Mapping the Environmental Cost of a Typical Citrus-Producing County in China: Hotspot and Optimization

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Abstract: The environmental sustainability of the largest citrus plantation globally is facing a great challenge in China. Further, there is a lack of quantitative, regional hotspot studies. In this study, the life cycle assessment (LCA) was used to quantify the environmental cost of citrus production based on 155 farmers’ surveys from typical citrus orchards in Danling County, southwest China, which produced 0.65% of the country’s total citrus production. The results showed that the average values of environmental risk indicated by global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) were 11,665 kg CO₂-eq ha⁻¹, 184 kg SO₂-eq ha⁻¹, and 110 kg PO₄-eq ha⁻¹, respectively. The production and utilization of fertilizer ranked the first contribution to the environmental impacts among all the environmental impacts, which contributed 92.4–95.1%, 89.4–89.8%, and 97.8–97.9% to global warming potential, acidification potential, and eutrophication potential, respectively. Specific to the contribution of fertilizers to environmental costs, the production and utilization of nitrogen (N) fertilizer accounted for more than 95% of the total environmental costs. Thus, the spatial distribution of environmental costs in this county was well matched with that of N input. Compared with the average values of investigated 155 orchards, the high yield and high N use efficiency (HH) orchard group with younger and better educated owners achieved a higher citrus yield and N use efficiency with less fertilizer input and lower environmental costs. Five field experiments conducted by local government and Danling Science and Technology Backyard were used to further certify the reduction potential of environment costs. These field results showed that the local recommendation (LR) treatment increased citrus yield and N use efficiency by 1.9–49.5% and 38.0–116%, respectively, whereas decreased environmental costs by 21.2–35.2% when compared with the local farmer practice in the HH orchard group. These results demonstrated that an optimum nutrient management based on the local field recommendation in citrus-producing areas is crucial.
for achieving a win-win target of productivity and environmental sustainability in China and other similar countries.

**Keywords:** environmental cost; life cycle assessment; citrus; nitrogen; optimization

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### 1. Introduction

Citrus is the top fruit crop with the largest cultivation area and highest production in the world [1]. China is the largest citrus producer with 28.3% of global cropping areas and 26.8% of global production [1]. However, the environmental sustainability of citrus production in China is facing a great challenge, because of its low yield but high inputs per unit area in agricultural materials [2]. Over the past 20 years, the citrus yield in China (15.0 t ha\(^{-1}\)) has increased by 2.1 times, but is still lower than global average yield and less than half of that in South Africa (32.9 t ha\(^{-1}\)) [1,3]. Driven by economic interests, fertilization has become the major approach to increase citrus yield in China. According to nationwide survey in China, the average application rate of nitrogen (N) fertilizer in citrus orchards is as high as 500 kg ha\(^{-1}\) [4,5], which is substantially higher than that in advanced citrus-producing countries such as Brazil (200 kg ha\(^{-1}\)) and USA (150–200 kg ha\(^{-1}\)) [6,7]. Such a high rate of N and other nutrient fertilization has far exceeded the requirement of citrus trees in China’s citrus orchards with low yield. This would also result in lower fertilizer use efficiency [4] and projected serious nutrient loss to environment, which will inevitably lead to environmental risks [8]. At present, global warming, acidification and eutrophication are becoming major challenges in intensive agriculture systems in China, which were mainly driven by excessive nutrient inputs [9–11]. Without doubt, the citrus producing system in China is in conflict with the goal of zero growth of chemical fertilizer and the green development of the citrus industry. Therefore, it is urgent to assess the environmental cost of typical citrus producing region in China, and to close the citrus yield gap through nutrient management for sustainable intensification.

In order to quantify environmental sustainability, methods have been developed and used in the agriculture section to identify the negative externalities produced during agricultural processes. These methods include healthy farmland system assessment framework (HFSAF), life cycle assessment (LCA), sustainability assessment of farming and the environment (SAFE), multi-temporal remote sensing images, and so on [12–15]. Among them, the LCA has been a preferential method to quantify the potential environmental impacts during agricultural production and processing and has been applied to agricultural systems since the 1990s [16,17].

Although many aspects of environmental costs in cereal and annual crop productions have already been investigated, the LCA of environmental indicators in the perennial fruit crops is still rare, mainly due to lack of methodological standardization [18,19]. For citrus research, environmental assessments of integrated citrus productions in Spain were firstly evaluated by LCA to detect the hot spots, including agrochemicals, energy, and agricultural practices [20]. Thereafter, the environmental assessment of citrus orchards by LCA has been conducted in Italy, Korea, Brazil, and Iran [18,21]. The LCA has been also used to compare the greenhouse gas (GHG) emission among orchards of citrus and other major fruit crops in China [22]. In similar studies, environmental costs have been quantified and major contributors have been sorted out [21,23,24]. Further, some optimal scenarios with fewer environmental impacts have been also suggested, although only a few studies are widely applied [25].

It is also known that the environmental costs of crop production systems vary greatly among different regions due to differences in soil types, climate condition, and management practices [18]. China’s citrus production is dominated by small-scale farmers, and there are great differences in management practices among regions [4]. Thus, it is expected that the contribution of different factors to environmental costs is different with high variability. By learning from farmer practices, farmer group with high yield and high nutrient efficiency represent the realizable potential to reduce
environmental cost in studied region [26–28]. Therefore, it is necessary to quantify the environmental cost and to detect their hotspots in typical citrus-producing areas in China, so as to provide scientific recommendations for regionally environmental and agricultural management.

