Land Use Policy 159 (2025) 107804

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Recultivating abandoned cropland intensifies the trade-off between climate change mitigation and food security within the Yangtze River Basin, China

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ARTICLE INFO

Keywords:
Cropland abandonment
Climate change mitigation
Food security
Carbon–food trade-off
Yangtze River Basin

ABSTRACT

Cropland abandonment and subsequent recultivation create a pressing trade-off between carbon sequestration and food production. In the fragile, mountainous landscapes of the Yangtze River Basin, how recultivation mediates this trade-off remains poorly understood. This study quantified annual carbon stock and grain yield changes from 2002 to 2020 at both provincial and 10 × 10 km grid scales, using Spearman's correlation coefficient to assess the trade-off. Our analysis revealed that abandoned cropland accrued 182.3 Mt C, only 48.1 % of the potential sequestration under continuous abandonment. Although recultivation curtailed potential carbon gains by 51.9 %, it limited grain production losses to 13.5 Mt. Without recultivation, this deficit would have reached 65.6 Mt. The net effect of recultivation thus improved food security—offsetting a grain deficit sufficient to feed 37.2 million people—yet intensified the trade-off between carbon storage and food production. This trade-off was pervasive across scales, observed in all provinces and in 99 % of grid cells. However, isolated synergies (1 %) emerged in areas with specific terrain features or targeted interventions, such as agroforestry and High-Standard Cropland policies. Our findings demonstrate that while recultivation is critical for mitigating food security risks, it intensifies the trade-off between climate change mitigation and food security. These observations highlight the imperative for developing terrain-specific, site-appropriate strategies to co-optimize climate and food objectives.

1. Introduction

Global warming increasingly threatens agricultural productivity and food security. Under high-emission scenarios, yields of staple crops like maize may decline by up to 24 % by 2100 (Jagermeyr et al., 2021; Lobell et al., 2011; Zhu et al., 2022). Concurrently, an estimated 828 million people experienced acute food insecurity in 2021 (FAO, 2022). Although agricultural intensification can reduce the need for new cropland (Zabel et al., 2019), population growth and higher per-capita consumption are projected to expand global cropland by 25–226 Mha over the next three decades (Popp et al., 2017; Riahi et al., 2017). Without strategic land-use planning, this expansion threatens to further degrade terrestrial ecosystems and undermine objectives related to climate mitigation and food system sustainability(Paz et al., 2020; Ray et al., 2022).

Food systems account for roughly one-third of global greenhouse gas emissions, with agriculture and land-use change contributing about one-quarter (Clark et al., 2020; Laborde et al., 2021). Nature-based solutions—such as forest and grassland restoration—could supply up to 30 % of the mitigation needed to keep warming below 2 °C (Roe et al., 2019). However, large-scale deployment of these measures often requires converting cropland back to natural vegetation. This requirement creates a fundamental tension between carbon sequestration and the need to increase food production (Fujimori et al., 2022; Gvein et al., 2023).

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https://doi.org/10.1016/j.landusepol.2025.107804
Received 24 July 2025; Received in revised form 29 September 2025; Accepted 4 October 2025
Available online 15 October 2025
0264-8377/

Cropland abandonment vividly exemplifies this tension. Between 2003 and 2019, an estimated 79 Mha of cropland worldwide were abandoned, particularly in Europe, Central Asia, Russia, and China (Crawford et al., 2022; Potapov et al., 2022; Zheng et al., 2023). Abandoned fields can recover soil carbon and biodiversity but at the cost of reduced local food production, especially in smallholder systems (Blair et al., 2018; Han et al., 2025). In China, recent policies have promoted restoring abandoned croplands that are suitable for production to bolster food security (i.e., "Emergency Circular on Restoring Abandoned Cropland Production", http://f.mnr.gov.cn/201702/t20170206_1436285.html). A rigorous assessment of the trade-offs and synergies between carbon sequestration and food production is therefore essential for designing effective restoration strategies.

Yet evaluating these interactions remains challenging. Recent studies highlight a substantial gap in understanding how abandoned cropland can simultaneously support carbon sequestration and food production (Dade et al., 2019; Zheng et al., 2023). Although assessing each ecosystem service is crucial for informed land-use decisions, policy goals do not always align with single-service assessments. The classic trade-off between carbon sequestration and food production highlights the need to balance ecological benefits with agricultural productivity (Qiu et al., 2021; Rimal et al., 2019; Zhong et al., 2020). Furthermore, spatial variability in abandonment duration critically influences fallow lands' capacity to address climate and food crises (Daskalova and Kamp, 2023). A further complication is the issue of scale: food security analyses often focus on municipal or provincial levels, whereas carbon sequestration estimates typically rely on national or global inventories, hindering the accurate quantification of trade-offs and synergies (Peng et al., 2017). To address this mismatch, research must span multiple spatiotemporal scales and optimize benefits at finer resolutions (Tilman et al., 2011; West et al., 2010). Given these complexities, targeted research is urgently needed to quantify the trade-offs and synergies associated with abandoned cropland to inform ecosystem service management.

The Yangtze River Basin, which encompasses 11 provinces, supplies over 20 % of China's rice and wheat yet has experienced extensive cropland abandonment driven by urbanization and rural out-migration (Duan et al., 2021; Long et al., 2024; Long et al., 2022). Simultaneously, natural vegetation (i.e., forest and grassland) in the upper Yangtze River Basin sequesters is nearly 80 Mt C annually (Quan et al., 2023). These contrasting dynamics provide a unique opportunity to explore how abandoned cropland affects both climate change mitigation and food security.

To capture interactions across scales, we adopt a comparative design at two spatial resolutions: the provincial level and a 10×10 km grid. The provincial scale reveals overarching trends that are directly relevant to regional policy, whereas the grid scale highlights local hotspots and spatial heterogeneity in service trade-offs. Contrasting these perspectives allows us to evaluate how scale mediates the observed relationships, identify where spatial patterns converge or diverge, and derive guidance for scale-appropriate policy interventions.

We focus on the interactions—trade-offs and synergies—between carbon sequestration (operationalized as annual carbon stock change, representing climate change mitigation) and food production (operationalized as annual grain yield change, representing food security), hereafter referred to as carbon–food trade-offs. In this study, we (i) quantify the magnitude and persistence of abandonment and recultivation; (ii) map the spatial patterns of carbon stock change and grain yield change following these land-use transitions, and (iii) diagnose carbon–food trade-offs and synergies using Spearman's rank correlation to compare scale dependence across provinces and grids. The remainder of this paper is organized as follows: Section 2 describes the study area, data, and methods; Section 3 presents the spatiotemporal results and cross-scale trade-offs and synergies; Section 4 discusses the comparative findings, policy implications, uncertainties, and limitations; Section 5 provides the concludes.

2. Material and methods

2.1. Study area

The Yangtze River Basin (97°21′–123°25′E, 21°08′–35°20′N) covers eleven provinces—Shanghai, Zhejiang, Jiangsu, Anhui, Hubei, Hunan, Jiangxi, Sichuan, Chongqing, Yunnan, and Guizhou—and spans approximately 2.05 million km^2 (21% of China's land area) (China Statistical Yearbook, NBSC, 2018) (Fig. 1). The basin exhibits pronounced climatic and topographic gradients, transitioning from tropical–subtropical to warm-temperate conditions and featuring elevations range from over 6000 m in the western highlands, gradually descending toward the eastern plains.

Ecologically, the Yangtze Basin is a major biodiversity hotspot and a critical water source. Agriculturally, the basin is a vital food production hub, contributing over 20 % of China's rice and wheat production. Economically, it supports some of the highest population densities in the country. Despite rapid socio-economic and technological advances, agricultural mechanization remains relatively low, contributing to widespread cropland abandonment (Guo et al., 2021; Qi et al., 2021). The ecological impacts of these land-use changes have recently drawn considerable academic and policy attention. Consequently, an assessment of the climate–food trade-offs and synergies in the context of cropland abandonment and recultivation is essential for sustainable management of this region.

2.2. Methodological framework

Our methodological flowchart is summarized in Fig. 2. The framework comprises three main stages. First, we identified cropland abandonment and recultivation from 2003 to 2020 using MODIS-NDVI time series. Second, we quantified the annual changes in carbon stock and grain yield resulting from these land-use transitions using the InVEST Carbon Sequestration module (Integrated Valuation of Ecosystem Services and Tradeoffs) and a statistical downscaling approach, respectively. Third, we analyzed the tradeoff and synergy relationships between these two ecosystem services at both provincial and 10×10 km grid scales. All spatial analyses were conducted in Google Earth Engine (GEE) and ArcGIS 10.2, while statistical analyses were performed in R (v. 4.3.1).

2.3. Data sources and pre-processing

Our analysis integrated multi-source datasets, including remote sensing imagery, meteorological records, agricultural statistics, and literature-based parameters.

MODIS-NDVI Time Series: We utilized the MOD13Q1 V6.1 product, providing 16-day composite Normalized Difference Vegetation Index (NDVI) data at a 250 m resolution. To mitigate noise from atmospheric conditions and sensor issues, we applied the Whittaker Smoother algorithm to reconstruct high-quality annual time series for each year from 2002 to 2020 (Atzberger and Eilers, 2011; Kong et al., 2019; Shao et al., 2016).

Carbon Density Parameters: Baseline carbon densities for cropland, grassland, and forest ecosystems were compiled from IPCC reports and peer-reviewed literature (Table S4–S14). These reference values represent four carbon pools: aboveground biomass, belowground biomass, soil organic carbon (SOC), and dead organic matter. The values were then calibrated for local conditions using meteorological records from the China Meteorological Administration (accessed 1 December 2022), as detailed in Supplementary Information 2.2.

