Article

Externalities of Pesticides and Their Internalization in the Wheat–Maize Cropping System—A Case Study in China’s Northern Plains

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Abstract: When the production or use of a product imposes a cost or benefit on a third party, this is referred to as an externality. Externalities of pesticides are associated with social and environmental costs. However, there is still a lack of a systematic method for evaluating and internalizing the externalities of pesticides. This study utilizes the pesticide’s environmental impact quotient and environmental accounting methods to assess the external costs associated with pesticide usage in the winter-wheat–summer-maize cropping system in China’s northern plains, with a specific focus on the pesticide use in Botou City during the year 2020 as a case study. Additionally, we introduce the concept of the net external value of pesticides and propose a methodology for its internalization, aiming to quantify the external costs induced by pesticide usage and explore the possibility of integrating them into market transactions. The results showed that the total external costs of pesticide use are 423.9 USD ha⁻¹, with a positive external value of 171.9 USD ha⁻¹ and a net external value of –252.0 USD ha⁻¹. The negative external costs associated with pesticide use outweigh the positive external values. External costs varied significantly according to environmental receptors, after retaining two significant figures: applicators accounted for 45% of the total external costs, followed by pickers (32%), consumers (11%), groundwater (4.5%), fish (3.9%), beneficial insects (1.7%), birds (1.3%), and bees (1.1%). The external costs of maize cultivation were 33% higher than those of wheat cultivation. The application of herbicides resulted in the highest external costs compared with fungicides and insecticides. Based on the internalization of the results, imposing an ecological tax on pesticide users is recommended, with rates of 3.29% for wheat and 6.76% for maize. This research contributes to sustainable agricultural development by providing valuable insights for farmers in selecting environmentally friendly pesticides and informing the implementation of ecological taxes on pesticide usage.

Keywords: pesticide pollution; environmental cost; agricultural sustainable development; eco-tax

1. Introduction

In 2020, the pesticide application rate in China was five times the global average, 4.03 times that in the UK, and 5.15 times that in the US [1]. Pesticides are heavily used to ensure food production and income from agricultural products. Pesticide emissions cause many environmental costs, for example, to pollination [2], water quality [3], biodiversity [4], and disease control [5]. Moreover, a crucial finding that demands attention is that merely 0.1% of pesticide application successfully reaches its designated target; in stark contrast, an astonishing 99.9% of chemical pesticides are directly released into the environment [6]. However, these external costs are not reflected or internalized in the market price, which may negatively influence human well-being and environmental protection costs [7–10].
Therefore, a comprehensive assessment of the external costs associated with the use of pesticides in crop production and their internalization at market prices is crucial [11,12].

Recently, efforts to quantify the externalities of pesticides have gained immense momentum. Based on data from 1989–2009 in the European region, Antonini and Maria [13] revealed that pesticide use increases implicit environmental costs and that farms’ environmental sustainability is negatively correlated with economic sustainability. A simulation study in sub-Saharan African countries found that pesticide use significantly increased crop productivity (output value); however, health expenditures and loss of labor work time due to pesticide-induced diseases were more severe [14]. Peter et al. [15] quantified the damage to human health caused by the use of 133 pesticides in Europe and found an average burden of 2.6 h of life lost per person or a cost of EUR 12 per person. Using data from papers covering the period of 1980–2014, Denis and Thomas estimated that the external costs of pesticide use in the United States in four areas, including regulatory costs, human health costs, environmental costs, and defensive expenditures, amounted to USD 47 billion [16].

Most studies assessing external costs from pesticides are based on toxicity impacts on humans and the environment; for instance, a modeling methodology utilizing transparent matrix algebra is employed to quantitatively assess the health effects of pesticide residue exposure in various directly processed grain crops [15]. The environmental impact quotient method of pesticides (EIQ) uses the toxicological properties of the active ingredients of pesticides to evaluate environmental damage [17,18]. Pesticide environmental accounting (PEA) uses economic methods to evaluate the externalities of pesticide use. The combination of the EIQ and PEA models has received an excellent appraisal of the externalities of pesticides [19,20]. For example, Praneetvatakul et al. calculated the external costs of pesticide use in Thailand using PEA and tools [21]. Pretty and Bharucha used the PEA and EIQ to calculate the external costs of pesticides in Asia and Africa and developed the corresponding integrated pest management (IPM) [22]. PEA and EIQ have been applied in many regions to determine the external costs of pesticides, but there are no studies on the winter-wheat–summer-maize (WWSM) system in China’s Northern Plain. The WWSM cropping system holds a pivotal position in China’s agriculture, contributing approximately 55% of the country’s total grain output. The WWSM system has found prominence in North China, primarily owing to the region’s well-suited cold winter and hot summer climate, favorable soil conditions, and significant demand in the food market. Consequently, North China has emerged as the principal planting area for the WWSM system. The WWSM system is the main cropping pattern in the North China Plain, where wheat and maize production account for approximately 50% and 40% of the total national production, respectively [23]. Although previous studies quantified the external costs of pesticides using the PEA and EIQ methods, they did not internalize the externalities into market prices. The EIQ and PEA provides a comprehensive and systematic evaluation of the impact of three types of pesticides on different ecological receptors. Applying this index allows for a ‘diagnosis’ of the environmental impact of pesticides in the winter-wheat–summer-maize cropping system in China’s North Plain from several perspectives: crops, pesticides, and receptors. It also suggests directions for efforts to reduce negative externalities.

