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Research Report

Irrigation strengthens climate resilience: Long-term evidence from Mali using satellites and surveys

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Abstract

Agriculture in the Sahel and much of sub-Saharan Africa remains to a large extent rainfed. At the same time, climate change is already causing less predictable rainfall patterns in the region, even as rising temperatures increase the amount of water needed for agricultural production. We assess to what extent irrigation can strengthen the climate resilience of farming communities. Our study sample consists of nearly 1,000 distinct locations in Mali in which small-scale, river-based irrigation was introduced over the past two decades, as weather conditions worsened and political upheaval erupted. Using the staggered roll-out of the irrigation and repeated observations over 20 years allows us to compare the pre- and postirrigation outcomes of locations while adjusting for confounding factors. We geospatially link data on irrigation interventions with agricultural conditions measured using satellite imagery and surveys, as well as child nutrition and health outcomes and conflict event data. Using a two-way fixed effects model to quasi-experimentally estimate counterfactual outcomes, we find that the introduction of irrigation led to substantial increases in agricultural production on supported fields, with these gains persisting even a decade later. Children in nearby communities are less likely to be stunted or wasted due to the irrigation, and conflict risks decrease in the closest communities. Some of these gains are offset by worsening conditions farther away from the newly installed irrigation. These findings suggest that, even with political conflicts in semi-arid areas already increasing, sustainable irrigation may offer a valuable tool to improve communities' long-term well-being and social cohesion.

Keywords: climate resilience, irrigation, remote sensing, satellite imagery, Africa

Significance Statement

The paper fills an important void in our current understanding of how to sustainably improve agricultural production and nutrition among some of the globe's most food-insecure and climate-affected populations. We assess the development impacts of small-scale irrigation, which to date has only rarely been studied and never over an adequately long time window. We integrate diverse methodologies to examine this irrigation rolled out over more than two decades in northern Mali. By combining remote-sensing evidence on farm production, water availability, and nearby ecological impacts with in situ measures of children's nutrition and health in nearby communities, we document both the sustained benefits of small-scale irrigation and several hidden costs in outlying areas.

Introduction

Agriculture in the Sahel and much of sub-Saharan Africa remains to a large extent rainfed, and farm productivity continues to lag behind attainable yields using irrigation in combination with improved inputs. Worsening climate conditions will entail rising temperatures and a lack of precipitation over longer periods in the coming decades. Without adaptation, the latest IPCC (1,) projections confirm the Sahel region as one of the world's most affected regions by water-related impacts of climate variability and change. Mali, for instance, is expected to experience temperature rises ranging from 2.0 to 4.6 °C by 2080. The country could see 59 more days each year with temperatures exceeding the physiologic threshold for human adaptability of 35 °C by 2080 (relative to 2000). At the same time, average annual precipitation is likely to continue to decline, and droughts are expected to become more frequent and longer in duration, while subsequent wet periods may become more extreme (2). Against this background the climate-resilient development of human and natural systems, in response to risks induced or exacerbated by climate variability, becomes key.

Introducing climate-resilient irrigation in small-scale farming has great potential to make rural communities less dependent on

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climatic fluctuations, most prominently those in precipitation (3–9). Yet past evaluations of irrigation interventions have focused on short-term outcomes—typically 2 to 4 years after project completion—without making explicit the link to resilience strengthening (4, 6). The only extant study exploring longer term effects of irrigation studied large dam-based systems, whose resilience and sustainability implications are quite different from small-scale systems (10). The literature thus offers little guidance in understanding whether community vulnerabilities have been durably reduced and whether farming communities have become resilient in dealing with future climate stressors and shocks. Many development projects see the deterioration of any positive benefits once projects are no longer supported or maintained by dedicated staff. In addition, short-term strategies that seem to make a positive contribution might turn out to be inadequate strategies for adapting to future climate conditions. We advance this research stream by looking at longer time frames and by explicitly addressing questions related to the sustainability of irrigation impacts.

We also provide one of the rare studies of the impacts of irrigation measures in the context of armed conflict. To the best of our knowledge, only one impact study so far has evaluated the effect of irrigation in such a context (11). While the risks associated with evaluating irrigation measures on the ground in an ongoing conflict are evident, the lack of evidence from such contexts is nonetheless problematic. The conflict may further aggravate climate-induced vulnerabilities (12), limit the effectiveness of adaptation projects (13) and the intervention might also aggravate the existing conflict. Relying on remote-sensing data and geocoded survey evidence allows us to evaluate irrigation impacts in a context where data collection on the ground would not be feasible due to security concerns. By integrating geocoded conflict data from the armed conflict and event data (ACLED) (14) into our statistical models, we also assess potential interrelations between the ongoing conflict and the development interventions.

