Requiem for Rivers? Global Dams, Environmental Impacts, and Agricultural Adaptation

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Abstract

Hydropower provides over 50% of global renewable electricity. However, its infrastructure, particularly dams, alters natural water flows, reduces sediment transport, and causes ecological fragmentation, which harms downstream ecosystems and agriculture. This paper examines the global-scale downstream impacts of dams, focusing on changes in microclimate, biodiversity, and agricultural productivity. We find that dam operations lead to increased downstream temperature levels and volatility, and a 25% decline in plant biodiversity. Agricultural activity also suffers, as farmland area shrinks by 2.2% and crop exports fall by 11%. In response, farmers adapt by shifting to vegetable cultivation, which is more resilient to temperature changes and requires less land. This adaptation results in a 2.3% increase in vegetable exports, offsetting 30% of the economic losses from declines in traditional crops. In contrast, aquaculture did not shift to shrimp farming: fish exports decreased by 18.9%, and there was no increase in shrimp exports. Our findings underscore the importance of considering both environmental impacts and behavioral adaptation strategies when evaluating the welfare implications of renewable energy development.

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1 Introduction

Renewable energy has grown rapidly in recent years, with hydropower playing a key role due to its capacity for large-scale, low-carbon electricity generation. Hydropower accounts for more than 50% of renewable electricity production globally, and 15% of total electricity generation from all sources in 2022 (International Energy Agency, 2021). The number of large dams has increased significantly from 45,000 in 1990 to over 60,000 by 2020, with the largest increases in Asia, Latin America, and sub-Saharan Africa (Perera et al., 2021). Apart from electricity generation, dams also provide essential services such as flood regulation and irrigation for agriculture.

While dams deliver substantial benefits, they also cause environmental and social disruptions, such as alterations to natural water flows, reduced sediment transport, and ecological fragmentation, leading to negative consequences for downstream ecosystems and human communities (Nilsson and Berggren, 2000; Richter et al.; Schmutz and Moog, 2018). The cumulative effects of these changes have sparked widespread policy debates, local protests, and growing concerns about the long-term sustainability of river-dependent ecosystems and agriculture. This leads to our research question: How do dams affect downstream environmental and agricultural outcomes at a global scale?

To answer this question, we start by estimating the first-order environmental impacts of dams on downstream areas, then move to the behavioral responses of affected communities. Dams, by altering water flow patterns and sediment transport, can have profound consequences on plant biodiversity, agricultural land, and local climate conditions. Disruptions to river ecosystems caused by dams can lead to biodiversity loss, especially for species that rely on seasonal floods and riverine habitats. In agricultural areas, dams can influence water availability and quality, with changes in flow regimes leading to reduced soil fertility and less predictable irrigation supplies. Furthermore, downstream temperature levels and volatility increase due to dam construction, which can further impact agriculture and the livelihoods of communities that depend on stable environmental conditions.

By integrating global dam data with river flow models, we identify the downstream basins affected by dam operations. Our two-way fixed effects model exploits variation in dam construction and downstream exposure to isolate the causal effects of dam

operation. We find that dam openings lead to significant increases in downstream surface temperatures and greater temperature variability within a 100 km radius of the dam site. Specifically, the operation of a dam results in an average temperature increase of 0.17% and an increase in temperature variance of 1.5%. Additionally, using global plant biodiversity datasets, we observe a decline in both species richness and plant populations in areas downstream of dams, with losses of 35% and 25% respectively. In terms of agricultural land use, we find that farmland area in downstream regions shrinks, decreasing by 2.24% relative to pre-dam baselines.

Given the negative environmental consequences of dam construction, we then turn to the adaptation strategies of farmers in downstream areas. The agricultural sector is highly sensitive to environmental risks, as yields and income are closely linked to conditions such as water availability and temperature. Farmers have been shown to adapt by changing crop types, adjusting planting schedules and sizes, and modifying saving behaviors in response to shifting weather patterns (Burke and Emerick, 2016; Cui, 2020b,a; Cui and Zhong, 2024; Cui and Tang, 2024). Therefore, we expect similar adaptations in downstream areas following the construction of dams, driven by changes in water flows, microclimate, and ecosystem dynamics.

In response to cropland shrinkage and surface temperature changes, farmers adapt by shifting to vegetable cultivation. Since vegetables require less land area and are less sensitive to temperature fluctuations compared to traditional crops, this shift helps mitigate the negative impacts of dams on agricultural productivity. We use trade data from the global trade database, as well as national customs data from China and Brazil, with detailed product codes for crops and vegetables. Our analysis shows that dam openings lead to a reduction in crop exports by 11%, with larger effects in Southeast Asian countries. At the same time, we observe a significant increase in vegetable exports by 2.3%. These effects are observed immediately after the dam opening and persist for at least 10 years. Additionally, we use satellite-derived yield measurements from the Enhanced Vegetation Index (EVI) and find no reduction in yield in the remaining land areas, despite a reduction in total cropland size.

The adaptation evidence suggests that farmers manage to avoid large welfare losses by adapting to the environmental changes induced by dams. Despite reductions in crop income, the compensation from vegetable income helps offset these losses.

A back-of-the-envelope calculation shows that the increase in vegetable income is 30% relative to the income reduction from crops, suggesting that adaptation through shifting agricultural practices can effectively mitigate the negative economic impacts of dam-induced environmental changes.

For the aquafarming sector, downstream regions affected by dams experience a reduction in fish exports of 18.9%. This decline is primarily driven by changes in water flow and quality. However, aquaculture farmers do not adapt by shifting from fish to shrimp farming, even though shrimp require less stable or clean water. We observe no significant change in shrimp exports. This may be due to legacy effects in aquafarming or reductions in water levels that are unsuitable for any aquaculture activities. Given the large share of aquaculture exports from developing countries, this insufficient adaptation raises concerns about inequality.

Our paper addresses three key challenges that existing studies have not fully tackled. The first challenge lies in data integration. Most studies on the impacts of dams focus on a single region or a specific type of dam, examining either local or downstream effects. In contrast, we focus on a global scale by using global dam, river flow, and downstream outcome data. This allows us to test for heterogeneity across regions and uncover the full range of cross-country externalities that might be overlooked in analyses focused on just one area or type of dam.

The second challenge is measurement. To assess plant biodiversity, we incorporate Botanical Information and Ecology Network (BIEN) data, which provides detailed geo-coded information on plant species distribution over decades. This measurement advances beyond most commonly used methods that either rely solely on forestation or vegetation indices without considering species differences, or use cross-sectional measurements that may have omitted variable bias when comparing across space.

The third challenge is incorporating behavioral dimensions when studying downstream effects. Most studies on dam impacts focus solely on first-order, one-dimensional effects, such as yield, income, or health changes (Duflo and Pande, 2007; Edwards and Smith, 2018; Mettetal, 2019; Chen et al., 2021; Lei, 2025). However, these studies may overlook the role of adaptation, which can significantly change welfare estimations and their implications. By accounting for behavioral responses, we provide a more accurate and complete picture of how dams affect the welfare of surrounding

communities.

Our paper is closely related to three strands of existing literature. The first is the impact of dam operations on local and downstream outcomes. A growing body of work shows that dams generate significant downstream and cross-border spillovers. For example, Duflo and Pande (2007) finds that dams do not increase local agricultural production and worsen poverty in India. However, downstream areas benefit from increased irrigation, resulting in higher agricultural production and lower poverty. Mettetal (2019) shows that dam-induced agricultural activities increase water pollution, reduce water availability, and, in turn, increase infant mortality in South Africa. Lei (2025) focuses on dams in the upper Mekong River and finds that dams boost agricultural activities and reduce fire risks in normal weather conditions. However, during extreme weather events, the effects of dams become negative, and the externalities flip. Our paper contributes to the literature by emphasizing behavioral responses to dam-induced environmental changes and by showing the global scale of these effects, as well as their heterogeneity across dam locations and types.

The second literature focuses on environmental adaptation in the agriculture sector. Agriculture is highly responsive to environmental conditions due to its outdoor nature and the relatively low cost of input adjustments. Existing literature has shown that agricultural adaptation can take several forms, including shifting crop types (Auffhammer and Carleton, 2018; Taraz, 2018; Kochhar and Song, 2023), adopting drought- or soil salinity-tolerant seeds (Boucher et al., 2021; Patel, 2023), changing planting timing (Kala, 2017), and adjusting inputs (Aragón et al., 2021). While shifts in crop types have been widely studied, our paper, in contrast, focuses on a broader form of agricultural adaptation: the shift from traditional crop farming to vegetable cultivation as a response to environmental pressures.

The third aspect of related literature is the spillover effect of environmental externalities on non-local areas. Existing research has documented that local shocks can transmit across space through various channels, such as human migration (Ehrlich and Kim, 2015), alumni networks (Enikolopov et al., 2020), supply chains (Giroud, 2013), and transportation hubs (Schlenker and Walker, 2016). In the environmental domain, stressors like pollution or unfavorable temperature have been shown to generate remote impacts via wind patterns (Anderson, 2020; Deryugina et al., 2019), river flows

(Do et al., 2018; Garg et al., 2018), and digital communication networks (Almond et al., 2022; Du, 2023). Our paper contributes to this literature by examining river flow as a transmission mechanism through which local environmental interventions such as dam construction produce spatially diffuse externalities.

From a policy perspective, we highlight the trade-offs of renewable energy development, particularly hydropower, and its unequal regional impacts. While hydropower provides benefits such as energy generation and flood control in areas near dams, the environmental costs are often felt downstream, affecting local communities and ecosystems. This underscores the need for policies that balance the benefits in dam regions with the costs imposed on downstream areas.

Our paper also underscores the need to incorporate adaptation into environmental decision-making. Policymakers may overlook the behavioral responses of affected communities, which can either mitigate or worsen the impacts of infrastructure projects like dams. Ignoring these adaptations may lead to an overestimation of negative externalities. Including these responses in policy assessments can help provide a clearer picture of the true costs and benefits of renewable energy projects, leading to more effective and equitable solutions.

The rest of the paper is organized as follows. Section 2 provides a brief background overview, and Section 3 describes the data sources. Section 4 details the empirical strategy and presents results on downstream environmental impacts. Sections 5 and 6 examine adaptation in the crop and fish sectors, including shifts toward vegetable and shrimp production, as well as the resulting welfare effects. Section 7 concludes.

2 Background

2.1 Global dam development

The construction of dams has expanded significantly over the past century, driven by increasing demands for hydropower, irrigation, flood control, navigation, and other water management functions. As of 2023, there are over 58,000 large dams worldwide, with China, the US, and India leading in dam construction (International Commission on Large Dams, 2023; Lehner et al., 2024).