China has 8.5% of the world’s arable land but uses 43% of the world’s pesticides [1]. High pesticide application rates in China may lead to higher external costs of pesticides, resulting in more severe market failure. Using WWSM as a case study, this study was conducted to estimate the external costs and internalize them into the market prices of wheat and maize crops. The objective of this study is to quantify the external costs caused by pesticide usage and explore the feasibility of internalizing these costs into market transactions. Specifically, this study aimed to (1) evaluate the externalities of pesticide use in the WWSM system, (2) identify hotspot pesticides in the WWSM system, and (3) internalize the externalities of pesticide use in the market price. This study can provide scientific support for the sustainable development of agriculture in the North Plain region.
of China, offer valuable insights for farmers in selecting environmentally friendly pesticides, and provide information for the implementation of an ecological tax on pesticide usage.

2. Material and Methods

2.1. Study Site and Data Collection

The study site is located in Botou City, Hebei Province, which is the main grain-production area in China’s Northern Plain (Figure 1). There are 84,900 hectares of farmland where WWSM is a typical cropping system. The city has a temperate humid continental monsoon climate, with an annual average temperature of 12.7 °C, a frost-free period of 187 days, an annual average sunshine of 2784 h, and an annual average precipitation of 543 mm. The local plant-protection station of Botou City provided data on pesticide use in the winter wheat and summer maize systems in 2020 (Table 1). Pesticide EIQ data are available from Cornell University’s New York State Integrated Pesticide Management website.

![Location of study site](image)

**Figure 1.** Location of study site.

**Table 1.** Types of pesticides used in wheat–maize rotation.

<table>
<thead>
<tr>
<th>Pesticide Type</th>
<th>Active Ingredient</th>
<th>Main Active Ingredients</th>
<th>Pesticide Usage (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbicide</td>
<td>3% Florasulam-Carfentrazone-ethyl</td>
<td>Dinitroaniline</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>40% MCPA-isooctyl-Florasulam</td>
<td>Dinitroaniline</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>25% Fenpyrazzone-Atrazine</td>
<td>Triazine</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>35% Nicosulfuron-Mesotrione-Atrazine</td>
<td>Triazine</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>30% Topramezone</td>
<td>Pyrazolones</td>
<td>0.12</td>
</tr>
<tr>
<td>Insecticide</td>
<td>10% Bifenthrin-Thiamethoxam</td>
<td>Neonicotinoid</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>Imidacloprid</td>
<td>Neonicotinoid</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>10% Emamectin-Benzoate-Indoxacarb</td>
<td>Carbamate</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>4% Emamectin-Benzoate-Beta-cypermethrin</td>
<td>Pyrethroid</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Table 1. Cont.

<table>
<thead>
<tr>
<th>Pesticide Type</th>
<th>Active Ingredient</th>
<th>Main Active Ingredients</th>
<th>Pesticide Usage (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Chemical Structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Classification</td>
<td></td>
</tr>
</tbody>
</table>

Fungicide
- Emamectin·Benzoate·Hexaflumuron: Carbamate, 0.52
- 30% Thiamethoxam: Neonicotinoid, 1.05
- Clothianidin·Imidacloprid: Neonicotinoid, 1.80
- 32.5% Difenoconazole·Azoxytrobin: Triazole, 0.60
- 3% Difenoconazole: Triazole, 1.80
- Triticonazole·Pyraclostrobin: Pyrazolinoine, 0.23
- 30% Tebuconazole·Prochloraz: Triazole, 0.53
- Total: 14.09

Note: Active ingredients are obtained from the pesticide label information, not the pesticide trade name. Pesticide use is the actual average amount of pesticide product used in the wheat-maize cropping system.

