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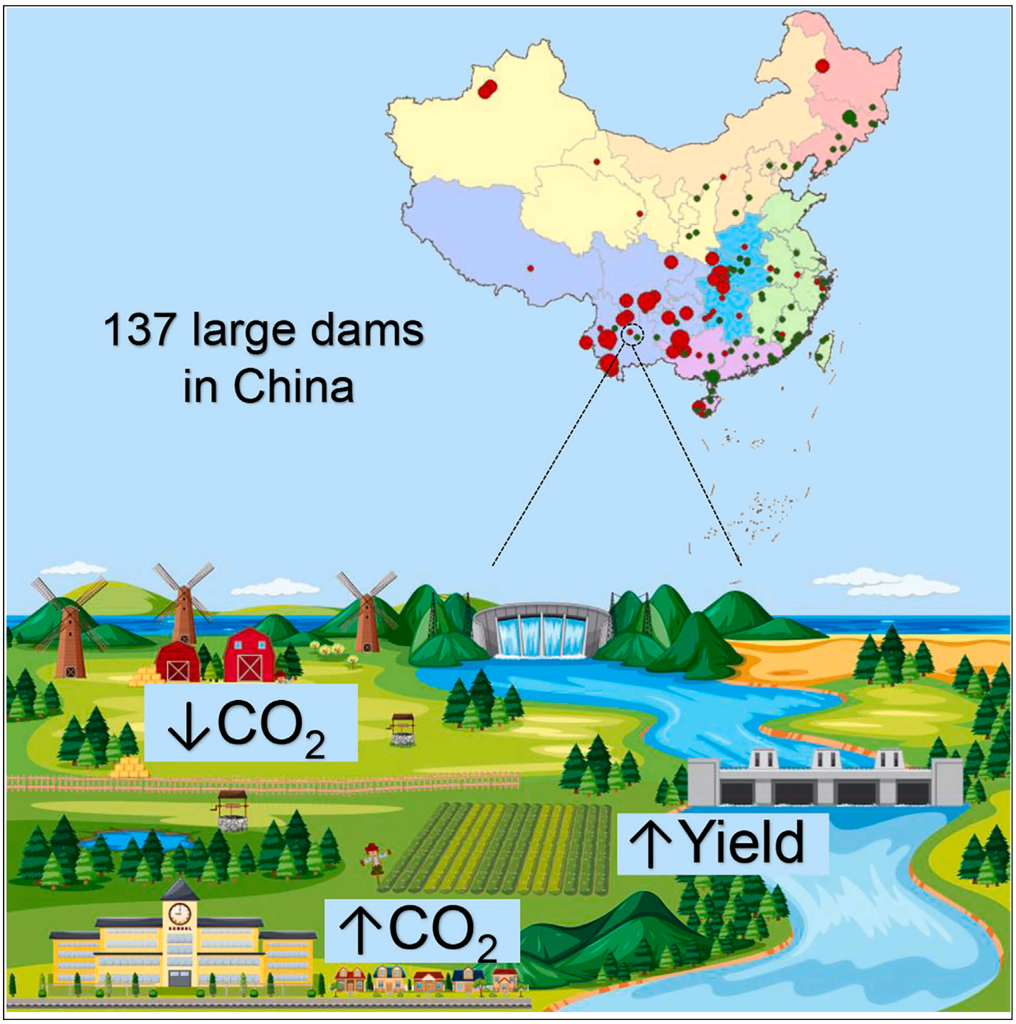

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Highlights

Studied land cover changes near China's 137 large dams, impacting carbon emissions

Dam-affected land cover varies significantly across different regions

Less increase in carbon emissions in dam-affected versus unaffected areas

Dams may positively impact carbon neutrality and food security

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Dynamics of land cover changes and carbon emissions driven by large dams in China

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SUMMARY

The recent surge in dam construction has sparked debates regarding their contribution to carbon neutrality and food security, focusing on trade-offs between production benefits and ecological drawbacks. However, how dams affect carbon emissions and land cover changes, including their spatial differentiations, remains unclear. We quantified spatiotemporal variations in carbon emissions and storage of 137 large dams in China from 1992 to 2020, resulting from land cover change in potentially affected areas. We observed a lesser increase in carbon emissions and a more pronounced increase in carbon storage driven by forest conservation and regeneration within dam-affected areas compared to unaffected areas. Additionally, we noticed an increased grain yield in nearby areas potentially due to increased water availability. Our findings highlight the importance of considering land cover change when assessing carbon neutrality or grain yield at regional and national scales. This study provides useful insights into optimizing dam locations to mitigate future carbon emissions effectively.

INTRODUCTION

In the quest for a clean energy transition and a stable irrigation water supply, the construction of numerous dams has been undertaken globally, with a significant surge observed in developing countries in recent decades.[1–3] For example, between 2000 and 2017, approximately 82% of the 520 large dams (heights above 15 m or reservoir capacity of over 0.1 billion m^3) built globally were in developing countries.[4] This trend will likely continue in the future since almost 80% of large hydropower dams are currently planned or under construction across developing countries.[5] However, the surge of large dams sets in motion a chain of interconnected processes that influence land use, carbon emissions, and food production.[6] Dam construction often entails significant alterations to land cover in the surrounding areas,[7] encompassing activities such as land flooding to create reservoirs, river courses modifications, changes in groundwater and runoff flow patterns, alterations in local microclimate, and the abandonment of cropland and scattered village due to migration.[8–10] These transformations can eventually reshape the region's carbon balance by influencing the flux of carbon dioxide from vegetation to the atmosphere,[11,12] concurrently affecting food production by balancing the diminished arable area with increased irrigation water.[13] Careful consideration of these dynamics is essential for formulating strategies that optimize the benefits of dams while mitigating their adverse environmental effects.