Hydropower has been a key factor in dam expansion, as dams convert the potential

energy of stored water into electricity. By controlling the release of water through turbines, dams provide a stable and renewable energy source, reducing dependence on fossil fuels and supporting grid reliability (International Energy Agency, 2022). Large-scale projects such as the Three Gorges Dam in China and the Itaipu Dam in Brazil-Paraguay contribute significantly to national electricity supplies, stabilizing energy production even during seasonal fluctuations in river discharge.

For irrigation and water supply, dams act as reservoirs that store water during periods of surplus and release it during dry seasons. This function stabilizes water availability, enabling year-round agricultural production and ensuring a reliable municipal and industrial water supply (UN Water, 2021). Flood control is another critical function of dams, achieved by storing excess runoff during heavy rainfall and gradually releasing it to prevent downstream flooding. By modifying peak river discharge, dams reduce the frequency and severity of extreme flood events, particularly in monsoon-affected regions or areas with rapid snowmelt (Ramya et al., 2023). Dams also enhance river navigation by stabilizing water levels and reducing flow variability. Controlled releases from reservoirs maintain navigable depths in otherwise shallow or seasonal rivers, facilitating the transportation of goods and reducing the economic costs of inland shipping. Additionally, dams with navigation locks allow vessels to bypass elevation changes along river courses, improving connectivity in trade networks.

Beyond these primary functions, dams contribute to groundwater recharge, environmental flow management, and recreation. Reservoirs can sustain ecological balance by maintaining minimum river flows during dry periods, supporting aquatic ecosystems. Additionally, many reservoirs provide opportunities for fishing, tourism, and water-based recreation. However, dam construction also raises environmental and social concerns, including habitat fragmentation, community displacement, and disruptions to sediment transport and water quality (Altinbilek, 2002; Ho et al., 2017).

2.2 Dam and ecosystem

Dams impose threats to downstream ecosystems, primarily by altering water levels, temperature, flow speed, water quality, and sediment transport. These modifications disrupt the natural habitat, water chemistry, and biodiversity in river systems, often leading to long-term environmental consequences (McCartney et al., 2001; Graf, 2006;

Wu et al., 2019).

The regulation of water levels by dams reduces the natural variability of water flow, which many species depend on for migration, spawning, and feeding. For example, migratory fish such as salmon rely on seasonal flow fluctuations for navigation and breeding. When dams regulate water levels, species that rely on these natural flow patterns may suffer from disrupted migration routes, reduced reproductive success, and loss of habitat. Stabilized water levels also contribute to the loss of riparian and wetland habitats, which are essential for maintaining biodiversity (Bergkamp et al., 2000; Fuller et al., 2015). Additionally, the creation of artificial reservoirs floods vast areas of land, displacing terrestrial species and altering the composition of ecosystems, leading to long-term ecological imbalances.

Water temperature changes caused by dams also significantly affect downstream ecosystems. Reservoirs store cooler water at deeper depths, and when this cooler water is released downstream, it disrupts the thermal balance of rivers (Kedra and Wiejaczka, 2018; Chandesris et al., 2019). Species adapted to warmer, more stable river temperatures may struggle to survive as they face unnaturally cold or fluctuating water conditions. Such temperature fluctuations can affect the life cycles of aquatic organisms, including fish, which may not be able to withstand the rapid shifts in temperature (Levin and Tolimieri, 2001; Zarri et al., 2022).

Changes in water speed and flow due to dams are another critical concern. Dams reduce the natural flow velocity of rivers, which impacts sediment transport and the movement of nutrients and organic material downstream (Kameyama et al., 2013; Estigoni et al., 2017). This disruption can lead to downstream erosion, changes in riverbed structure, and reduced fertility of floodplains which are vital areas for agriculture, wildlife, and biodiversity. The alteration of flow can also affect the movement of aquatic organisms, further disturbing the ecological balance.

Finally, dams can degrade water quality downstream by trapping pollutants, nutrients, and organic material in reservoirs. Once these substances are released, they can cause significant water quality issues, such as eutrophication, which promotes algal blooms that deplete oxygen levels, negatively impacting aquatic life. The accumulation of pollutants in the sediment trapped behind the dam can also lead to the release of harmful substances into the downstream water, further affecting ecosystem health and

biodiversity.

2.3 Dam and agriculture

Dams have long been recognized for their positive contributions to agriculture, particularly through irrigation. By regulating water supply and creating reservoirs, dams provide a reliable source of water for crops, thereby improving agricultural productivity in areas prone to water scarcity (Biemans et al., 2011). Irrigation dams help expand arable land and increase crop yields in regions where natural water resources are insufficient. Additionally, for downstream areas that are flooded by dam reservoirs, agriculture can benefit from enriched soils, as sediment and nutrients deposited by the water provide natural fertilizer, promoting the growth of crops.

However, for non-flooded downstream areas, the impact of dams on agriculture is often negative. The regulation of water flow can lead to reduced water availability during critical periods for farming, especially in regions that depend on seasonal flood events for irrigation. As water flow becomes more controlled and less predictable, downstream agriculture can face difficulties with irrigation, particularly in areas that rely on natural river cycles. Furthermore, alterations in water levels downstream can lead to a reduction in crop size, as decreased water availability combined with temperature fluctuations may stress crops and result in diminished yields. In some cases, reduced flow of water can exacerbate drought conditions, negatively impacting agricultural productivity in the long term.

The changes in water temperature caused by dams can also have a detrimental effect on downstream agriculture. Water released from reservoirs is often cooler than natural river water, which can alter the surrounding microclimate and affect the growing conditions for crops. These temperature shifts, along with changes in water flow and availability, can hinder crop growth, reduce agricultural productivity, and make farming more challenging. In some regions, this disruption can lead to soil moisture imbalance, affecting crop resilience and ultimately lowering yields (Wisser et al., 2010).

3 Data

3.1 Dam and river connectivity

We obtain dam information from the Global Dam Tracker (GDAT) (Zhang and Gu, 2023). The dataset covers 35,140 dams worldwide, including their coordinates, catchment areas, start years, and primary functions. GDAT integrates data from government agencies, academic research, and nonprofit organizations, with geolocations verified using tools like Google Earth. Dams are categorized by function, including irrigation, hydroelectricity, water supply, flood control, and navigation. Figure 1 shows the locations of dams in our sample that began operations between 2000 and 2022.

To figure out each dam's downstream area, we use basin geolocations from HydroBASINS (Lehner and Grill, 2013), which provides a vectorized representation of global river basin networks. The dataset includes all river basins with a catchment area of at least 10 km^2 or an average river flow of at least 0.1 m^3/s. Derived from HydroSHEDS, HydroBASINS incorporates hierarchical Pfafstetter codes that allow for consistent identification of upstream and downstream connectivity across nested basin levels.

We filter the basin network to retain only those basins that intersect with dams. For each dam, we trace its downstream basins and define the downstream area using a 100 km threshold at the level 10 basin resolution. Using the Mekong and Lancang Rivers as examples, Figure S1 and S2 display the locations of our sample downstream basins.

3.2 Downstream temperature

We measure downstream temperature using land surface temperature data. While our primary interest lies in water temperature, global ground-based monitoring data is sparse and not comparable over space. Remote sensing data provides an alternative, though land temperature measurements tend to be more reliable than water temperature due to noise from water reflectance.

Surface temperature data is sourced from the MOD21A1D product. It provides daily temperature measurement at a 1 km spatial resolution. To assess the impact of dam openings on surface temperature, we focus on land surface temperature within the downstream basin area.

3.3 Biodiversity

We obtain plant biodiversity data from the Botanical Information and Ecology Network (BIEN) (Enquist et al., 2016), a data portal for plant species occurrence records, plant traits, and phylogeny. The dataset aggregates specimen observations from GBIF (Global Biodiversity Information Facility) and other vetted sources. BIEN data have been widely used to analyze plant diversity patterns and their environmental drivers (Echeverría-Londoño et al., 2018; Šímová et al., 2019; Hannah et al., 2020; López-Tobar et al., 2023).

We downloaded the most recent occurrence data release, covering 333,778 plant species and 4,798,206 observations. Each observation includes a species name, study source, date, and geographic coordinates (if recorded). We focus on dam downstream basin areas and aggregate microdata at the 100 km-year level. To measure biodiversity, we consider both the total number of plants and the number of unique species.

Figure 2 shows the global variation in biodiversity. We collapse data from the grid-year level into the grid level for 2000–2023. In general, we observe higher biodiversity in tropical regions and lower biodiversity in arid and polar regions.

3.4 Yield

We use the Enhanced Vegetation Index (EVI) to measure agricultural yield. EVI data is obtained from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, available at 16-day intervals with a spatial resolution of 250 meters. EVI is calculated as:

$$EVI = G \times \frac{NIR - R}{NIR + C_1 \times R - C_2 \times B + L}$$

where NIR, R, and B represent reflectance in the near-infrared, red, and blue spectral bands, respectively. The coefficients G, C_1, C_2, and L are set to standard MODIS values: $G = 2.5$, $C_1 = 6$, $C_2 = 7.5$, and $L = 1$.

EVI values range from -1 to +1, with higher values indicating healthier, denser vegetation. For each 0.01-degree pixel within a dam's downstream basin, we extract the annual maximum EVI as a proxy for yield at the pixel-year level.

3.5 Land use

To measure cropland size change, we use land cover data from the Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type (MCD12Q1) product. The data is at the grid-year level from 2001 to 2022, with a spatial resolution of 500 meters. The MCD12Q1 product is derived from MODIS Terra and Aqua reflectance. Land cover types are classified using the International Geosphere-Biosphere Programme (IGBP), University of Maryland (UMD), Leaf Area Index (LAI), BIOME-Biogeochemical Cycles (BGC), and Plant Functional Types (PFT) classification schemes. The supervised classifications then undergo additional post-processing, incorporating prior knowledge and ancillary information to further refine specific classes.

Each pixel-year is classified into one of 13 land types, including croplands, forests, water bodies, and grasslands. We calculate the amount of cropland within 100 km downstream of each dam over time to examine how cropland area changes following dam construction.

3.6 Trade

Trade data is sourced from three databases. First, we use global trade data from the UN ComTrade database, which records export and import data for each country at the product-trade partner-month level. Our analysis focuses on fish, shrimp, crop, and vegetable-related products to examine the first-order response to dam openings and subsequent adaptation efforts. Products are identified using HS6 codes.

