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# Spillover Impacts of the Utilization of Winter Fallow Fields on Grain Production and Carbon Emissions

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**Abstract:** Abandoned cropland is a widespread issue globally, with the impacts of utilizing abandoned cropland, such as grain production and carbon emissions, raising increasing concern. However, existing studies have largely overlooked the potential spillover effects on other regions through grain flows when increasing grain production in one region by utilizing abandoned cropland. Therefore, this study aimed to comprehensively estimate the impacts of using winter fallow fields (a typical seasonal abandoned cropland) on grain production and carbon emissions, particularly its neglected spillover impact. Focusing on Zhejiang province, this study used remote sensing techniques to identify winter fallow fields in 2018 and then assessed the impact of using those winter fallow fields on grain production based on grain yield data from the FAO, as well as its local and spillover impacts on carbon emissions based on the Greenhouse Gas Emission Factor method and a transportation carbon emission model. The results indicate the following: (1) The winter fallow fields in Zhejiang cover 5,161,000 hectares, accounting for 40.8% of the total cropland, with a notable prevalence in Jiaxing, Huzhou, Jinhua, and Quzhou. (2) Using winter fallow fields would increase grain production by 1,870,000 tons. (3) At the same time, local carbon emissions would rise by 261,000 tons if using winter fallow fields, but this would be paired with a reduction of 668,000 tons of carbon emissions from other regions (that is, a spillover impact), reflecting a net reduction (−447,000 tons) in overall emissions. In conclusion, using winter fallow fields can achieve a 'win–win' effect, increasing grain production while reducing carbon emissions. This study highlights that the spillover effects of using winter fallow fields on carbon emissions significantly surpass the localized impact, underscoring a critical aspect that has been traditionally undervalued, which should be paid more attention when policymakers formulate and implement cropland use policies. This study not only contributes to the academic discourse on sustainable land management but also serves as a practical guide for policymakers seeking to optimize agricultural productivity while curtailing the carbon footprint, thereby advancing towards a more secure and environmentally responsible food system.

**Keywords:** abandoned cropland; spillover impact; grain production; carbon emission; grain flows

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## 1. Introduction

Ending global starvation and achieving zero hunger by 2030 is one of the 17 Sustainable Development Goals (SDGs) set by the United Nations [1]. However, due to various challenges such as a growing global population, the COVID-19 pandemic, the conflict in Ukraine, and rising prices for food, agricultural inputs, and energy, between 690 and 783 million people worldwide faced hunger in 2022, leaving us far off track from achieving SDG2 [2]. Estimates suggest that by 2050, global agricultural production must increase by 70–110% to meet the rising demands of human consumption and livestock feed [3,4]. This need will undoubtedly place additional pressure on agriculture, driving efforts to boost production and necessitating the development of effective strategies to enhance future food production [5]. Cropland is crucial in sustaining food production and security [6]. While cropland expansion has partially met the increased food demand in recent decades, further expansion is unlikely due to the limitations imposed by planetary boundaries [7,8], and it is even decreasing due to urbanization and other factors [9,10]. Scientifically improving the output of cropland use, such as using abandoned cropland, improving the cropping frequency, and inputting more agricultural materials to ensure that existing agrarian systems become more productive is an important avenue through which agriculture may achieve sustainable development [11–13].

The issue of abandoned cropland is a global concern, and utilizing such land has the potential to increase the grain yield, with benefits for food security. Abandoned cropland refers to agricultural land that is dormant or desolate due to ineffective cultivation or management practices [14]. Since the 1950s, over 400 million hectares of cropland have been abandoned worldwide, and this trend is expected to continue [15]. China alone has 392,156 $\text{km}^2$ of abandoned cropland, accounting for 13.03% of its total cropland [16,17]. Abandoned cropland poses a threat to food security and has environmental effects [18,19], and yet the impact of using abandoned cropland raises increasing concerns. On the one hand, utilizing abandoned cropland could be an attractive option for increasing agricultural production while mitigating some adverse effects associated with abandonment [20–22]. Strategically repurposing abandoned cropland globally for re-cultivation or re-forestation helped to meet food security and address climate change between 1992 and 2020 [22]. Using abandoned cropland also has the potential to bring massive co-benefits, including enhanced biodiversity conservation, improved water and air filtration, and better soil quality [23–26]. On the other hand, using abandoned cropland affects carbon emissions by changing the input of agricultural materials. In detail, from the full life cycle perspective, carbon emissions are attributed to the manufacture, transportation, and application of agricultural materials (e.g., pesticides, fertilizers, plastic films, and machinery) and electricity used for irrigation [27]. The existing studies have explored the impacts of using abandoned cropland on grain production and the environment; however, most studies have focused on local impacts, neglecting the potential effects on other regions through grain flows (that is, the spillover effect generated through grain transport after using abandoned cropland). Specifically, an increase in grain production in one region by utilizing abandoned cropland can have spillover effects on other areas through grain flows [28], such as easing the pressure on grain production in different areas and thus reducing carbon emissions. One study found that over 60% of the increased carbon emissions related to grain transport in China between 1990 and 2015 were due to grain production displacement [28]. Therefore, it is crucial to consider not only the local impact but also the potential spillover impact of using abandoned cropland.

The grain system is a complex network that involves multiple sectors, regions, and interfaces, with interconnected relationships [29–31]. From a spatial perspective, production activities in cropland not only impact the land itself but also have significant spillover effects on agricultural products and ecological improvements across different regions [32,33]. The utilization of abandoned land also presents strong environmental trade-offs [34] and synergy [22]. For instance, cropland abandonment in Europe may lead to changes in land use in regions outside Europe, such as Southeast Asia and South America [35,36]. The use of abandoned land also affects the local pattern of grain production and distribution. Studies have shown that cropland abandonment in southern China has shifted the traditional "grain transported from the south to the north" pattern to "grain transported from the north to the south" [37–39]. However, current research on the effects of using abandoned cropland focuses on assessing yield improvements within a region, neglecting systematic and quantitative analyses of the comprehensive environmental effects across regions. Achieving food production and carbon reduction, which are important goals of the SDGs, often involves trade-offs; hence, it is crucial to systematically assess the local and spillover impacts of using abandoned cropland on grain production and carbon emissions, and then analyze the trade-off/synergy of grain production and carbon emissions.