While the impact of dam construction on the surrounding area can be driven by several factors, such as the dam's age, function (e.g., irrigation, hydroelectric power), size, geographic location, and affected range, the environmental and socioeconomic changes caused by land cover changes around dams are still unclear.[14] Previous studies have found that dam construction can destroy vegetation along rivers and also flood forests and grasslands upstream by raising the surface water level.[15,16] Additionally, water and energy supplied by dams can lead to the conversion of agriculture and urban areas into forests and grasslands.[17,18] While the negative environmental and socioeconomic consequences of dam construction (e.g., loss of biodiversity and habitats, migration out of dam-constructed area, loss of farmlands, and changes in livelihood) are undeniable, there may be some positive ecological outcomes in the long run.[19,20] For example, inhabited areas around dams could convert back to natural vegetation through the regeneration of forests and grasslands,[18,21] conversion of croplands to natural vegetation,[22,23] and large-scale plantations, promoting environmental protection.[24,25]

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Though the land cover changes driven by dams can change the dynamics of the carbon pools in terrestrial ecosystems, eventually altering carbon cycles between terrestrial ecosystems and the atmosphere,[26] such dynamics are not adequately emphasized in projects, particularly dams, in China.[27] Much like the role of ecological construction in reducing carbon emissions,[28] studies supporting the promotion of carbon stock through dams argue that dams can stimulate the regeneration of vegetation on unoccupied lands.[29,30] This process involves the absorption of carbon dioxide from the atmosphere through photosynthesis, leading to the storage of carbon in various forms, including biomass (such as trunks, branches, roots, and leaves), dead organic matter (litter and dead wood), and soil.[31,32] However, other studies posit that the increased availability of water resources resulting from dam construction can encourage the expansion of both cropland and built-up areas to a certain extent.[33,34] The expansion of agriculture and urban areas is typically accompanied by large fossil energy consumption, which results in increased carbon emissions.[35,36] Despite carbon emissions from land cover changes have accounted for up to 33% of the global carbon emissions over the past 150 years,[37] previous studies on dam impacts in China have not focused on the issue of carbon emissions caused by potential land change. Another land use change effect of dam construction that remains controversial is the potential balance between farmland loss and increased productivity. For example, while farmland extents may be lost due to dam construction, increased water availability may offset production loss by increasing crop productivity, especially for dams used for irrigation purposes. Given China's strong focus on ensuring food security[38,39] and achieving carbon neutrality by 2060,[40] it is important to understand the impacts of large dam constructions in China on carbon balance and food production at the national scale.

To date, a comprehensive national-scale investigation of the impacts of dams on carbon emissions, carbon storage, and grain yield in China remains nonexistent. Such an investigation is crucial for not only China but also other developing countries that are undergoing rapid land cover and land use changes and facing the challenge of achieving specific carbon emission reduction and food security goals. Quantifying the environmental impacts of dam construction in China can provide lessons for other developing countries to understand the potential impacts of future dam construction and implement targeted measures to achieve carbon neutrality and food security.

To determine how land cover changes within the potentially affected areas of large dam changed regional carbon emissions, carbon storage, and grain yield, we investigated 137 large dams (height >15 m or reservoir capacities >0.1 billion m^3) in China for which relatively adequate data were available, including location, operation year, reservoir area, storage capacity, catchment area, and primary function (Figure S1; Table S1). We address the following two questions: (1) What are the impacts of dam-induced land cover change on regional carbon emissions, carbon storage, and grain yield? and (2) Is the rapid expansion of hydropower and irrigation dams increasing the regional carbon emissions and grain yield, respectively?

To answer these questions, we first investigated six land cover types within regions affected by dam construction from 1992 to 2020, encompassing agriculture, forest, grassland, settlement, water, and other land use types (with less areas, such as sparse vegetation, wetland, bare areas, lichens, mosses, and permanent snow and ice). Second, we quantified the spatiotemporal distribution of carbon emissions, carbon storage, and grain yield using the carbon emission factors and carbon density of different land cover types and global historical yields for major crops (see STAR Methods for details). Third, according to the previous studies,[4,41,42] we defined the dam-affected area as a concentric circular region, with the damsite serving as the central point and the catchment's outermost boundary as its radius (Figure S2). Dam's catchment area was approximated as a circular region, with the diameter of this circle defining the catchment's outermost boundary. Similarly, we approximated the reservoir area around the dam as a circular region, using the diameter of this circle to establish the radius of the core influence area (Zone I). The distance extending from the dam's core influence zone to the outermost catchment boundary was subsequently divided into four zones (Zone II–Zone V) based on their proximity to the dam. The area beyond the catchment's outermost boundary was designated as Zone VI (control group), representing the region unaffected by the dam. Finally, the changes in carbon emissions, carbon storage, and grain yield in the zones around dams with different functions, scales, and construction years were statistically analyzed.

RESULTS

Land cover change induced by dams

Results showed that dam construction supported forest growth in the dam-affected areas from 1992 to 2020 (Figure 1; Table S2). For example, the forest areas in the dam-affected zones increased by 0.84% on average while those in regions not affected by dams decreased by 24.87% (Table S2). Notably, in slightly farther Zones II and III, forest areas increased by 6.08% and 3.08%, respectively, while grasslands decreased minimally (0.73% and 0.81% in Zones II and III, respectively). Agriculture and other lands exhibited a significant average downward trend of 2.12% and 13.21% within dam-affected zones, in contrast to an upward trend of 7.43% and 2.05% in Zone VI, respectively. In addition, regions closer to the dam experienced lower spatial variations in land cover (Figure 1). The spatial variation ratio (see STAR Methods) increased from 0.20% in the nearest influence zone (Zone I) to 9.67% in a farther zone not affected by the dam (Zone VI).

We found that the dam construction in China has increased the direct and indirect use of non-forest and non-agricultural classes, such as sparse vegetation, wetlands, bare areas, lichens, mosses, and permanent snow and ice. For example, within dam-affected regions, several non-forest land cover types were transformed into forests and grasslands, while several grassland types were reclaimed into agricultural lands to meet the increasing food demands of settlement (Figure 1). In contrast, the opposite was seen in regions outside the dam-affected zones, as forest and agricultural lands were likely converted into other classes.