As a basic administrative region, study at a county level can provide insight into the overall status of citrus production in China. Danling County, located in Sichuan province of southwest China, is one of top 30 citrus producing counties in China [2]. Through 30 years’ cultivation and improvement, citrus orchards (10,667 ha) with the dominant variety of Shiranuhi have been developed in Danling County. This cropping area accounts for 0.41% of the citrus in China and 0.11% of global citrus. Whereas the total production of citrus in Danling county is 266,000 tons and their output value reaches 2.66 billion Yuan, accounting for 2.1% of the national output value of citrus [1,3]. Preliminary surveys conducted by the Danling Science and Technology Backyards have showed that this typical high-yield and high-benefit citrus production system also feeds more than 500 agricultural material distributors. However, the environmental sustainability of citrus production in Danling County remains unknown. Therefore, taking the Danling County as an example, the aims of this study were: 1) to quantify and locate the environmental cost of citrus production by a county-level farmer investigation and the LCA method; 2) to assess the achievable potential to reduce the environmental impact by a farmer grouping strategy; and 3) to test the further potential of reducing environmental cost by addressing the detected prominent problems through field demonstrations. This study would be an example for other citrus-producing counties in China or other countries to identify and manage the hotspots of environmental impacts.

2. Materials and Methods

2.1. Studied Region

The study was conducted in Danling County of Sichuan Province, located in the southwest edge of Chengdu Plain, southwest China (103.23°~103.58°E, 29.87°~30.13°N). This region has a subtropical humid climate zone with mild climate. The annual average temperature is 16.7 °C. The annual average precipitation is around 1,158mm (932.7mm between May and September). The primary soil type is yellow soil, and the soil texture is clay. Citrus is the main economic crop in this area, accounting for 58% of the county’s cultivated area (Supplementary Figure S1a). This research was conducted by the Danling Science and Technology Backyard (STB) (Supplementary Figure S1b), which was jointly established by Southwest University, China Agricultural University, Citrus Research Institute of the Chinese Academy of Agricultural Sciences, and the Danling County People’s Government in January 2017. It involves in agricultural scientists living in villages among farmers for advancing participatory innovation and technology transfer and the Danling citrus industry to improve quality, efficiency, and the green development of agriculture.

2.2. Data Collection and Processing

2.2.1. Data Collection

According to the method of a farmer survey, 3–4 villages were randomly selected in each township, and 5–10 farmers were randomly surveyed from each village. Main questions in the survey questionnaire were given in two parts: (1) basic information of the orchard, including citrus yield, area, density, planting years, etc. (2) Orchard input, including fertilizer, pesticides, irrigation, the energy consumption of land preparation and weeding mechanical. Finally, a total of 155 valid questionnaires were collected.

2.2.2. Life Cycle Assessment

Life cycle assessment (LCA) is a method for analyzing the environmental impact of products from the cradle to the grave in their life cycle [29]. According to the ISO 14040, each LCA project
has four essential phases: goal and scope definition, inventory analysis (inputs and outputs), impact assessment, and interpretation.

Goal, Scope Definition and Inventory Analysis

The study goal was assessing the life cycle of citrus production in Danling County, Sichuan, in southwest China. As for the system boundary, a cradle-to-farm-gate boundary was defined, which included two stages: the agricultural materials production stage (MS) and the arable farming stage (FS) (Figure 1). The MS included the production stages for fertilizers, pesticides, fuels and electricity, as well as transportation to the farm. The FS included the application of fertilizers (organic fertilizer and commercial synthetic fertilizer), pesticides, and the use of diesel by machinery. The functional units were per hectare and per ton of fresh citrus production.

Impact Assessment

In this study, the global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) were selected as evaluation objects, which were mainly driven by nutrient management [26]. The various life cycle impacts were calculated in accordance with International Organization for Standardization standards 14,040 and 14,044 [30,31].

The assessment formulas are as follows:

\[ EI_t = EI_t \text{ direct} + EI_t \text{ indirect}, \]

where \( EI_t \) represents the total potentials for \( t \) environmental impact (EI) category, \( t = 1, 2, 3 \) representing the impact category that includes GWP (kg CO\(_2\)-eq unit\(^{-1}\)), AP (kg SO\(_2\)-eq unit\(^{-1}\)) and EP (kg PO\(_4\)-eq unit\(^{-1}\)). \( EI_t \) direct refers to the potential emission value of environmental impact caused by inputs (fertilizers, pesticides, and diesel of machinery) in the process of their direct use in the arable farming stage. \( EI_t \) indirect means the potential emission value of environmental impact generated by various inputs in the production and transportation stages of agricultural materials.

\[ EI_t \text{ direct} = \Sigma (IR_t \times EF_{tFS}), \]
EI indirect = \( \Sigma (IR_i \times EF_{iMS}) \),

where \( IR_i \) represents the input rates (IR) of item i (fertilizers and pesticides consumption unit are kg, electricity consumption is kWh, diesel oil is L). \( EF_{iFS} \) means the emission factor (EF) of the input item i in the process of direct use in the arable farming stage. \( EF_{iMS} \) is the emission factors of the input of item i in the process of production and transportation. The emission factors of each input link on each environment are shown in Tables 1 and 2.