Additionally, we incorporate more granular trade data from national customs agencies. Given the large number of recently opened dams, we focus on export responses in China and Brazil. For China, we use trade data from Chinese national customs, which provides firm-level records of exports at the HS8-trade partner-month level. Similarly for Brazil, we use national trade data from Comex Stat, which records trade at the municipality-trade partner-product-month level. Products in this dataset are identified using HS4 codes.

For all three datasets, we merge each dam's downstream basin location with the corresponding country, Chinese prefecture, or Brazilian municipality to determine

treatment timing and location. Regions not covered by dam basins are excluded from our analysis.

4 Dam and downstream environment

4.1 Empirical strategy

We first study the first-order effect of dam opening on downstream environmental conditions, including cropland area, surface temperature, and plant biodiversity. For the first outcome, we use a two-way fixed effects model at the dam-year level. The estimation specification is as follows:

$$Y_{jt} = \beta \times Post_{jt} + Dam_j + Year_t + \varepsilon_{jt}$$

where the sample is at the dam basin-year level from 2000 to 2022. For each dam j, we filter the downstream river basin using a 100 km threshold. The outcome variable measuring cropland area within 100 km downstream of dam j in year t.

On the right-hand side, $Post_{jt}$ is a dummy variable that equals one if dam j has already started operating in year t and zero otherwise. We add dam fixed effects and year fixed effects to control for dam-specific time-invariant factors and global yearly differences.

When studying plant biodiversity and surface temperature, we estimate a similar two-way fixed effects model at the grid-year level using the following specification:

$$Y_{ijt} = \beta \times Post_{jt} + Grid_i + Year_t + \varepsilon_{ijt}$$

The sample is at the grid-year level from 2000 to 2022. For each dam j, we use a 10 km grid—rather than aggregating all grids within a 100 km downstream river basin—to better align with the spatial resolution of plant diversity observations in the BIEN database. For plant biodiversity, the outcome variables include the number of plant populations or the number of unique plant species observed in grid i downstream of dam j in year t. Grid-years with no BIEN observations are coded as zero. For surface temperature, the outcome is the average land surface temperature near dam j in year t, measured using the same spatial buffer. To avoid double counting, we restrict the

analysis to non-overlapping areas, such that each grid falls within 100 km downstream of only one dam. The coefficient of interest, β, captures the impact of dam construction on downstream environmental conditions.

Our identifying assumption relies on the exogenous timing of dam openings. From the background, dam openings are likely driven by hydropower development, local irrigation, or flood control needs. These underlying drivers are likely to originate in dam-local areas and are less likely to be correlated with environmental conditions in downstream areas after controlling for dam and year fixed effects. From an econometric perspective, we assume that not-yet-treated grids with upstream dams scheduled to open in later years and treated grids should follow parallel trends in the absence of treatment. We test this assumption by reporting pre-trends in a dynamic difference-in-differences figure.

4.2 Effects on crop land area

Table 1 reports how dam operation affects downstream cropland area. In Column (1), we use the cropland area within 20 km of dams as the dependent variable. The estimate on the interaction term $Post_{jt}$ is negative, suggesting a significant reduction in cropland size after a dam opening, compared to the same dam before the opening and controlling for global yearly differences. We also control for crop-type fixed effects, which is important because we do not want to capture changes specific to certain crops. The estimated effect is a reduction of 6.3 grid cells, equivalent to 2.4% relative to the mean cropland size.

In Columns (2) to (4), we gradually increase the distance from the dam, thereby including more downstream areas. As a result, the sample size increases, and the outcome mean also rises, since these areas include less water surface compared to the dam basin immediately adjacent to the dam. The estimates on $Post_{jt}$ remain statistically significant and negative, with similar magnitudes. The effect size ranges from a 6.6-7.2 grid-cell reduction in cropland area, equivalent to 2.2-2.5% relative to the average cropland size. This suggests a consistent negative effect on cropland area following a dam opening.

Our findings are consistent with existing evidence that cropland area is negatively affected by dam operation (e.g., He, 2023; Ouma et al., 2024). One underlying

mechanism could be changes in water levels caused by dam regulation. The alteration of natural flow patterns can lead to fluctuations in water availability, which directly impacts crop irrigation and overall water supply to downstream areas. These changes can reduce the reliability of water sources for agriculture, especially in areas that depend heavily on seasonal water flow from rivers. Another potential mechanism is changed soil salinity. Dams block the natural transport of beneficial sediments and essential nutrients, depriving downstream agricultural lands of these valuable resources. Additionally, the reduced flow can exacerbate seawater intrusion, particularly in coastal areas, which raises soil salinity. Elevated salinity levels can hinder crop growth, reduce yields, and in some cases, make land unsuitable for farming.

4.3 Effects on surface temperature

Next we test changes in downstream surface temperature. We use land surface temperature, which incorporates input signals from the land surface but has been shown to be correlated with surrounding water temperatures and air tempearture (Worrall et al., 2022; Akbar et al., 2022; Naserikia et al., 2023). Water bodies, such as reservoirs downstream of dams, may affect the thermal properties of the surrounding land. Therefore, we consider land temperature changes to capture both land and water temperature shifts induced by dam operations.

In Table 2 Panel A, we estimate the impact of dam opening on downstream temperature levels, measured as the average temperature over each grid-year. The estimates on $Post$ remain positive and statistically significant. The magnitudes decrease after adding grid fixed effects and become even smaller after including year and crop-type fixed effects. In Column (4), we find that post-dam operation leads to a temperature increase of 0.013 Kelvin. This is a notable effect size, especially given that it reflects changes in annual average temperature. For comparison, the 1930s Great Plains Shelterbelt in the US has been shown to reduce downstream temperatures by up to 0.28°C (Grosset-Touba et al., 2024). Large-scale irrigation over the Ogallala Aquifer has been found to reduce the upper tail of the temperature distribution by 3°C in August (Braun and Schlenker, 2023).

Table 2 Panel B reports the impacts on temperature volatility. Since dams affect water flows, temperature may not only be higher but also more volatile, potentially

leading to more extreme events. Using annual temperature variance as the outcome variable, the estimates on $Post$ remain positive and statistically significant across different fixed effects and time trend specifications. In Column (4), we find that temperature volatility increases by 0.015, or 1.5% relative to the average variance. This suggests a higher risk faced by agricultural activities that require stable temperature conditions.

4.4 Effects on plant biodiversity

We also study how dam operation affects plant biodiversity, measured by the number of unique species and the number of plants. The latter is similar to a forest measure that captures the abundance of the plant ecosystem, while the former focuses on diversity. Given the altered water flow, increased temperature levels, and greater temperature volatility, plant biodiversity that has adapted to previous environmental conditions tends to be negatively affected by dam operation.

Figure S3 displays the event study graph. The X-axis shows the number of years relative to the dam opening, and the Y-axis shows the relative change in the number of species within 100 km downstream of the dams, relative to year -1 which serves as the baseline. In the pre-period, we observe no statistically significant estimates, suggesting that changes in the unique species count are similar to those in year -1, indicating no pre-trends. This supports the validity of our identifying assumption that the timing of dam openings is orthogonal to other factors that also affect plant diversity. In the post-period, the number of species significantly decreases starting in year 2, with a similar pattern in subsequent years. This effect persists for at least up to year 10. The estimated effect size is around -0.05 species per 100 km grid per year.

In Figure S4, we observe similar patterns when using plant count as the dependent variable. In the pre-period, the estimates remain statistically insignificant. In the post-period, the point estimates are mostly negative, although their magnitude and precision are lower compared to those in Figure S3. In years 6 and 7 after dam opening, plant counts significantly decrease by about 0.1 per grid-year.

We report the tabular results in Table 3. In Panel A, the number of unique species decreases by 0.1 per grid-year after dam opening, relative to the same grid's biodiversity before the opening. The estimates on $Post$ remain negative and highly robust

across alternative specifications. Despite the modest point estimate, this corresponds to a 35.8% reduction relative to the mean species count—likely reflecting the limited number of sampling sites in the BIEN data.

In Panel B, we observe similarly negative estimates on $Post$, indicating that total plant counts also decline after dam opening. For each grid-year, plant count drops by 0.06, or 25% relative to the average. Compared with Panel A, the effect size is slightly smaller, suggesting a stronger negative impact on species diversity than on overall plant abundance.

5 Adaptation to crop land shrink

5.1 Crop to vegetable

Given the negative effects of dams on downstream environmental conditions, we next test how crop sectors are negatively affected and how farmers adapt to these changes. We focus on cereal exports as a major crop and use trade data rather than local production to ensure that exports are comparable across space and time. In Figure S5, we plot event study figures, where the Y-axis represents cereal exports in downstream regions affected by dams. In the pre-period, we observe no pre-trends, consistent with Figures S3 and S4, supporting the validity of our identifying assumption. In the post-period, there is a sharp reduction in cereal exports by 1% in year 0, immediately following dam construction. The effect size gradually increases and becomes twice as large in year 10. This impact is long-lasting, with cereal exports only returning to pre-treatment levels by year 15.

Since vegetable cultivation requires less land and can be done in indoor environments, farmers facing challenges in crop production have incentives to adapt by switching to vegetable farming. In Figure 4, we present a similar event study, using vegetable exports as the dependent variable. Once again, we observe no significant estimates in the pre-period before dam construction. In the post-period, there is an increase in vegetable exports starting in year 0, with a steadily growing effect size through year 8. From year 10 onward, the effect size stabilizes, showing an increase of 0.5% units in vegetable exports compared to the base year -1. This pattern suggests adaptive behavior in downstream areas, with farmers shifting from cereal

crop production to vegetable farming in response to the dam opening.

Estimation results in Table 4 Panel A, show a negative and statistically significant estimate on Post, confirming a significant reduction in cereal exports after the dam opened. On average, cereal exports declined by 2% per region-year. The weighted results, based on export quantities, indicate a larger magnitude, suggesting that the reduction was primarily driven by regions that previously exported large volumes of cereal.

Similarly, we observe a 0.4% increase in vegetable exports, as reported in Table 4 Panel B. Column (4) shows an even larger effect, indicating a stronger shift in regions with a pre-existing comparative advantage in vegetable production. These findings highlight the farming sector's adaptation to dam-induced unfavorable environmental changes by shifting from cereal crops to vegetable cultivation.

5.2 Yield effect

Conditional on planting, we also study changes in yield using EVI as the dependent variable. The results in Table S1 report positive and significant estimates for $Post$. This suggests an increase in plant yield, either from crops or from vegetables in downstream areas within 100 km of the dam opening. However, this does not imply an overall increase in yield, but rather an increase in yield per area despite the decreased total area available for crop growing. We also control for crop type, so we have already accounted for adaptation efforts in changing crop mixes.