Dam's effects on carbon emissions

Results revealed that large dams may have the potential to provide advantages in terms of carbon emissions reduction and carbon storage, especially for hydropower dams located in southwestern China built in or after the 1992 (Figures 2, 3, and S1). The average increase in carbon

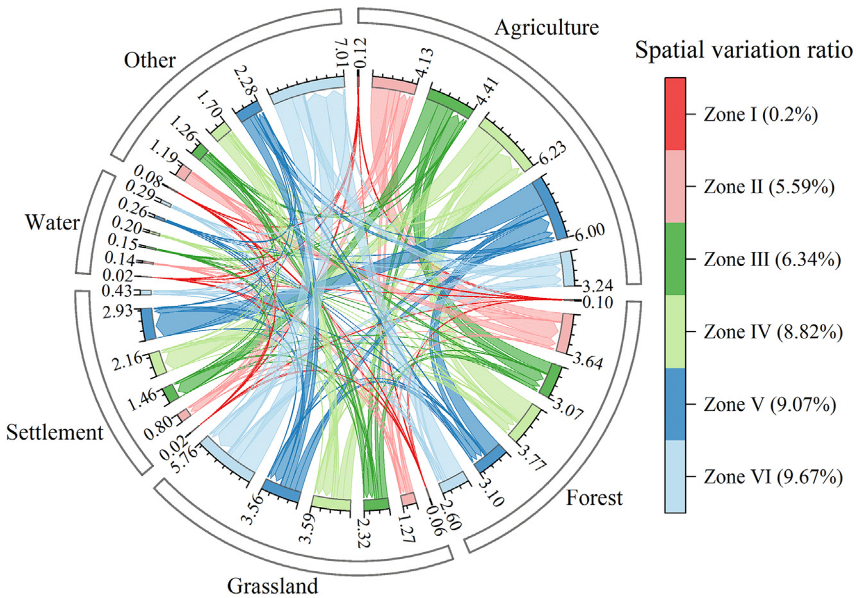

Figure 1. Land cover transfer flow (spatial variation ratio of land cover in each affected zones, %) within dam-affected zones from 1992 to 2020
The percentages in parentheses represent the spatial variation rate of change in the land cover change in each affected zone.

emission within the dam-affected area from 1992 to 2020 was 5.97 tC/ha, which was lower than the national average of 6.41 tC/ha (Figure 2A). Over the past three decades, southwestern China, which was considered the hotspot of dam construction in China, emitted less carbon than other regions largely by avoiding massive urbanization and agricultural expansion (Figures 2A and S2). During this period, southwestern provinces with a large number of new large dams, such as Sichuan, Guizhou, Yunnan, and Guangxi, emitted 6 tC/ha, whereas provinces with fewer new dams, such as Hebei, Jiangxi, Beijing, and Heilongjiang, emitted more than 8 tC/ha. Meanwhile, carbon storage around these hydropower dams with a water storage capacity of over 1 billion m^3 increased by 2.12 tC/ha, in stark contrast to the national decrease of 0.11 tC/ha (Figure 3).

Changes in carbon emissions and carbon storage differ based on the distance of impact, size, function, and construction year of dams (Figure 2). Dams built after the 1990s with a water storage capacity of over 1 billion m^3 are primarily used for hydroelectric power generation and are located in southwestern China (Figure S1). Regarding distance of impact, the largest increase of carbon emissions within the dam-affected regions occurred in Zone IV, at 8.79 tC/ha, 129.58% more than that in Zone I (Figure 2C). Regarding size, dams with a larger water storage capacity (>10 billion m^3) showed an average carbon emission increment that was 6.14 tC/ha lower than that of dams with a smaller water storage capacity (<0.1 billion m^3) over the study period (Figure 2D). Areas affected by large dams with a storage capacity of over 1 billion m^3 stored almost 3.62 tC/ha more carbon than those affected by dams with a storage capacity of less than 0.1 billion m^3 (p value = 0.006) (Figure 3D). Regarding function, the areas affected by flood control and water supply dams emitted more carbon (4.16 tC/ha) than those affected by hydroelectric dams (1.59 tC/ha, p value = 0.021, Figure 2E). The carbon storage in the areas affected by hydropower dams was 3.39 tC/ha higher than that of other dams (p value = 0.005) (Figure 3E). Regarding construction year, carbon emission increment in the affected area of dams built after the 1990s was about 5.57 tC/ha lesser than those built before 1992 (p value = 0.002; Figure 2F). Conversely, the increase in carbon storage in areas around dams built after the 1990s was 2.04 tC/ha higher than that in areas around dams built before 1992 (p value = 0.015; Figure 3F).

Grain yield around dams

Results revealed that the grain yield per unit area in Northeast and North China, as well as Southwest China, has experienced greater increases from 1992 to 2020 in the dam-affected areas, reaching up to 6.58 t/ha (Figures 4A and 4B). Specifically, the dam-affected areas exhibited a substantial yield increase of 0.53 t/ha, which was significantly higher than the observed increase of 0.20 t/ha in non-dam-affected regions. Interestingly, a closer proximity to the dam was associated with a more substantial increase in grain yield, as depicted in Figure 4C. This phenomenon is reasonably explained by the assertion that dam construction enhances water availability to crops, either directly from natural sources (such as increased regional rainfall or rising groundwater table) or indirectly through human management (such as irrigation). This observation corresponds with the conclusion that the forest area closer to the dam experienced a more significant increase, excluding the core reservoir area (Zone I) covered by rising surface water (Table S2; Figure 1). Additionally, areas closer to the dam experienced lesser loss of cropland, that is, less arable was transferred to other land types compared to unaffected zones (Table S2). The simultaneous increase in grain yield per unit area and cropland area underscores the significant potential of dams in advancing regional food security. In addition, the size, operation time, and function of the dam did not have a significant impact on the increase in grain yield (Figures 4D–4F).