Cropland abandonment is a widespread issue in China due to rapid urbanization. This includes cropland that has been abandoned for several years, as well as seasonal cropland, which has not received sufficient attention, such as winter fallow fields. Winter fallow fields refer to cropland left fallow after the autumn harvest until the spring planting of the following year, which are suitable for cultivating at least one seasonal crop [40]. This is common in southern China, where such land exceeds 20 million hectares, accounting for 45% to 49% of cropland. Zhejiang province, located in southern China, is a major grain consumption area. The use of winter fallow fields in Zhejiang not only impacts local grain production and carbon emissions but also affects other provinces involved in grain trade with Zhejiang. Thus, taking Zhejiang as the study area, this study aimed to (1) identify the spatial distribution of winter fallow fields in Zhejiang in 2018 using remote sensing techniques, (2) assess the potential for increasing grain production by utilizing winter fallow fields (focusing on winter wheat, a traditional and primary winter crop), and (3) evaluate the local and spillover impacts of using winter fallow fields on carbon emissions, both at the grain production stage and from grain transport. This article has significant value as it addresses the gap in understanding the spillover impact of using winter fallow fields and provides a reference for policymakers seeking to optimize agricultural productivity while reducing the carbon footprint.

## 2. Materials and Methods

### 2.1. Study Area

Zhejiang is located in the Yangtze River Delta region, between 118°01′ and 123°10′ E and between 27°02′ and 31°11′ N (see Figure 1). This area experiences a subtropical humid monsoon climate, and it boasts rich ecosystems and diverse climate resources. However, natural resources are relatively scarce, with the land area making up only about 1.1% of the country's total land area. Cropland resources are limited, with per capita availability at only 24% of the national average. The grain self-sufficiency rate is also low, with the per capita grain output in 2020 approximately 20% of the national average, though it is the second-largest grain-consuming region in China. Due to factors such as rapid industrialization and urbanization, ongoing population growth, and relatively low grain cultivation benefits, issues of cropland abandonment and the conversion of cropland to non-grain uses are significant. The winter fallow rate exceeds 50% in some areas, posing a great risk to the regional food supply and security. More than 50% of the winter fallow fields in Zhejiang are entirely suitable for growing crops such as wheat, winter rape, potatoes, and Chinese milk vetch after the rice harvest (usually in late August or early/mid-September). Zhejiang province has always attached great importance to grain production and the reuse of cropland, and initiated a comprehensive action plan earlier in 2024 to rehabilitate abandoned cropland and utilize winter fallow fields, to increase land utilization rates. Field investigations revealed the large-scale planting of winter wheat in Zhejiang's winter fallow fields. In summary, evaluating the local and spillover impacts of using winter fallow fields on grain production and carbon emissions in Zhejiang is both feasible and representative, and it holds significant value for evaluating policy implementation effects and ensuring regional food security.

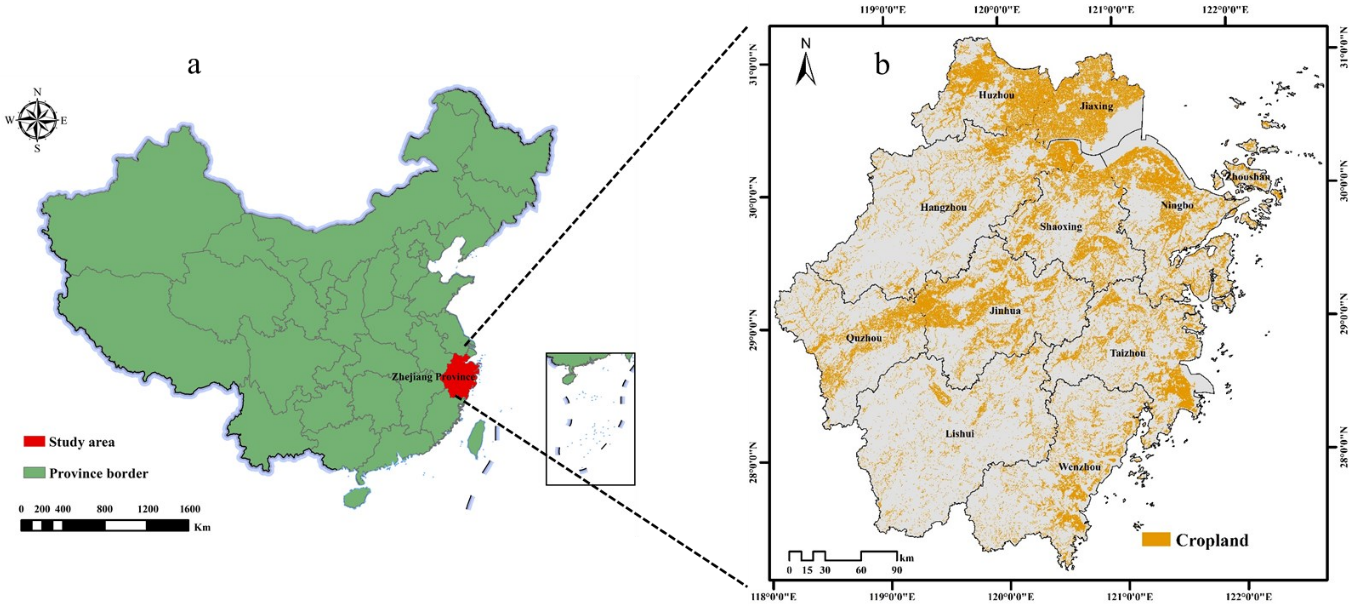

**Figure 1.** Maps of the study area: location of study area (**a**), and distribution of cropland in the study area (**b**).

## 2.2. Framework

Figure 2 illustrates the research framework used to assess the impact of using winter fallow fields on grain production and carbon emissions (including the local and spillover impacts) in Zhejiang in 2018.

(1) Identification of winter fallow fields: based on the annual MCF (multiple cropping frequency) maps, the cropland abandonment index (CAI) was applied to extract winter fallow fields.

(2) Impact assessment of using winter fallow fields on grain production: based on data of the grain yield ascertained with the GAEZ model from the FAO, we assessed the changes in grain production due to the utilization of winter fallow fields.

(3) Local and spillover impact assessment of using winter fallow fields on carbon emissions: Firstly, to study the local impact of using winter fallow fields on carbon emissions, since using winter fallow fields in Zhejiang requires the input of more agricultural materials on cropland, such as fertilizer, pesticide, and machinery, the carbon emissions in the grain production stage in Zhejiang will change when considered from the full life cycle perspective. The Greenhouse Gas Emission Factor method was adopted to calculate the carbon emissions at the grain production stage. Additionally, when using winter fallow fields, the spatial distribution of grain production in each municipality will change, which causes the inner grain flows among the municipalities of Zhejiang to also change. Therefore, the changes in carbon emissions from inner grain transport will change. The carbon emissions at the grain transport stage were calculated by the transportation carbon emission model generated by combining the Spatial Interaction Model, Transport Model, and Greenhouse Gas Emission Factor method (the details are given in Section 2.3.4). Secondly, considering that changes in grain production in Zhejiang will also cause changes in the amount of grain necessary to produce in other provinces (which transport grain to or from Zhejiang) as well as the inter-provincial grain flows, the carbon emissions at the grain production stage and from grain transport will change. The results of this process are spillover impacts of using winter fallow fields on carbon emissions. In detail, the spillover impacts of the utilization of winter fallow fields on carbon emissions for regions transporting grain to and from Zhejiang were assessed.