The magnitude suggests that the dam opening increases downstream yield by 0.04 units, or 7.7% relative to the average EVI level. Even though less land is available for crop growing, farmers manage to utilize the remaining land extensively, resulting in a yield increase. We interpret the yield change as another adaptation strategy that farmers use to make the most of the remaining resources.

We also test whether yield effects vary across areas with different levels of soil nutrition. The intuition is that dam-induced water loss and environmental changes may be more detrimental in areas with poor soil fertility. We use data from the Harmonized World Soil Database (HWSD), developed by the FAO and IIASA, which classifies soils into five categories of nutrient availability based on characteristics such as texture, organic carbon, pH, and total exchangeable bases.

Heterogeneity results in Table S2 show positive and significant estimates on the interaction term $Post \times Nutrient\ \ Level$, indicating that yield gains after the dam opening are more pronounced in areas with higher soil nutrient levels. This suggests that soil quality plays a role in shaping farmers' ability to adapt to environmental change.

5.3 Welfare effect

Given the adaptive shift from traditional crops to vegetables, we evaluate the overall revenue losses and gains using total export revenue. Our analysis relies exclusively on customs data, omitting domestic market revenue, which we assume is positively correlated with export performance. We also abstract from external factors such as shifts in foreign demand or supply-side substitutions in global markets.

Using total export revenue as the dependent variable and back-of-the-envelope calculations, Table S3 presents the overall decline in cereal exports alongside the corresponding gains from vegetable exports. Together, these crop-switching responses offset about 30% of the dam-induced revenue losses in downstream areas.

6 Adaptation to water environment change

We now focus on the aquafarming sector's response to dam-induced changes in the water environment, particularly water level reduction, increased water temperature, and greater temperature volatility. These conditions lead to a decline in fish exports. As shown in Figure 3, there are no pre-trends, but fishery exports significantly decrease after the dam opening. The effect size is around 0.5% in year zero, gradually increasing to a 2% reduction by year 10, and then stabilizing at that level until year 15. This pattern mirrors the reduction in cereal exports, confirming that fish farming is also negatively and persistently affected by dam-induced environmental changes.

Tabular results in Table 5 Panel A, show a significant reduction in fish exports following dam openings. In Column (1), fish export quantity decreases by 3.8 percentage points per region-year, which corresponds to a 22.9% reduction relative to the mean. In Column (2), the result remains robust when using a weighted regression that assigns greater weight to major fish-exporting regions, although the magnitude

becomes smaller. This suggests that regions less dependent on fish exports — likely those with less water-intensive aquaculture — are more negatively affected by dam-induced downstream changes.

In Table 5 Panel B, we use shrimp exports as the dependent variable, given that shrimp farming requires less stringent water quality and temperature stability compared to fish farming. We find small and statistically insignificant estimates on the $Post$ indicator in both columns, suggesting minimal changes in shrimp exports after dam openings. This indicates that the aquaculture sector does not adapt to dam-induced environmental changes by shifting from fish to shrimp farming.

Why did aquafarming not adapt? One potential explanation is that the decline in water levels was severe enough to undermine all types of aquaculture, not just fish farming. This is plausible given the substantial reduction in downstream water availability caused by upstream dam operations (Barbier, 2003; Lee et al., 2019). For example, in the Mekong River, a 70% decline in surface water volumes largely attributed to dam construction resulted in an estimated 10–26% loss in aquafarming productivity (Orr et al., 2012; Normandin et al., 2024). Another possible reason is the legacy and rigidity of fish farming systems. Transitioning from fish to shrimp farming may involve high fixed costs, different infrastructure, or regulatory barriers, making it difficult for producers to switch practices in response to environmental change.

As there is no evidence of adaptation to fishery losses resulting from dam construction, back-of-the-envelope calculations suggest that the average annual loss in fishery export revenue amounts to $535 million per dam, as shown in Table S3.

7 Discussion and conclusion

Our paper estimates the environmental and economic trade-offs associated with hydropower development by examining its impact on downstream biodiversity, environmental conditions, and agricultural outcomes. Using a global dataset of 1,971 dams and river flow data, we document significant ecological disruptions following dam construction, including reduced plant species and population, warmer water temperatures, and shrinking cropland areas. These environmental changes create unfavorable conditions for both land-based and water-based food production systems.

While these findings confirm the environmental costs of hydropower, they also reveal important differences in the capacity of sectors to adapt. In agriculture, farmers effectively adjust by reallocating resources toward more resilient crops, such as vegetables, which require less land and water. This shift is reflected in improved yields and higher vegetable exports, mitigating much of the welfare loss from reduced cropland. However, adaptation in aquaculture is much more limited. Fish farming suffers from decreased export levels, and no significant shift to more resilient species like shrimp is observed. This contrast highlights the uneven adaptive capacity across sectors exposed to environmental stress.

Our results have broader implications for how we understand and model climate damages. Many economic estimates of climate-related losses tend to overlook behavioral responses, assuming static production and land use. Our findings suggest that such models may overstate welfare losses in sectors where adaptation is feasible and responsive. However, the failure to adapt in sectors like aquaculture serves as a reminder that adaptation is neither automatic nor universally effective. As such, policy assessments must incorporate sector-specific responses to more accurately evaluate the true costs and risks of climate change and environmental interventions.

Future research should extend this analysis to examine longer-term adaptation dynamics and how dam-induced environmental change may reshape global patterns of comparative advantage. If certain regions consistently lose agricultural or aquaculture viability, production may shift geographically, altering trade flows and competitive dynamics. A deeper understanding of these transitions could inform international trade policy and investment in agricultural innovation and climate resilience.

References

Arya J Akbar, Ashar Muda Lubis, et al. Analysis of land and sea temperatures trend during 1985-2021 period to understand local or global warming effect in bengkulu city. *Indonesian Review of Physics*, 5(1):16–24, 2022.

Douglas Almond, Xinming Du, and Alana Vogel. Reduced trolling on russian holidays and daily us presidential election odds. *Plos one*, 17(3):e0264507, 2022.

Doğan Altinbilek. The role of dams in development. *Water Science and Technology*, 45 (8):169–180, 2002.

Michael L Anderson. As the wind blows: The effects of long-term exposure to air pollution on mortality. *Journal of the European Economic Association*, 18(4):1886–1927, 2020.

Fernando M Aragón, Francisco Oteiza, and Juan Pablo Rud. Climate change and agriculture: Subsistence farmers' response to extreme heat. *American Economic Journal: Economic Policy*, 13(1):1–35, 2021.

Maximilian Auffhammer and Tamma A Carleton. Regional crop diversity and weather shocks in india. *Asian Development Review*, 35(2):113–130, 2018.

Edward B Barbier. Upstream dams and downstream water allocation: The case of the hadejia-jama'are floodplain, northern nigeria. *Water resources research*, 39(11), 2003.

Ger Bergkamp, Matthew McCartney, Pat Dugan, Jeff McNeely, Mike Acreman, et al. Dams, ecosystem functions and environmental restoration. *Thematic review II*, 1:1–187, 2000.

Hester Biemans, Ingjerd Haddeland, Pavel Kabat, Fulco Ludwig, Ronald WA Hutjes, Jens Heinke, Werner von Bloh, and Dieter Gerten. Impact of reservoirs on river discharge and irrigation water supply during the 20th century. *Water resources research*, 47(3), 2011.

Stephen R Boucher, Michael R Carter, Jon Einar Flatnes, Travis J Lybbert, Jonathan G Malacarne, Paswel Marenya, and Laura A Paul. Bundling stress tolerant seeds and insurance for more resilient and productive small-scale agriculture. 2021.

Thomas Braun and Wolfram Schlenker. Cooling externality of large-scale irrigation. Technical report, National Bureau of Economic Research, 2023.

Marshall Burke and Kyle Emerick. Adaptation to climate change: Evidence from us agriculture. *American Economic Journal: Economic Policy*, 8(3):106–140, 2016.

André Chandesris, Kris Van Looy, Jacob S Diamond, and Yves Souchon. Small dams alter thermal regimes of downstream water. *Hydrology and Earth System Sciences*, 23 (11):4509–4525, 2019.

Ting Chen, Chong Liu, and Sen Ma. Environmental change, water scarcity, and farmers' differentiated adaptations: Evidence from the three gorges dam. *SSRN Electronic Journal*, 2021. doi: 10.2139/ssrn.3789033. URL `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3789033`.

Xiaomeng Cui. Beyond yield response: weather shocks and crop abandonment. *Journal of the Association of Environmental and Resource Economists*, 7(5):901–932, 2020a.

Xiaomeng Cui. Climate change and adaptation in agriculture: Evidence from us cropping patterns. *Journal of Environmental Economics and Management*, 101:102306, 2020b.

Xiaomeng Cui and Qu Tang. Extreme heat and rural household adaptation: Evidence from northeast china. *Journal of Development Economics*, 167:103243, 2024.

Xiaomeng Cui and Zheng Zhong. Climate change, cropland adjustments, and food security: Evidence from china. *Journal of Development Economics*, 167:103245, 2024.

Tatyana Deryugina, Garth Heutel, Nolan H Miller, David Molitor, and Julian Reif. The mortality and medical costs of air pollution: Evidence from changes in wind direction. *American Economic Review*, 109(12):4178–4219, 2019.

Quy-Toan Do, Shareen Joshi, and Samuel Stolper. Can environmental policy reduce infant mortality? evidence from the ganga pollution cases. *Journal of Development Economics*, 133:306–325, 2018.

Xinming Du. Symptom or Culprit? Social Media, Air Pollution, and Violence. CESifo Working Paper Series 10296, CESifo, 2023. URL `https://ideas.repec.org/p/ces/ceswps/_10296.html`.

Esther Duflo and Rohini Pande. Dams*. *The Quarterly Journal of Economics*, 122(2):601–646, 05 2007. ISSN 0033-5533. doi: 10.1162/qjec.122.2.601. URL `https://doi.org/10.1162/qjec.122.2.601`.

Susy Echeverría-Londoño, Brian J Enquist, Danilo M Neves, Cyrille Violle, Brad Boyle, Nathan JB Kraft, Brian S Maitner, Brian McGill, Robert K Peet, Brody Sandel, et al. Plant functional diversity and the biogeography of biomes in north and south america. *Frontiers in Ecology and Evolution*, 6:219, 2018.