The rural economy of Mali is strongly dependent on annual rainfall patterns and hence fluctuates with climate variability (15). Agriculture accounts for 37% of Mali's gross domestic product (GDP) (and employs 75% of the workforce), while 95% of its production is exclusively rainfed (16). Precipitation events have been evidently erratic in recent years. Already, observable changes and existing future projections are underlining the need for agriculture to become less dependent on fluctuations from rainfall. In addition to these challenging environmental conditions, recurring multidimensional conflicts further reinforce climate-induced vulnerabilities and increase the population's vulnerability.

In Northern Mali, the German development agencies Kreditanstalt für Wiederaufbau (KfW) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) implemented a range of irrigation interventions over the past two decades. Our study examines the installation of irrigation with water pumped from the Niger River and its tributaries and used to irrigate small perimeters of up to 40 ha, as well as the valorization of floodplains ("Mares"), in which rainwater in times of heavy rain or river flooding is stored and crops are grown in these floodplains and fish are cultivated in basins. These investments reflect the Government of Mali's broader strategy relying on similar small-scale irrigation projects in the central inner delta of the Niger River to improve food security and secure the incomes of smallholder farmers (17).

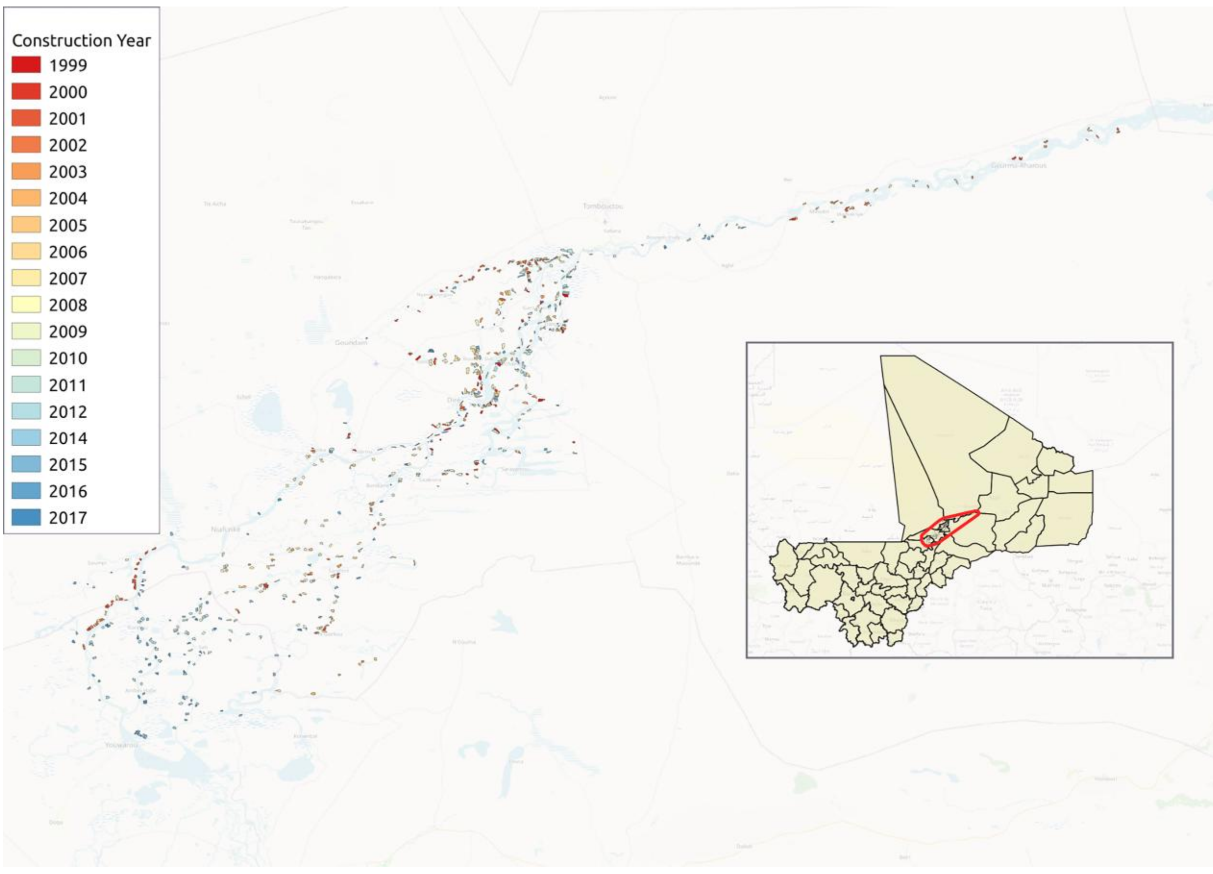

Fig. 1. Intervention sites in Northern Mali.

To assess the impacts of irrigation improvements, we use geolocated activities on 792 pump-based irrigation perimeters and 150 “mares” in the provinces of Mopti and Timbouctou (see Fig. 1). For the newly established irrigation perimeters, water from the Niger River and its tributaries was pumped up to canals, which then used gravity to channel water to individual fields within the perimeters. The program generally aimed to increase the production of staple crops by improving water access and quantities in the main growing season, as direct precipitation on the fields was often inadequate (and river levels were too low in the dry season to allow for pumping for irrigation uses). This land was generally unfarmed at baseline, and equitable allocation of fields to nearby community members was a major focus of the program. The improvements on “mares” consisted of rehabilitating these frequently flooded lands to allow for more precise water management for farming both deep-water rice varieties and cereals postflooding.

These improvements were rolled out between 1999 and 2020, allowing us to compare changes in outcomes near irrigated sites and those that have not yet been irrigated (but would eventually be). To quasi-experimentally identify the effects attributable to the introduction of irrigation, we rely on the geographic and temporal variation in the roll-out of irrigation. Two-way fixed effects (TWFE) estimates allow adjustment for time-invariant unobserved factors specific to each irrigated site, as well as for shocks common to each region (province) in a given year. Our primary estimating equation for agricultural production outcomes is the following:

$$\text{AgOutcom}_{irt} \quad \sum_{y\, irt\, irt\, irt\, i\, rt\, irt}^{10+} \tag{1}$$

where:

- AgOutcom_{irt} is the outcome (discussed below) in polygon i in region r in year t,
- $\sum_{y\, irt}^{10+}$ represents a set of coefficients and dummies indicating year-to-treatment bins,
- Preci_{irt} and Tem_{irt} are the total precipitation and mean temperature in the polygon-year, and
- $_{i\, rt}$ is a set of fixed effects for polygon and region-year.

We confirm that using this quasi-experimental approach, the timing of irrigation at a given site is not correlated with its preceding changes in weather conditions, agricultural outcomes, or community health. We also incorporate recent advances in TWFE methodology (18), which account for potential bias due to duration-dependent treatment effects. These effectively estimate each year-to-treatment factor described in Eq. 1 by only including comparisons between those reaching each year-to-treatment (i.e. “switchers” in each period) and those who had not yet reached this year-to-treatment (i.e. “the not-yet-treated”).

To capture outcomes on fields and nearby communities, we use a combination of remotely sensed measures and those derived from household surveys. Our primary measures of water availability (normalized difference water index, NDWI) and vegetative greenness (the normalized difference vegetation index, NDVI) are derived from remote sensing. To develop these measures, we utilize cloud-free composite images from Landsat 5, 7, and 8, sourced from collection 2 within the United States Geological Survey (USGS) level 2 archive and processed within the google earth engine (GEE). The dataset encompasses surface reflectance data that has been corrected for atmospheric influences (processed using the landsat ecosystem disturbance adaptive processing system [LEDAPS] algorithm for Landsat 5 and 7 series imagery and using the LaSRC algorithm for Landsat 8). The spatial resolution of the underlying images is 30-m and carries multiple bands both in the visible and infrared portion of the electromagnetic spectrum. For each year, we created a mosaiced image from all cloud-free images available for May, a key period during the primary growing season when crop greenness is most clearly observable. We then spatially aggregated the NDWI and NDVI values for each irrigation site by taking the mean values across all pixels within the irrigation polygon. We repeated this exercise using images from November, a key period before the onset of the rainy season. We thus obtain the mean NDWI and NDVI for each irrigation project site for both the growing season and prerainy season for each year from 1986 to 2021 (91.4% of all site-years are observed, with the remaining 8.6% of site-years missing due to cloud cover during the primary growing season window).