Agricultural Statistics: Provincial agricultural statistics from 2000 to 2020 were sourced from the China Statistical Yearbook (NBSC, 2000–2020). We focused on the six dominant crops in the basin: rice, wheat, maize, soybean, potato, and rape (Guo et al., 2021; Wang et al., 2023). These data served as the basis for our grain yield downscaling

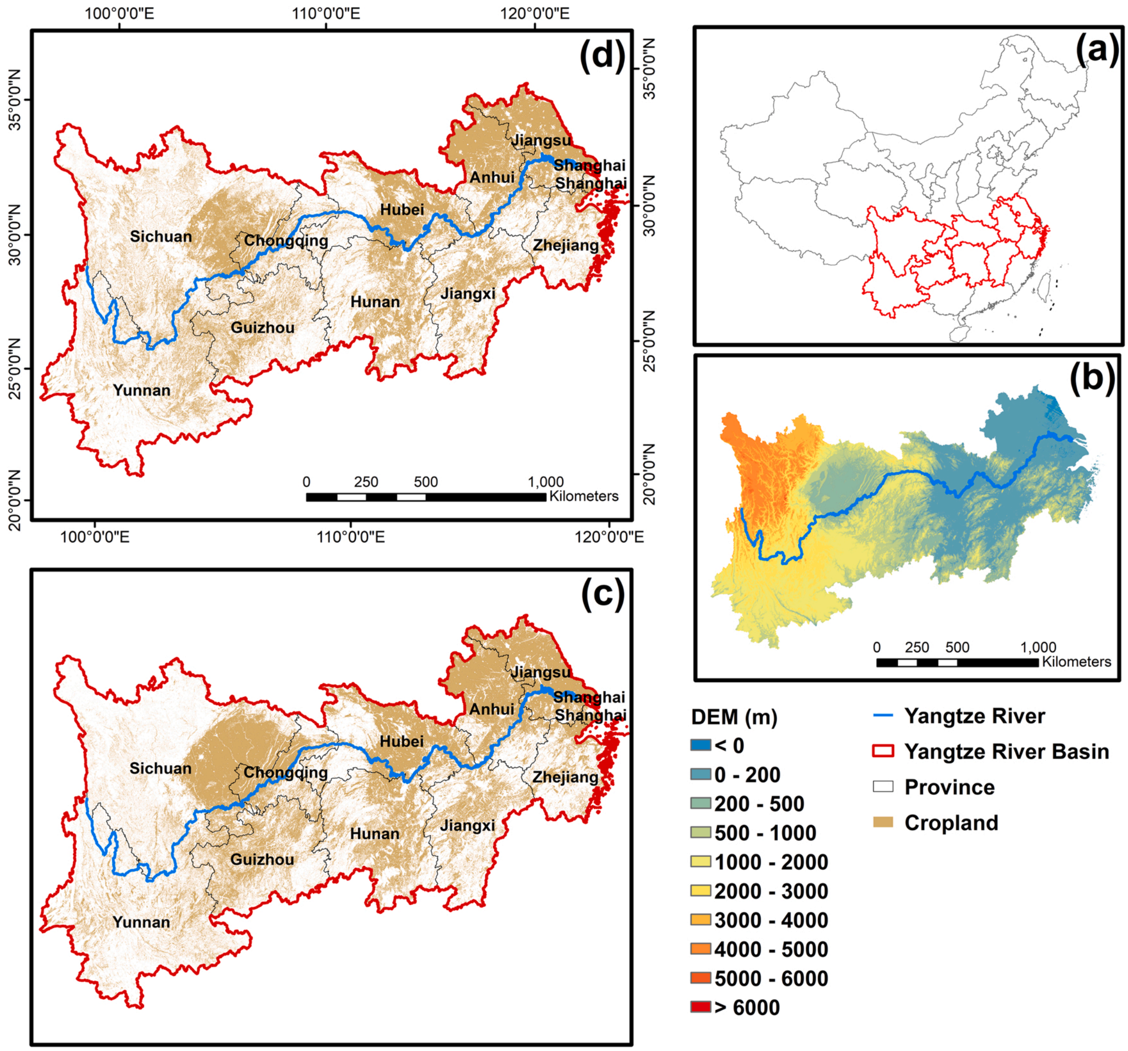

Fig. 1. The study area of the Yangtze River Basin, China. (a) Location of the Yangtze River Basin within China; (b) the topography of basin, shown by the Digital Elevation Model (DEM); (c) and (d) The spatial pattern of cropland in 2000 and 2020.

model.

2.4. Mapping cropland dynamics

Following established definitions (FAO, 2006; GrĂDinaru et al., 2020), we classified a pixel as "abandoned cropland" if it remained uncultivated for a minimum of two consecutive years. The year in which cultivation ceased marks the onset of abandonment. A previously abandoned pixel that returned to active cultivation was subsequently labeled as "recultivated". Pixels converted from abandoned cropland to impervious surface were categorized separately as "urbanization". The detailed methodology for this classification is described in Long et al. (2024).

2.5. Quantifying ecosystem service changes

1) Carbon stock change

We used the InVEST Carbon Sequestration module (Jiang et al., 2021) to estimate pixel-level carbon stocks. The model partitions total carbon into four pools: aboveground biomass, belowground biomass, soil organic carbon (SOC), and dead organic matter ("humus carbon"). Province-level carbon density pools values (Table S4–S14) were assumed constant from 2002 to 2020. Total carbon at any pixel is given by:

$$C_{total} = C_{above} + C_{below} + C_{Soil} + C_{dead} \quad (1)$$

Where, C_{total}, C_{above}, C_{soil} and C_{dead} represent total of carbon stock (TOC, ton/ha), aboveground biomass (ton/ha), below biomass (ton/ha), soil organic carbon (SOC, ton/ha), and humus carbon (ton/ha), respectively.

$$\Delta C_{stock} = (C_j - C_i)/T_{i,j} \quad (2)$$

We followed IPCC Tier 1 guideline (IPCC, 2003, 2019) and recent literature on secondary successional carbon sequestration. Carbon stock change (ΔC_{stock}) between two land-cover states i and j over a transition period $T_{i,j}$ is calculated as:

Where, ΔC_{stock}, C_j and C_i indicate annual change in carbon stocks in changes (ton/ha/yr), carbon stock of current land cover j (ton/ha) and carbon stock of previous land cover i (ton/ha). The model assumes a default transition period $T_{i,j}$ of 20 years for carbon to reach equilibrium after land-use change.

For the "natural regeneration" phase on abandoned land, we assumed a constant sequestration rate of 2.38 tons C/ha/yr, a value validated for China by Cook-Patton et al. (2020). Changes in SOC during regeneration used data from the Soils Revealed database (Sanderman et al., 2023).

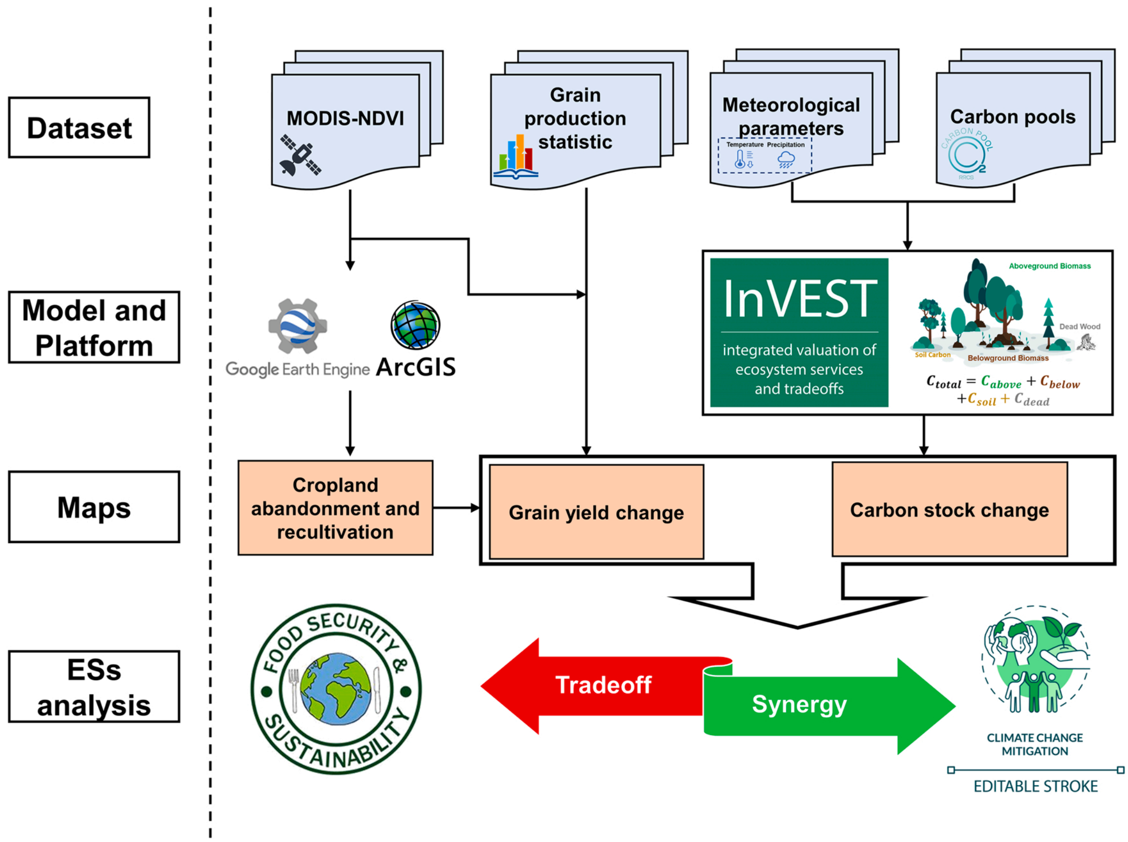

Fig. 2. Flowchart of study.

2) Pixel-based grain yield change

To estimate grain yields at 250 m pixel resolution, we downscaled provincial production statistics to the pixel level, using annual integrated NDVI as a proxy for productivity. The grain yield for a specific pixel m in province r, and year y was calculated by proportionally allocating the total provincial production $G_{r,y}$ based on the pixel's NDVI value relative to the sum of NDVI values across all cropland pixels in that province:

$$G_{m,r,y} = NDVI_{m,r,\ \ y} / NDVI_{sum,r,y} \times G_{r,y} \quad (3)$$

$Y_{m,r,y} = G_{m,r,y}/Area$(4)

$$\Delta Y = Y_{m,r,y+1} - Y_{m,r,y} \quad (5)$$

Where, $G_{m,r,y}$ indicates grain production allocated by the pixel m of cropland in the province r and year y (ton). $G_{r,y}$ indicates total grain production of cropland in the province r. $NDVI_{m,r,y}$ indicates the NDVI value allocated by the pixel i of cropland in the province j and year y, and $NDVI_{sum,r,y}$ represents the sum value of cropland NDVI in the province r. $Y_{m,r,y}$ represent grain yield allocated by the pixel m of cropland in the province r (ton/ha). In our study, *Area*.