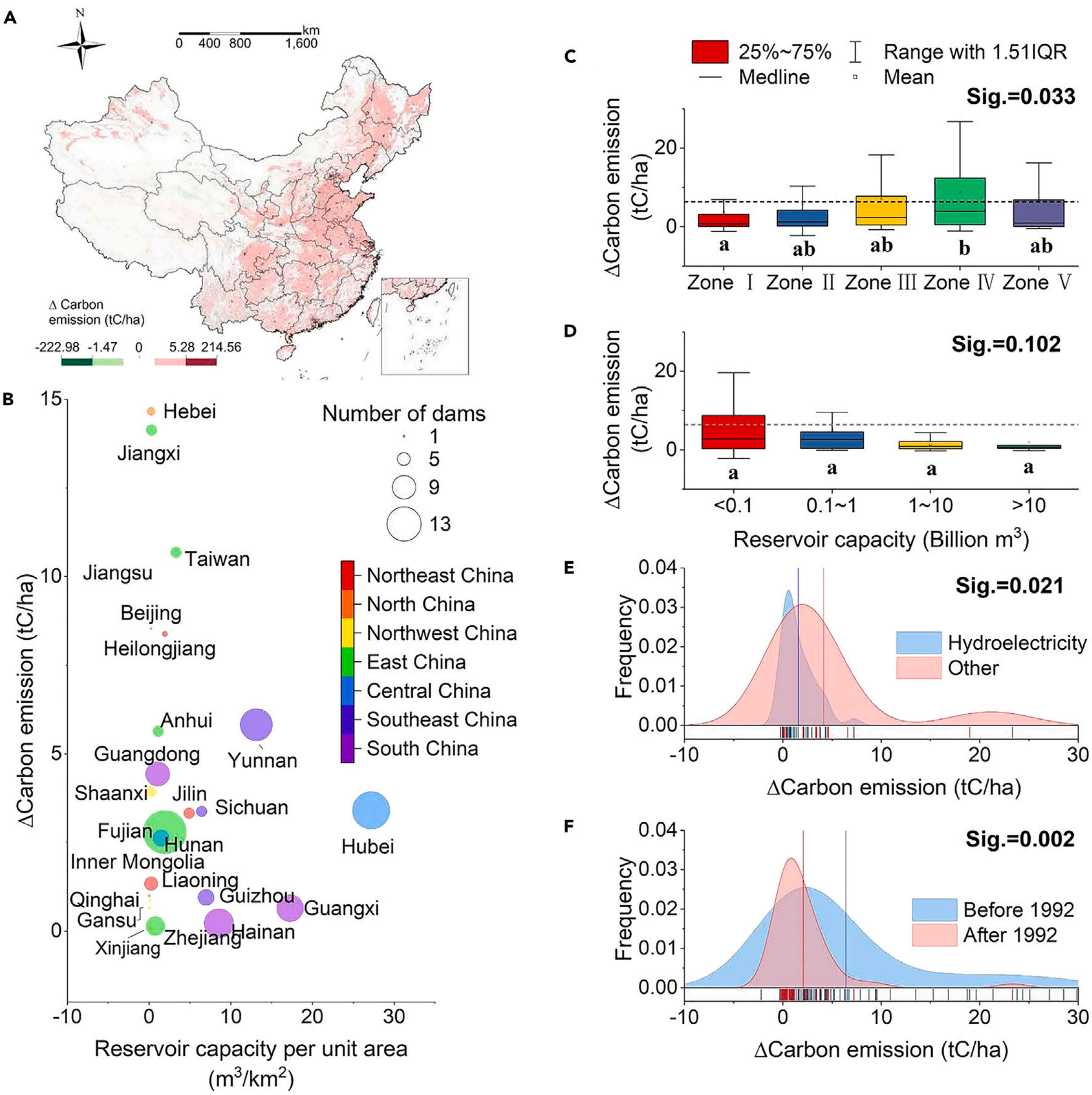

Figure 2. Changes in carbon emissions from 1992 to 2020 within the dam-affected area

(A) Spatial distribution in carbon emissions from land cover change from 1992 to 2020; (B) Changes in carbon emissions in the affected areas of provinces with dam-affected zones; (C) Changes in carbon emissions within different impact distances (Zone I–V) within dam-affected areas; (D) Changes in carbon emissions of different dams (compared by reservoir capacity); (E) Probability distribution of carbon emission changes within the dam-affected area for hydroelectric dams and other dams (irrigation, flood control, and water supply); (F) Probability distribution of carbon emission changes around the dam constructed before and after 1992. The dotted line means the national average. The differences among the groups were analyzed using one-way ANOVA with Duncan's multiple range test at $p < 0.05$ as the criterion of significance. Boxplots within a treatment bearing the same lowercase letter have means that are not significantly different ($p > 0.05$).

DISCUSSION

Dams in operation after 1992 exhibited a notable impact in fostering forest growth and preventing nearby areas from urbanization, resulting in a lower rate of carbon emissions increase. These large dams increased water availability and created additional space to allow forests to regenerate in barren lands. As a result, regions in close proximity to large dams experienced a significantly reduced rate of carbon emissions increase, approximately 70% less than areas unaffected by dam construction. Most of these dams were designed to produce hydropower and are located in the mountainous areas of southwestern China, which are rich in water, renewable energy, and forest resources.[43] Unlike eastern China, agricultural expansion and urbanization in the dam-affected areas of southwestern China are limited by topographical complexities.[44] Over the past two decades, the newly increased agricultural land and settlements in southwestern China have been lower than those in other regions (Figure S3). In addition to reducing carbon emissions by enhancing forest growth, as other studies have found, large dams are found to offset increased emissions during construction much faster than the smaller hydropower dams (Figure 2B).[45,46]