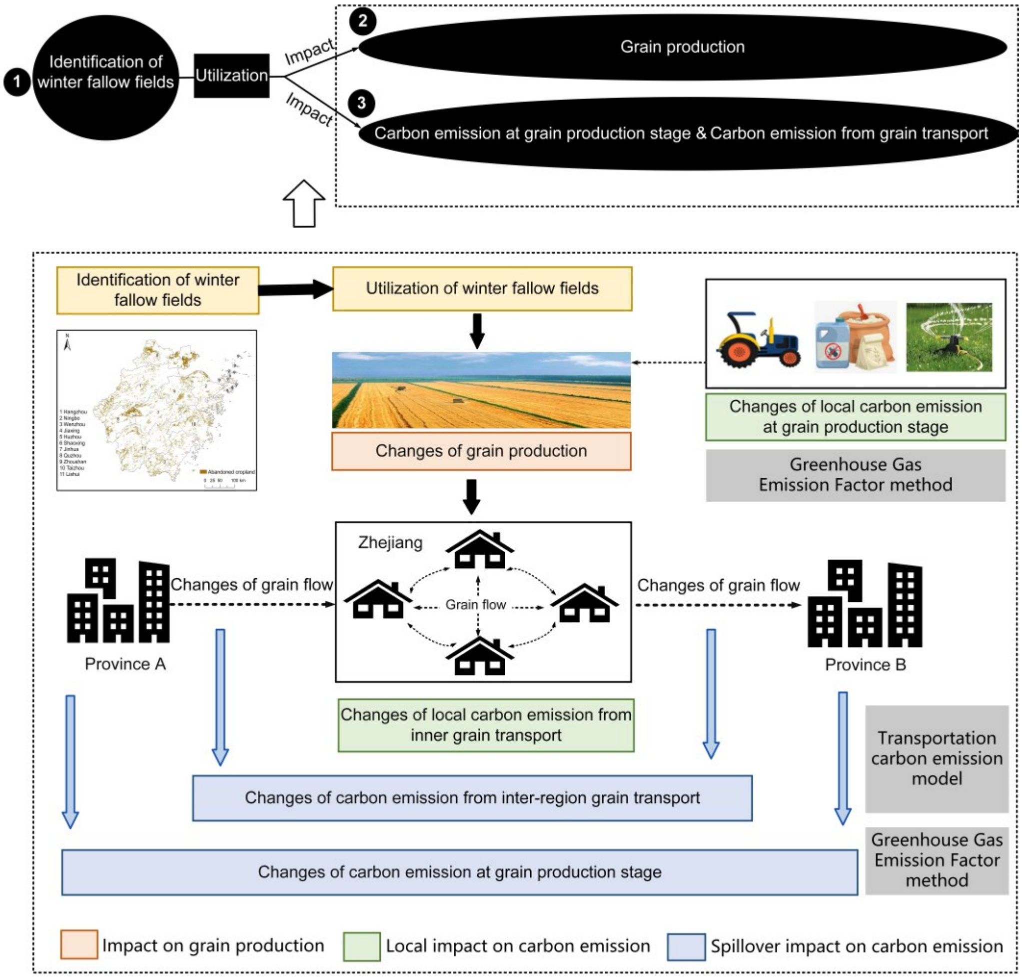

**Figure 2.** Research framework for assessing the impacts of utilization of winter fallow fields on grain production and carbon emissions.

## 2.3. Methods

### 2.3.1. Identification of Winter Fallow Fields

The cropland abandonment index (CAI) was adopted to extract information about seasonal cropland abandonment (SCA) [41]. In detail, (1) the annual results of the multiple cropping frequency (MCF) in Zhejiang were extracted from 2014 to 2018 using the quadratic difference method based on the yearly EVI2 (Two-band Enhanced Vegetation Index) time series curve. The method used followed that applied in the existing research [42]. (2) We monitored the SCA using the CAI based on the annual MCF maps [41]. The CAI was calculated based on the annual cropping cycle maps as follows:

$$CAI = \frac{MCF_{max} - MCF}{MCF_{max}} MCF_{max} \neq 0 \tag{1}$$

where $MCF$ denotes the number of cropping cycles in the current year, and $MCF_{max}$ denotes the maximum number of cropping cycles in the past 5 years. When the $CAI$ falls between zero and one, SCA occurs.

The previous results only identified abandoned cropland without specific timing information. Based on the characteristics of the planting system in the research area, this study selected abandoned cropland that occurred in paddy fields as seasonal abandoned cropland (that is, winter fallow fields in the study area).

### 2.3.2. Greenhouse Gas Emission Factor Method

The Greenhouse Gas Emission Factor method has been widely used to calculate greenhouse gas emissions [43,44]. This method applies to estimating greenhouse gas emissions at a macro scale and is easy to operate, so it was also used in this study. The formula for calculating greenhouse gas emissions is the following:

$$Emission = ES \times EF \tag{2}$$

where $ES$ is the number of sources of greenhouse gas emissions, and $EF$ is the corresponding emission factor.

$CO_2$, $CH_4$, and $N_2O$ are the dominant types of greenhouse gas emissions causing climate change [27,45–47], so these three types of emissions were included in this study. Thus, we calculated these three types of greenhouse gas emissions and unified them into the equivalent of carbon emissions, $CO_2$-eq. At the same time, the greenhouse gas emissions at the grain production stage include direct and indirect greenhouse gas emissions. The details are shown in Supplementary 1.

### 2.3.3. Calculation of Grain Consumption

Since data on grain consumption at the municipal scale were not available, we calculated the grain consumption at the municipal scale in 2018 based on an estimation of grain consumption for rations, animal feed, and others (such as industry, seeds, waste, etc.) [48,49]. The formula for calculating greenhouse gas emissions was the following, and the detailed process is shown in Supplementary 2.

$$GC_{total} = \sum_1^i GC_i = \sum_1^i \left( GC_{i\_ration} + GC_{i\_feed} + GC_{i\_others} \right) \tag{3}$$

where $i$ represents the municipalities, $GC_{total}$ is the total amount of grain consumption $GC_i$, and $GC_{i\_ration}$, $GC_{i\_feed}$, and $GC_{i\_others}$ are the grain consumption for rations, animal feed, and others, respectively.

### 2.3.4. Transportation Carbon Emission Model

The Spatial Interaction Model, Transport Model, and Greenhouse Gas Emission Factor method were combined to build the transportation carbon emission model [28], which was adopted to calculate the carbon emissions from grain transport (Figure 3).