2.2. Evaluation of Pesticides’ Externalities

2.2.1. Environmental and Health Impact Assessment with EIQ

The EIQ model evaluates the environmental and health effects of the active ingredients of pesticides on eight environmental receptors: applicator effects, picker effects, consumer exposure potential, groundwater leaching, fish, birds, bees, and other beneficial organisms. For each receptor, this evaluation considers several factors, including acute LC\(_{50}\) for mammalian skin contact; toxicity to fish, birds, bees, and beneficial insects; long-term effects on mammalian health; residual time of pesticides on soil and plant surfaces; runoff; and leaching potential of pesticides. For each active ingredient, EIQ generates an index for each receptor to reflect its impact on the environment and health by weighing these factors, as shown in Equation (1).

\[
EIQ = \frac{C[DT \times 5] + (DT \times P) + [(C \times ((S + P)/2) \times SY) + (L)] + [(F \times R) + (D \times ((S + P)/2) \times 3) + (Z \times P \times 3) + (B \times P \times 5)]}{3}
\]  

where \(DT\) is the toxicity of pesticides to human skin, \(D\) is the toxicity to birds, \(C\) is the chronic toxicity to humans, \(S\) is the soil half-life, \(SY\) is the systemic toxicity (the ability of the pesticide to be absorbed by plants), \(Z\) is the toxicity to bees, \(F\) is the toxicity to fish, \(B\) is the beneficial arthropod toxicity, \(L\) is the leaching potential, \(R\) is the surface loss coefficient, and \(P\) is the plant surface half-life.

In addition, if a pesticide contains multiple active ingredients, the EIQ index of the pesticide is the sum of all active ingredients.

2.2.2. PEA

PEA classifies the index from EIQ into three coefficient levels of potential risk that correspond to 0.5 (low), 1.0 (medium), and 1.5 (high) times the average external cost of an active ingredient [18]. In this study, the average external cost of an active ingredient in each receptor is referred to in the UK, Germany, and the United States [18]. Therefore, we introduce the adjustment coefficients, i.e., the ratios of per capita GDP between China and the three countries, to reflect the scenario of China. We assume that lower-income countries have lower labor and external costs, government supervision costs, and ecological restoration costs. Thus, we applied the adjustment coefficient \(F_g\) to reflect the scenario in China, as shown in Equation (2).

\[
C_r = F_g \times C_{Dr} = \frac{PGDP_C}{PGDP_D} \times C_{Dr}
\]  

where \(C_r\) is the average external cost in terms of receptor \(r\) in China, USD kg\(^{-1}\); \(r\) is one of the eight pesticide receptors, including applicators, pickers, consumers, groundwater, fish, birds, bees, and beneficial organisms from 1 to 8; \(F_g\) is the adjustment coefficient; \(C_{Dr}\) is the average external cost in terms of receptor \(r\) in the UK, Germany, and the United States [24].
PGDP\textsubscript{C} is the per capita GDP of China; and PGDP\textsubscript{D} represents the average per capita GDP of the United Kingdom, Germany, and the United States [25]. Finally, we consider inflation over the last decade. Thus, the average external cost of the active pesticide ingredients in China was calculated (Table 2).

Table 2. Average external cost of pesticide active ingredients in China (USD kg\textsuperscript{-1}).

<table>
<thead>
<tr>
<th>EIQ Category</th>
<th>Applicators</th>
<th>Pickers</th>
<th>Consumers</th>
<th>Groundwater</th>
<th>Fish</th>
<th>Birds</th>
<th>Bees</th>
<th>Beneficial Insects</th>
</tr>
</thead>
<tbody>
<tr>
<td>External cost</td>
<td>5.69</td>
<td>4.08</td>
<td>26.89</td>
<td>6.21</td>
<td>7.30</td>
<td>2.93</td>
<td>2.30</td>
<td>2.93</td>
</tr>
</tbody>
</table>

Then, each pesticide’s negative externality value (NEV) was calculated using Equation (3).

\[
NEV_p = \sum_{j=1}^{n} \left( R_p \times A_{pj} \times \sum_{r=1}^{8} \{ C_r \times F_{rj} \times (F_{ar}|r = 1, 2) \} \right)
\]  

(3)

where \( NEV_p \) (negative externality value) is the negative externality cost of pesticide \( p \), USD ha\textsuperscript{-1}; \( R_p \) denotes the application rate of pesticide \( p \), kg ha\textsuperscript{-1}; \( A_{pj} \) represents the proportion of active ingredient \( j \) in pesticide \( p \) (%); \( C_r \) is the average external cost of active pesticide ingredient in China, USD kg\textsuperscript{-1}; \( F_{rj} \) is the potential risk coefficient of receptor \( r \) in terms of active ingredient \( j \); and \( F_{ar} \) is the adjustment coefficient of the agricultural worker and refers to Equation (3). The greater the number of farmers in a country, the greater the risk of pesticide exposure, and hence, the greater the possibility of being affected by pesticide exposure. Hence, we used an adjustment coefficient to reflect this scenario in China. This coefficient applies only to the first two receptors: pesticide users and pickers. \( F_{ar} \) was calculated using Equation (4).

\[
F_{ar} = \frac{FW_C}{FW_D}
\]  

(4)

where \( FW_C \) represents the proportion of Chinese farmers to total employees, and \( FW_D \) is the average proportion of farmers in the United Kingdom, Germany, and the United States.