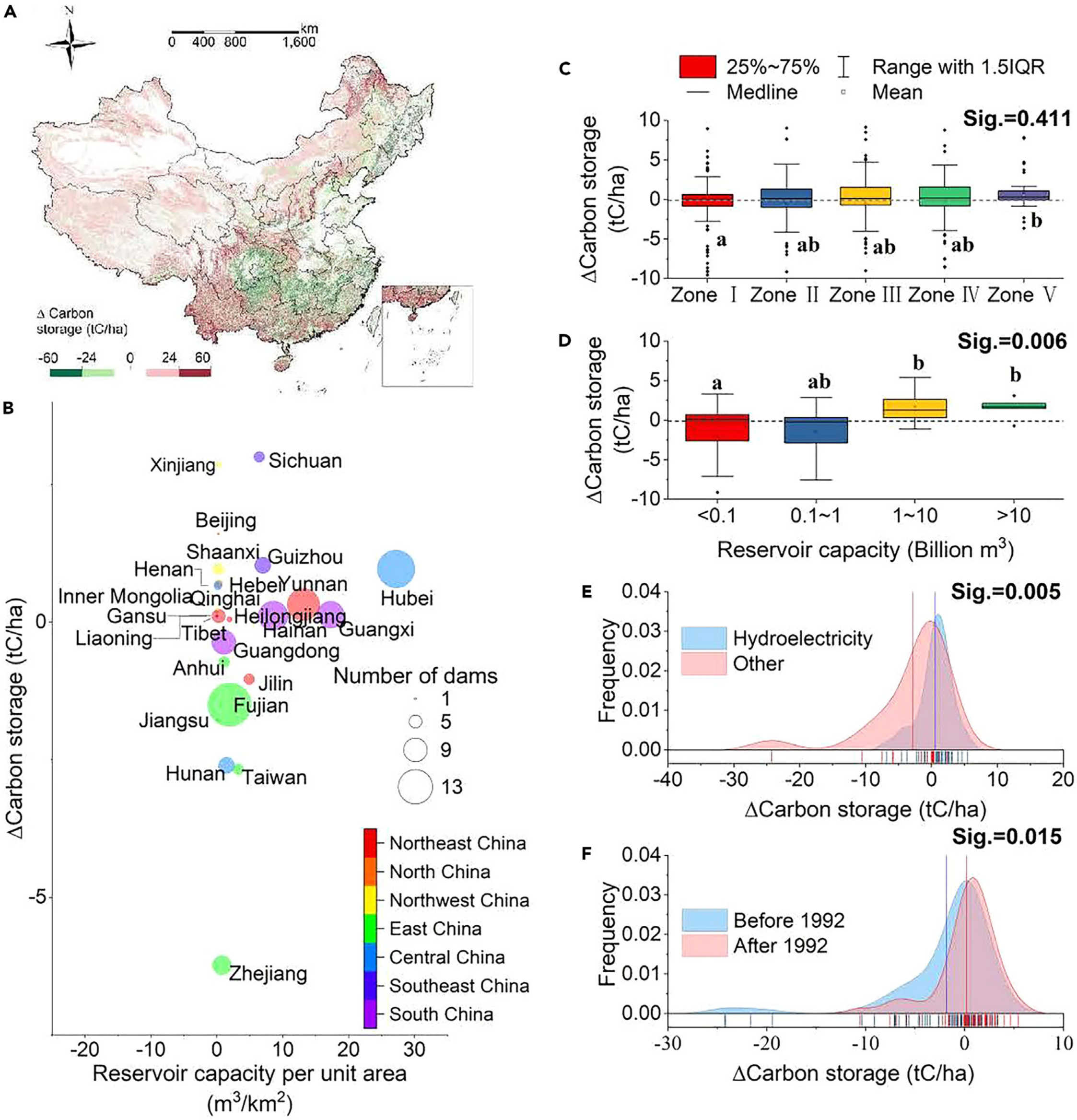

Figure 3. Changes in carbon storage from 1992 to 2020 within the dam-affected area

(A) Spatial distribution in carbon storage from land cover change across the country; (B) Changes in carbon storage in the affected areas of provinces with dam-affected zones; (C) Changes in carbon storage within different impact distances (Zone I–V) within dam-affected areas; (D) Changes in carbon storage of different dams (compared by dam scale (reservoir capacity)); (E) Probability distribution of carbon storage changes within the dam-affected area for hydroelectric dams and other dams (irrigation/flood control/water supply); (F) Probability distribution of carbon storage changes around the dam constructed before and after 1992. The differences among the groups were analyzed using one-way ANOVA with Duncan's multiple range test at $p < 0.05$ as the criterion of significance. The same letters in the boxplots (a or b) indicate that there is no significant difference between groups.

Many studies have demonstrated that irrigation dams can enhance grain yield by increasing arable land, irrigated farmland, and cropping frequency.[9,47] Others have shown that anthropogenic factors associated with water transfer (e.g., the construction of canals and pipelines, power generation) lead to more carbon emissions in irrigated agriculture than in rainfed agriculture.[48,49] While, we found that croplands around large dams in China showed increased yield with no net increased emissions. This sheds light on an intriguing discovery: the carbon stored in the newly regenerated forest can offset increased carbon emissions from new croplands around irrigation dams. While we cannot directly attribute the increased yield entirely to irrigation dams, we found that emissions may not be exacerbated by the large irrigation dams in China. These dams might be contributing to China's food security by contributing to growth in yield through irrigation, which is a topic for future investigation. These findings suggest that a proper allocation of water and land resources for agricultural and forest systems can not only help maintain carbon emissions but also mitigate crop losses from extreme events.[50,51]