(1) First, the Transport Model was applied to calculate the shortest route between each pair of sources of grain supply and demand by different transport modes. Here, we mainly considered three modes: railway, road, and waterway.

(2) Second, the transport cost was calculated based on the transport distance of grain and its transport modes adopted. Considering that the actual data are unavailable, based on the transport cost, the spatial distributions of actual grain production and that of grain consumption, and the spatial flows of grain (the ton-km of grain from the supply origin to the destination), were generated by a doubly constrained Spatial Interaction Model.

(3) Finally, based on the ton-km of grain, the corresponding transport modes, and carbon emission conversion factors, the carbon emissions at the grain transport stage from the grain origin to its destination at the municipal level were determined by the Greenhouse Gas Emission Factor method. In this study, the consumption area undertakes the carbon emissions of grain transport.

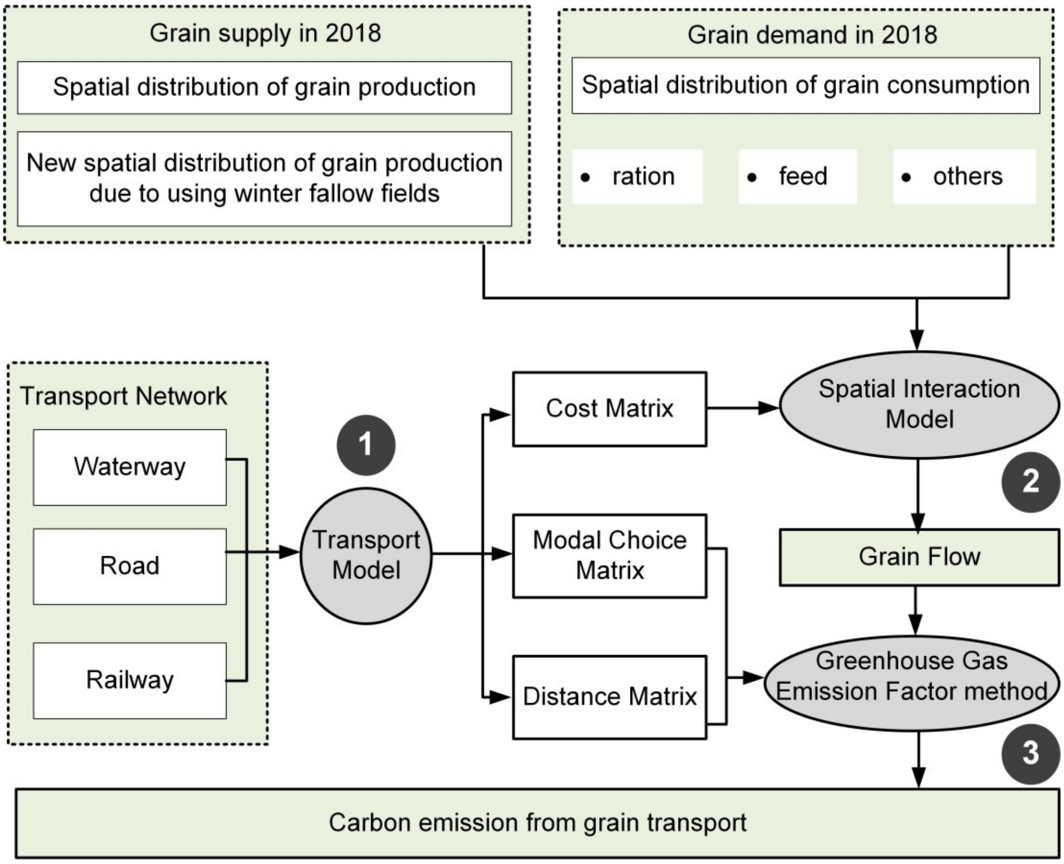

**Figure 3.** The framework of the transportation carbon emission model.

### *2.4. Data*

(1) We collected MODIS Surface Reflectance Product (MOD09Q1) data from 2014 to 2018 at a spatial resolution of 250 m (https://ladsweb.modaps.eosdis.nasa.gov/, accessed on 2 January 2023). The MODIS reprojection tool (MRT) was used for the projection, conversion, and assembly of the images (https://lpdaac.usgs.gov/tools/, accessed on 16 January 2023). We selected the MODIS time series dataset because it offers a high temporal resolution (8 days), which is crucial for smoothing the vegetation index. Additionally, it provides continuous observations beginning from the early 21st century [42]. We calculated the EVI2 and developed a yearly EVI2 time series curve for MCF mapping, with the support of a data smoothing method referred to as the harmonic analysis of time series (HANTS), which can reduce noise caused by atmospheric contamination, illumination angles, and cloud interference [42]. EVI2 has the advantages of improved sensitivity in high-biomass regions and minimized atmospheric and soil influence for monitoring the crop growth condition.

(2) We collected National Land Cover Data (NLCD) from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn, accessed on 6 February 2023) to obtain the cropland mask before processing the remote sensing data. To reduce the influence of cropland change, we extracted the intersection of four periods of the cropland mask (i.e., 2000, 2005, 2010, and 2015) as the research range of croplands. Agricultural production data of wheat were adopted from GAEZ v4 (https://gaez.fao.org/, accessed on 12 February 2023). The Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) have cooperated over several decades to develop and implement the Agro-Ecological Zones (AEZ) modeling framework and databases. The agricultural production spatial data were produced by aggregating national production statistics to individual spatial units (grid cells) used a "down-

scaling" method, with a 5 arc-minute resolution for 26 major crops/crop groups. We resampled all spatial data to the same spatial resolution of 250 m.

(3) Agricultural materials (e.g., pesticides, fertilizer, irrigation, plastic film, and machinery) on cropland at a municipal scale were collected from the yearbook of each province in China [50–52]. The corresponding carbon emission factors of agricultural materials were obtained from the IPCC, the authorities, and published studies (Table 1). The amount of utilization of winter fallow fields equates to the increase in sown area. So, based on the agricultural materials per unit of sown area in 2018 in each municipality and their corresponding carbon emission factor, we calculated the carbon emissions at the production stage per unit of sown area.