### Table 1. Emission index of global warming potential, acidification potential, and eutrophication potential in the agricultural materials production stage.

| Item                             | Unit     | Global Warming (kg CO\(_2\)-eq Unit\(^{-1}\)) | Acidification (kg SO\(_2\)-eq Unit\(^{-1}\)) | Eutrophication (kg PO\(_4\)-eq Unit\(^{-1}\)) | Reference |
|----------------------------------|----------|-----------------------------------------------|---------------------------------------------|-----------------------------------------------|-----------|
| Nitrogen production and transportation | kg N     | 8.28                                          | 0.0252                                      | 0.00303                                       | [S1,S2]  |
| Phosphorus production and transportation | kg P\(_2\)O\(_5\) | 0.79                                          | 0.0006                                      | 0.00008                                       | [S1,S2]  |
| Potassium production and transportation | kg K\(_2\)O | 0.55                                          | 0.00048                                     | 0.00006                                       | [S1,S2]  |
| Pesticides                        | kg       | 19.1                                          | 0.0105                                      | 0.0119                                        | [S3,S4]  |
| Diesel                            | L        | 3.75                                          | 0.0658                                      | 0.0119                                        | [S4,S5]  |
| Electricity                        | KW h     | 0.75                                          | 0.0145                                      | 0.0084                                        | [S2,S6]  |

\(^1\) Supplemental references for emission indexes are shown in the supplementary materials.

### Table 2. The quantity of pollutants emitted (expressed as percentage of inputs) in the arable farming stage.

| Pollution Emission | Emission Factors | References |
|--------------------|------------------|------------|
| NH\(_3\) emission  | 11.1% of nitrogen (N) fertilizer input | [S7]       |
| NO\(_3\) emission  | 9.97% of N fertilizer input          | [S8]       |
| N\(_2\)O emission  | 1.25% of N fertilizer input          | [S9,S10]  |
| Direct N\(_2\)O emission | 1.25% of N fertilizer input | [S9,S10]  |
| Indirect N\(_2\)O emission | 1% NH\(_3\) emission +2.5% NO\(_3\) emission | [S10,S11] |
| NO\(_X\) emission  | 10% of the N\(_2\)O emission         | [S10]      |
| Phosphorus loss     | 0.2% of total P\(_2\)O\(_5\) fertilizer input | [S12,S13] |

\(^1\) Supplemental references for emission indexes are shown in the supplementary materials.

### Result Interpretation

The excel 2016 and Duncan test by the Kruskal–Wallis one-way ANOVA in SPSS (20.0 version) were used to analysis the result of LCA. Results are explained at this phase to identify the key factors of the environmental impacts of citrus production in the Danling County, Sichuan, southwest China.

#### 2.2.3. Farmer Grouping by Yield and Nitrogen Fertilizer Use Efficiency

The study adopted a farmer grouping method by yield and partial factor productivity of N fertilizer (PFP-N) [28] to analyze the relationship between various environmental impacts and related management practices among farmers. Based on average yield and PFP-N (Figure 2), the survey data of 155 farmers were divided into the following four groups: HH (high yield and high PFP-N), HL (high yield and low PFP-N), LH (low yield and high PFP-N), LL (low yield and low PFP-N) (Figure 1). The numbers of farmers in the LL, LH, HL, and HH groups were 62, 17, 30 and 46, respectively. The partial factor productivity of N fertilizer (PFP-N) (yield (kg ha\(^{-1}\)) divided by N application rate (kg ha\(^{-1}\)) means the amount of N fertilizer applied when producing unit yield, which is a significant index of N fertilizer efficiency in crop production [32,33].
155 farmers’ surveys are given in Table 3. For the input items, the average amounts (range) of N, phosphate (P), and potassium (K) fertilizer were 847 kg N ha\(^{-1}\) (140–2094 kg N ha\(^{-1}\)), 443 kg P\(_2\)O\(_5\) ha\(^{-1}\) (84.6–1400 kg P\(_2\)O\(_5\) ha\(^{-1}\)), and 693 kg K\(_2\)O ha\(^{-1}\) (130–1754 kg K\(_2\)O ha\(^{-1}\)), respectively. Chemical fertilizer accounted for 67.8–75.2\% of total fertilizer input. In addition, the average input of pesticide, electricity used for pesticide application and irrigation, and diesel used for mechanical weeding was 21.2 kg ha\(^{-1}\), 79.1 kWh ha\(^{-1}\) and 28.9 L ha\(^{-1}\), respectively. For the output of citrus production (Table 3), the average yield (range) was 24.4 t ha\(^{-1}\) (1.88–56.3 t ha\(^{-1}\)), resulting in an averaged PFP-N of 34.0 kg kg\(^{-1}\).

Figure 2. Relationships between citrus yield and partial factor productivity of nitrogen fertilizer (PFP-N) in Danling County, Sichuan, southwest China based on returned survey questionnaires from 155 farmers in 2017 and 2018. The black dotted lines represented the mean of citrus yield and PFP-N. Based on the average yield and PFP-N, the survey data obtained from the 155 farmers were divided into the following four groups: HH (high yield and high PFP-N), LH (low yield and high PFP-N), HL (high yield and low PFP-N), and LL (low yield and low PFP-N). The numbers of farmers in the LL, LH, HL, and HH groups were 62, 17, 30 and 46, respectively. The black circle represented the mean (with 95% confidence interval) of the yield and PFP-N in each group.