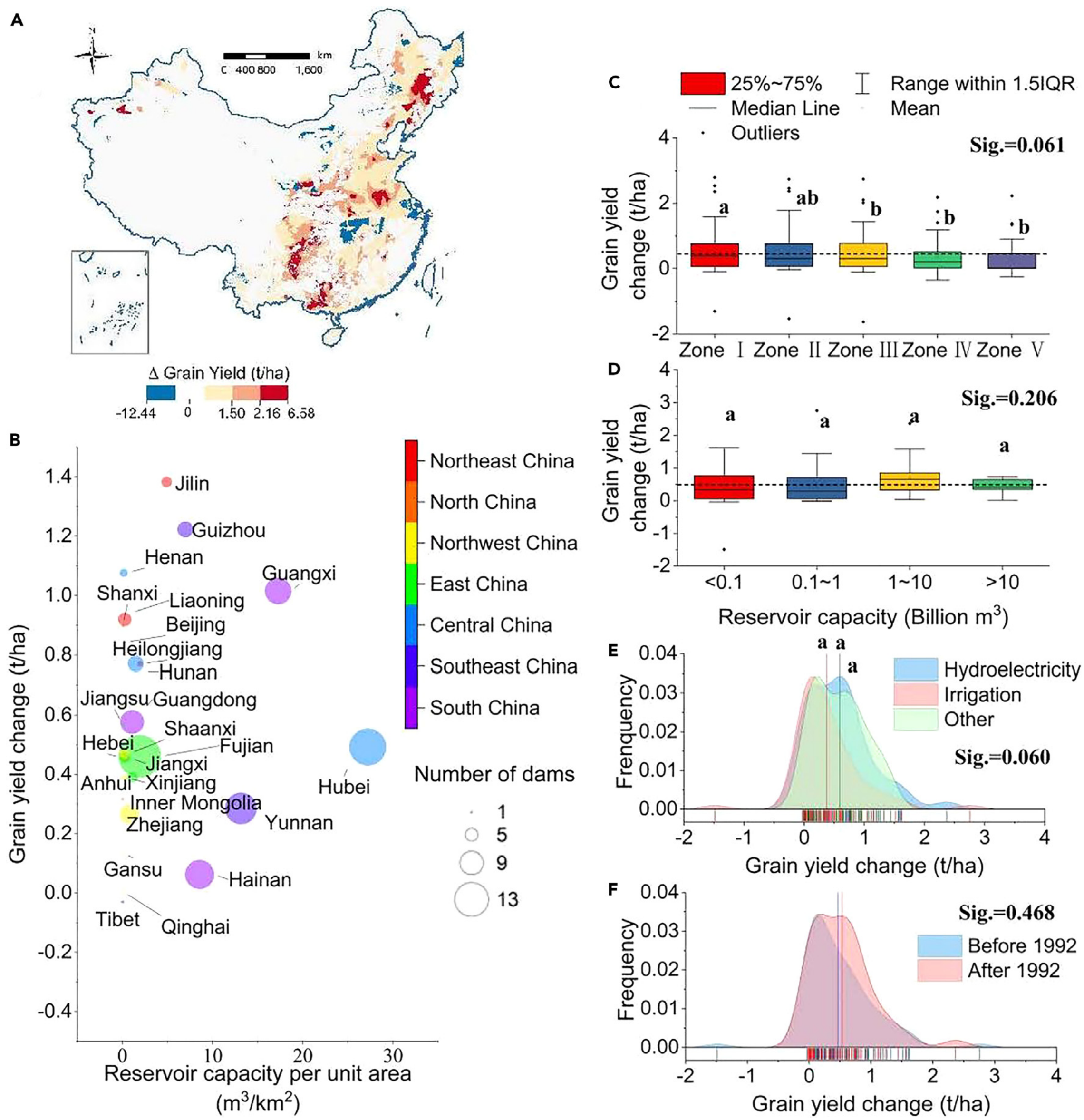

Figure 4. Changes in grain yield from 1992 to 2020 within the dam-affected area

(A) Spatial distribution of rates of grain yield change across the country; (B) Grain yield change rate in the affected areas of provinces with dams; (C) Grain yield change rate within different impact distances (Zone I–V) within dam-affected areas; (D) Boxplot of grain yield change rate of different dams (compared by dam size (reservoir capacity)); (E) Probability distribution map of grain yield change rate within the dam-affected area for hydroelectric dams and other dams (irrigation/flood control/water supply); (F) Probability distribution map of grain yield change rate around the dam constructed before and after 1992. The differences among the groups were analyzed using one-way ANOVA with Duncan's multiple range test at $p < 0.05$ as the criterion of significance. The same letters in boxplots (a or b) indicate that there is no significant difference between groups.

We also found that land use and land cover change patterns vary with the distance from the dam. This highlights the need for collaborative, transparent, and scientific management of dams across states or provinces within a country or across countries to address any transboundary water issues. We found that areas closer to the dam reservoir region experienced an increase in forest growth and a reduction in carbon emission (Figure 2; Table S2). This supports the findings from previous studies that suggest agricultural lands abandoned by migration due to dams can be replaced by forests.[52–55] Larger dams, however, can promote urbanization and agriculture in distant locations,[4,56,57] as dam construction often leads to population relocation away from reservoir areas. Thus, transboundary hydrological dams should consider these issues and be more transparent in making science-informed policies that can benefit all neighboring states, provinces, or countries.

Conclusion and limitations

We investigated how land cover change from 1992 to 2020 caused by 137 large dams (height >15 m and reservoir capacity >0.1 billion m^3) in China impacts carbon neutrality and food security from a national perspective. In comparison to areas unaffected by large dams, dam-affected regions exhibited lower increases in carbon emissions, while greater gains in carbon storage and gain yield. The findings underscore the significance of considering the substantial reduction in carbon emissions from the nearby areas of dam construction in national-scale carbon accounting.

Due to data limitations, we employed a straightforward inventory-based approach to quantify carbon storage and emissions in dam-affected areas, ignoring the intricacies of carbon emission processes within ecosystems. Future research endeavors could benefit from advancements in *in situ* measurements of ecosystem carbon flux at finer temporal scales. By integrating hydrological models, ecosystem process model, topographic features, and river direction data, more precise estimates of carbon emissions and storage can be achieved. This comprehensive analysis would shed light on the directional impact of dam construction within the actual catchment area, facilitating the formulation of tailored management strategies based on spatial differentiations of dam impacts. In addition, studying the superimposed impact of multiple dams within a catchment area is crucial for optimizing resource allocation, enhancing water and land resource utilization, and protecting the ecological environment. These new insights, when combined with information about large dams and historical land cover changes, can support informed policymakers to design future dam construction plans and climate change mitigation strategies.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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- QUANTIFICATION AND STATISTICAL ANALYSIS

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.109516.