The use of NDVI as a metric for estimating crop yield is supported by previous studies which suggest that predictions of agricultural productivity from high-resolution (HR) satellite imagery are as accurate as the survey-based measures traditionally used in crop yield research (19). For example, Roznik et al. (20) observed improvement in crop yield models with NDVI from HR remotely sensed satellite imagery (9). Likewise, Fuller (7) observed statistically positive correlations between trends in maximum NDVI and field measures of rangeland and crop production.

We also use visual inspection of very high-resolution (VHR) satellite imagery for a subsample of locations to assess changes in the fraction of each irrigated perimeter that is planted and the number of crops grown in the perimeter. Figure 2 offers an example of conversion from bare soil to irrigated cultivation observed using VHR imagery. Since visual analysis does not directly allow the detection of specific crop types, we use differences in the hue of farms to count the number of different crops sown for each irrigated site.

We corroborated these remotely sensed outcomes with qualitative evidence from focus group discussions (FGDs) with both farmers and project staff in Mali. These FGDs also covered the irrigation’s impacts on the well-being of nearby communities, complementing our statistical analysis using large-scale household survey data collection. We also consider impacts on nearby communities via five repeated rounds of the Demographic and Health Surveys (DHS) carried out in 1996, 2001, 2006, 2013, and 2018. Calorie intake per capita in Mali is one of the lowest in the world, with a prevalence of undernourished people fluctuating at a high level of around 6% (21). Food security in Mali largely depends on subsistence farming (22), which is almost entirely based on rainfall (16). The improvements in agricultural production we detect are thus hypothesized to increase food consumed by nearby households. Improvements in food security and composition are particularly impactful on child nutrition and health, and the effects of increases in the quantity or quality of calories are often first observable among children. We thus examine irrigation impacts on stunting and wasting among children under 5 years old, using biometric measures recorded during household visits, as well as other measures of child health based on maternal recall as part of the broader concept of resilience.

Mali has long struggled with armed conflict, including repeated coups d’état and extensive violent uprisings. Our study sample spans the fragile democratic governments in the 1990s and 2000s, as well as the Tuareg rebellion in 2012 (22), the declaration of the independence of the Asawad in northern Mali, and ongoing political and violent conflicts in northern and central Mali. This