2.3. Experimental Design and Management

During the 2018 and 2019 cropping seasons, five field experiments were conducted in the main citrus producing area of Danling County, and two treatments were set in each field experiment: local fertilization recommendation (LR) and farmer practice (FP) in HH group. The soil properties used for field experiments were shown in Table S1. The fertilizer rate of LR treatment was determined basing on soil nutrient status and fertilizer recommendation by agricultural extension personnel of local government (Table S2). All field experiments were conducted in farmers’ orchards. Except for fertilizer application, the treatments were managed by farmers in the same manner.

2.4. Data Analysis and Statistics

In order to compare the spatial distribution difference of environmental impacts in citrus orchards in Danling County, the spatial interpolation method of ArcGIS10.2 was used for geostatistical analyses (Figure 5). The excel 2016 was used to compare the data analysis and statistics. The Duncan test by the Kruskal–Wallis one-way ANOVA in SPSS (20.0 version) was used to test the significant differences at \(p < 0.05\) (Figures 6, 7 and 10).

3. Results

3.1. The Input, Output and Environmental Impacts of Citrus Production System in Danling County

The investigated inputs and outputs of the citrus production in Danling County based on the 155 farmers’ surveys are given in Table 3. For the input items, the average amounts (range) of N, phosphate (P), and potassium (K) fertilizer were 847 kg N ha\(^{-1}\) (140–2094 kg N ha\(^{-1}\)), 443 kg P\(_2\)O\(_5\) ha\(^{-1}\) (84.6–1400 kg P\(_2\)O\(_5\) ha\(^{-1}\)), and 693 kg K\(_2\)O ha\(^{-1}\) (130–1754 kg K\(_2\)O ha\(^{-1}\)), respectively. Chemical fertilizer accounted for 67.8–75.2\% of total fertilizer input. In addition, the average input of pesticide, electricity used for pesticide application and irrigation, and diesel used for mechanical weeding was 21.2 kg ha\(^{-1}\), 79.1 kWh ha\(^{-1}\) and 28.9 L ha\(^{-1}\), respectively. For the output of citrus production (Table 3), the average yield (range) was 24.4 t ha\(^{-1}\) (1.88–56.3 t ha\(^{-1}\)), resulting in an averaged PFP-N of 34.0 kg kg\(^{-1}\).
Table 3. Inputs and outputs of the citrus production in Danling County, Sichuan, southwest China based on returned survey questionnaires from 155 farmers in 2017 and 2018.

| Item                                                                 | Mean  | Median | Range       | Standard Error |
|----------------------------------------------------------------------|-------|--------|-------------|----------------|
|                                                                      | Max   | Min    | Max         |                |
| **Total fertilizer (kg ha\(^{-1}\))**                               |       |        |             |                |
| N                                                                    | 847   | 802    | 2094        | 30.4           |
| P\(_2\)O\(_5\)                                                       | 443   | 395    | 1400        | 17.9           |
| K\(_2\)O                                                             | 693   | 643    | 1754        | 24.6           |
| Chemical fertilizer (kg ha\(^{-1}\))                                |       |        |             |                |
| N                                                                    | 598   | 603    | 1420        | 19.5           |
| P\(_2\)O\(_5\)                                                       | 324   | 286    | 953         | 14.0           |
| K\(_2\)O                                                             | 535   | 513    | 1237        | 18.7           |
| Organic fertilizer (kg ha\(^{-1}\))                                 |       |        |             |                |
| N                                                                    | 249   | 169    | 1171        | 20.7           |
| P\(_2\)O\(_5\)                                                       | 119   | 75     | 846         | 11.2           |
| K\(_2\)O                                                             | 158   | 102    | 1171        | 14.8           |
| Pesticide (kg ha\(^{-1}\))                                          | 21.2  | 17.8   | 96.6        | 1.36           |
| Electricity (kWh ha\(^{-1}\))                                       | 79.1  | 57.0   | 327         | 5.48           |
| Diesel (L ha\(^{-1}\))                                              | 28.9  | 18.8   | 169         | 2.45           |
| **Yield (t ha\(^{-1}\))**                                          | 24.4  | 23.8   | 56.3        | 1.88           |
| **PFP-N (kg kg\(^{-1}\))**                                         | 34.0  | 28.0   | 154         | 1.95           |

The invisible environmental cost of citrus production is shown in Table 4. The average GWP, AP, and EP were 11,665 kg CO\(_2\)-eq ha\(^{-1}\), 184 kg SO\(_2\)-eq ha\(^{-1}\), and 110 kg PO\(_4\)-eq ha\(^{-1}\), respectively. For producing one ton of citrus fruit, the average values of GWP, AP, and EP were 642 kg CO\(_2\)-eq t\(^{-1}\), 9.97 kg SO\(_2\)-eq t\(^{-1}\), and 5.97 kg PO\(_4\)-eq t\(^{-1}\), respectively. Each item of environmental impact showed great variability among farmers, as indicated by their range and standard error (Table 4).