We calculated interannual grain yield change at each pixel to determine year-to-year changes. This approach relies on two key assumptions: (1) that intra-provincial variation in NDVI accurately reflects relative agricultural productivity, and (2) that official statistics capture the total grain output.

2.6. The trade-off /synergy analysis

To evaluate the relationship between climate change mitigation and food security, we analyzed the spatiotemporal correlation between annual carbon stock change and grain yield change. This analysis was performed at two distinct scales: provincial and a 10 × 10 km grid. Prior to correlation analysis, both indicators were standardized using min-max normalization to a common scale ranging from 0 to 1 (John B and Anthony W, 2012)

$X'_{u,y} = (X_{u,y} - X_{u,\min})/(X_{u,\ \max} - X_{u,\min}),\ Y'_{u,y} = (Y_{u,y} - Y_{u,\min})/(Y_{u,\ \max} - Y_{u,\min})$(6)

Where $X'_{u,y}$ and $Y'_{u,y}$ are the normalized value of the indicator of unit u (province or grid), $X_{u,y}$ and $Y_{u,y}$ are the value of the indicator for each ecosystem services, and $X_{u,\min}$, $X_{u,\max}$, $Y_{u,\min}$ and $Y_{u,\max}$ are the minimum and maximum value of each considered indicator variable over the production situations, respectively.

We then applied Spearman's rank-order correlation to identify positive (synergy) or negative (tradeoff) relationships between carbon stock change and grain yield change (Cord et al., 2017; Kalfas et al., 2019). A detailed justification for using Spearman's correlation is provided in Supplementary Information 4. Let $r^X_{u,y}$ and $r^Y_{u,y}$ be their ranks of for $X'_{u,y}$ and $Y'_{u,y}$. In each region or grid cell, we calculated:

$$\rho_u = \sum (r^X_{u,y} - \bar{r}^X_{u,y})(r^Y_{u,y} - \bar{r}^Y_{u,y}) \Big/ \sqrt{\sum (r^X_{u,y} - \bar{r}^X_{u,y})^2} \times \sqrt{\sum (r^Y_{u,y} - \bar{r}^Y_{u,y})^2} \quad (7)$$

$t_u = \rho_u / \sqrt{\frac{1-\rho_u^2}{n-2}},\ p_u = 2\mathrm{P}(t_{n-2} \geq |t_u|)$(8)

Where, ρ_u represents correlation coefficient in unit u. t_u is the test statistic, and p_u is the two-tailed p-value under the Student's t distribution with $n-2$ degrees of freedom. n represents number of observations.

A significantly positive correlation ($\rho_u > 0$, $p_u < 0.05$) indicates a synergy, meaning both carbon stock change and grain yield change move in the same direction (either both increasing or both decreasing). We further distinguish "positive synergy" (both increasing) from "negative synergy" (both decreasing). Conversely, a significantly negative correlation ($\rho_u < 0$, $p_u < 0.05$) indicates a trade-off, where carbon and grain changes move in opposite directions.

By mapping ρ_u across provinces and grid cells, we identified geographic hotspots of trade-offs and synergies, revealing how the interplay between carbon sequestration and food production is shaped by land-use dynamics.

3. Results

3.1. Maps of cropland abandonment and duration

From 2002–2020, approximately 21.5 Mha of cropland were abandoned at least once across the 11 provinces of the Yangtze River Basin (Fig. 3a)(Long et al., 2024). The proportion of abandoned cropland relative to the provincial total varies widely among province, ranging from 0.3 % in Shanghai to 49 % in Sichuan. Spatially, the distribution of abandonment is highly heterogeneous. Abandoned fields are concentrated in the northwestern and southern highlands in Sichuan. Yunnan and Guizhou show similar patterns, with abandonment clustered in their eastern and western mountainous zones, respectively. In contrast, abandonment in Hubei and Jiangxi is often observed near urban fringes (Fig. 4).

Despite this widespread abandonment, much abandoned land did not remain idle for long. By 2020, a substantial portion of this area had transitioned to other uses: 74 % of initially abandoned pixels had been recultivated at least once (Fig. 3b and Figure S1), while 7 % had converted to impervious surfaces through urban or industrial expansion (Fig. 3c and Figure S2). On average, provinces achieved a 73 % (SD = 8 %) recultivation rate and a 14 % (SD = 8 %) urban-conversion rate. Consequently, the net abandoned area decreased to 4.03 Mha by 2020. The extent of recultivation varied by province, ranging from a 63 % reduction in Jiangsu to an 87 % reduction in Guizhou, while conversion

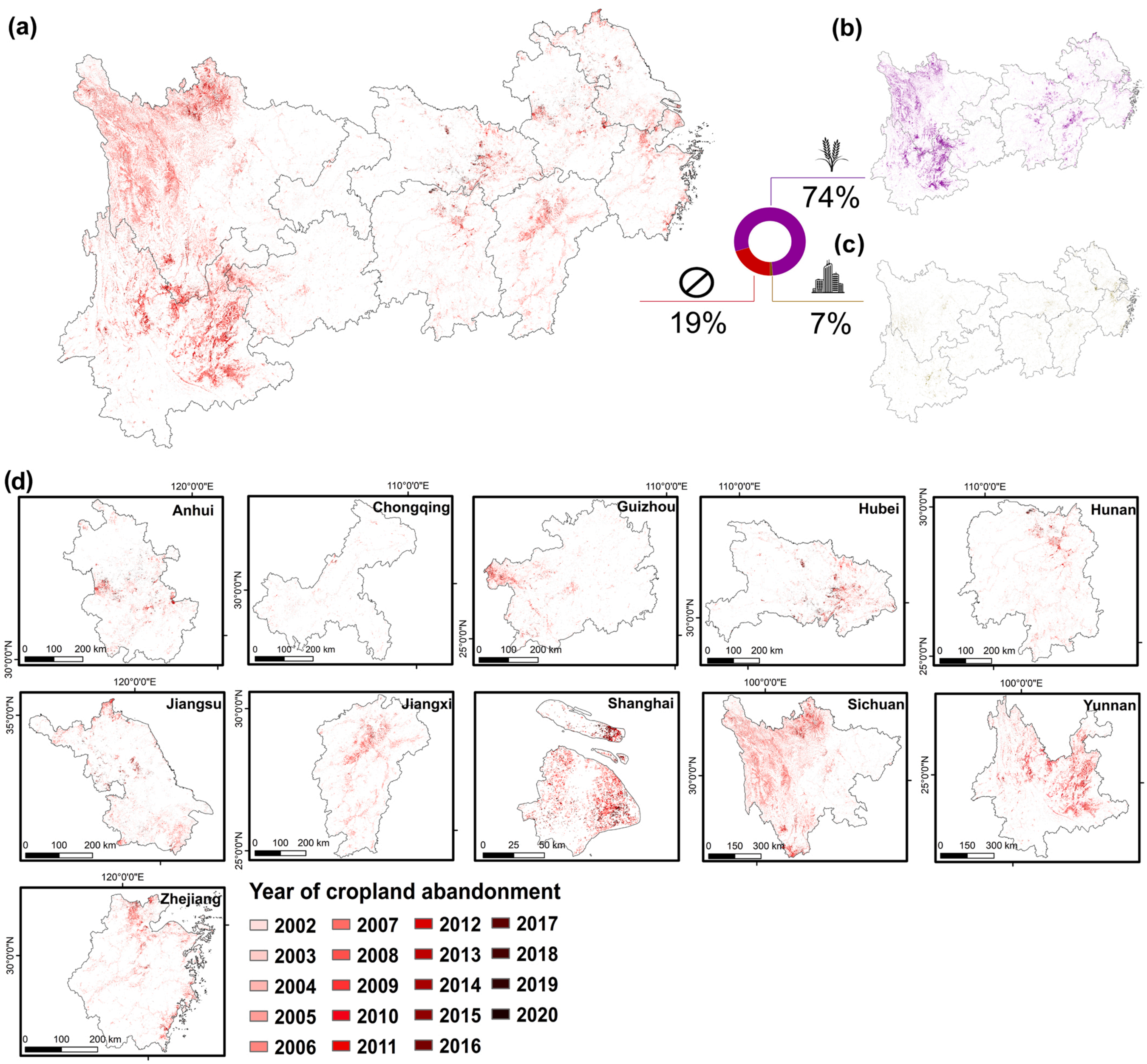

Fig. 3. Spatial patterns and fate of abandoned cropland in the Yangtze River Basin (2002–2020). (a) The overall Abandoned cropland extent and abandoned croplands loss for (b) recultivation and (c) impervious surfaces. Proportions (donut chart) and spatial distribution (maps) of three conversion of abandoned cropland: recultivation (74 %), impervious surfaces and others (7 %) or remaining abandonment until 2020 (19 %). (d) Abandoned cropland extent in each province.