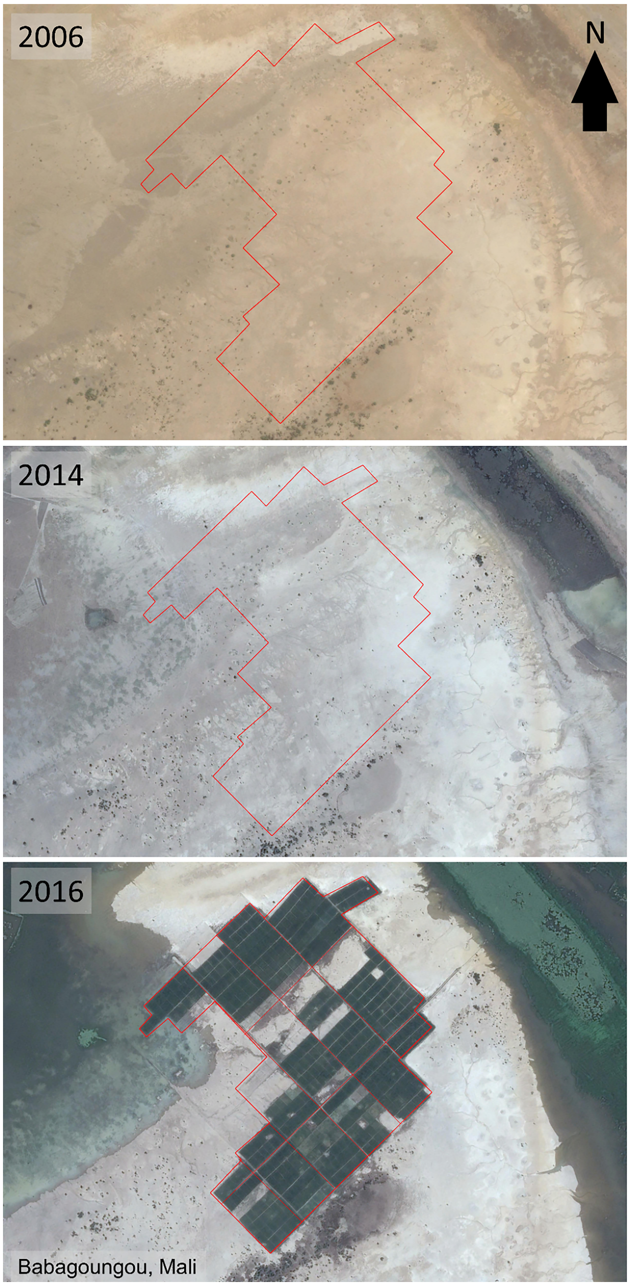

Fig. 2. Very HR imagery confirms no cultivation at the Babagoungou site before irrigation in 2016, and intensive cultivation thereafter. Pictured is the Babagoungou irrigated perimeter in Northern Mali, providing an example of visual analysis confirming change in cultivation after irrigation.

ongoing conflict dramatically worsens communities' vulnerabilities: due to the armed conflict, GDP shrank significantly between 2010 and 2015, accompanied by a sharp rise in rates of children who were underweight or stunted (23). Such armed conflict may limit the effectiveness of development interventions, either by directly interrupting project activities (attacks on infrastructure, intimidation, or forced migration of farmers) or by increasing the risk of future losses and thereby increasing farmers' hesitancy to invest in agricultural productivity and adopt new technologies.

At the same time, the newly introduced irrigation could itself reduce or increase the risk of conflict. Increased agricultural production and better food security could alleviate grievances among populations and hence decrease their incentives to support or join rebel groups, akin to the opportunity cost theory of conflict participation (24). Throughout the Sahel, expanding conflicts between agricultural and transhumant pastoralist communities are driven in part by competition over land and water resources (25). Expanding agriculture through irrigation may cause reductions in livestock grazing and breeding areas and thus intensify the competition between agriculturalists and pastoralists competition over land or water thereby worsening conflict risk (1, 17).[a] In addition to conflicts within treatment communities, the intervention could also spark conflict with neighboring communities if irrigation activities here negatively affect water availability elsewhere, for example.[b]

We examine the impact of irrigation on conflict risk, with the ACLED dataset serving as our primary data source because of its broad spatial and temporal coverage, as well as the extent of its event coverage in each year and location. ACLED includes a broad range of event types such as battles, violence against civilians, explosions, riots, and protests which can be further refined based on actors involved, type of interactions (i.e. pairing of actors involved), and fatalities.

In addition to the relationship of irrigation with nearby conflict conditions, we also consider the potential for ecological impacts from newly introduced irrigation. The community resilience impacts of pump-based irrigation drawing on the Niger River and its tributaries are also dependent on the irrigation's ecological impacts, which themselves shape the communities' vulnerabilities. For example, the interventions may positively impact ecological conditions by increasing soil moisture and protecting against erosion[c] and thereby alleviating land degradation caused by climate change. At the same time, the irrigation infrastructure may have facilitated worsening soil erosion or reductions in soil moisture and groundwater so that nearby communities may see the gains from agricultural production decline over time (potentially even leading to net declines in production and nutrition). To understand these potential ecological impacts, we sampled 33 irrigation sites across eight clusters for visual interpretation analysis using VHR (QuickBird—0.65-m; WorldView-1/2/3–0.46-m, etc.), and HR (PlanetScope—3 m) satellite imagery. This sample was limited to irrigation introduced between 2015 and 2018, ensuring VHR imagery is available before, during, and after implementation and allowing for an assessment of changes over time.

We utilize elements of visual interpretation (e.g. tone, shape, pattern, association, et c.) to identify ecological impacts (i.e. soil erosion, soil moisture/groundwater, and broader infrastructure development). Color contrast and patterns between the top and subsoils due to soil erosion are utilized to detect and map soil erosions, including linear soil erosion features, such as rill, gully, and

[a] The project interventions we study aimed to be "conflict-sensible" by minimizing the risk of conflict (particularly land conflict). This was supposed to take place via a program advisory board (Comité Consultatif), consisting of traditional representatives of the Tuareg, Songhrai, Fulbe, and other ethnic groups, which decides unanimously on the locations of new irrigation perimeters situated in northern Mali. Moreover, all groups of farmers that applied for an irrigation project in their village were required to facilitate a peace agreement of all stakeholders in the village, in order to avoid land conflicts (1). Other project components focused on increasing interactions and dialogue between different ethnic groups and/or conflict parties through activities in advisory boards or user committees.