**Table 1.** Carbon emission factors of agricultural materials applied on cropland.

| Emission Source | Factor | Unit | References |
|---|---|---|---|
| Pesticide | 4.94 | t $CO_2e$/t | [53] |
| Fertilizer | 0.86 | t $CO_2e$/t | [53] |
| Electricity applied in irrigation | 0.19 | t $CO_2e/hm^2$ | Average $CO_2$ factors of China's regional power grids in 2011 and 2012, published by China Climate Change Information Network;<br>Greenhouse gas reporting: Conversion factors 2018, published by UK government;<br>China Development and Reform Commission;<br>Summary of cost and income of agricultural products in China in 2018 |
| Plastic film | 3.15 | t $CO_2e$/t | Greenhouse gas reporting: Conversion factors 2018, published by UK government |
| Agricultural machinery | 0.06 | t $CO_2e$/kW | IPCC, 2006; Greenhouse gas reporting: Conversion factors 2018, published by UK government |

(4) The transport network data were extracted from CIESIN and OpenStreetMap. Meanwhile, since the carbon emission conversion factors for different transport modes adopted in China (National Standards IV in 2015) are equivalent to the UK standards (Euro IV in 2015) since 2000, we adopted the UK GHG Conversion Factors to approximate the corresponding factors in China [28] (Table 2).

**Table 2.** Carbon emission conversion factors for different transport modes.

| Transport Mode | Carbon Emission Conversion Factor ($kgCO_2e$/ton-km) |
|---|---|
| Road | 0.11364 |
| Railway | 0.02601 |
| Waterway | 0.01315 |

(5) The grain consumption coefficients of livestock and poultry meat, milk and milk products, eggs, and aquatic products were obtained from public works in the literature (Table 3).

**Table 3.** Grain consumption coefficient of feed–meat products.

| Products | Grain Consumption Coefficient (kg/kg) | Data Sources |
|---|---|---|
| Livestock and poultry meat | 2.29 | [44,54] |
| Milk and milk products | 0.39 | [55] |
| Eggs | 1.70 | [44,55] |
| Aquatic products | 1.02 | [55] |

## 3. Results

### *3.1. Spatial Distribution of Winter Fallow Fields*

The winter fallow fields made up 5,161,000 hectares in 2018, accounting for 40.8% of the total amount of cropland. This result is consistent with the average ratio of winter fallow in the middle and lower reaches of the Yangtze River. Spatially, as Figure 4 shows, all regions of Zhejiang exhibit a prominent phenomenon of winter fallow, especially Jiaxing, Huzhou, and Jinhua, which have a higher proportion of winter fallow than other regions. A possible reason for this is increased costs of labor, fertilizers, and equipment and a relatively low price of grain, making farming unprofitable.

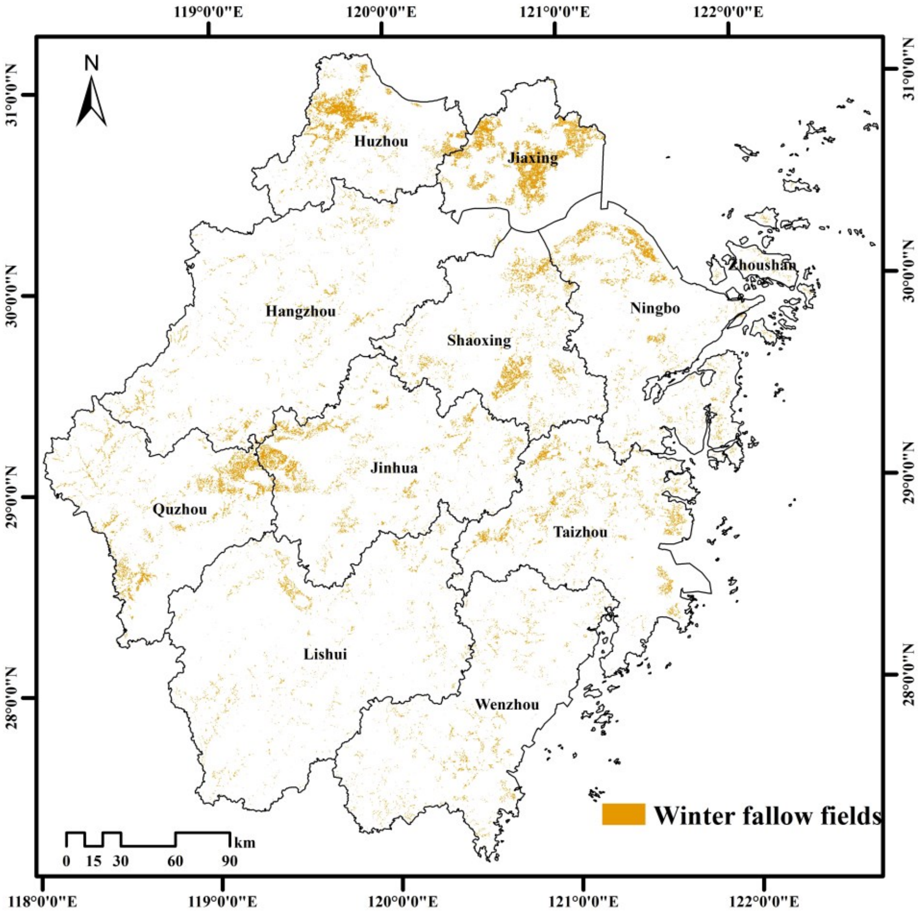

**Figure 4.** Winter fallow fields in 2018 in Zhejiang.

### *3.2. Impacts of the Utilization of Winter Fallow Fields on Grain Production*

Using winter fallow fields offers a promising opportunity for substantial growth in grain production. As Figure 5 shows, the results indicate a 31% increase in total grain production, climbing from 6 million tons to 7.8 million tons following the utilization of winter fallow fields. It is important to emphasize that the municipality Jiaxing currently leads in grain production; furthermore, it is poised to experience the most significant surge, at 1.3 million tons (an increase of 38%), closely followed by Shaoxing with an anticipated rise of 1 million tons (an increase of 24%). Thus, using winter fallow fields contributes to food security in the region and can produce economic benefits for farmers. A continued emphasis on improving the frequency of cultivation will be critical in realizing these gains and ensuring long-term productivity in grain farming.

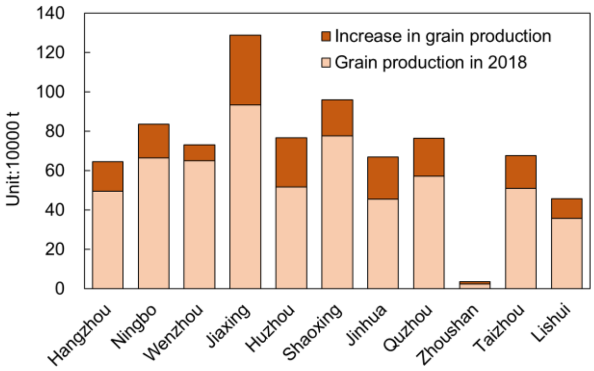

**Figure 5.** Impacts of the utilization of winter fallow fields on grain production.

### *3.3. Local Impacts of the Utilization of Winter Fallow Fields on Carbon Emissions*

Figure 6 illustrates that the utilization of winter fallow fields would lead to an increase in carbon emissions both at the grain production stage (with 258 thousand tons) (Figure 6a) and from grain transport (with 3 thousand tons) (Figure 6b) in Zhejiang. Specifically, after using winter fallow fields, the total carbon emissions at the grain production stage would increase by 31%. The municipality Jiaxing would experience the most significant increase, with 50 thousand tons, due to its massive winter fallow fields and high potential for investment in agricultural materials. This would be followed by Huzhou, Jinhua, Quzhou, and Zhoushan, with 30 thousand tons each. Comparatively, the changes in carbon emissions from grain transport would be less, increasing by 26%. The municipality Shaoxing would experience the most significant increase, with 2 thousand tons (increase rate is 24%).