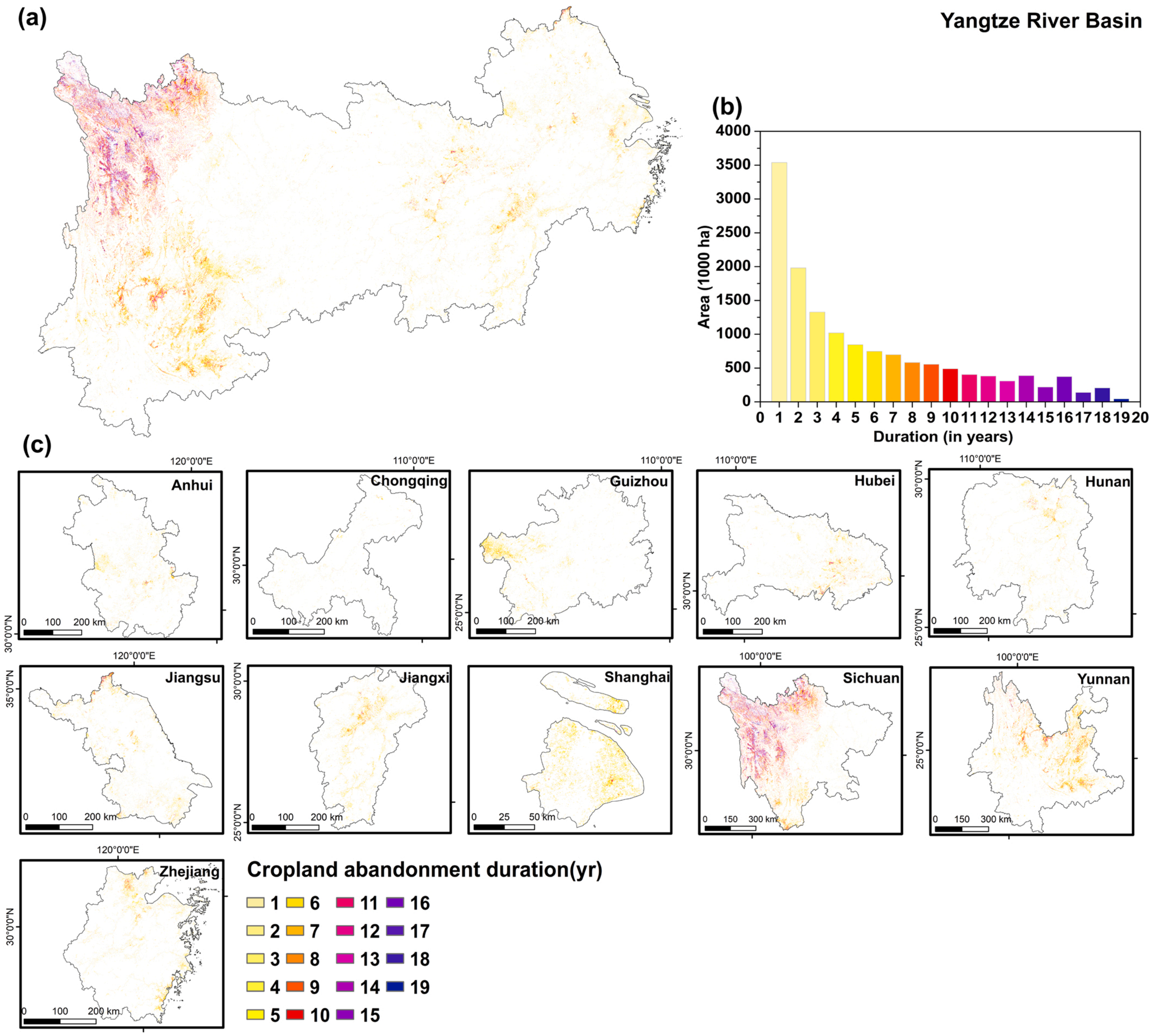

Fig. 4. Real abandonment duration across the Yangtze River Basin (2002–2020). (a) Spatial distribution of the cumulative abandonment duration for all affected pixels. (b) Bar chart showing the total area of land corresponding to each specific abandonment duration. (c) Province-level maps of abandonment duration. Note that these patterns include multiple periods of abandonment for those pixels that experienced abandonment and abandoned lands loss multiple times during the time series.

to impervious surfaces ranged from 4 % (Sichuan) to 27 % (Zhejiang) (Fig. 3d).

We distinguish "real abandonment duration" (the average observed fallow period) from "scenario abandonment duration" (the hypothetical duration if no recultivation or conversion occurred). Real durations are highly skewed toward short-term fallows, with a basin-wide average of 3.2 ± 1.7 yr (range: 2.0 yr in Chongqing to 8.1 yr in Sichuan (Fig. 5)). Spatially, fallows of less than three years dominate alluvial plains and peri-urban zones, whereas longer-term fallows (4–8 yr or more) are concentrated in the remote highlands of Sichuan and Yunnan. An analysis of fallow durations reveals a clear pattern: short-term abandonment (1 year) accounts for approximately 3.5 Mha, while medium-term fallows (2–3 years) cover an additional 3.0 Mha. Longer durations are progressively less common: fallows of 4–6 years each account for under 1 Mha, those lasting 7–10 years total 1.2 Mha, and continuous abandonment beyond ten years is rare (< 0.5 Mha).

By comparison, the scenario abandonment duration would extend to 11.7 ± 1.2 yr, ranging from 9.3 yr in Hubei to 14.0 yr in Guizhou (Figure S3–S4). This remarkable contrast underscores that under current socioeconomic and policy regimes, most cropland abandonment is transient. Consequently, only marginal and remote terrains remain fallow long enough to allow for significant ecological recovery.

3.2. *Annual carbon stock change and grain yield change*

The transient nature of cropland abandonment directly influenced carbon sequestration outcomes. Across the eleven provinces, the mean annual carbon stock change on lands that remained abandoned ranged from 0.04 tons C/ha/yr (Shanghai) to 1.10 tons C/ha/yr (Sichuan) (Fig. 6 and Table 1). By 2020, an estimated total of 182.3 Mt C had accumulated across the 11 provinces, a figure 51.9 % lower than the scenario accumulation of 379.2 Mt C that would have occurred without recultivation or conversion (Figure S5). This shortfall in carbon accumulation varied by province, with reductions from scenario

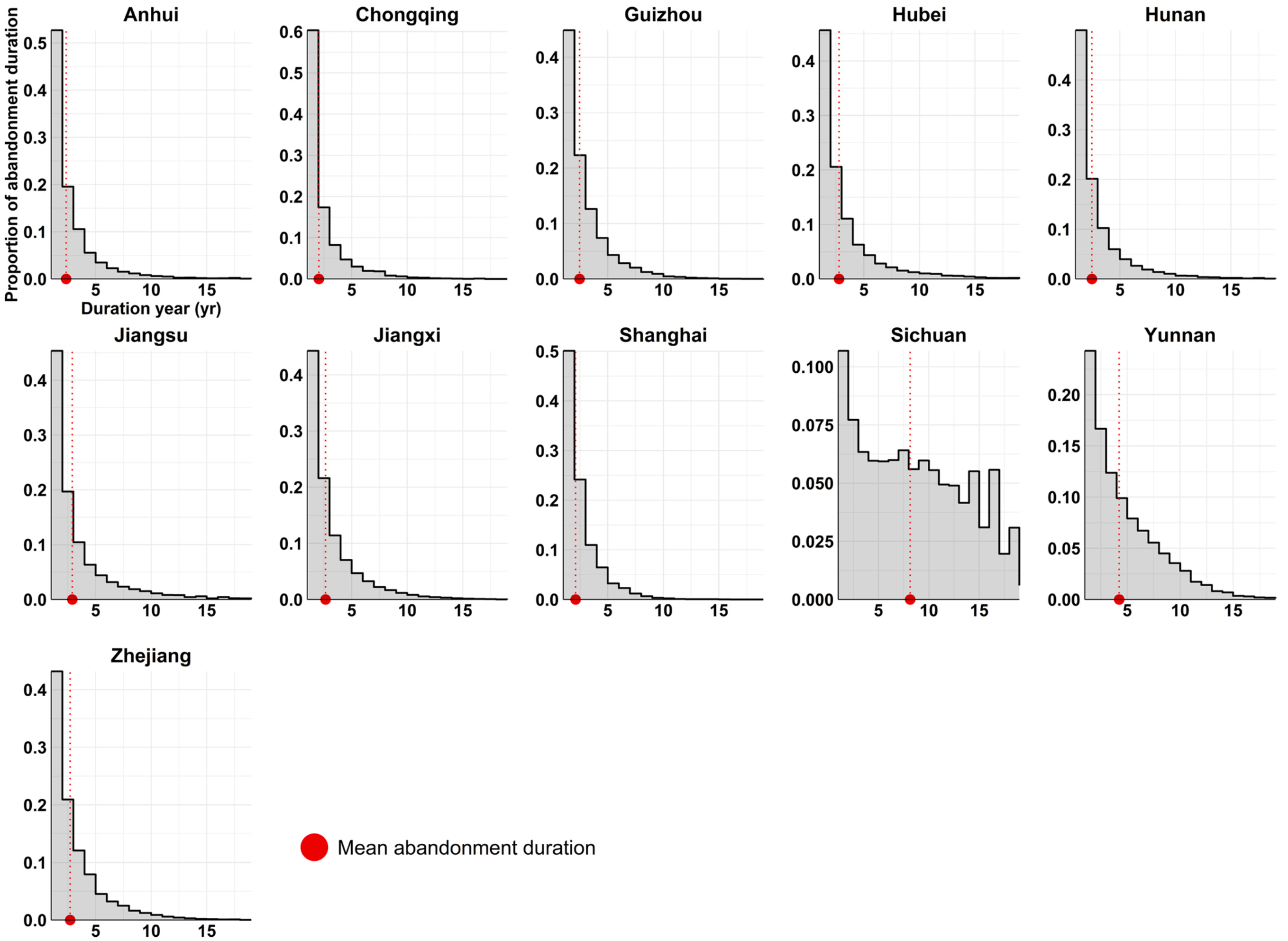

Fig. 5. Distribution of real abandonment duration by province, 2002–2020. Each panel displays a histogram showing the frequency of abandonment durations. The x-axis represents the duration in years, while the y-axis indicates the proportion of a province's total abandoned area corresponding to each duration. The red point and vertical dashed line in each panel mark the mean abandonment duration for that province. Note: The duration is calculated as the cumulative number of years a pixel was classified as abandoned during the study period.

accumulation ranging from 24.9 % (Sichuan) to 95.6 % (Shanghai). This highlights how rapid land-use turnover, especially in peri-urban areas, curtails carbon storage by shortening fallow periods.