Eric C. Edwards and Steven M. Smith. The role of irrigation in the development of agriculture in the united states. *The Journal of Economic History*, 78 (4):1022–1026, 2018. doi: 10.1017/S0022050718000608. URL `https://www.cambridge.org/core/journals/journal-of-economic-history/article/role-of-irrigation-in-the-development-of-agriculture-in-the-united-states/0B167527CEE1E625FD5489884724FAC0`.

Isaac Ehrlich and Jinyoung Kim. Immigration, human capital formation, and endogenous economic growth. *Journal of Human Capital*, 9(4):518–563, 2015.

Ruben Enikolopov, Alexey Makarin, and Maria Petrova. Social media and protest participation: Evidence from russia. *Econometrica*, 88(4):1479–1514, 2020.

Brian J Enquist, Rick Condit, Robert K Peet, Mark Schildhauer, and Barbara M Thiers. Cyberinfrastructure for an integrated botanical information network to investigate the ecological impacts of global climate change on plant biodiversity. Technical report, PeerJ Preprints, 2016.

Marcus Vinicius Estigoni, Renato Billia Miranda, and Frederico Fabio Mauad. Hydropower reservoir sediment and water quality assessment. *Management of Environmental Quality: An International Journal*, 28(1):43–56, 2017.

Matthew R Fuller, Martin W Doyle, and David L Strayer. Causes and consequences of habitat fragmentation in river networks. *Annals of the new York Academy of Sciences*, 1355(1):31–51, 2015.

Teevrat Garg, Stuart E Hamilton, Jacob P Hochard, Evan Plous Kresch, and John Talbot. (not so) gently down the stream: River pollution and health in indonesia. *Journal of Environmental Economics and Management*, 92:35–53, 2018.

Xavier Giroud. Proximity and investment: Evidence from plant-level data. *The Quarterly Journal of Economics*, 128(2):861–915, 2013.

William L Graf. Downstream hydrologic and geomorphic effects of large dams on american rivers. *Geomorphology*, 79(3-4):336–360, 2006.

Florian Grosset-Touba, Anna Papp, and Charles Taylor. Rain follows the forest: Land use policy, climate change, and adaptation. *Available at SSRN 4333147*, 2024.

Lee Hannah, Patrick R Roehrdanz, Pablo A Marquet, Brian J Enquist, Guy Midgley, Wendy Foden, Jon C Lovett, Richard T Corlett, Derek Corcoran, Stuart HM Butchart, et al. 30% land conservation and climate action reduces tropical extinction risk by more than 50%. *Ecography*, 43(7):943–953, 2020.

Xi He. Dams, cropland productivity, and economic development in china. *China Economic Review*, 81:102046, 2023.

Michelle Ho, Upmanu Lall, Maura Allaire, Naresh Devineni, Hyun Han Kwon, Indrani Pal, David Raff, and David Wegner. The future role of dams in the u nited s tates of a merica. *Water Resources Research*, 53(2):982–998, 2017.

International Commission on Large Dams. World commission on dams: 2023 global dams data. 2023. URL `https://www.icold-cigb.org/`.

International Energy Agency. *Hydropower Special Market Report: Analysis and Forecast to 2030*. OECD Publishing, 2021.

International Energy Agency. Hydropower. 2022. URL `https://www.iea.org/reports/hydropower`. Accessed: 2025-04-02.

Namrata Kala. Learning, adaptation, and climate uncertainty: Evidence from indian agriculture. *MIT Center for energy and environmental policy research working paper*, 23, 2017.

Satoshi Kameyama, Hiroto Shimazaki, Seiichi Nohara, Tatsuaki Sato, Yoshiaki Fujii, and Keita Kudo. Hydrological and sediment transport simulation to assess the impact of dam construction in the mekong river main channel. *American Journal of Environmental Sciences*, 9(3):247, 2013.

Mariola Kedra and Łukasz Wiejaczka. Climatic and dam-induced impacts on river water temperature: Assessment and management implications. *Science of the Total Environment*, 626:1474–1483, 2018.

Rajat Kochhar and Ruozi Song. Does market power in agricultural markets hinder farmer climate change adaptation. Technical report, Working Paper, 2023.

Gwanjae Lee, Hye Won Lee, Yong Seok Lee, Jung Hyun Choi, Jae E Yang, Kyoung Jae Lim, and Jonggun Kim. The effect of reduced flow on downstream water systems due to the kumgangsan dam under dry conditions. *Water*, 11(4):739, 2019.

Bernhard Lehner and Günther Grill. Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. *Hydrological Processes*, 27(15):2171–2186, 2013.

Bernhard Lehner, Penny Beames, Mark Mulligan, Christiane Zarfl, Luca De Felice, Arnout van Soesbergen, Michele Thieme, Carlos Garcia de Leaniz, Mira Anand, Barbara Belletti, et al. The global dam watch database of river barrier and reservoir information for large-scale applications. *Scientific Data*, 11(1):1069, 2024.

Yu-Hsiang Lei. Cross-border spillover effects of dams along international rivers, 2025. Working paper.

Phillip S Levin and Nicholas Tolimieri. Differences in the impacts of dams on the dynamics of salmon populations. In *Animal Conservation forum*, volume 4, pages 291–299. Cambridge University Press, 2001.

Rolando López-Tobar, Robinson J Herrera-Feijoo, Rubén G Mateo, Fernando García-Robredo, and Bolier Torres. Botanical collection patterns and conservation categories of the most traded timber species from the ecuadorian amazon: the role of protected areas. *Plants*, 12(18):3327, 2023.

MP McCartney, C Sullivan, Michael C Acreman, and DE McAllister. Ecosystem impacts of large dams. *Background paper*, 2, 2001.

Elizabeth Mettetal. Irrigation dams, water and infant mortality: Evidence from south africa. *Journal of Development Economics*, 138:17–40, 2019. ISSN 0304-3878. doi: https://doi.org/10.1016/j.jdeveco.2018.11.002. URL `https://www.sciencedirect.com/science/article/pii/S0304387818300166`.

Marzie Naserikia, Melissa A Hart, Negin Nazarian, Benjamin Bechtel, Mathew Lipson, and Kerry A Nice. Land surface and air temperature dynamics: The role of urban form and seasonality. *Science of The Total Environment*, 905:167306, 2023.

Christer Nilsson and Kajsa Berggren. Alterations of riparian ecosystems caused by river regulation: Dam operations have caused global-scale ecological changes in riparian ecosystems. how to protect river environments and human needs of rivers remains one of the most important questions of our time. *BioScience*, 50(9):783–792, 2000.

Cassandra Normandin, Frédéric Frappart, Luc Bourrel, Fabien Blarel, Sylvain Biancamaria, Jean-Pierre Wigneron, Léonie Galenon, Emilie Bernard, Ludovic Coulon, Bertrand Lubac, et al. Sharp decline in surface water resources for agriculture and fisheries in the lower mekong basin over 2000-2020. *Science of the Total Environment*, 950:175259, 2024.

Stuart Orr, Jamie Pittock, Ashok Chapagain, and David Dumaresq. Dams on the mekong river: Lost fish protein and the implications for land and water resources. *Global Environmental Change*, 22(4):925–932, 2012.

Yashon O Ouma, Boipuso Nkwae, Phillimon Odirile, Ditiro B Moalafhi, George Anderson, Bhagabat Parida, and Jiaguo Qi. Land-use change prediction in dam catchment using logistic regression-ca, ann-ca and random forest regression and implications for sustainable land–water nexus. *Sustainability*, 16(4):1699, 2024.

Dev Patel. Learning about a warming world: Attention and adaptation in agriculture. *Available at SSRN 4636825*, 2023.

Duminda Perera, Vladimir Smakhtin, Spencer Williams, Taylor North, and Allen Curry. Ageing water storage infrastructure: An emerging global risk. *UNU-INWEH Report Series*, 11:25, 2021.

Ambikapathi Ramya, Ramesh Poornima, Ganesan Karthikeyan, Sengottiyan Priyatharshini, Kalyanasundaram Geetha Thanuja, and Periyasamy Dhevagi. Climate-induced and geophysical disasters and risk reduction management in mountains regions. In *Climate Change Adaptation, Risk Management and Sustainable Practices in the Himalaya*, pages 361–405. Springer, 2023.

Brian D. Richter, Sandra Postel, Carmen Revenga, Thayer Scudder, Bernhard Lehner, Allegra Churchill, and Morgan Chow. Lost in development's shadow: The downstream human consequences of dams. *Water Alternatives*, 3(2):14.

Wolfram Schlenker and W Reed Walker. Airports, air pollution, and contemporaneous health. *The Review of Economic Studies*, 83(2):768–809, 2016.

Stefan Schmutz and Otto Moog. Dams: ecological impacts and management. In *Riverine Ecosystem Management: Science for Governing Towards a Sustainable Future*, pages 111–127. 2018.

Irena Šímová, Brody Sandel, Brian J Enquist, Sean T Michaletz, Jens Kattge, Cyrille Violle, Brian J McGill, Benjamin Blonder, Kristine Engemann, Robert K Peet, et al. The relationship of woody plant size and leaf nutrient content to large-scale productivity for forests across the americas. *Journal of Ecology*, 107(5):2278–2290, 2019.

Vis Taraz. Can farmers adapt to higher temperatures? evidence from india. *World Development*, 112:205–219, 2018.

UN Water. Progress on water-use efficiency – 2021 update, 2021. URL `https://www.unwater.org/publications/progress-water-use-efficiency-2021-update`. Accessed: 2025-04-06.

Dominik Wisser, Steve Frolking, Ellen M Douglas, Balazs M Fekete, Andreas H Schumann, and Charles J Vörösmarty. The significance of local water resources captured in small reservoirs for crop production–a global-scale analysis. *Journal of Hydrology*, 384(3-4):264–275, 2010.

Fred Worrall, Nicholas JK Howden, Tim P Burt, and David M Hannah. River water temperature demonstrates resistance to long-term air temperature change. *Hydrological Processes*, 36(11):e14732, 2022.