Table 4. Main environmental impact (indicated by global warming, acidification, and eutrophication potential) expressed as per hectare or per ton of citrus production in Danling County, Sichuan, southwest China based on returned survey questionnaires from 155 farmers in 2017 and 2018.

| Item                                                                 | Mean  | Median | Range     | Standard Error |
|----------------------------------------------------------------------|-------|--------|-----------|----------------|
|                                                                      | Max   | Min    | Max       |                |
| **Per hectare of the citrus production**                             |       |        |           |                |
| Global warming potential (kg CO\(_2\)-eq ha\(^{-1}\))                | 11,665| 11,785 | 26,987    | 349            |
| Acidification potential (kg SO\(_2\)-eq ha\(^{-1}\))                | 184   | 176    | 445       | 6.26           |
| Eutrophication potential (kg PO\(_4\)-eq ha\(^{-1}\))                | 110   | 105    | 271       | 3.90           |
| **Per ton of the citrus production**                                 |       |        |           |                |
| Global warming potential (kg CO\(_2\)-eq t\(^{-1}\))                 | 642   | 483    | 3629      | 41.2           |
| Acidification potential (kg SO\(_2\)-eq t\(^{-1}\))                 | 9.97  | 7.85   | 55.0      | 0.64           |
| Eutrophication potential (kg PO\(_4\)-eq t\(^{-1}\))                | 5.97  | 4.67   | 33.1      | 0.38           |

Further analyses showed that the production and application of fertilizers contributed 45.6–46.2% and 46.2–49.5% to GWP, respectively. Similarly, the application of fertilizers was the major contributor to the AP (89.4–89.8 %) and EP (97.8–97.9 %) (Figure 3). Specific to the contribution of fertilizers to environmental costs, the production and application of N fertilizer accounted for more than 95% of the total environmental costs expressed either per hectare of citrus cropping area or per ton of yield production (Figure 4). In contrast, the inputs of pesticide, diesel, and electricity contributed less than 5% to GWP, AP, and EP under both function units (Figure 3).
Figure 3. Contribution of individual input to the environmental impact (indicated by global warming, acidification, and eutrophication potential) in Danling County, Sichuan, southwest China based on returned survey questionnaires from 155 farmers when expressed as per hectare of citrus planted area (a) or per ton of citrus production (b). MS and FS represented the agricultural materials production stage and arable farming stage, respectively.

Figure 4. Contribution of fertilizers input to the environmental impact (indicated by global warming, acidification, and eutrophication potential) in Danling County, Sichuan, southwest China based on returned survey questionnaires from 155 farmers when expressed as per hectare of citrus planted area (a) or per ton of citrus production (b). MS and FS represented the agricultural materials production stage and arable farming stage, respectively.
Furthermore, the geographic information system (GIS) map showed large spatial variation in N fertilizer input and environmental costs (Figure 5). The spatial distribution of environmental costs of citrus production in Danling County was overall matched with that of N fertilizer input (Figure 5). In addition, the N input and environmental cost of citrus production in the newly developing areas of Danling County were lower than those in the major citrus production areas of Danling County (Figure 5; Supplementary Figure S1).

![Figure 5](image_url)

**Figure 5.** Geographical distribution of total nitrogen fertilizer input (a), global warming potential (b), acidification potential (c), and eutrophication potential (d) when expressed as per ton of citrus production in Danling County, Sichuan, southwest China based on returned survey questionnaires from 155 farmers in 2017 and 2018.

### 3.2. Potential of Emission Reduction Based on Grouping of Farmers Practice

Grouping methods according to citrus yield and PFP-N (Figure 2), the inputs and outputs of these four groups are shown in Table 5. The HH group had highest averaged yield (37.1 t ha⁻¹) and PFP-N (58.0 kg kg⁻¹), which were 52% and 70.6% higher than these average values of all 155 orchards, respectively. On the other hand, the HH group used fewer fertilizers than the other 155 orchards (Tables 3 and 5).
Table 5. Inputs and outputs of citrus production system among the four groups in Danling County, Sichuan, southwest China based on returned survey questionnaires from 155 farmers in 2017 and 2018.

| Item                        | Input                                | Orchard Group 1 |
|-----------------------------|--------------------------------------|-----------------|
|                             | LL                                   | LH              | HL              | HH              |
| Total fertilizer (kg ha⁻¹)  | N                                    | 857 ± 45.6b     | 456 ± 41.5c     | 1247 ± 56.1a   | 717 ± 37.1b     |
|                             | P₂O₅                                 | 442 ± 28.9b     | 243 ± 31.0c     | 592 ± 34.5a    | 421 ± 29.6b     |
|                             | K₂O                                  | 707 ± 37.4b     | 427 ± 46.1c     | 923 ± 58.8a    | 624 ± 35.1b     |
| Chemical fertilizer (kg ha⁻¹)| N                                    | 631 ± 31.3b     | 385 ± 41.6c     | 763 ± 31.4a    | 526 ± 32.5b     |
|                             | P₂O₅                                 | 323 ± 21.1a     | 203 ± 31.8b     | 389 ± 30.6a    | 327 ± 27.1a     |
|                             | K₂O                                  | 565 ± 30.6a     | 381 ± 46.1b     | 613 ± 38.7a    | 502 ± 32.7a     |
| Organic fertilizer (kg ha⁻¹)| N                                    | 226 ± 25.7b     | 70.5 ± 16.8c    | 484 ± 64.0a    | 191 ± 28.5b     |
|                             | P₂O₅                                 | 119 ± 16.7b     | 39.9 ± 10.0c    | 203 ± 26.6a    | 94.4 ± 21.3bc   |
|                             | K₂O                                  | 142 ± 17.3b     | 45.6 ± 12.3c    | 310 ± 47.2a    | 122 ± 23.4bc    |
| Pesticide (kg ha⁻¹)         |                                      | 17.6 ± 1.84bc   | 15.7 ± 3.72c    | 26.7 ± 3.72a   | 24.4 ± 2.49ab   |
| Electricity (kWh ha⁻¹)      |                                      | 62.2 ± 7.91b    | 70.9 ± 14.9ab   | 99.0 ± 14.6a   | 92.1 ± 9.76ab   |
| Diesel (L ha⁻¹)             |                                      | 34.5 ± 4.71ab   | 44.1 ± 7.36a    | 20.0 ± 3.70b   | 21.6 ± 3.24b    |