Widespread recultivation led to complex and varied impacts on grain yield across the basin (Fig. 7 and Table 1). By 2020, provinces with high recultivation rates ($>$ 80 %), such as Jiangxi and Guizhou, realized small net yield gains of 0.02 tons/ha/yr and 0.004 tons/ha/yr, respectively. In contrast, regions with lower recultivation rates, such as Jiangsu, experienced yield declines of -0.08 tons/ha/yr. Across the region, these recultivation activities produced an estimated 13.5 Mt of grain production, substantially mitigating a potential production deficit that would have otherwise reached 65.6 Mt. This deficit under a no-recultivation scenario would have ranged from 0.2 Mt in Chongqing to 30.3 Mt in Sichuan (Figure S6). These divergent outcomes illustrate fundamental tradeoffs: provinces that recultivate aggressively reduce food security shortfalls but sacrifice substantial carbon sequestration potential. Conversely, areas that maintained longer fallows captured more carbon at the expense of regional grain supply whereas areas that preserve longer fallows capture more carbon at the expense of regional grain supply.

3.3. *Trade-offs and synergies of carbon–food*

At the provincial scale, annual changes in carbon stocks and grain yields exhibit a consistently negative correlation (Fig. 8). Spearman's ρ ranges from approximately -0.95 to -0.40, with the most pronounced trade-offs in Anhui and Chongqing ($\rho\approx -0.95$ to -0.85) and more moderate values in Guizhou, Yunnan, Zhejiang and Sichuan. Over the 2002–2020 period, the correlation in Jiangxihas declined slightly (slope < 0, $p< 0.001$), indicating an intensifying trade-off, whereas Hunan and Sichuan show a marginal, non-significant weakening relationship (slope > 0, $p > 0.1$). No province exhibits a positive correlation ($\rho > 0$), confirming that at this aggregated scale, gains in carbon consistently come at the expense of grain.

Analysis at the finer 10 × 10 km grid scale reveals significant sub-provincial heterogeneity (Fig. 9). To interpret these patterns, we categorized the correlation coefficients into five levels: strong trade-offs ($\rho = -1.0$ to -0.6), moderate trade-offs ($\rho = -0.6$ to -0.2), weak relationships ($\rho = -0.2$–0.2), moderate synergies ($\rho = 0.2$–0.6), and strong synergies ($\rho = 0.6$–1.0). Although nearly 99 % of grid cells exhibit a negative correlation ($\rho < 0$), the strength of this relationship varies. Strong tradeoffs ($\rho < -0.6$) are found in 66 % of cells (Fig. 9b), forming hotspots in the Yunnan–Guizhou highlands, central Jiangxi, and northern Anhui (Fig. 9c). The remaining 33 % of cells show moderate to weak trade-offs ($\rho = -0.6$–0), commonly found in western Sichuan and scattered elsewhere. Crucially, about 1 % of grid cells register positive correlations ($\rho > 0$), marking localized synergy zones where carbon gains and yield recovery move in tandem. Thus, while both scales confirm a pervasive carbon-food trade-offs, the grid-level analysis uncovers not only rare instances of synergy but also a wider spectrum of

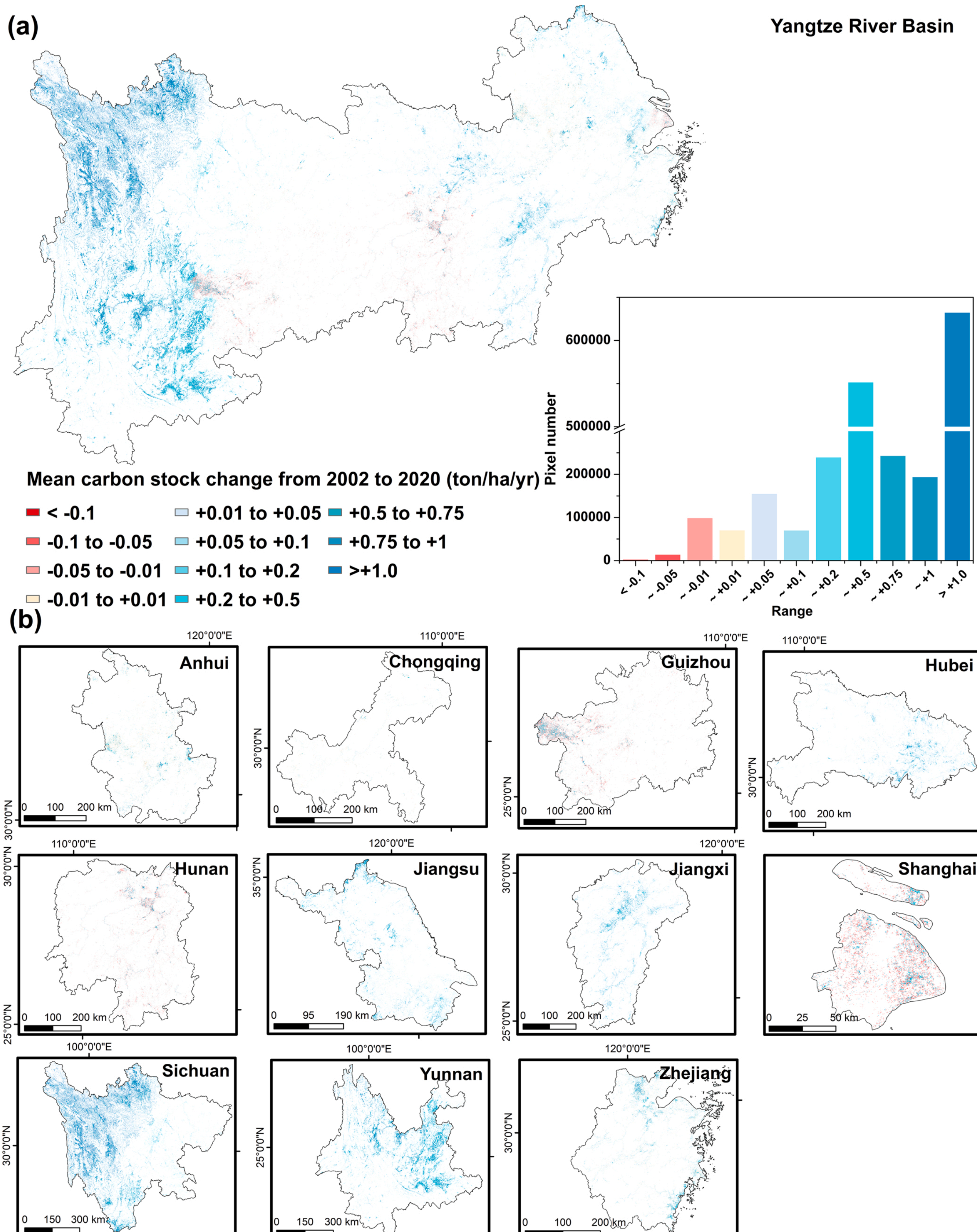

Fig. 6. Mean annual carbon stock change on lands experiencing abandonment and recultivation from 2002 to 2020, in terms of ton/ha/yr. The figure shows (a) the spatial distribution of carbon stock change across the entire Yangtze River Basin, alongside a histogram of the pixel counts for each change category, and (b) the same data disaggregated by province. The change values represent the mean annual rate across the sum of aboveground biomass, belowground biomass, and soil organic carbon pools over the study period at a 250 m resolution.

Table 1
Mean carbon stock change and grain yield change at each province as of 2020. ± represents standard deviations (SD).

Province	Mean carbon stock change (SD) (ton/ha/yr)	Mean grain yield change (SD) (ton/ha/yr)
Anhui	0.14 (±0.27)	−0.06(±0.12)
Chongqing	0.10 (±0.21)	−0.05 (±0.12)
Guizhou	0.08 (±0.22)	0.01 (±0.10)
Hubei	0.20 (±0.32)	−0.05 (±0.12)
Hunan	0.09 (±0.25)	−0.05 (±0.11)
Jiangsu	0.27 (±0.35)	−0.08 (±0.13)
Jiangxi	0.17 (±0.26)	0.02 (±0.14)
Shanghai	0.04 (±0.14)	−0.05 (±0.11)
Sichuan	1.13 (±0.65)	−0.09 (±0.10)
Yunnan	0.50 (±0.40)	−0.02 (±0.10)
Zhejiang	0.18 (±0.28)	−0.08 (±0.13)

interaction strengths. This finding highlights the importance of sub-provincial variation analysis for understanding ecosystem services dynamics.

4. Discussion

4.1. Consistence with previous studies

The 73 % recultivation rate we observed in the Yangtze River Basin by 2020 is consistent with the 92 % rate reported by Hou et al. (2021) for the Lower Yangtze urban agglomeration, yet it significantly exceeds the national average estimate of 36 % for the period of 1990–2023(Wu et al., 2025). In contrast, Dara et al. (2018) reported a much lower only 20 % recultivation rate of only 20 % for abandoned cropland in a steppe region of Northern Kazakhstan, which is substantially lower than our finding. This discrepancy can likely be attributed to two main factors: (1) variations in the operational definitions of "abandonment" and "recultivation", as our criteria may encompass shorter fallow periods; and (2) differences in remote sensing data resolution, as our coarser 250 m imagery might average land-use patterns that are captured as distinct patches in finer 30 m resolution data.

Our abandonment durations were much shorter than those found in a global average [= 14 years; (Crawford et al., 2022)], with the Chongqing results (2 years) shorter than the Chongqing region in the global study (13 years). But our abandonment duration was similar to Song (2019)(3.45 years). This pattern of short-term abandonment is consistent with trends observed in other regions under high land-use pressure. For instance, in the Brazilian Amazon, where secondary forests regrow rapidly, 50 % of these forests are cleared for recultivation within 5–8 years, and 80 % are less than 20 years old (Chazdon et al., 2016; Nunes et al., 2020; Schwartz et al., 2020; Smith et al., 2020)). Similarly, across the wider tropics, only 33 % of forests regenerating on cleared sites exceed 10 years in age, which reinforces the predominance of short fallow cycles in areas with high land-use pressure.

Our carbon stock change rates (0.08–1.10 tons C/ha/yr) are positioned between the 1.38 ton C/ha/yr reported for karst reforestation in southwest China(Yang et al., 2016) and the 0.66 ton C/ha/yr documented for Siberian cropland regrowth (Wertebach et al., 2017). This range is environmentally plausible: rapid early carbon accumulation in the karst region is driven by fertile soils and fast-growing pioneer species, while succession in cold boreal climates proceeds more slowly. The subtropical broadleaf forests of the Yangtze River Basin represent an intermediate condition between these two extremes. Methodologically, our approach involved identifying cropland-to-natural-vegetation transitions from 250 m annual maps and subsequently calculating mean carbon changes over a minimum of two successive fallow years using the IPCC Tier 1 linear model (IPCC, 2003, 2019). Our calculations integrated a literature-validated biomass accumulation rate of (Cook-Patton et al., 2020) and soil-organic-carbon data (Sanderman et al., 2023). Although this linear assumption simplifies succession, empirical evidence indicates that carbon accumulation follows non-linear trajectories (Poeplau et al., 2011). Therefore, future work should aim to integrate non-linear response curves and disturbance regimes to improve basin-wide carbon estimates.