[b] See Duflo and Pande (26) on how the effects of irrigation on rural poverty can be a paradox. The intervention may decrease water availability for other users, particularly downstream from project locations (and also for other sectors). In the supplementary analysis, we find no evidence of negative downstream "spillover" effects in this context.

[c] The projects guard against erosion by creating stone contour walls and planting trees and hedges (23).

stream channels (27). Since the HR and VHR imagery do not carry shortwave infrared (SWIR) bands, we analyzed temporal VHR images to identify color contrast, vegetation patterns, and hue elements for analyzing soil moisture. We utilized elements of photo interpretation (e.g. shape, site, association, and tone/color) to visually analyze VHR images for exploring infrastructure relocation due to irrigation facilities on project sites (28). To complement this visual analysis, we also statistically analyzed changes in water and vegetation indices along the banks of the Niger River and its tributaries to assess the extent of erosion and soil moisture due to irrigation investments. We further assessed changes in these indices immediately outside the irrigation perimeters to examine whether these buffer areas are impacted (positively or negatively).

Results

The pump-based irrigation improved agricultural conditions on irrigated perimeters, as well as child nutrition in nearby communities. These effects are long-lasting and suggest that pump-based investments can help improve community resilience.

Examining remotely sensed outcomes for pump-based irrigation, we find a statistically significant improvement in NDWI, reflecting the increased availability of water for crop growth (see Fig. 3 for an event-study graph). These effects grow in the first year after the introduction of irrigation and then stabilize and remain similarly sized even a decade after the irrigation is completed, suggesting sustained maintenance and use. We also confirm that there is no significant pattern of changes in NDWI before the introduction of irrigation, validating our causal estimates. Table S1 shows the corresponding regression-based results, again confirming large gains due to irrigation that have been sustained over a decade.

We next examine vegetative greenness using average NDVI, both before and during the rainy season (i.e. the rainfed growing season). We find significant increases in greenness in both seasons due to the pump-based irrigation. The increase in NDVI before the rainy season is relatively small, suggesting that the growing season may be extended via irrigation, although not dramatically so.

Gains in NDVI during the rainy season are much larger, begin as soon as the following year after the irrigation is complete, and appear stable between 1 and 15 years postirrigation. Figure 3 presents these results in an event-study graph, indicating the stability of NDVI leading up to the onset of irrigation being installed, followed by the subsequent jump once an irrigation system is completed. We also find no evidence of differential pretrends in NDVI that correlate with the timing of irrigation, again validating the counterfactual changes we estimate. The increase in NDVI is 32% above counterfactual levels; a proportional increase in rice yields would be equivalent to approximately half a ton per hectare (mean regional rainfed rice yields are ∼1.6 t/ha (29)). Consistent with these statistical results, both farmers participating in the irrigation schemes and project staff reported in FGDs that much larger rice yields were attained following the introduction of irrigation. Taken together, these findings provide compelling evidence that the pump-based irrigation drawn from the Niger River and its tributaries led to sustained improvements in water availability and agricultural production.

Our approach considers the changes in overall production following the introduction of irrigation, including changes due to other inputs or practices used by farmers on these plots once irrigation became available. We consider these complementary changes to be important pathways for the overall impacts of irrigation on production (future cost-benefit analyses that focus on the productivity of irrigation water specifically would need to net these changes out). At the same time, KfW project records indicate that the vast majority of fields were already farmed prior to irrigation using rainfed or less effective river-based irrigation approaches. Thus, the irrigation impacts we find are not likely due to the conversion of unfarmed land to irrigated farming.

We also use VHR imagery to assess land use changes and identify increases in crop diversity following the implementation of irrigation. We confirm that project sites reflected landscapes initially classified as grassland, bare earth, or shrubs that were differentially converted into farmland after the irrigation interventions and then cultivated extensively over time. Visual analysis also suggests increasing crop diversity after the irrigation interventions, with project clusters having six to eight different crop types, including orchards in the vicinity.