Output

| Item                        | Yield (t ha⁻¹) | PFP-N (kg kg⁻¹) |
|-----------------------------|---------------|-----------------|
|                             | LL            | LH              | HL              | HH              |
| Yield (t ha⁻¹)              | 13.6 ± 0.71d  | 18.9 ± 1.07c    | 31.1 ± 1.19b    | 37.1 ± 1.51a    |
| PFP-N (kg kg⁻¹)             | 17.2 ± 0.93c  | 46.6 ± 4.61b    | 25.5 ± 0.83c    | 58.0 ± 4.07a    |

¹ Based on average yield and average partial factor productivity of nitrogen-fertilizer (PFP-N), the survey data obtained from the 155 farmers were divided into the following four orchard groups: HH (high yield and high PFP-N), LH (low yield and high PFP-N), HL (high yield and low PFP-N), and LL (low yield and low PFP-N). The numbers of orchards in the LL, LH, HL, and HH groups were 62, 17, 30, and 46, respectively. The PFP-N was an accessible index of N use efficiency in crop production, which was calculated as yield (kg ha⁻¹) divided by N application rate (kg ha⁻¹). ² Values are means ± standard error and different letters after the values in the same row indicate significant differences between orchard groups at p < 0.05.

There were also significant differences in GWP, AP, and EP among the four groups under both function units (Table 3, Table 5). When expressed as per ha of citrus cropping area, the average GWP of HH group was decreased by 14.1%, 34.8%, and 12.0% than that of LL group, HL group, and the average values of all 155 orchards, respectively. Similarly, the average AP was decreased by 16.1%, 41.0%, and 14.8%, respectively; and the EP was decreased by 16.2%, 42.0%, and 15.2%, respectively (Figure 6). When expressed as per ton of yield production, the average GWP of HH group was decreased by 72.5%, 25.4%, 44.9%, and 55.5% than that of LL group, LH group, HL group, and the average values of all 155 orchards, respectively. Similarly, the average AP was decreased by 73.0%, 20.3%, 49.9%, and 56.6%, respectively; and the EP was decreased by 73.0%, 18.1%, 50.7%, and 56.6%, respectively (Figure 7).

Less application of N fertilizer, especially chemical N fertilizer resulted in lower environmental costs in HH group (Figures 6 and 7). Such management was related with among HH group orchards and other orchards (Figure 8). In term of farmer age, the proportion of farmers less than 50 years old was 58% in HH group, which was higher than that in other groups. For education level, 84% of family major labor in HH group received junior high school and above education, which was better than other groups. In addition, more than 64% of orchards are managed by less than two labors. For orchard conditions, high yield orchards were planted in sloping and/or flat fields with proper planting density (625–1112 plant ha⁻¹). Furthermore, the proportion of citrus orchards fertilized less than four times was 47% in HH group, which was obviously higher than other groups (Figure 7).
Figure 6. Global warming potential (a), acidification potential (b), and eutrophication potential (c) per hectare of citrus production in four groups of investigated farmers in Danling County, Sichuan, southwest China. The four groups included: HH (high yield and high PFP-N), LH (low yield and high PFP-N), HL (high yield and low PFP-N), and LL (low yield and low PFP-N) groups, respectively. MS and FS represented the agricultural materials production stage and arable farming stage, respectively. The bars were means + standard error; The column with different letters indicated significant difference at p < 0.05.

Figure 7. Global warming potential (a), acidification potential (b), and eutrophication potential (c) per ton of citrus production in four groups of investigated farmers in Danling County, Sichuan, southwest China. The four groups included: HH (high yield and high PFP-N), LH (low yield and high PFP-N), HL (high yield and low PFP-N), and LL (low yield and low PFP-N) groups, respectively. MS and FS represented the agricultural materials production stage and arable farming stage, respectively. The bar indicated mean + standard error; The columns with different letters indicated significant difference at p < 0.05.
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1.9–49.5% than that with farmers' fertilization practice, and the PFP-N with LR treatment was increased with the FP treatment, the average values of GWP, AP and EP in the LR treatment were decreased by 33.5%, 34.8%, and 38.0–116% than that with the farmers' fertilization practice (Figure 9). Whereas, the fertilizer input of LR treatment was decreased by 13.4–30.8% than that of the farmers' fertilization practice (Supplementary Table S2).