2.3. Evaluation of Pesticides’ Net Value

Food security can be considered a significant positive externality in numerous instances [26–28]. A positive externality refers to a scenario of market failure wherein the advantages resulting from the economic activities of an agent are not entirely captured by market prices but instead yield gains for society as a whole or for individuals. The utilization of pesticides can effectively control the prevalence and spread of crop pests and diseases, leading to a reduction in crop damage. Consequently, this improves both crop yields and quality, thereby ensuring a stable food supply. A stable food supply has a positive impact on society at large by fulfilling people’s nutritional requirements, maintaining food security, and stabilizing market prices. It not only generates economic benefits for farmers but also has broader positive implications for society and the environment that are not adequately reflected in the benefits realized by individual farmers. Thus, the role of pesticide use in stabilizing the food supply can be defined as a positive externality of pesticide use.

Drawing upon this theory, we have conducted calculations to determine the positive externality of pesticide use. The underlying logic of these calculations is to consider China’s financial expenditure on agriculture as the total input for ensuring food security. In other words, the aim is to estimate the positive externalities of pesticide use by leveraging the data from China’s agricultural fiscal expenditure. This total input is then divided by the national increase in food production resulting from that expenditure, yielding the value of security per unit of increased food production. By multiplying the value of security per unit of increased food production by the food production recovered from pesticide use, we
obtain the value of the positive externality of pesticide use. On a global scale, pesticide use has, on average, recovered 21% of wheat yields and 37% of maize yields [29]. According to Li’s study, China’s financial expenditure on supporting agriculture has contributed 57% to grain production [30]. Additionally, The State of Food Security and Nutrition in the World 2022, published by the FAO, states that stabilizing the food supply contributes 4% to maintaining food security [31]. Hence, we incorporate this correction for the value of increased food production in relation to food security, as illustrated in Equations (5) and (6).

\[
SY = \frac{ESA}{TGO \times C_{gl}}
\]  

(5)

where SY is the input of unit grain yield increase required to maintain a stable grain supply (USD kg\(^{-1}\)); ESA denotes China’s total fiscal expenditure on supporting agriculture, obtained from the Fiscal situation of China [32], with a value of RMB 239.04 billion; TGO is China’s total grain production, with the data sourced from the China Statistical Yearbook 2020 [33], indicating a value of 669.5 billion kilograms; an \(C_{gl}\) represents the contribution of China’s fiscal expenditure on supporting agriculture to grain production, estimated at 57% [30].

\[
PEV_{pc} = CY \times RF \times SY \times C_{fe}
\]  

(6)

where \(PEV_{pc}\) is the positive external value of pesticide p use on crop c. \(CY\) is the crop yield for the season. \(RF\) is the recovery of the yield loss rate: 21% for wheat and 37% for maize [29]. \(C_{fe}\) represents the contribution of maintaining food supply to ensuring food security, which is considered to be 4% [31]. \(CY\) and \(RF\) are derived from the average production and price data of wheat and maize in Botou City in 2020, obtained from the Hebei Provincial Bureau of Statistics [34].

The difference between positive value and negative externalities is the net externality of pesticide use, as shown in Equation (7).

\[
NV_{p} = PEV_{p} - NEV_{p}
\]  

(7)

where \(NV_{p}\) is the net value of pesticide use (USD ha\(^{-1}\)); \(PEV_{p}\) is the positive external value of the pesticide use (USD ha\(^{-1}\)); and \(NEV_{p}\) is the pesticides’ external cost (USD ha\(^{-1}\)).

2.4. Internalization of Externalities

The external costs of pesticide use must be internalized and reflected in the market [35]. Pesticide usage can lead to a series of potential negative effects on the environment, ecosystems, and human health. These adverse impacts may not be directly reflected in the costs borne by producers or users but are instead borne by society and the environment. The internalization of these external costs aims to ensure a more equitable, sustainable, and environmentally friendly approach to agriculture and food production. The traditional life cycle cost (LCC) is used to internalize the external cost of pesticides, as shown in Equation (8).

\[
Eco_{price} = Internal_{price} + External_{price} = \frac{LCC\times (1+\gamma)}{Y} + \frac{NV_{p}}{Y}
\]  

(8)

where \(Eco_{price}\) is the theoretical price of agro-products, accounting for both internal costs and externalities (USD kg\(^{-1}\)). The internal price is the price of agro-products based on internal farm costs. External price is the agro-product price according to its internalities, USD kg\(^{-1}\). LCC is the life cycle cost of agro-products and their transportation to the market (USD ha\(^{-1}\) yr\(^{-1}\)). \(Y\) is the cost–benefit ratio of LCC, and the cost–benefit ratios of wheat and maize in Hebei Province in 2020 are −1.97% and 16.38%, respectively [36]. \(Y\) is the yield of the agro-products (kg ha\(^{-1}\)). \(NV_{p}\) is the same as that in Equation (7).