Finally, our grain yield loss ratio of 3.1 ton/ha sits between 5.5 ton/ha in Jiang et al. (2023) and 3.4 ton/ha in Guo et al. (2023), a result that likely reflects the lower agricultural productivity typical of mountainous cropland. Collectively, these comparisons demonstrate that regional context, data resolution, and methodological choices are critical factors that shape the estimates of both carbon sequestration and food production impacts. By combining dual-scale mapping with an annual time series, our study effectively captures both broad provincial trends and fine-scale heterogeneity, thereby advancing the understanding of how abandonment and recultivation jointly drive ecosystem service outcomes across the Yangtze River Basin.

4.2. The role of recultivation in mediating carbon–food trade-offs

We isolated the impact of cropland recultivation by quantifying cumulative changes under two conditions: (i)the real pathway with recultivation and (ii)a scenario without recultivation (Figures S5–S6). Under the real pathway, recultivation reduced potential carbon sequestration by up to 51.9 % basin-wide but limited cumulative grain production losses to 13.5 Mt. Conversely, in the scenario without recultivation, grain deficits would have nearly quadrupled to 65.6 Mt, while carbon gains would have approached their theoretical maximum of 379 Mt C. Thus, targeted recultivation emerges as a key lever for reducing carbon-food tradeoffs, balancing modest carbon forfeiture against substantial food security benefits.

Temporal dynamics clarify how the timing and intensity of recultivation drive these trade-offs (Fig. 8). Following abandonment, carbon stocks increase slowly and typically require about a decade of uninterrupted fallow before entering a rapid-accumulation phase (Schierhorn et al., 2013). In the Yangtze Basin, however, the mean fallow duration is only 3.2 years, so most plots are recultivated well before reaching that inflection point. As a result, nascent carbon gains are truncated, producing very strong negative correlations ($\rho \approx -0.95$ to -0.85) in provinces with short fallow periods, such as Anhui (2.3 years) and Chongqing (2.0 years). By contrast, grain yield collapse immediately upon abandonment but rebound sharply within the same year of recultivation. Because yield recovery is almost instantaneous, no province exhibits a positive correlation ($\rho > 0$); recultivation curtails carbon accumulation yet prevents prolonged food security deficits. In Sichuan, where mean fallows are longer (over 8.0 years), modest carbon accumulation can occur before replanting, producing less severe trade-offs ($\rho \approx -0.60$ to -0.40).

At the 10 × 10 km grid scale, nearly all cells (99 %) exhibit negative correlations between annual carbon stock change and grain yield change, but the strength of this trade-off varies with terrain and management (Fig. 9). In the Yunnan-Guizhou Plateau, for instance, steep slopes and limited irrigation prolong fallows, allowing some carbon to accumulate but delaying yield recovery, which manifests as a very strong trade-off. Conversely, in the lowland plains of Jiangsu and Anhui, fertile soils and ample water enable rapid recultivation. This truncates carbon accrual but restores yields quickly, also resulting in a strong trade-off. In western Sichuan, where fallows are more extended (5–8 years), more substantial carbon accumulation occurs before recultivation, weakening the trade-off. However, a few grid cells in the middle and lower Yangtze—particularly in Hunan and Zhejiang—exhibit moderate trade-offs or even positive correlations ($\rho > 0$). These pockets of local synergy correspond to agroforestry systems near riparian buffers (Távora et al., 2022; Zhou et al., 2025) and High-Standard Farmland construction (Hao et al., 2023; Li et al., 2023), where carbon gains and yield improvements occur in tandem.

Beyond biophysical and management factors, socio-economic drivers such as land tenure arrangements also shape recultivation timing and

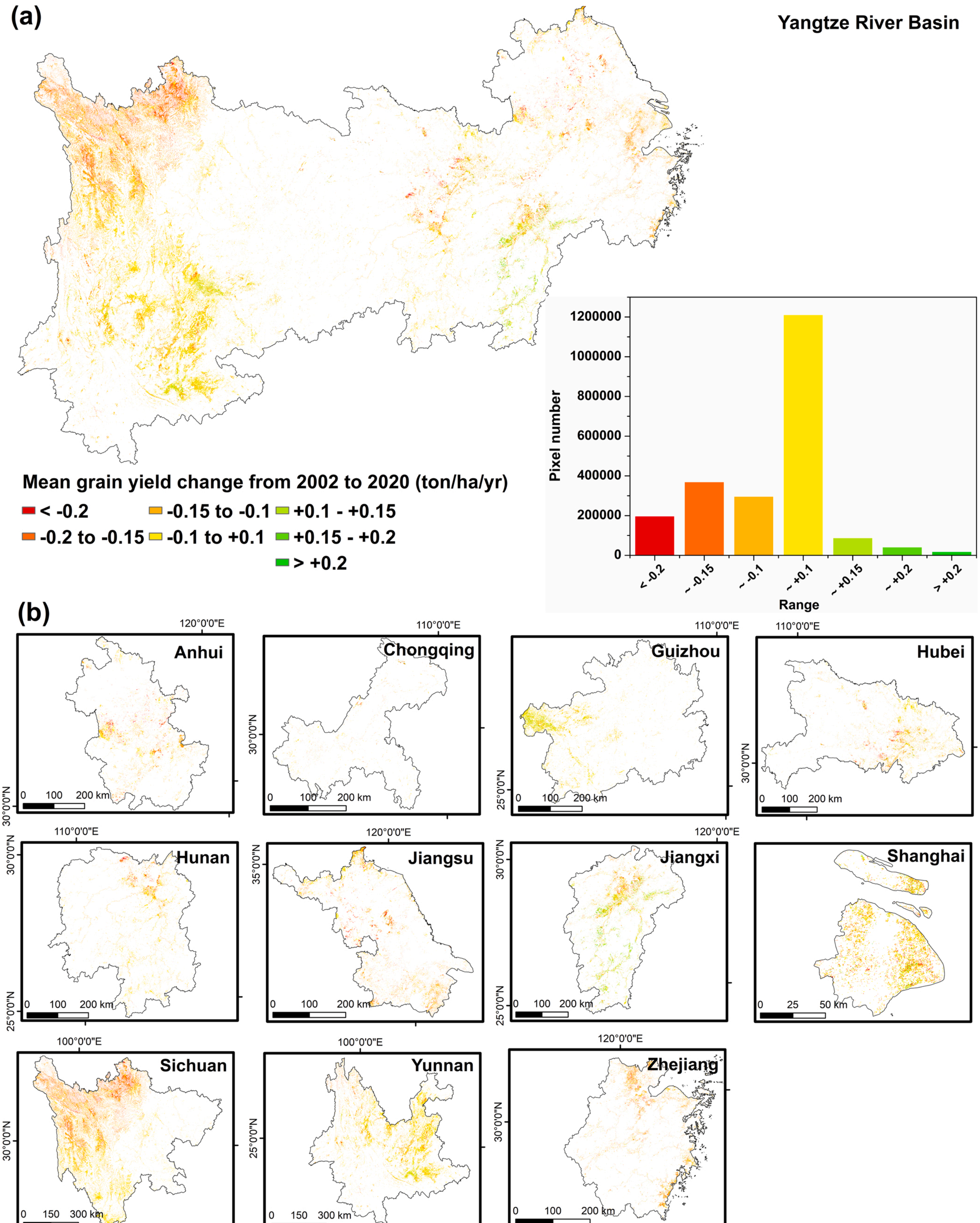

Fig. 7. Mean annual grain yield change in abandoned croplands and recultivation lands from 2002 to 2020, in terms of ton/ha/yr. The figure shows (a) the spatial distribution of grain yield change across the entire Yangtze River Basin, alongside a histogram of the pixel counts for each change category, and (b) the same data disaggregated by province. The change values represent the mean annual rate of grain yield change over the study period at a 250 m resolution.

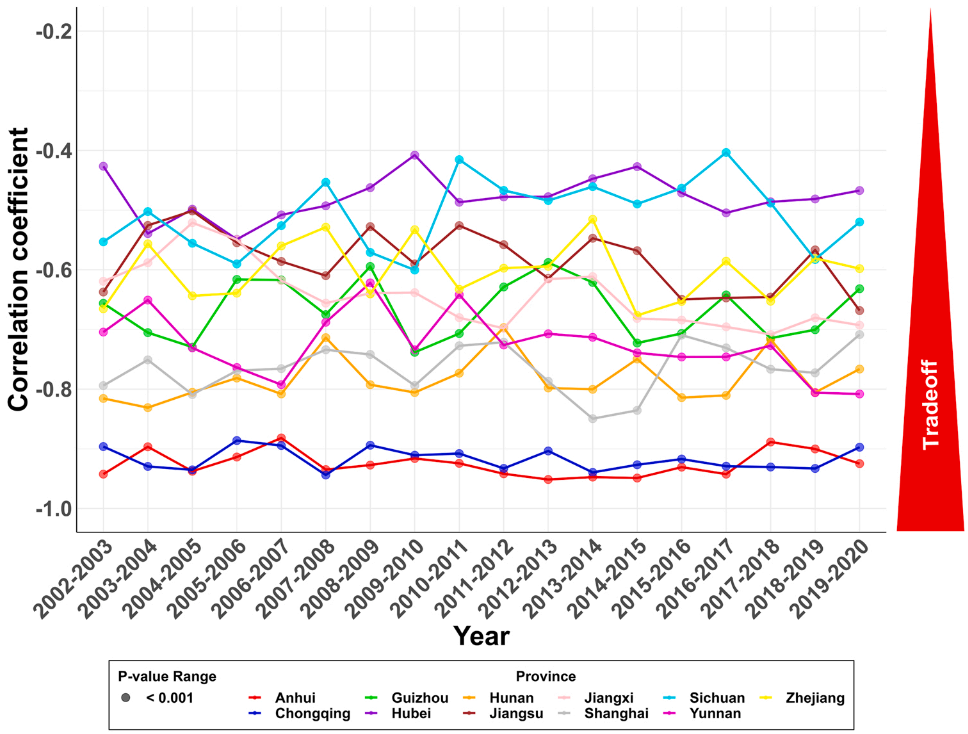

Fig. 8. Temporal evolution of the carbon–food trade-off at the provincial level, 2002–2020. The line chart illustrates the annual Spearman's correlation coefficient (ρ) between carbon stock change and grain yield change for each province. Each colored line represents an individual province. Negative ρ value indicates a trade-off relationship, with values closer to -1.0 signifying a stronger trade-off. All correlation coefficients depicted are statistically significant ($p < 0.001$).

intensity (Wang et al., 2022), thereby conditioning the observed carbon–food trade-offs. Secure and long-term tenure rights can encourage farmers to extend fallows, allowing for partial soil recovery and enhanced fertility before recultivation, which can mitigate the trade-off. By contrast, short-term leases, insecure use rights, or fragmented holdings incentivize early recultivation, truncating potential carbon accumulation while prioritizing yield recovery (Chigbu, 2023; Chigbu et al., 2022). This finding is consistent with global evidence indicating that tenure insecurity discourages restoration investments and exacerbates negative trade-offs among ecosystem services (Lovo, 2016; Lyu et al., 2024).

