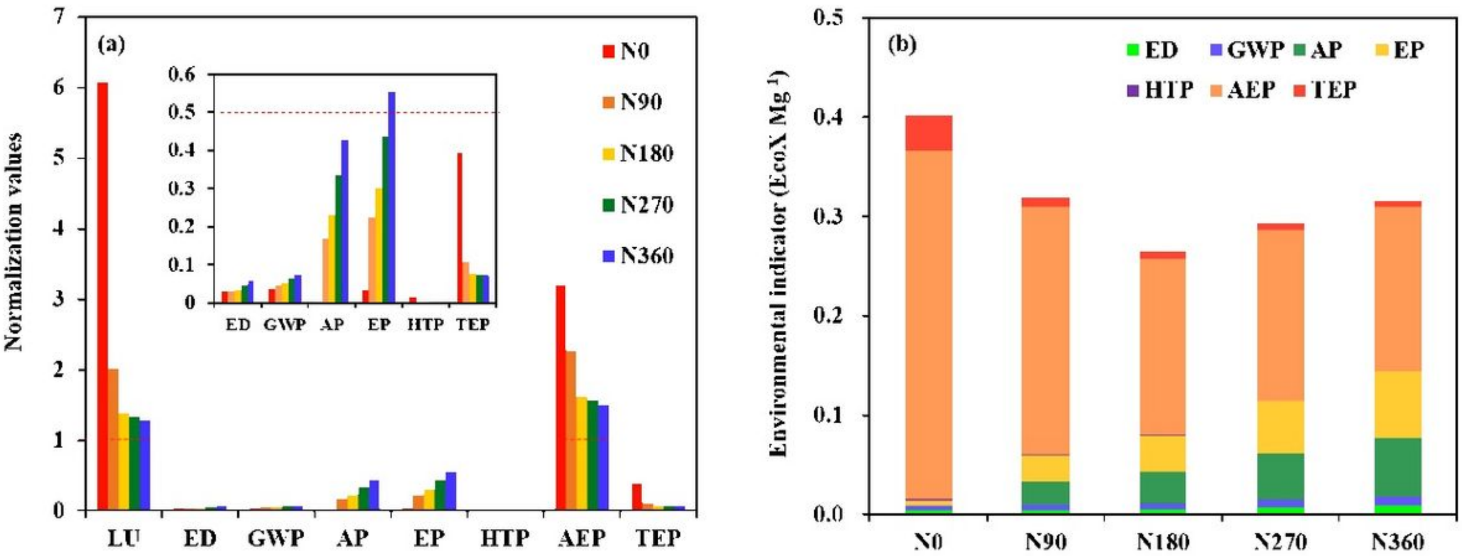

Figure 6

The 2-year mean normalization values (a) and environmental indicator (b) per Mg grain production as affected by N rate treatments. N0 (control, CK), N90 (90 kg N ha^{-1}), N180 (180 kg N ha^{-1}), N270 (270 kg N ha^{-1}), and N360 (360 kg N ha^{-1}, farmer's practice rate). LU, land resource use; ED, energy depletion potential; GWP, global warming potential; AP, acidification potential; EP, eutrophication potential; HTP, human toxicity potential; AEP, aquatic ecotoxicity potential; TEP, terrestrial ecotoxicity potential.

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