Agro-ecological taxes can serve as an effective economic instrument to internalize the external costs associated with pesticide use and impose financial penalties accordingly [37].
Agro-ecological taxes are a mechanism that internalizes the negative impacts of agricultural activities on the environment and ecosystems by imposing taxes on farmers and agricultural enterprises. This tax system incentivizes environmentally friendly practices, promotes efficient resource utilization, and supports ecological restoration. It plays a pivotal role in steering agriculture towards a more sustainable and eco-friendly direction, safeguarding the environment, and ensuring the long-term sustainability of agriculture. By implementing an ecological tax on pesticide users, farmers can be incentivized to transition to more sustainable and environmentally friendly agricultural practices, reducing their reliance on pesticides and mitigating the adverse environmental and ecological impacts. The eco-tax can serve as a reference for the government to levy pesticide taxes on farmers or enterprises. The eco-tax ratio can be used as a reference and is calculated using Equation (9).

\[
Eco_{\text{ratio}} = \frac{Eco_{\text{price}} - Mk_{\text{price}}}{Mk_{\text{price}}} \times 100\%
\]

where \(Eco_{\text{ratio}}\) is the eco-tax ratio (%), \(Mk_{\text{price}}\) is the market price of wheat and maize (USD \(\text{kg}^{-1}\)), and \(Eco_{\text{price}}\) is the same as that in Equation (8).

3. Results

3.1. External Costs of Pesticide Use

Under the WWSM system, the total external costs of pesticide use were 423.9 USD ha\(^{-1}\) (Figure 2). The external cost of pesticide use of maize (283.2 USD ha\(^{-1}\)) was 200% higher than that of wheat (140.7 USD ha\(^{-1}\)) (Figure 2). The damage value of each environmental receptor of maize was also higher than that of wheat. The externalities varied from environmental receptors; applicators accounted for 45% of the total WWSM system externalities, followed by pickers (32%), and consumers (11%).

3.2. Net Value of Pesticide Use

Ensuring a stable food supply and safeguarding food security are among the positive external values of pesticide usage. According to Equations (5) and (6), the positive external value of pesticide use is 171.2 USD ha\(^{-1}\) for the WWSM system, summed from wheat (59.3 USD ha\(^{-1}\)) and maize (111.9 USD ha\(^{-1}\)). The negative external value of pesticide use...
significantly surpasses the positive external value, with a ratio of 2.5:1 (Figure 3). According to Equation (7), the net value of pesticide use is $-252.0 \text{ USD ha}^{-1}$, with a breakdown of $-81.4 \text{ USD ha}^{-1}$ for wheat and $-171.3 \text{ USD ha}^{-1}$ for maize. This indicates that pesticide use incurs external costs rather than external benefits.

![Figure 3. Net externality value of pesticide use. Note: NEV is the negative pesticide value, PEV is the positive value of pesticide use, and NV is the net value of pesticide use.](image)

### 3.3. The Hotspot Analysis of Pesticides

Fungicides contributed the most (45%) to the total external costs of wheat production, whereas herbicides contributed the most (60%) to maize production (Figure 4a). Regarding the WWSM system, herbicides accounted for 52% of the total external costs, followed by insecticides (24%) and fungicides (23%). The herbicides resulted in the highest external costs (Figure 4a).

![Figure 4. Contributors of total external costs in the wheat, maize, and WWSM system production based on pesticide type (a) and active ingredients (b).](image)

In the comparison of external costs between maize and wheat, it is evident that pesticides used in maize production constituted the majority (283.2 USD ha$^{-1}$, 66.8%) of...
the total external costs in the WWSM cropping system. These findings underscore the significant environmental impact associated with pesticide usage in maize cultivation. The four pesticides with the highest external costs in WWSM are mainly from maize cultivation, which were 25% fenpyrazone·atrazine (21%), 35% nicosulfuron·mesotrione·atrazine (18%), 32.5% difenoconazole·azoxystrobin (16%), and clothianidin·imidacloprid (15%) (Figure 4b).