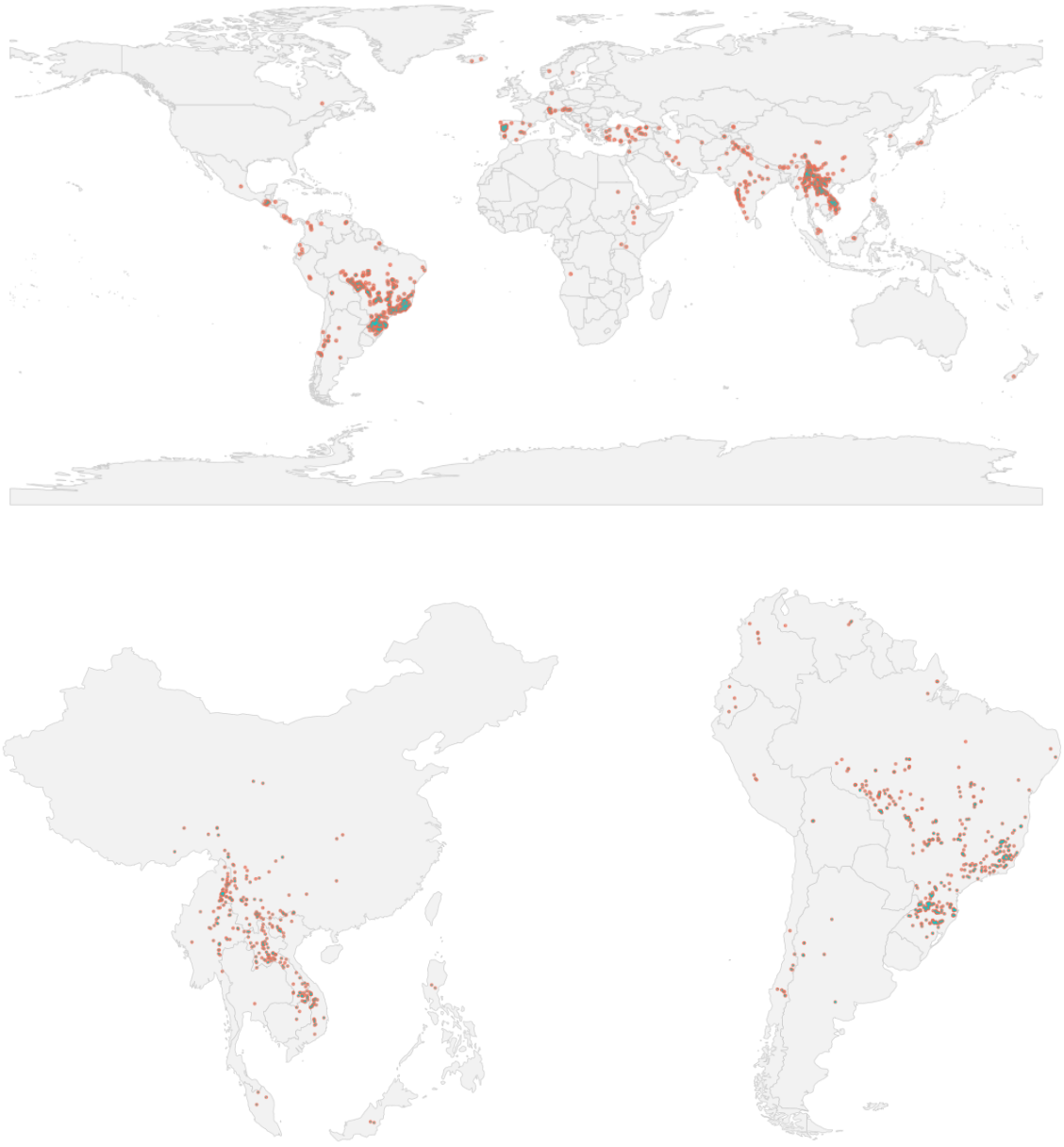
Haipeng Wu, Jin Chen, Jijun Xu, Guangming Zeng, Lianhai Sang, Qiang Liu, Zhengjie Yin, Juan Dai, Dacong Yin, Jie Liang, et al. Effects of dam construction on biodiversity: A review. *Journal of cleaner production*, 221:480–489, 2019.

Liam J Zarri, Eric P Palkovacs, David M Post, Nina O Therkildsen, and Alexander S Flecker. The evolutionary consequences of dams and other barriers for riverine fishes. *BioScience*, 72(5):431–448, 2022.

Alice Tianbo Zhang and Vincent Xinyi Gu. Global dam tracker: A database of more than 35,000 dams with location, catchment, and attribute information. *Scientific data*, 10(1):111, 2023.

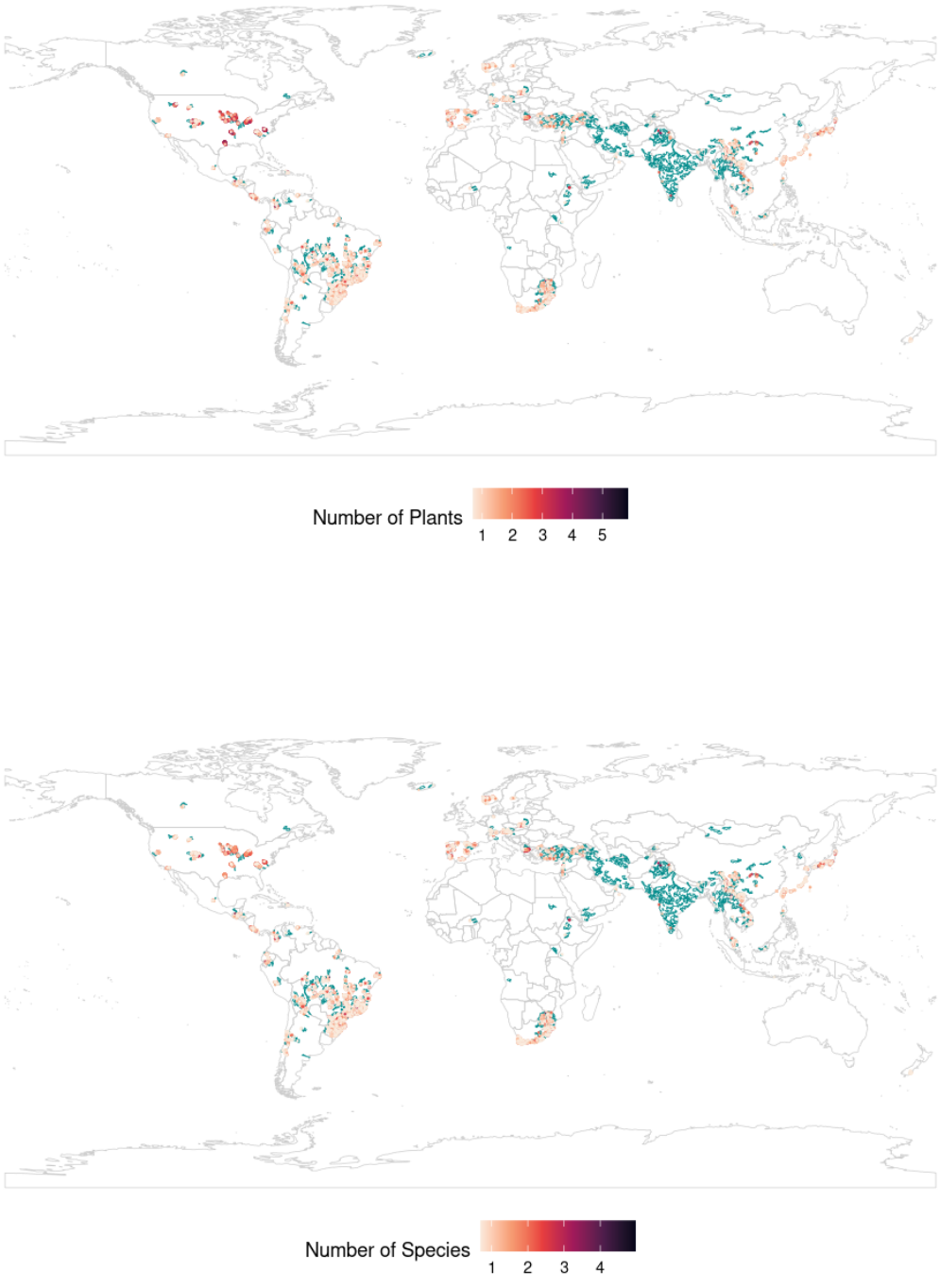
Figures and tables

Figure 1: Global Distribution of Hydropower Dams



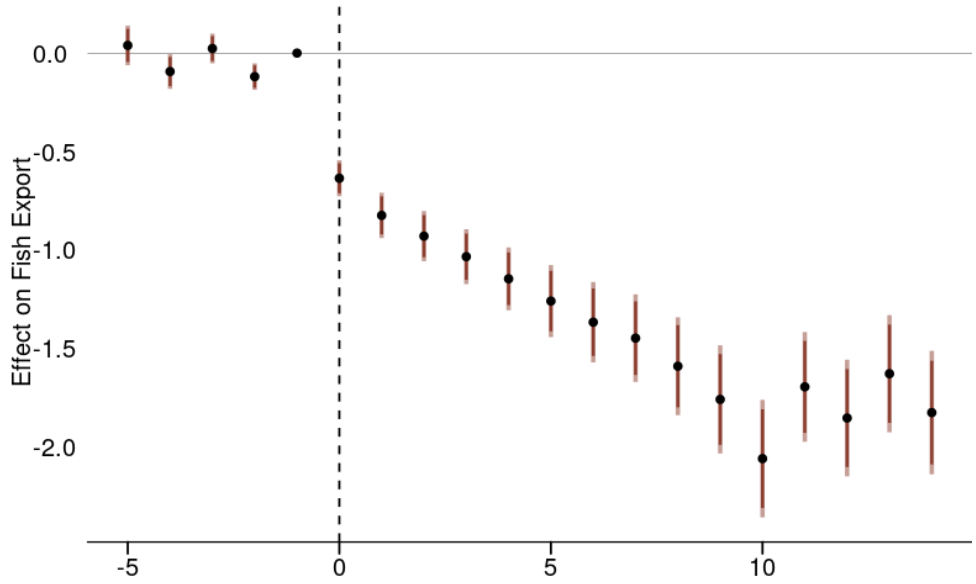
Note: Dam locations are based on data from the Global Dam Tracker (GDAT). A total of 924 hydropower dams were constructed globally after the year 2000, with 398 located in Asia and 436 in South America.