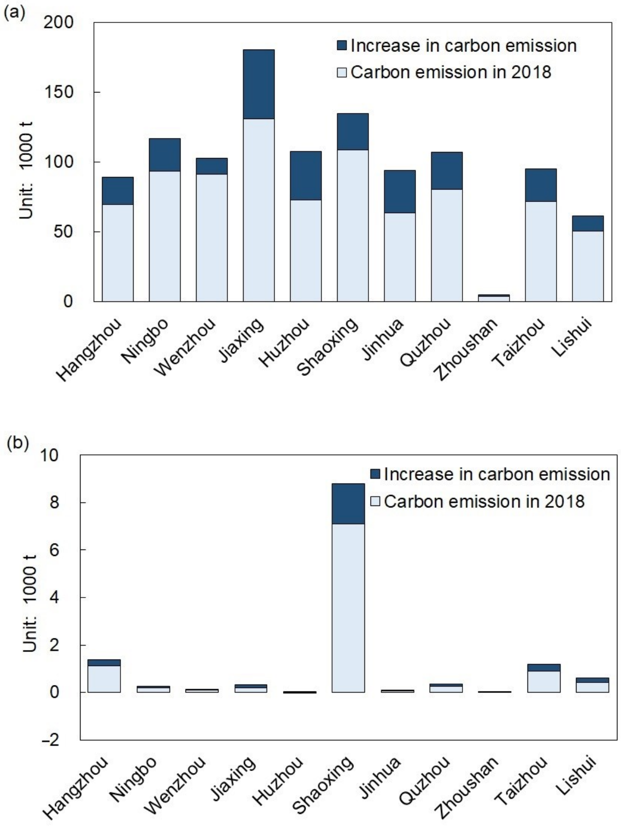

**Figure 6.** Local impacts of the utilization of winter fallow fields on carbon emissions at the grain production stage (**a**) and from grain transport (**b**) in Zhejiang.

### *3.4. Spillover Impacts of the Utilization of Winter Fallow Fields on Carbon Emissions*

(1) Spillover impacts of the utilization of winter fallow fields on carbon emissions for the regions transporting grain to Zhejiang

When comparing grain flows from other provinces to Zhejiang before and after using winter fallow fields (Figure 7a,b), the total spillover impact on carbon emissions for the regions transporting grain to Zhejiang would be −617 thousand tons (Figure 7c). This indicates that the use of winter fallow fields in Zhejiang would help to reduce carbon emissions for the regions transporting grain to Zhejiang. In detail, in Figure 7a,b, the amount of grain from other provinces to Zhejiang decreases by about 1210 thousand tons, which eases the pressure on grain production for other provinces, especially for Liaoning (decreases by 263 thousand tons) and Jiangsu (decreases by 237 thousand tons). In this case, for these provinces, the carbon emissions from grain production would significantly decrease, by 574 thousand tons, while the carbon emissions from grain production would decrease by 44 thousand tons (Figure 7c). In detail, the highest reduction in carbon emissions from grain production would occur in Jiangsu, with 177 thousand tons, followed by Anhui (−151 thousand tons) and Liaoning (−113 thousand tons). Comparatively, Liaoning would experience a considerable decrease of 12 thousand tons in carbon emissions from grain transport. This trend would also apply to provinces like Inner Mongolia, Jilin, and Heilongjiang.