3.4. The Internalization of Externalities

Table 3 shows the results of internalizing the external costs of pesticides. Eco-prices incorporate environmental costs into the market prices. After the external costs were added, the eco-prices for wheat and maize were 0.3391 USD kg\(^{-1}\) and 0.3126 kg\(^{-1}\), respectively. Utilizing Equation (9), we computed the ecological tax rates for pesticide usage in wheat and maize as −3.29% and −6.67%, respectively. Negative eco-tax rates signify the dominance of economic costs and environmental impacts over the benefits derived from pesticide use, thereby necessitating the imposition of taxes on pesticide users. This observation highlights the need to rectify the imbalances and externalities associated with pesticide use by implementing an appropriate taxation mechanism. By holding pesticide users accountable for the negative consequences of their actions, such taxation measures can incentivize the adoption of sustainable agricultural practices and contribute to the preservation of the environment and overall societal well-being.

Table 3. Internalization results of pesticide externalities.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Externality Price (USD kg(^{-1}))</th>
<th>Market Price (USD kg(^{-1}))</th>
<th>Eco-Price (USD kg(^{-1}))</th>
<th>Eco-Tax Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wheat</td>
<td>−0.0115</td>
<td>0.3506</td>
<td>0.3391</td>
<td>−3.29</td>
</tr>
<tr>
<td>maize</td>
<td>−0.0227</td>
<td>0.3352</td>
<td>0.3126</td>
<td>−6.76</td>
</tr>
</tbody>
</table>

Note: the externality price is based on calculations in this study, the market price is the actual price of wheat and maize at the study site in the current year, the eco-price is the price at which external costs are internalized, and the eco-tax represents the ratio of the internalized price to the actual market price.

4. Discussion

4.1. Externalities of Pesticide Use and Comparisons between Other Regions

The external costs of pesticide use in Botou are higher than those in other regions (Table 4). The external cost of pesticide use in the US is 42 USD ha\(^{-1}\) [38], which is only 12% of that in Botou. The external costs of pesticide use in Germany amount to 121 USD ha\(^{-1}\) [39], which is approximately 29% of the corresponding costs observed in Botou.

Table 4. Comparison of pesticide external costs in different regions.

<table>
<thead>
<tr>
<th>Country</th>
<th>Pesticide External Costs (USD ha(^{-1}))</th>
<th>Multiples of Botou vs. Other Countries</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>51</td>
<td>8.3</td>
<td>[38]</td>
</tr>
<tr>
<td>Germany</td>
<td>121</td>
<td>3.5</td>
<td>[39]</td>
</tr>
<tr>
<td>Thailand</td>
<td>30</td>
<td>14.1</td>
<td>[21]</td>
</tr>
</tbody>
</table>

Note: “Multiples of Botou vs. other countries” refers to the external cost Botou divided by the score of other countries. The external costs of pesticides in various regions are recalculated to reflect 2020 values, considering the impact of inflation.

The heavy use of pesticides in Botou has led to high external costs. These external costs primarily manifest themselves in applicators, pickers, and consumers; that is, they mainly increase risks to human health. Our research data show that the pesticide usage in Botou City in 2020 is 14.09 kg ha\(^{-1}\) (Table 1), which is much higher than the world average pesticide usage on cropland, which is only 1.8 kg ha\(^{-1}\) [40]. In recent years, the Botou municipal government has actively promoted a series of policies aimed at reducing pesticide usage. These initiatives include limiting the intensity of pesticide application and advocating for the adoption of green prevention and control measures. As a result, farmers’
awareness of and inclination towards green and environmentally friendly agricultural practices have been steadily increasing. In addition, in Section 4.2, we have provided comprehensive guidance on pesticide use strategies. These findings serve as valuable insights to support government efforts in promoting the adoption of more environmentally friendly pesticides and sustainable agricultural practices. Therefore, Botou has great potential for pesticide reduction and efficiency improvement.

The applicators are the most vulnerable among the environmental receptors, which is similar to some previous studies [41,42]. Pesticides cause the most harm to farm workers (applicators and pickers) (Figure 2). Pesticide dust is the most crucial source of exposure for farm workers; pesticide residues in air, water, and food may also lead to farm worker exposure [43]. In general, pesticides enter into the human body by the following mechanisms: (1) through the skin—pesticides stain the skin and enter into the human body, for example, when preparing pesticide dilutions, during the application process, and when flushing medicine; (2) through the respiratory tract—pesticides in the form of vapor, dust, or fine droplets suspended in the air can be inhaled through the nostrils and cause poisoning; and (3) through the digestive tract, when accidentally taking pesticides or accidentally eating food contaminated by pesticides.

The risk can be minimized by wearing personal protective equipment (PPE), including appropriate protective clothing and protective equipment (e.g., gas mask and protective apron), as required by the FAO [44]. Although China has introduced relevant guidelines, field research has found that most agricultural workers wear only gloves and masks [45], which is insufficient protection. Additionally, more than 90% of China’s farmlands are self-sufficient smallholders [46]. The applicator and picker are usually the same, and the pesticide damage they face is the sum of that of the applicator and picker. The PEA and EIQ models do not consider the reducing effect of PPE on pesticide toxicity. If farmer workers wear PPE, their risk of pesticide exposure is reduced; thus, the externality of pesticides is reduced. The PEA should set a coefficient to characterize this relationship.