3.3. The Environmental Impacts of the Citrus Production with Local Recommendation of Fertilization

Five field demonstrations with local recommendation of fertilization (LR) were further conducted to explore the potential to reduce environmental impact based on orchards of HH group. Under the same farmer management practice except fertilization, the citrus yield with LR treatment was increased by 1.9–49.5% than that with farmers' fertilization practice, and the PFP-N with LR treatment was increased by 38.0–116% than that with the farmers' fertilization practice (Figure 9). Whereas, the fertilizer input of LR treatment was decreased by 13.4–30.8% than that of the farmers' fertilization practice (Supplementary Table S2).

Taken together, the LR treatment resulted in significantly lower environmental impacts than the farmer's fertilization practice (Figure 10). When expressed as per ha of citrus cropping area, comparing with the FP treatment, the average values of GWP, AP and EP in the LR treatment were decreased by 21.2%, 23.1%, and 23.5%, respectively. When expressed as per ton of yield production, comparing with the FP, the average values of GWP, AP and EP with the LR treatment were decreased by 33.5%, 34.8%, and 35.2%, respectively.

| Group | Age | Education level | Population engaged in agriculture | Orchard topography | Planting density | Fertilization frequency per year |
|-------|-----|-----------------|-----------------------------------|--------------------|-----------------|----------------------------------|
| LL    | 44%| 21%             | 36%                               | 21%                | 22%             | 17%                              |
| LH    | 44%| 21%             | 36%                               | 21%                | 22%             | 17%                              |
| HL    | 44%| 21%             | 36%                               | 21%                | 22%             | 17%                              |
| HH    | 44%| 21%             | 36%                               | 21%                | 22%             | 17%                              |

Figure 8. Farmer practice for citrus production among the four groups in Danling County, Sichuan, southwest China based on returned survey questionnaires from 155 farmers in 2017 and 2018. The investigated items of farmer practice included age, education level, population engaged in agriculture, orchard topography, planting density (plants ha⁻¹), and fertilization frequency per year. The four groups included: HH (high yield and high PFP-N), LH (low yield and high PFP-N), HL (high yield and low PFP-N), and LL (low yield and low PFP-N) groups, respectively.
Figure 9. The correlation of yield (a) and PFP-N (b) between the local recommendation (LR) treatment and farmer practice (FP) treatment in five field experiments in Danling County, Sichuan, southwest China. The PFP-N was an index of nitrogen (N) use efficiency in crop production, which was calculated as yield (kg ha\(^{-1}\)) divided by N application rate (kg ha\(^{-1}\)).

Figure 10. The means of global warming potential (a, d), eutrophication potential (b, e), and acidification potential (c, f) in five field experiments when expressed as per hectare of citrus production (a-c) or per ton of the citrus production (d-f). LR and FP represented treatments of local recommendation and farmer practice, respectively. The bar indicated mean + standard error; The columns with different letters indicated significant difference at \( p < 0.05 \).
4. Discussion

4.1. A High Environmental Risk Existed in Citrus Production System in Danling County

The findings of this study indicate a high environmental risk for citrus production in Danling County (Table 4). Under the same system boundary in China, the value (expressed per ha of citrus cropping area) of the GWP of citrus production in Danling County was about 1.2–2.0 times higher than that of other fruit production [22,27], and about 2.9–5.1 times higher than that of vegetable and cereal crop production [22,25,26,34,35]. Specific to the citrus production system, the value (expressed per hectare of citrus cropping area) of the GWP was 1.6, 1.5, and 1.1 times higher than the previous reports of citrus in China [22], Iran [21], and Spain [21,24]. Similarly, higher values of AP and EP were also found in citrus production in Danling County when compared with previous studies conducted in other countries, including Iran [21], Spain [23,24,36], and Italy [23]. Furthermore, the environmental costs (expressed per one ton of citrus yield production) in this study were even higher than previous studies [21,24,26,27,37]. Considering the substantial difference of environmental cost in citrus production in Danling County and other regions [22], the whole environmental cost of the citrus production in China deserves further studies, with a detection of more hotspots at the county level.

The production and utilization of fertilizer were the most important factor to the environmental impacts which contributed 92.4–95.1%, 89.4–89.8% and 97.8–97.9% to the potential of GWP, AP and EP, respectively (Figure 3). This was consistent with previous studies finding that fertilizer related processes were the major contribution to environmental costs [21,22,26,27]. However, the extremely high fertilizer input resulted in substantially higher contribution to the environmental costs (Tables 3 and 4). The average inputs of chemical N, P\textsubscript{2}O\textsubscript{5}, and K\textsubscript{2}O fertilizer for citrus production were about 1.5–3.6, 1.33–6.3, and 4.0–5.2 times higher in this study than that in previous studies in other countries [21,24], and also higher than those for horticultural crops and cereal crops in China [22,25,26,34]. The reason for the high fertilizer input was due to the high benefit of citrus production and their misconception about plant requirements for nutrients. It is generally believed by farmers that a greater fertilizer input would yield more products and greater returns [4,38]. Furthermore, the production and application of N fertilizer accounted for more than 95% of the total costs derived from fertilizer related processes (Figures 3 and 4), thus the hotspots of environmental risk were spatially correlated with N fertilizer input (Figure 5). Therefore, the first option for reducing environmental impacts of the citrus production in this county would be to optimize nutrient management and reduce the fertilizer input.