4.3. Implications for recultivation policy and management

By 2020, approximately 21.5 Mha of cropland lay fallow in the Yangtze River Basin—land that could have sequestered up to 379 Mt C if left uncultivated. Although widespread fallows provide co-benefits, including enhanced biodiversity, improved soil structure, and better water and air quality (Feng et al., 2005; Fischer et al., 2012; Khanal and Watanabe, 2006), these gains entail significant production costs: cumulative grain losses on abandoned cropland from 2002 to 2020 totaled 13.5 Mt, equivalent to 29.9 Pcal (1 Pcal = 10^{12} kcal) and sufficient to feed 37.2 million people at 2200 kcal/day (China Food and Nutrition Development Outline, https://www.gov.cn/govweb/zwgk/2014–02/10/content_2581766.htm)(Table S15). This balance is further complicated by socio-economic dynamics: rural out-migration may reduce on-farm emissions but raise overall fossil-fuel demand (Bu et al., 2022; Shi and Chang, 2023), while dietary shifts toward meat divert over 34 % of crop output to animal feed, amplifying land demand and constraining both food production and carbon sequestration (Long et al., 2018; Shukla et al., 2019; Tang et al., 2015; Zhao et al., 2021). These dual pressures make abandonment and recultivation a governance challenge, requiring integrated responses linking land management with socio-economic and tenure dynamics.

Our paired-yield analysis shows that while recultivation improves productivity relative to abandoned land, the gains are modest (Fig. 10). Mean yields on recultivated plots only slightly exceed pre-abandonment levels and remain below provincial and national averages, consistent with short fallows (mean 3.2 yr) that hinder full soil-fertility recovery. To make recultivation both effective and sustainable, policy interventions should address these constraints holistically. This requires a multi-pronged strategy that includes: (i)extending fallows in targeted marginal uplands to allow for biophysical recovery before replanting; (ii)deploying cross-sectoral incentives (i.e., Payments for Ecosystem Services, soil-restoration grants) to lower the cost of soil-building practices and precision resource management (Crawford et al., 2022); (iii)investing in post-harvest infrastructure and market integration to improve food access and smallholder viability (Wang et al., 2019; Webb et al., 2006); (iv)advancing sustainable intensification through improved agronomy and precision agriculture (Long et al., 2022); and (v)incorporating demographic trends and land-suitability analyses to optimize restoration timing and location (Schneider et al., 2022; UNFCCC, 2021).

Recent global assessments highlight that secure tenure is a prerequisite for successful land restoration and for achieving objectives such as Land Degradation Neutrality (UNCCD, 2022). In contexts like the Yangtze River Basin, where short fallows truncate potential carbon gains, tenure is a decisive factor shaping farmers' incentives. Secure and predictable rights reduce uncertainty, thereby increasing farmers' willingness to extend fallows, invest in soil health, and adopt sustainable practices that mitigate the carbon–food trade-off (Țopa et al., 2025; Xu et al., 2018). Conversely, fragmented or insecure tenure discourages long-term investment and perpetuates premature recultivation. Beyond the farm level, effective tenure systems facilitate coordinated, landscape-scale investments—such as shelterbelts, riparian buffers, and irrigation upgrades—that simultaneously increase carbon stocks and stabilize production amid climate variability (Sun et al., 2025; Zhong et al., 2020). In this regard, participatory governance and the integration of local knowledge translate tenure security into effective restoration outcomes, ensuring that institutional frameworks and

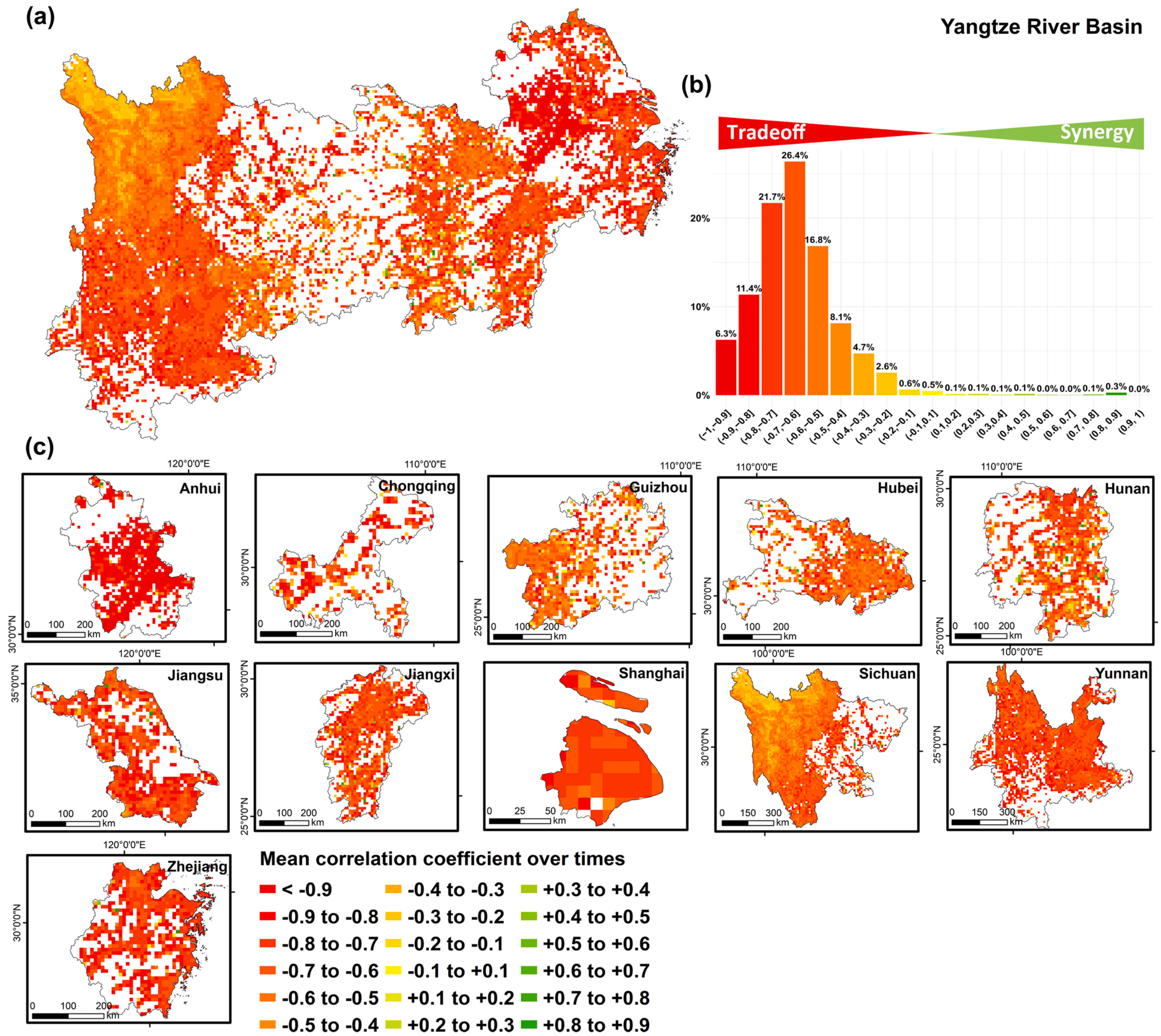

Fig. 9. Spatial distribution of the mean temporal correlation between carbon stock and grain yield changes (2002–2020). The figure shows (a) a map of the mean correlation coefficient for each 10 × 10 km grid cell across the Yangtze River Basin, (b) a histogram illustrating the frequency distribution of these correlation coefficients, with labels indicating the percentage of grid cells in each bin, and (c) province-level maps detailing the spatial patterns. Note: The mean value for each grid cell was calculated from its annual correlation coefficients over the study period; years with null values were excluded. The annual correlation maps for each province are available in Supplementary Figs. S10–S20.

on-the-ground practices reinforce one another (Liu et al., 2022). Therefore, embedding tenure considerations in recultivation policy is crucial for reconciling carbon and food objectives, recognizing tenure as a critical enabling condition rather than a panacea (Elahi et al., 2024; Liu et al., 2025).

Finally, abandoned cropland also offers potential opportunities beyond food production, notably for renewable-energy siting and bioenergy cultivation. Across the Yangtze River Basin, demand for bioenergy crops is projected to rise substantially (Tian et al., 2021) to help meet climate targets (Næss et al., 2021). Without careful spatial planning, bioenergy expansion can intensify land-use competition and trigger indirect land-use change, potentially offsetting carbon gains (Meyfroidt et al., 2022). Siting renewable energy infrastructure, such as solar and wind farms, on abandoned rather than productive cropland is a land-sparing strategy that protects prime farmland (Hernandez et al., 2015). Failing to adopt such targeted siting may displace agriculture from productive fields, inducing land clearing elsewhere and thereby undermining both food security and broader environmental goals (Timothy et al., 2008; Wright et al., 2017).