Figure 2: Biodiversity Downstream of Dams



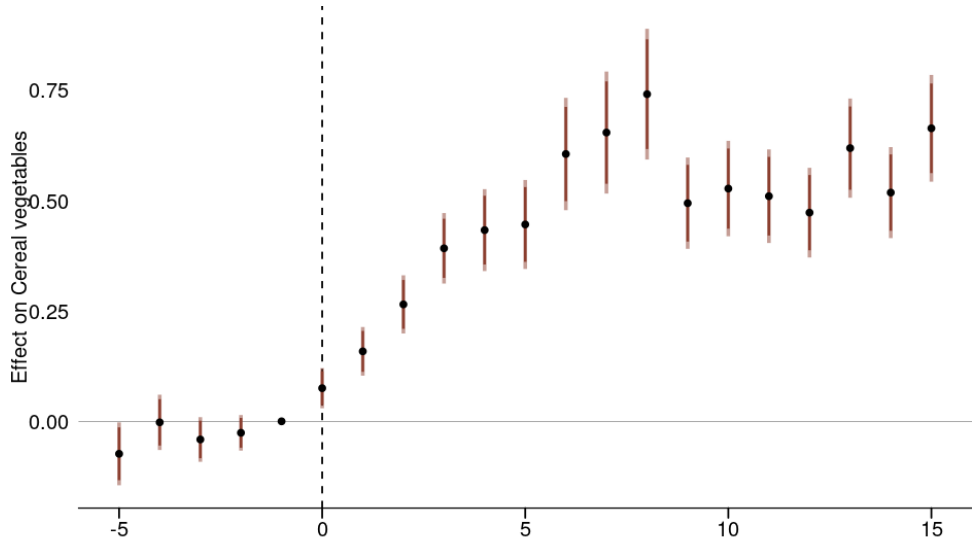
Note: Biodiversity data, measured by the number of individual plants and species, is sourced from BEIN. This figure displays the distribution and variation in plant biodiversity downstream of global dams. The blue areas represent downstream basins originating from each dam's location. The number of plants and species is expressed as the logarithm of the average values over the period 2000 to 2022.

Figure 3: Impact of Dams on Fishery Export



Note: Fishery export (HS2-03) data are sourced from UN ComTrade at the country level, national customs data at the provincial level for China, and Comex Stat at the municipal level for Brazil. The analysis sample is at the country-year or region-year level from 2000 to 2022. The year immediately preceding dam construction is omitted and serves as the reference period. The regression includes country or region and year fixed effects, with standard errors clustered at the country or region level. The figure displays point estimates of the effects of dam construction on fishery exports, along with 90% (dark red) and 95% (light red) confidence intervals for each post-construction year. The unit of Y-axis is log(kg).

Figure 4: Impact of Dams on Vegetable Export



Note: Vegetable export data (HS2-07) are sourced from UN ComTrade at the country level, national customs data at the provincial level for China, and Comex Stat at the municipal level for Brazil. The analysis sample is at the country-year or region-year level from 2000 to 2022. The year immediately preceding dam construction is omitted and serves as the reference period. The regression includes country or region and year fixed effects, with standard errors clustered at the country or region level. The figure displays point estimates of the effects of dam construction on vegetable exports, along with 90% (dark red) and 95% (light red) confidence intervals for each post-construction year. The unit of Y-axis is log(kg).

Table 1: Effects on Cropland Size

	Cropland Area			
	(1) 20km Downstream	(2) 60km Downstream	(3) 80km Downstream	(4) 100km Downstream
Post	-6.30*	-7.21***	-6.99***	-6.64*
	(3.37)	(3.55)	(3.58)	(3.60)
Fixed-effects				
Dam	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Crop-type	Yes	Yes	Yes	Yes
Outcome.mean	264.46	286.21	292.21	296.26
No. observations	77,330	185,064	235,444	286,088
R^2	0.98	0.98	0.98	0.98

Note: This table reports estimates from the two-way fixed effects difference-in-differences specification in Equation (2), where the outcome variable is the area of cropland within the 100 km downstream basin of each dam. Cropland data are derived from the MODIS Land Cover Type (MCD12Q1) product, using 500-meter resolution grid cells classified as cropland within the downstream basin. The sample in all columns is at the dam-year level from 2001 to 2022. Dam and year fixed effects are included, with standard errors clustered at the dam level. Each column corresponds to estimates based on cropland areas located 20 km to 100 km downstream of the dam. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 2: Effects on Surface Temperature

	(1)	(2)	(3)	(4)
Panel A: Level of Temperature (Kelvin)				
Post	0.495***	0.207***	0.022***	0.013***
	(0.015)	(0.001)	(0.002)	(0.002)
Outcome mean	292.386	292.386	292.386	292.386
R^2	0.001	0.991	0.993	0.994
Panel B: Volatility of Temperature (Kelvin)				
Post	0.493***	0.101***	0.015***	0.015***
	(0.006)	(0.001)	(0.001)	(0.001)
Outcome mean	4.341	4.341	4.341	4.341
R^2	0.006	0.977	0.980	0.981
Fixed effects				
Grid		Yes	Yes	Yes
Year			Yes	Yes
Crop-type			Yes	Yes
Dam-specific time trend				Yes
No. observations	1,009,355	1,009,355	1,009,355	1,009,355

Note: This table reports estimates from the two-way fixed effects difference-in-differences specification in Equation (2), where the outcome variables are the level and volatility (measured as within-year standard deviation) of land surface temperature within the 100 km downstream basin of each dam. Land surface temperature data are sourced from the MOD21A1D product, which provides daily temperature measurements at a 1 km spatial resolution. The sample in columns (1) to (4) is at the grid-year level from 2000 to 2022. Grid, year, and crop-type fixed effects are included, with standard errors clustered at the dam level. Column (5) additionally includes a dam-specific time trend to control for unobserved, dam-specific trends over time. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 3: Effects on Plant Biodiversity

	(1)	(2)	(3)	(4)
Panel A: Number of Species				
Post	-0.097***	-0.115***	-0.065***	-0.062***
	(0.008)	(0.011)	(0.017)	(0.019)
Outcome mean	0.173	0.173	0.173	0.173
R^2	0.001	0.001	0.002	0.012
Panel B: Number of Plants				
Post	-0.121***	-0.148***	-0.056***	-0.057***
	(0.012)	(0.015)	(0.026)	(0.029)
Outcome mean	0.227	0.227	0.227	0.227
R^2	0.001	0.006	0.007	0.018
Fixed effects				
Grid		Yes	Yes	Yes
Year			Yes	Yes
Dam-specific time trend				Yes
No. observations	92,631	92,631	92,631	92,631

Note: This table reports estimates from the two-way fixed effects difference-in-differences specification in Equation (1), where the outcome variable is plant biodiversity measured as the number of species and the number of individual plants within the 100 km downstream basin of each dam. Plant biodiversity data are sourced from the Botanical Information and Ecology Network (BIEN), which provides daily plant observations at the geographic coordinate level. The sample in columns (1) to (4) is at the grid-year level from 2000 to 2022. Grid and year fixed effects are included, with standard errors clustered at the grid level. Column (4) additionally includes a dam-specific time trend to control for unobserved, dam-specific trends over time that may affect biodiversity independently of dam construction. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 4: Effects on Agricultural Export

	Export Quantity Log(kg)			
	Cereal		Vegetables	
	(1)	(2)	(3)	(4)
Post	-2.04***	-5.05***	0.39***	1.07***
	(0.15)	(0.31)	(0.15)	(0.14)
Fixed-effects				
Dam	Yes	Yes	Yes	Yes
Region	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Weighted		Yes		Yes
Outcome.mean	18.1	18.1	16.6	16.6
No. observations	188,278	188,278	188,278	188,278
R^2	0.59	0.59	0.72	0.72

Note: This table reports estimates from the two-way fixed effects difference-in-differences specification in Equation (1), where the outcome variable is the quantity of agricultural exports (measured as the log of kilograms). Agricultural export data (HS2 codes 07 and 10) are sourced from UN ComTrade at the country level, national customs data at the provincial level for China, and Comex Stat at the municipal level for Brazil. The analysis sample is at the country-year or region-year level from 2000 to 2022. The regression includes country or region and year fixed effects, with standard errors clustered at the country or region level. Columns (2) and (4) use weighted export quantities, calculated based on the proportion of the downstream basin of a dam that intersects with each downstream country or region. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 5: Effects on Aquaculture Export

	Export Quantity Log(kg)			
	Fish		Shrimp	
	(1)	(2)	(3)	(4)
Post	-3.83***	-3.16*	-2.37	-2.61
	(1.52)	(1.88)	(1.56)	(1.76)
Fixed-effects				
Dam	Yes	Yes	Yes	Yes
Region	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Weighted		Yes		Yes
Outcome.mean	16.7	16.7	16.9	16.9
No. observations	36,271	36,271	19,757	19,757
R^2	0.57	0.59	0.69	0.69

Note: This table reports estimates from the two-way fixed effects difference-in-differences specification in Equation (1), where the outcome variable is the quantity of fishery exports (measured as the log of kilograms). Agricultural export data (HS2 codes 03) are sourced from UN ComTrade at the country level, national customs data at the provincial level for China, and Comex Stat at the municipal level for Brazil. The analysis sample is at the country-year or region-year level from 2000 to 2022. The regression includes country or region and year fixed effects, with standard errors clustered at the country or region level. Columns (2) and (4) use weighted export quantities, calculated based on the proportion of the downstream basin of a dam that intersects with each downstream country or region. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Online Appendix