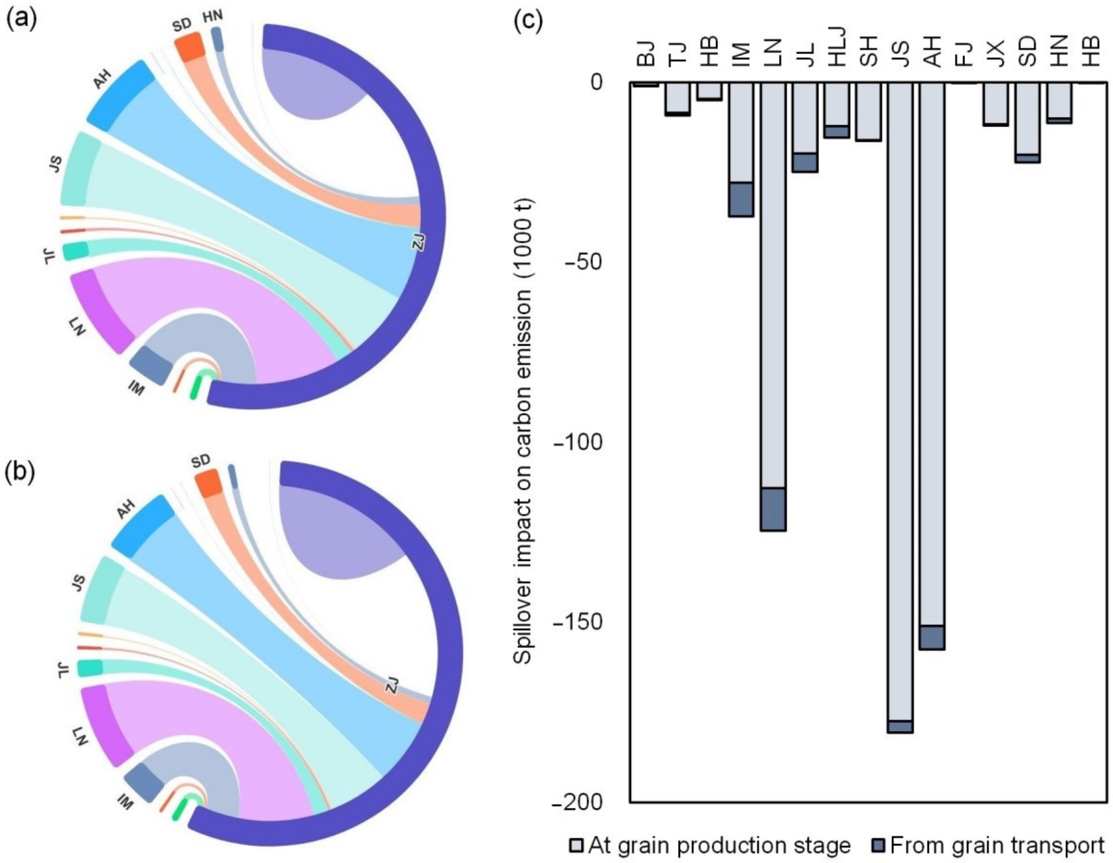

**Figure 7.** Grain flows from other provinces than Zhejiang before (**a**) and after (**b**) the utilization of winter fallow fields, causing spillover impacts on carbon emissions (**c**). ZJ: Zhejiang, BJ: Beijing, TJ: Tianjin, HB: Hebei, IM: Inner Mongolia, LN: Liaoning, JL: Jilin, HLJ: Heilongjiang, SH: Shanghai, JS: Jiangsu, AH: Anhui, FJ: Fujian, JX: Jiangxi, SD: Shandong, HN: Henan, HB: Hubei, HN: Hunan, GD: Guangdong, GX: Guangxi.

(2) Spillover impacts of the utilization of winter fallow fields on carbon emissions for the regions transporting grain from Zhejiang

When comparing grain flows from Zhejiang other provinces before and after using winter fallow fields (Figure 8a,b), the total spillover impact on carbon emissions for the regions transporting grain from Zhejiang would be −51 thousand tons (Figure 8c). This indicates that an increase in grain production in Zhejiang from using winter fallow fields could provide more grain to other provinces, and thus help to reduce carbon emissions for the regions transporting grain from Zhejiang. In detail, as shown in Figure 8a,b, the amount of grain from Zhejiang to other provinces would increase by about 33 thousand tons, which would ease the pressure on grain production for other provinces, especially for Fujian (with 27 thousand tons) and Guangdong (with 4 thousand tons). In this case, for these provinces, using winter fallow fields in Zhejiang would help reduce the carbon emissions from grain production by 52 thousand tons, while slightly increasing the carbon emissions from grain transport by 0.52 thousand tons (Figure 8c). Fujian would experience the most substantial reduction in carbon emissions, with a decrease of 43 thousand tons, although the carbon emissions from grain transport would slightly increase by 0.4 thousand tons. This would be followed by Guangdong, where the carbon emissions at the grain production stage would decrease by 7 thousand tons, although the carbon emissions from grain transport would slightly increase by 0.1 thousand tons.

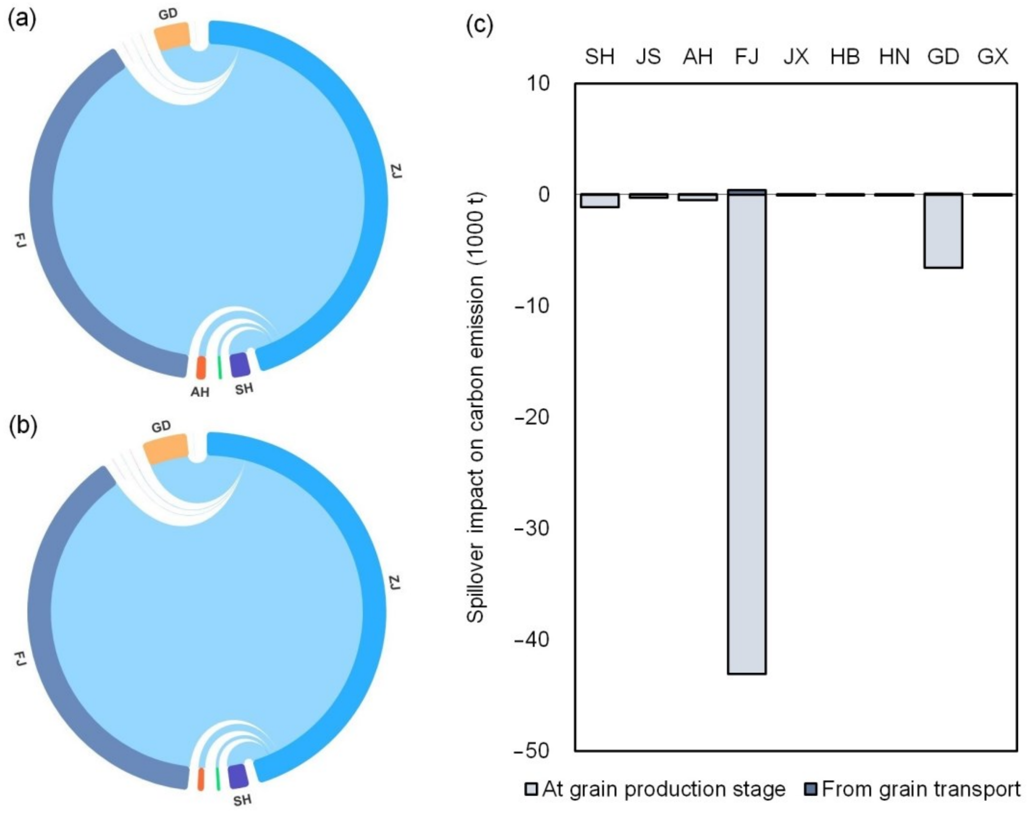

**Figure 8.** Grain flows from Zhejiang to other provinces before (**a**) and after (**b**) the utilization of winter fallow fields, causing spillover impacts on carbon emissions (**c**). ZJ: Zhejiang, SH: Shanghai, JS: Jiangsu, AH: Anhui, FJ: Fujian, JX: Jiangxi, HB: Hubei, HN: Hunan GD: Guangdong, GX: Guangxi.

### *3.5. Trade-Off/Synergy between Grain Production and Carbon Emissions*

Table 4 depicts that using winter fallow fields would increase grain production by 1870 thousand tons and reduce carbon emissions by 407 thousand tons. Notably, the spillover impact of the utilization of winter fallow fields on carbon emissions would be about three times the local impact. This indicates that if we only focus on the local impact, there is a conflict between the increase in grain production and the reduction in local carbon emission; however, if the spillover impact on carbon emissions is considered, synergy will be achieved (increasing grain production and reducing carbon emissions).