4.2. Pesticide Environmental Receptor Analysis and Selection Strategy

Five of the seven insecticides considered in this study were neonicotinoids and pyrethroids (Table 1). In the past two decades, neonicotinoids and pyrethroids have replaced organophosphates and carbamates as the leading chemical pesticides used on farmland worldwide [47]. Even though neonicotinoid and pyrethroid insecticides are applied at a relatively low rate, they can result in severe damage to fish and insects because of their high toxicity and long persistence time in the environment [48], while neonicotinoids are more likely to cause groundwater contamination through runoff and leaching [49]. This is the reason for the high external costs for fish, groundwater, and beneficial insects and the low external costs for birds and bees.

The profound implications of biodiversity loss on ecosystems extend well beyond primary habitats and are particularly evident in agroecosystems. Beneficial insects, birds, and bees are directly or indirectly threatened by pesticides. Pesticides directly kill insects, whereas herbicides reduce insect abundance and biodiversity by ruining their habitats (plants). It is crucial to highlight that both wheat and maize crops do not rely on pollinators for their reproductive processes. Nevertheless, it is essential to recognize that the use of pesticides in wheat and maize cultivation can inadvertently expose pollinators to these chemicals, leading to potential adverse effects on these vital insects. Pesticides applied to maize, in particular, by remaining on pollen and being ingested by insects such as bees, harm the pollinators responsible for plant pollination and other beneficial insects. In addition to the indirect effects of pesticides, birds are directly exposed to the threat of pesticide-contaminated crop seeds and water. Insects are an essential food source for many birds. Birds that eat seeds also feed on fledglings of insects during the breeding season. Pyrethroids and neonicotinoids are far less toxic than organophosphorus and carbamate insecticides to birds and mammals [50]. In the UK, the bird toxicity load of
pesticides decreased by 81% from 1990 to 2016, mainly because of the replacement of organophosphorus pesticides with pyrethroids [51].

The top two active ingredients in WWSM are sourced only from maize production (Figure 4b). They are the primary source of external costs. Both contain atrazine, which damages long-term ecosystem services [52]. Atrazine is prone to leaching and spreading in the environment, causing large-scale watershed pollution and harming fish, aquatic invertebrates, and plants [53]. In the EIQ database, atrazine had an EIQ value of 22.85, which is more harmful to the environment than 47% of the pesticides in the database [54]. However, as the main active ingredient of herbicides, the EIQ value of azafenidin was only 8.00. Thus, azafenidin could replace atrazine as its main active ingredient and reduce external costs.

The pesticide 32.5% difenoconazole-azoxystrobin ranked third in WWSM and has been used in both maize and wheat cultivation for fungal eradication. It is a highly effective and broad-spectrum fungicide but has significant effects on environmental quality, with an EIQ index of up to 68.42. Triticonazole-pyraclostrobin has the same efficacy as difenoconazole-azoxystrobin, but the former has lower toxicity [55], with an EIQ of 38.74. Therefore, using triticonazole-pyraclostrobin as an alternative to difenoconazole-azoxystrobin as a seed dressing for fungal eradication is more environmentally friendly.

Clothianidin imidacloprid is a new seed-treating suspension for insecticides on maize; the EIQ index is 68.77 and accounts for 15% of total external costs. Clothianidin is a new type of highly effective and selective neonicotinoid insecticide. It is compounded with imidacloprid and is used as a seed dressing, which has the advantages of broad-spectrum prevention, root strengthening, and seedling preservation. However, Benzidane’s experiments have shown that imidacloprid is a partial agonist of insect nicotinic acetylcholine receptors, while clothianidin is a full agonist of the same receptors. Although the toxic onset time of clothianidin is shorter, the overall effect is similar to that of imidacloprid [56]. This means the same effect could theoretically be achieved with a single application of imidacloprid. Therefore, we recommend using imidacloprid alone for insect pest control, which had an EIQ of only 36.71.

The pesticide 30% tebuconazole-prochloraz accounted for only 6% of the total external costs in WWSM, although it accounted for 18% of the external costs of wheat. The reason for its smaller share of the total external costs in WWSM is not because its toxicity is low (EIQ index is 62.56) but because of the low application rate. It is a broad-spectrum systemic therapeutic fungicide with good systemic conductivity, high fungicidal activity, and a long shelf life. However, triticonazole–pyraclostrobin has lower toxicity (EIQ index of 38.74) and can replace it as the leading fungicide.