4.2. Great Potential of Reducing Environmental Impact by Learning from Good Farmers

The great variation in citrus yield, PFP-N, environmental costs of citrus production within Danling County (Tables 3 and 4; Figures 2 and 5) raised the possibility to reduce the environmental impact by learning from excellent farmers [26,27,39]. The HH group had better performances in citrus yield, PFP-N, but with less fertilizer input and consequential lower environmental costs (Table 5; Figures 6 and 7). These differences might be explained by their management. On average, farmers in HH group are younger and have received a better education than farmers in other groups (Figure 8), and are conducive to the faster acquisition, update and apply new knowledge and technology [4]. In addition, the farmers in HH group applied fertilizer with less application times than others (Figure 8), which was correlated with less fertilizer input (Table 5). For the orchard establishment, orchards planted in sloping and/or flat fields with proper planting density were easier to realize high yield and high efficiency of nutrient management (Figure 8; Table 5). Therefore, learning the management pattern of HH group by other groups would be useful for formulation of regional industrial policies and demonstration to simultaneously achieve high yield, high economic benefit and low environmental cost at the county level.
4.3. Further Potential to Reduce Environmental Impact by Local Recommendation of Fertilization

It is noticeable that there is substantial potential to further reduce environmental impact of the citrus production from the HH group (Table 5), because such an impact was still much higher than previous studies [21,24]. Preliminary demonstrations conducted by local government and Danling STB have confirmed the possibility. With less fertilizer input (Table S1), the LR treatment resulted in higher citrus yield, higher PFP-N, and consequently lower environmental impacts than the farmer’s fertilization practice (Figure 9, Figure 10). Such results are consistent with previous studies indicating that cereal production with high yield and low environmental cost could be realized by integrative soil-crop nutrient management [25,39]. Considering that the inputs of N, P, and K fertilizer (Table S1) in the LR treatment is still higher than that in the expert recommendation in China [4], the 13–24% reduction of fertilizer input from farmer practices to the LR treatment was expected to have no negative effect on yield. A previous study also revealed that there were large opportunities to reduce the environmental impact of agriculture by eliminating nutrient overuse, while allowing for an approximately 30% increase in the production of major cereals [40]. Thus, it is reasonable to predict a further reduction of environmental cost for citrus production in Danling County, by optimizing fertilization strategy, including the right rate, right source, right place, and right time [41]. For example, citrus yield, N use efficiency, and water use efficiency can be greatly improved by fertigation technology [42].

4.4. The Last Mile to Realize the Sustainable Citrus Production in China’s County Level

The adoption of advanced knowledge and management techniques by farmers is the vital key to achieve sustainable citrus production at the county level in China. This study has provided evidence in facilitating the role of technical training in the adoption of more environmentally-friendly practices in agriculture [43]. Enhanced management measures had potential impacts on the sustainable development of agriculture under the smallholder farming practice [39,44]. Thus, the Danling STB was set up in 2017 to explore the limiting factors of the sustainable citrus production, and to conduct field trials, technical training, field demonstration and participatory innovation (Supplementary Figure S1). The farmers are intended to adopt recommended management practices when these limitations and farmers’ concerns are addressed [45]. In addition, policymakers should realize appropriate policy interventions and adjustments, such as enacting regulatory policies related to the use of fertilizer [42]. Finally, new media like Wechat, mobile Apps, and short videos could also be used to publicize the specific measures of scientific agronomic practices. Through these measures, the last mile could be eliminated to be close to sustainable citrus production in China’s county level.

5. Conclusions

This study was the first attempt to address the hotspots and optimization of the environmental cost of a typical citrus-producing county in China. The findings indicated that high environmental risks existed in the citrus production in the studied Danling County. Fertilization was identified as the most important factor contributing to the GWP, AP and EP under both function units. Meanwhile, the spatial distribution of environmental cost in this county was well matched with that of N input. Under the scenario of learning from excellent farmers, the HH orchard group with younger and more educated owners achieved better performances in citrus yield, PFP-N, while with less fertilizer input and lower environmental cost. Preliminary field experiments had confirmed that optimizing nutrient management could achieve higher yield, higher nutrient use efficiency, and lower environmental cost than the traditional fertilization practice in HH group at the local level. As the connex of local government, university, agro-material supplier and farmers, the Danling STB might facilitate to eliminate the current obstacles to realize the sustainable citrus production at county level. Overall, this study highlighted the importance to optimize farmer practices, especially their nutrient management in citrus production, which should be crucial for achieving the win-win target of productivity and
environmental sustainability. Considering the substantial differences in the citrus production, including soil type, climate condition, and orchard management in different regions, the whole environmental cost of the citrus production in China deserves further studies with more hotspots at the county level.

**Supplementary Materials:** The following information is available online at http://www.mdpi.com/2071-1050/12/5/1827/s1, Figure S1, the locations of the citrus production in Danling County and the Danling Science and Technology backyards (Danling STB); Table S1, the soil properties used for field experiments at five sites; Table S2, the fertilizer inputs of five field experiments; and Supplemental references for emission index.

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