4.4. Uncertainty and future prospect

Our reliance on the InVEST Carbon Sequestration module, calibrated with provincial carbon-density pool inputs, gives rise to several uncertainties. First, the coarse resolution of the carbon density layers omit key biophysical heterogeneity—such as soil texture, pesticide residues, and species-specific growth rates—that likely affects carbon-stock dynamics (O'Bryan et al., 2022; Oechaiyaphum et al., 2020; Wang et al., 2021). Although we adjusted density values using meteorological covariates, future research would benefit from integrating process-based carbon models that explicitly simulate vegetation succession and soil-organic-carbon turnover, incorporating finer-resolution soil maps

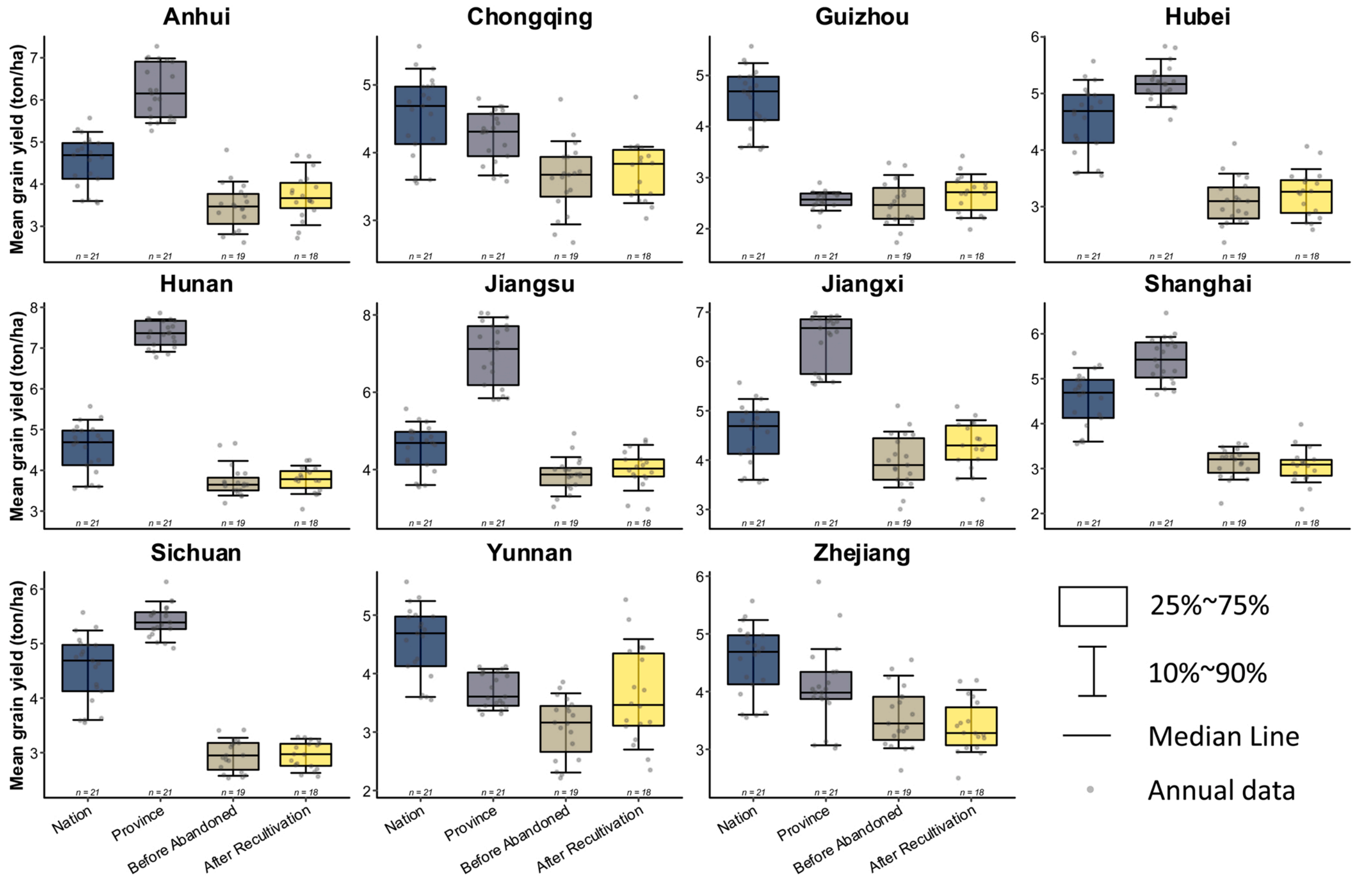

Fig. 10. Comparison of grain yields before abandonment and after recultivation against national and provincial benchmarks (2000–2020). The box plots in each panel compare the distribution of annual mean grain yield for four distinct categories: (1) the national average, (2) the respective provincial average, (3) yield on specific cropland parcels in the year prior to their abandonment ("Before Abandoned"), and (4) yields on the same parcels after they were returned to cultivation ("After Recultivation"). Grey points represent the annual data for each category.

and vegetation data. Second, our use of a literature-based trajectory simplifies non-linear successional dynamics documented over decadal to centennial scales (Meersmans et al., 2016).

The estimation of grain yield change is also subject to data limitations. Provincial statistics may mask reporting inaccuracies at subnational levels, particularly in topographically complex areas (Liu et al., 2020). Furthermore, using NDVI to downscale yield introduces further uncertainty, as mixed-use pixels (i.e., forest–cropland mosaics) can confound NDVI signals and inflate yield estimates (Butt, 2018). These challenges underscore the need for higher-resolution, crop-specific yield maps to capture spatial heterogeneity more accurately.

Our analysis focused exclusively on two ecosystem services—climate regulation(carbon stock change) and food production (grain yield change)—and may overlook other services (i.e., water regulation, habitat provisioning) that also respond to cropland abandonment (Fastre et al., 2020). Our focus on annual changes may also obscure time-lagged ecosystem responses to drivers such as extreme weather events or policy shifts (Tomscha and Gergel, 2016). Future assessments should incorporate additional service indicators provide a more holistic understanding (Zhang et al., 2016).

Although our multiscale comparison proved robust in identifying widespread trade-off and rare synergy, the results are critically shaped by the duration of the time series and the chosen spatial grain. Longer time series would better capture slow successional processes and market cycles, while finer spatial units (i.e., sub-watersheds) could reveal localized management hotspots (Qiao et al., 2019). Future studies should therefore explore nested scales to tailor interventions to specific ecological and socio-economic contexts.

A significant data limitation is the absence of spatially explicit information on land tenure and governance (i.e., ownership rights, contract duration, parcel fragmentation). Without such granular data, our correlation diagnostics may partly reflect unobserved institutional heterogeneity. Future work should aim to link cadastral datasets to abandonment histories and embed tenure-responsive variables in spatial models to better isolate institutional effects from biophysical drivers.

Despite these limitations, our approach advances previous work by mapping spatiotemporal patterns and quantifying multiscale trade-offs and synergies on abandoned croplands. Looking ahead, integrating key drivers—such as climate variability, policy incentives, and market forces—into socio-ecological models will be crucial for clarifying the sustainability of repurposing these fallow agricultural lands. Assessing how these lands can be managed to optimize human well-being through strategic afforestation, diversified food production, or habitat restoration remains a critical next step (Zheng et al., 2023). Careful attention to scale, data quality, and the diversity of ecosystem services will be essential for leveraging abandoned croplands to achieve genuinely sustainable land management.

5. Conclusion

Recent agricultural land-use changes in the Yangtze River Basin have reshaped both carbon and food systems. Our study reveals that while 21.5 Mha of cropland were abandoned between 2002 and 2020, 74 % was subsequently recultivated, creating significant spatiotemporal heterogeneity in ecosystem services. While natural regrowth on abandoned land held the potential to sequester up to 1.1 ton C/ha/yr, the realized carbon accumulation by 2020 reached only 48.1 % of its potential, as widespread recultivation truncated fallow periods. On the food security front, these dynamics resulted in a net grain production loss of 13.5 Mt. However, this deficit would have been far greater—an estimated 65.6 Mt—had no land been returned to cultivation, highlighting recultivation's critical role in mitigating food security risks.

A pervasive trade-off between carbon stock change and grain yield change was evident at both the provincial and 10 × 10 km scales. Our analysis showed that 99 % of grid cells exhibited such trade-offs, with a marginal 1 % showing localized synergies. These patterns underscore our key finding: that the timing and intensity of recultivation are critical determinants of a landscape's trajectory toward either carbon sequestration or food production.

Moving forward, land-use strategies must be science-based and context-specific, aiming to transform these prevalent tradeoffs into synergies where possible. For instance, extending fallow durations in marginal areas, paired with practices like agroforestry and soil conservation, could enhance carbon storage while balancing food production goals. Conversely, in fertile lowlands, rapid recultivation combined with sustainable intensification can safeguard food security while minimizing carbon losses. Adopting such targeted approaches is essential for aligning national policies with global commitments, such as the Paris Agreement and Sustainable Development Goals 2 (Zero Hunger) and 15 (Life on Land), and will ultimately help the Yangtze River Basin navigate its dual challenges.

CRediT authorship contribution statement

Jing Sun: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Gilles Colinet:** Supervision. **Yuqiao Long:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Jian Peng:** Writing – review & editing. **Joost Wellens:** Supervision. **Xiuchun Dong:** Visualization, Software, Funding acquisition. **Wenbin Wu:** Writing – review & editing, Supervision, Funding acquisition. **Jeroen Meersmans:** Writing – review & editing, Supervision, Conceptualization. **Chuya Wang:** Validation. **Ping Huang:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by National Natural Science Foundation of China (42271276), National Key Research and Development Program of China (2022YFD2001105), Science and Technology Program of Sichuan Academy of Agricultural Sciences (2022ZZCX031). The authors acknowledge the Chinese Academy of Agricultural Sciences – Uliège, Gembloux Agro-Bio Tech, jointed PhD program.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2025.107804.

Data availability

No data was used for the research described in the article.

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