Only 4% of the external cost of WWSM was due to 30% thiamethoxam. However, this accounted for the highest external cost among the insecticides. Thiamethoxam (30%) is a second-generation, low-toxicity nicotine insecticide with stomach, touch, and endotoxic activities against pests. The dosage of 30% thiamethoxam was ranked second among the seven insecticides investigated in this study (Table 1). However, its EIQ index is only 33.30, which is the smallest EIQ index among the insecticides.

4.3. Internalization Methods and Their Necessity

The findings shown in Figure 3 indicate that the negative impacts of pesticide use surpass the positive benefits, leading to a negative net value outcome. This negative net value reaches a significant magnitude of 252.0 USD ha\(^{-1}\), underscoring the economic implications of pesticide use in crop cultivation. Although pesticides may serve as a means to control pests and diseases, the cumulative negative effects on the environment, human health, and ecosystems, along with their associated costs [57], result in a negative net assessment of the benefits derived from pesticide use.

This negative net result further emphasizes the need to internalize the external costs associated with pesticide use. Internalization involves incorporating the negative impacts and associated costs into the decision-making process for economic activities and holding
economic agents accountable for them and their costs. In the case of pesticide use, the need for internalization is evident. Firstly, internalizing external costs can provide a more accurate measure of the true costs of agricultural production. By incorporating the negative impacts and associated costs of pesticide use into economic calculations, the viability and benefits of agricultural production can be more accurately assessed. This can help farmers and policymakers understand the real economic benefits of pesticide use and provides a reliable basis for decision making. Secondly, internalizing external costs can encourage sustainability and environmental friendliness in agricultural production. By considering the environmental and ecosystem damage caused by pesticide use in economic decisions, farmers can be incentivized to adopt more environmentally friendly agricultural management practices. Additionally, internalizing external costs promotes social justice and responsibility. The external costs of pesticide use are often shared by society as a whole, rather than solely by farmers. Internalizing these costs ensures that farmers do not bear a disproportionate financial burden and promotes fair distribution and social equity. This can be achieved through the establishment of environmental taxes and the development of relevant policies and regulations that can guide farmers toward more sustainable agricultural practices and reduce reliance on pesticides.

The negative eco-tax rates presented in Table 3 strongly support the necessity of levying taxes on pesticide users. These negative ecological tax rates unequivocally signal that the economic costs and environmental impacts stemming from pesticide use outweigh the associated benefits. Consequently, it is imperative to implement corrective measures to address the adverse consequences of pesticide use while concurrently fostering the adoption of sustainable and environmentally conscious agricultural practices. The urgency of internalizing these externalities is underscored, emphasizing the importance of taking immediate action. By implementing taxes on pesticide users, we can effectively incentivize the transition toward more sustainable agricultural practices, reduce dependence on pesticides, and proactively contribute to environmental preservation [58]. In previous studies, the primary method of internalizing externalities was to impose Pigovian taxes or grant subsidies [59]. However, it is difficult to determine the respective taxes or subsidies for each farm in terms of marginal private benefits and marginal external costs in terms of internalizing the externalities of pesticide use. In this study, we propose that the discrepancy between the ecological price and the market price (3.29% for wheat and 6.67% for maize) can serve as a benchmark for determining the ecological tax. By considering this proportion, policymakers can establish an appropriate ecological tax rate that reflects the environmental and social costs associated with agricultural practices. This approach ensures a more accurate assessment of the economic and ecological impacts of pesticide use, paving the way for the implementation of effective policies that incentivize sustainable farming practices while internalizing the externalities caused by conventional agricultural methods.

5. Conclusions

This study presents a novel method for calculating the positive externalities of pesticide usage, considering the contribution of pesticides to food security as a positive externality. By integrating the PEA and EIQ models, we quantified the external costs of pesticide usage and successfully measured the net external value of pesticide usage. Additionally, we introduced a mechanism for internalizing the external costs of pesticides using an ecological tax, and this approach was implemented for the first time in the China’s northern plains.

The negative external costs resulting from pesticide use in the Botou area outweigh the positive external values, indicating that the economic costs and environmental impacts associated with pesticide use surpass the benefits it generates. A pesticide hotspot analysis reveals that herbicide usage yields more detrimental effects than insecticide and fungicide usage, with pesticide use posing the most severe risks to the workers involved.

Based on the internalized outcomes, we propose the introduction of an ecological tax on pesticide users. The suggested tax rate would vary based on the crop, with a proposed
rate of 3.29% per kilogram for wheat and 6.67% per kilogram for maize. We provide a fundamental method for quantifying and internalizing pesticide usage, but in future research, more comprehensive evaluation indicators should be considered. For instance, factors such as pollinator yield losses and research investments for reducing pesticide usage costs will deserve more attention.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151612365/s1, Table S1. Different pesticides, environmental receptors and total negative external costs.

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