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AUTHOR CONTRIBUTIONS

Z.X. and L.H. designed the research and analyzed and interpreted the results; Z.X., N.B., and L.H. wrote the initial draft of the manuscript; L.H. contributed data and calculated the results; Y.P., N.J., P.Z., G.Y., Z.B.L., and S.W. provided edits and comments on the manuscript. All authors overviewed the results and reviewed the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
ArcGIS for Desktop Basic (RRID:SCR_011081)	ESRI	https://www.esri.com/en-us/arcgis/about-arcgis/overview
Origin (RRID:SCR_014212)	OriginLab	https://www.originlab.com/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Zhenci Xu (xuzhenci@hku.hk).

Materials availability

This study did not generate new unique reagents.

Data and code availability

The basic data are available in supplemental information, and the detailed data associated with the article is available from the lead contact on reasonable request.

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Selection of large dams in China

We screened 137 large dams in China with detailed information (i.e., locations, operation year, main function, catchment surface area, reservoir surface area, and reservoir capacity) from the Global Reservoir and Dam (GRanD) database[58,59] and China Power Website (http://www.chinapower.com.cn/) through two-rounds selection (Figure S1; Table S1). Initially, the selected dams were restricted to those with a storage capacity exceeding 0.1 billion m^3 and a minimum dam height of 15 m. Rigorous selection criteria involved exclusively opting for well-verified dams from GRanD database, operational prior to 2017, with data quality labels of "Verified", "Good", and "Fair". These parameters underwent meticulous proofreading and cross-referencing with the data available on Chinese Power Website. Additionally, dams lacking a water source (river or lake) within a 1 km radius were excluded, as determined by the World water bodies dataset provided by ArcGIS (https://hub.arcgis.com/content/e750071279bf450cbd510454a80f2e63/about) and global river networks.[60] These dams within a 1km buffer were relocated to the nearest water boundary using spatial alignment. More than 80% of the dams, especially those built after the 1990s with a reservoir capacity exceeding 1 billion m^3, are located in southern China, where water resources are abundant and surface vegetation is dense. All data used in this study, along with their sources, are presented in Table S3.

Buffer determination

The significant spatial differences among different levels of the dam-affected areas were confirmed based on Fan et al.[4] We assumed that dams with different sizes would have different distances of impact on the surrounding environment. According to the hydrology of the surrounding area, the environmental impacts of dams can be tracked as far as the outer edge of the catchment area. Determining the catchment area of multiple dams on a national scale through hydrological models is challenging because of the complexity and dynamics of the river flow direction, topography, and geomorphology. Meanwhile, since catchment areas are mainly situated upstream of dams, relying solely on catchment-based determinations for dam-affected areas might not adequately represent downstream environmental alterations. Hence, following the "buffer analysis" approach from previous studies,[4,41,42] we approximated the catchment and reservoir surface areas as concentric circular on the dam site with a diameter that reflected the farthest and nearest impact distances from the dam center (Figure S2). We divided the potentially affected area of the dam into five proportional zones from the reservoir surface area (Zone I) to the catchment surface area (Zone V). Areas not potentially affected by the dam were set as the control group (Zone VI). The detailed calculations are as follows:

Zone I is defined as the affected areas located closest to the dam, and it is calculated from the dam center to the diameter of the approximate circle of the reservoir surface area of each dam as follows:

$$R_{1,i} = 0.2 \times \sqrt{A_i/\pi} \quad \text{(Equation 1)}$$

where $R_{1,\,i}$ is the radius (km) of Zone I for the i^{th} dam and A_i is the surface area (ha) of the i^{th} reservoir.

Zone V is defined as the affected areas farthest from the dam, and it is calculated from the area of catchment draining into the reservoir (C) of each dam as follows:

$$R_{5,i} = 0.2 \times \sqrt{C_i/\pi} \quad \text{(Equation 2)}$$

where $R_{5,\,i}$ is the buffer radius (km) of furthest affected boundary of the i^{th} reservoir and C_i is the catchment area of the i^{th} reservoir (ha).

Dynamic analysis of land change

Changes in land cover directly influence the spatial changes in regional carbon emissions, carbon storage, and grain yield. Land cover classification maps (300 m spatial resolution) from 1992 to 2020 were obtained from the Copernicus Climate Change Service[61] and reclassified using the United Nations Food and Agriculture Organization's (UNFAO) Land Cover Classification System (LCCS). We summarized six land cover types, namely, agriculture, forest, grassland, settlement, water, and others, based on the IPCC classification scheme (Table S4). The process and trends of land cover changes can be represented by the variation amplitude. We calculated the temporal variation[62] in land cover type k as follows:

$$R_{tk} = (U_{ak} - U_{bk}) \times 100\% \,/\, U_{ak} \quad \text{(Equation 3)}$$

where R_{tk} represents the calculated amplitude of the temporal variation of land type k and U_{ak} and U_{bk} represent the area of land type k at the beginning and end of the study period (ha), respectively.

We calculated the spatial variation ratio R_{sk} of land cover[63] as follows:

$$R_{sk} = (\Delta U_{ink} - \Delta U_{outk}) \times 100\% \,/\, U_{ak} \quad \text{(Equation 4)}$$

where ΔU_{ink} represents the area of other land cover types transformed into land cover type k and ΔU_{outk} represents the area of land cover type k transformed into other land cover types.

Carbon emissions

Land cover-based carbon emissions generally refer to direct or indirect impacts on the carbon cycle of terrestrial ecosystems caused by anthropogenically induced changes in land cover classes.[64] Carbon emissions from different land cover types can be divided into two main categories: natural and artificial ecosystems. Natural ecosystems mainly comprise forests, grasslands, and water, and the plants in these ecosystems absorb atmospheric carbon dioxide through photosynthesis and fix it in vegetation and soil. Artificial ecosystems include farmland and settlements that are frequently affected by anthropogenic activities and associated with carbon emissions through energy consumption. The carbon emissions of these two ecosystems were calculated based on formulas provided by the 2006 IPCC National Greenhouse Gas Emission Guidelines.[65] The carbon emissions of natural ecosystems were calculated as follows:

$$E_{k\,ij} = K_{ij} \times EF_k \quad \text{(Equation 5)}$$

where $E_{k\,ij}$ is the carbon emissions per unit area at point ij, t C/ha. Point ij belongs to natural ecosystems K_{ij}, like forests, grasslands, water, and other. EF_k is the carbon emission coefficient for natural ecosystem type k (t C/ha) (See Table S4 for special values).