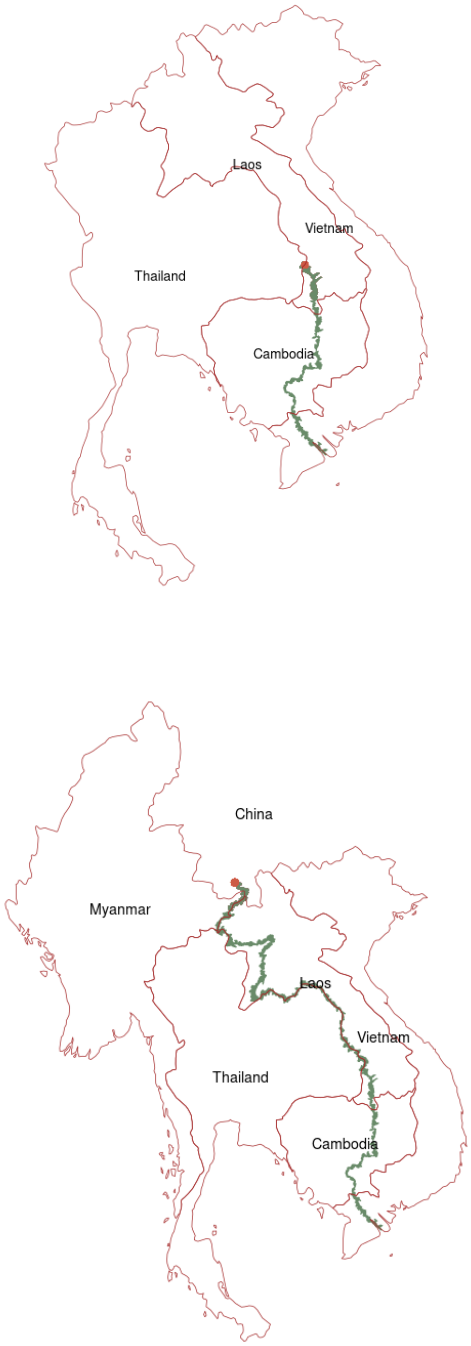
A Additional figures

Figure S1: Dams and Downstream Regions along Mekong and Lancang Rivers



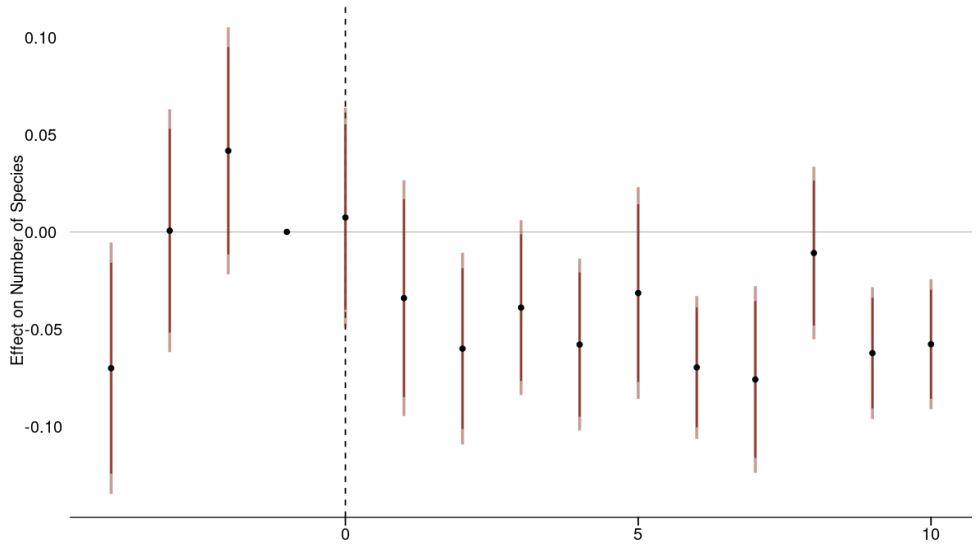
Note: Dam locations along the Mekong and Lancang Rivers are based on the Global Dam Tracker (GDAT). Red points indicate dam sites along the river system, while blue lines represent downstream river flow paths derived from HydroRIVERS data spanning multiple countries.

Figure S2: Individual Dam and Downstream Regions: Examples from the Mekong and Lancang Rivers



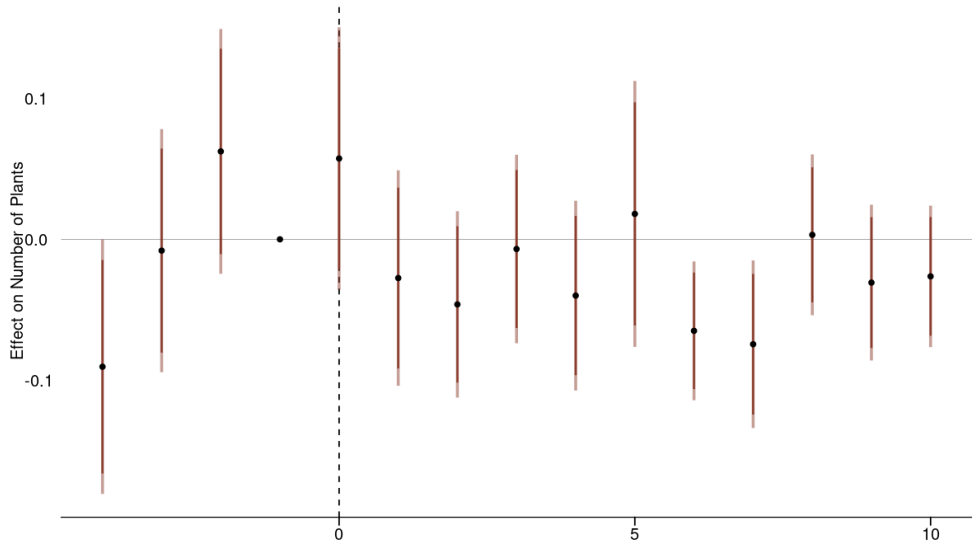
Note: Dam locations are based on the Global Dam Tracker (GDAT), and downstream water basins are derived from HydroBASINS. This figure shows two example dams along the Mekong and Lancang Rivers in China and Vietnam. The green areas represent the downstream basins originating from each dam's location. These basins extend across multiple countries, highlighting the transboundary nature of the river systems. We use countries and regions located within 100 km downstream of each dam to examine the effects of dam construction on agricultural exports.

Figure S3: Impact of Dams on Plant Biodiversity



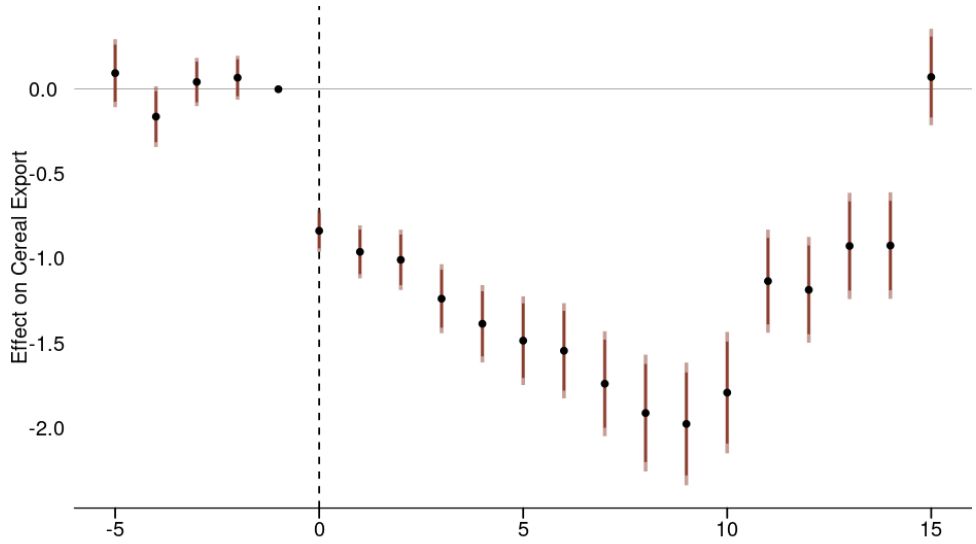
Note: Biodiversity data, measured as the number of individual plants, are sourced from the Botanical Information and Ecology Network (BIEN), which provides daily plant observations at the geographic coordinate level. The analysis sample is at the grid-year level from 2000 to 2022. Grid and year fixed effects are included, with standard errors clustered at the grid level. The figure displays point estimates of the effects of dam construction on the average annual number of unique species within 100 km downstream basins, along with 90% (dark red) and 95% (light red) confidence intervals for each post-construction year.

Figure S4: Impact of Dams on Plant Abundance



Note: Biodiversity data, measured as the number of plant species, are sourced from the Botanical Information and Ecology Network (BIEN), which provides daily plant observations at the geographic coordinate level. The analysis sample is at the grid-year level from 2000 to 2022. Grid and year fixed effects are included, with standard errors clustered at the grid level. The figure displays point estimates of the effects of dam construction on the average annual number of plant species within 100 km downstream basins, along with 90% (dark red) and 95% (light red) confidence intervals for each post-construction year.

Figure S5: Impact of Dams on Cereal Export



Note: Cereals export data (HS2-10) are sourced from UN ComTrade at the country level, national customs data at the provincial level for China, and Comex Stat at the municipal level for Brazil. The analysis sample is at the country-year or region-year level from 2000 to 2022. The year immediately preceding dam construction is omitted and serves as the reference period. The regression includes country or region and year fixed effects, with standard errors clustered at the country or region level. The figure displays point estimates of the effects of dam construction on cereal exports, along with 90% (dark red) and 95% (light red) confidence intervals for each post-construction year. The unit of Y-axis is log(kg).

B Additional tables

Table S1: Effects on Agriculture Yield

	EVI			
	(1)	(2)	(3)	(4)
Post	0.022***	0.054 ***	0.002***	0.004***
	(0.000)	(0.000)	(0.000)	(0.000)
Fixed-effects				
Grid		Yes	Yes	Yes
Year			Yes	Yes
Crop-type			Yes	Yes
Dam-specific time trend				Yes
Outcome.mean	0.52	0.52	0.52	0.52
No. observations	430,965	430,965	430,965	430,965
R^2	0.005	0.098	0.904	0.919

Note: This table reports estimates from the two-way fixed effects difference-in-differences specification in Equation (1), where the outcome variable is the Enhanced Vegetation Index (EVI) within the 100 km downstream basin of each dam. EVI data are derived from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS), available at 16-day intervals with a spatial resolution of 250 meters. The sample in all columns is at the grid-year level from 2000 to 2022. Grid and year fixed effects are included, with standard errors clustered at the grid level. Columns (1) to (4) present estimates using grid, year, and crop-type fixed effects. Column (5) additionally includes a dam-specific time trend to control for unobserved, dam-specific trends over time that may affect vegetation independently of dam construction. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table S2: Effects on Agriculture by Soil Nutrient Level

	EVI		
	(1)	(2)	(3)
Post	0.044***	-0.003***	-0.003***
	(0.000)	(0.000)	(0.000)
Post × Nutrient Level	0.004***	0.003***	0.004***
	(0.000)	(0.000)	(0.000)
Fixed-effects			
Grid	Yes	Yes	Yes
Year		Yes	Yes
Crop-type			Yes
No. observations	1,020,648	1,020,648	1,020,648
R^2	0.822	0.921	0.921

Note: This table reports estimates from a regression that includes an interaction between the post-construction indicator and the soil nutrient index. The outcome variable is the Enhanced Vegetation Index (EVI) within the 100 km downstream basin of each dam. The results indicate that areas with higher soil nutrient levels experience greater agricultural productivity increase following dam construction, suggesting that regions with lower nutrient levels are more vulnerable to its impacts. Soil nutrient data are derived from the Harmonized World Soil Database (HWSD). The sample in all columns is at the grid-year level from 2000 to 2022. Grid and year fixed effects are included, with standard errors clustered at the grid level. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table S3: Change in Export Revenue by Dam (Millions USD)

Sector	Revenue Change (Millions USD)
Fishery	−$535.07
Vegetable	$31.98
Cereal	−$100.93

Note: Revenue changes are calculated as the difference in average annual export value per dam–downstream country–year observation, comparing pre- and post-construction periods. Values are aggregated across all relevant observations and reported in millions of USD. A negative value indicates a decline in export revenue following dam construction.