**Table 4.** Trade-off/synergy between grain production and carbon emissions with the utilization of winter fallow fields.

| Impact on Grain Production (1000 t) | Impact on Carbon Emissions (1000 t) | | |
|---|---|---|---|
| | Local Impact | Spillover Impact | Total Impact |
| 1870 | 261 | −668 | −407 |

## 4. Discussion

Abandoned cropland is an increasing concern [22,56,57], and some have studies explored the impacts of using abandoned cropland on grain production and carbon emissions [22,57,58]. Previous studies demonstrated that using abandoned cropland can increase grain yields [57] and affect carbon emissions [22]. For example, the maximum production potential of abandoned cropland in the three main grain-producing areas of China equates to 8.5 million tons of grain [57]. Furthermore, from a global perspective, the abandoned cropland concurrently holds 29 to 363 Peta-calories $\text{yr}^{-1}$ of food production potential and 290 to 1066 $\text{MtCO}_2$ $\text{yr}^{-1}$ of net climate change mitigation potential [22]. Our study suggests a similar situation in the case study region: the utilization of abandoned cropland would increase grain production but cause an increase in carbon emissions due to machinery, fertilizers, and other inputs for the local area. Beyond this, the spillover effect of using abandoned cropland is rarely explored, but this study has highlighted that the spillover effect of the utilization of abandoned cropland on carbon emissions (about three times the local impact on carbon emissions) cannot be ignored for any longer. In Zhejiang, a grain-consuming area, an increase in grain production thanks to using winter fallow fields would affect the grain flows between Zhejiang and other regions, especially for grain production areas, such as Jiangsu, Anhui, and Liaoning. The framework and methods proposed in this study can also be applied in other regions to assess the visual and potential (spillover) effects of the utilization of abandoned cropland on grain production and carbon emissions.

The findings from this study on the impact of utilizing abandoned cropland have significant policy implications for agricultural and environmental management. The results highlight the dual benefits of increased grain production and a net reduction in carbon emissions through the strategic use of abandoned cropland. Here are the key policy implications: Firstly, the promotion of abandoned cropland utilization: Policymakers should encourage the use of abandoned cropland, particularly winter fallow fields, to boost grain production. This study shows that utilizing these fields can significantly increase grain output, which is vital for food security. Secondly, the incorporation of spillover effects in policy decisions: It is crucial for policies to be formulated considering not only the local impacts but also the spillover effects of using abandoned cropland. This study indicates that while local carbon emissions may increase, the overall net effect is a reduction in carbon emissions due to decreased emissions in other regions. This broader perspective can lead to more informed and effective policymaking. Thirdly, incentives for farmers: To encourage farmers to utilize abandoned cropland, governments could provide incentives such as subsidies, tax breaks, or technical support. These incentives can help offset the initial costs and motivate farmers to adopt new practices. In summary, this study underscores the importance of considering both local and spillover effects when formulating cropland use policies. By focusing on the utilization of abandoned cropland, policymakers can achieve a win–win situation of enhanced grain production and reduced carbon emissions. This holistic approach not only supports sustainable land management but also contributes to a secure and environmentally responsible food system. Therefore, incorporating these insights into policy frameworks can lead to more effective and sustainable agricultural practices.

This study has investigated the effects of the utilization of winter fallow fields on grain production and carbon emissions. However, it is important to note that the impact of the utilization of abandoned cropland extends beyond these aspects. It also affects soil health, biodiversity, ecosystem services, and socioeconomic development [59–61], among others.

These effects are interconnected and complex, so it is crucial to comprehensively evaluate both the positive and negative effects of the utilization of abandoned cropland to ensure effective cropland management and sustainable agriculture. Existing studies suggest that the utilization of abandoned cropland can bring significant benefits in terms of soil health, biodiversity, ecosystem services, and socioeconomic development. Notably, realizing these benefits also depends on implementing sound land management practices when using abandoned cropland to enhance the productivity of these lands while also preserving ecological balance supporting local communities, and addressing challenges such as soil degradation and invasive species. Therefore, the benefits are not solely determined by the act of using abandoned cropland but also by how it is utilized.

This study leads us to propose planting winter maize (a suitable and universal crop type during the winter season in the study area) on winter fallow fields as a way to ensure food security. However, in reality, cropland abandonment is a heterogeneous land-use change process [62–64], the choice to use abandoned cropland or not and the choice of crop ultimately depend on the decisions of farmers, which are influenced by various factors such as the natural environment, labor force, agricultural development level, and socioeconomic conditions [65–67], with socioeconomic factors being the most significant [10,65]. For instance, some farmers may give up planting winter maize because they may not find significant financial benefits and may determine that the costs outweigh the benefits. For environmental protection, sowing green manure is often considered a low-cost alternative that can have positive effects such as carbon sequestration and soil restoration. We used the CASA (Carnegie–Ames–Stanford approach) model to calculate the potential for carbon sequestration from such cropland, which we found to be 100 tons. This indicates that sowing green manure is a feasible option for using abandoned cropland.

There were several limitations of our study. First, our primary focus was on grain production and carbon emissions. However, it is necessary to consider other effects such as carbon sequestration, biodiversity, and soil restoration resulting from using abandoned cropland in the estimation system. In addition, considering the consistency and completeness of the data collection, 2018 was selected as the period in this study. It is necessary to explore the local and spillover effects since then of temporal–spatial changes in winter fallow fields in further studies. This will afford us a more all-encompassing understanding of the impact of utilizing abandoned cropland and furnish decisionmakers with a more scientific and equitable basis for their decisions. Secondly, this study, based on the identification of seasonal fallowing, simply recognized the seasonal fallowing in paddy fields as winter fallow fields by considering regional planting characteristics. This approach has certain limitations, and the next step should involve combining cropland phenology for precise identification. The carbon emission factors utilized in this study were not derived from biogeochemical or sampling methods. The Greenhouse Gas Emission Factor method overlooks the discrepancies in carbon emissions of agricultural materials. For example, the carbon emissions from fertilizers produced in different factories vary, highlighting the need to account for these differences in carbon emission factors [68]. Conducting additional field experiments has the potential to yield more precise, region-specific results. Finally, it should be acknowledged that in estimating the spillover effects of carbon emissions from grain transport, we focused solely on domestic grain trade and did not take international grain trade into account. To ensure a more comprehensive simulation of grain flow between regions, it is imperative to consider the influence of international grain trade in the future.

## 5. Conclusions

This study underscores the pivotal role of using abandoned cropland in achieving a "win–win" outcome: increasing grain production and mitigating carbon emissions. Furthermore, the spillover effects of using abandoned cropland on carbon emissions significantly surpass the localized impact, underscoring a critical aspect that has traditionally been undervalued. Consequently, this study advocates for a paradigm shift in policy formulation, with us urging local policymakers to adopt a comprehensive assessment framework that considers both the direct and indirect environmental repercussions of abandoned cropland utilization. The methodological framework and analytical techniques employed in this study provide a robust template for impact assessment, offering a replicable methodology for other regions confronting similar agricultural and environmental challenges. By providing a scientific underpinning to decision-making processes, this research equips policymakers with the necessary evidence base to achieve the sustainable use of cropland.

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land13081300/s1, Supplementary 1: Detailed processes to calculate greenhouse gas emissions; Supplementary 2: Detailed processes to calculate grain consumption [27,44,46,47,50,54].

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