Carbon emissions from land cover changes in artificial ecosystems are mostly associated with anthropogenic activities and changes in energy consumption patterns. For example, in agricultural lands, an enormous amount of carbon emissions is generated by production inputs to increase grain yield, including fertilizer, pesticide, agricultural film mulching, mechanical fuel consumed by agricultural machinery (e.g., leveling, land preparation, and harvest), and electricity for irrigation and drainage.[66,67] Carbon emissions from crop respiration accounted for only a small proportion and were often negligible. Here, we adopt the average carbon emissions derived from the inputs associated with the three primary food staples (wheat, maize, and rice) as the representative carbon emissions for agricultural land. The inputs encompass various production materials such as fertilizer, pesticide, agricultural film, agricultural machinery fuel, and electricity. These data are collected from the *National Agricultural Product Cost-income Data Compilation*.[68] Recognizing variations in natural conditions and management levels, we account for yearly fluctuations in these production inputs. Regional differences are not considered in our study. Carbon emissions from agricultural land were calculated as follows:

$$E_{a\,ij} = A_{ij} \times EF_a \quad \text{(Equation 6)}$$

$$EF_r = \sum_{m=1}^{M} EF_m \times Q_m \quad \text{(Equation 7)}$$

where $E_{a\,ij}$ is the carbon emissions (t C/ha) in point ij (point ij belongs to agricultural land A_{ij}), A_{ij} represents the type of agricultural land (rainfed cropland, irrigated cropland, and mosaic cropland). EF_a is the carbon emission coefficient for different types of agricultural land. EF_r is the carbon emissions factor for rainfed cropland, EF_m is the carbon emissions coefficient for production material m (fertilizer, pesticide, agricultural film, and agricultural machinery fuel).[69] Q_m is the input of production material m (t/ha).

In comparison to rainfed cropland, the calculation of the carbon emission coefficient for irrigated cropland takes into account the input of irrigation electricity. For mosaic croplands, which represent heterogeneous surfaces with a combination of farmland and natural vegetation, including shrubs and trees. Based on this definition, we assume that the carbon emission coefficient factor for mosaic cropland is 50% of that for rainfed cropland. The calculation values of carbon emissions coefficient of various cropland are shown in Table S4.

We assumed that all settlements had the same annual carbon emissions per unit area each year.[70] We chose coal, oil, natural gas, and electricity as representatives of the carbon emissions generated in the energy production processes on settlement land.

$$E_{s\ ij} = \sum_{n=1}^{N} Q_{n\ ij} \times EF_n \qquad \text{(Equation 8)}$$

where $E_{s\ ij}$ is the carbon emissions (t C/ha) in point ij (point ij belongs to settlement), $Q_{n\ ij}$ is the annual energy consumption per unit area (t/ha) of four energy, coal, oil, natural gas, and electricity, which is derived from China Energy Statistical Yearbook in 1992 and 2020. EF_n is the carbon emission coefficient by the energy consumption of type n (t C/t), which derived from Liu et al. (2015).[71] The calculation values of carbon emissions coefficient of settlement land is shown in Table S4.

Carbon storage

Carbon storage refers to the amount of carbon retained within an ecosystem, primiarly indicating variations in the biomass of various vegetation types, including trees, herbs, and soil (typically within a depth of 100 cm). In this study, we excluded the carbon storage of cropland, settlement, bare land, and water bodies, as their contribution can be negligible compared to the carbon storage of forests.[72] Given the uniform grid size (300 m × 300 m) across all areas, we quantified the carbon storage per unit area for each vegetation type as the vegetation's carbon density (specific values are shown in Table S4).[73]

Grain yield

We conducted an analysis of the change in grain yield from 1992 to 2020 by overlaying the of cropland, extracted from the land cover map, with the yield data. To estimate grain production, we used the average yield of wheat, corn, and rice as a proxy for overall grain production.[74] These yield data were obtained from Iizumi and Sakai's (2020)[75] global historical yields dataset for major crops, which combines agricultural census statistics and satellite remote sensing at a spatial resolution of 0.5°. By default, no grain yield was considered on non-cropland areas. By resampling, we unified the resolution of the yield to 300m of the same resolution as the land cover map. Since NDVI (Normalized Difference Vegetation Index) was taken into account in this yield data, we did not differentiate between different types of cultivated land (rainfed, dry-cultivated, or cultivated land with mosaic) and utilized the crop yield distribution data provided by Iizumi and Sakai[75] directly. We detrended the effect of agricultural science and technology progress from yield data to reveal the underlying fluctuations not attributed to advancements in technology. Given the continuous improvement in agricultural technology, we treated time as an independent variable and fitted a linear regression model to determine the contribution rate of agricultural science and technology ($p < 0.001$). The contribution rate of agricultural science and technology represents the extent to which scientific and technological progress contributes to the growth rate of agricultural output share. These data were obtained from statistical data provided by the Ministry of Agriculture and Rural Addairs of the People's Republic of China (http://zdscxx.moa.gov.cn:8080/nyb/pc/search.jsp). After estimating the yield gained in the current year due to the increase in agricultural technonlogy, we subtracted this yield from the raw yield data to obtain the grain yield after removing the trend of technological progress. Additionally, we measured the yield per unit of land area, not per unit of cultivated land area, within the influence area of dams, taking into consideration the changes in both yield and cultivated land area from dam construction.

QUANTIFICATION AND STATISTICAL ANALYSIS

All statistical analyses were performed in ArcGIS 10.8 and Origin Pro 2023. The specific test used is listed directly before every reported p value in the text and/or figure legend.