Unlike these gains from pump-based irrigation, we observe no significant gains from the valorization of floodplains in northern Mali using the same remotely sensed agricultural outcomes. In

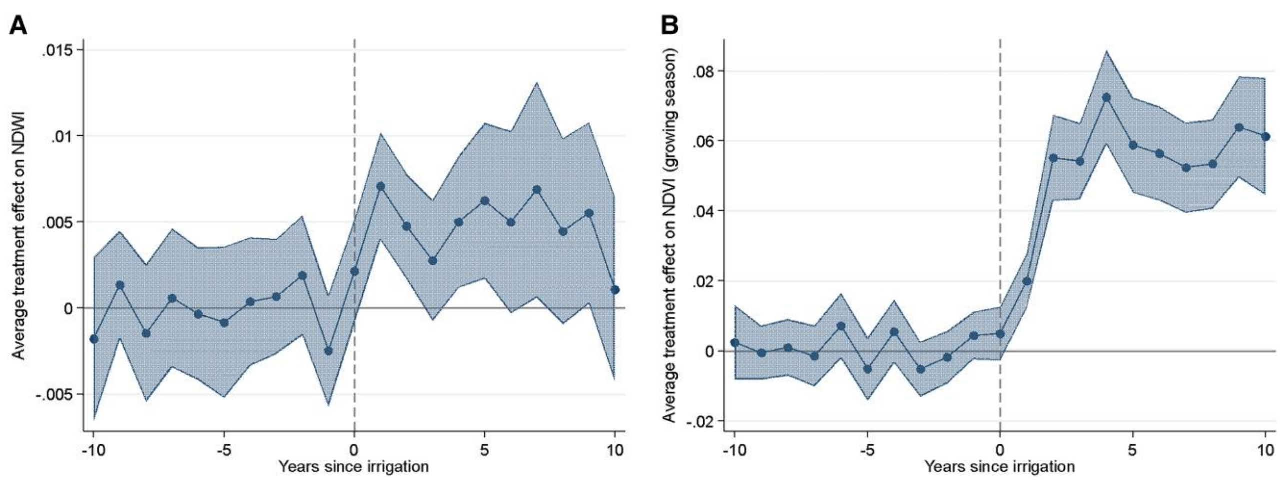

Fig. 3. Event-study analyses show increases in mean growing season NDWI (A) and NDVI (B) beginning shortly after the irrigation and continuing thereafter. Sample of 16,410 observations, reflecting annual measurements of 30 m × 30 m grid cells within 942 irrigation perimeters. Dots indicate point estimates of regression coefficients using de Chaisemartin and D'Haultfoeuille (18) estimation, with grid cell and year fixed effects; shaded region indicates 95% CIs.

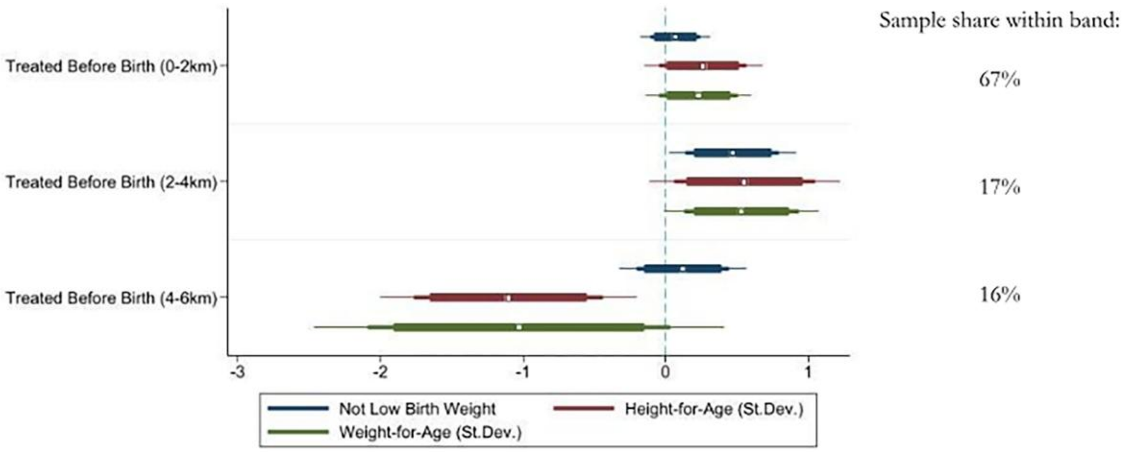

Fig. 4. Improvements in nutrition among the many children living closest to irrigation sites, partly offset by worsening nutrition among those living farther away. Sample of 1,603 children living in cluster locations within 6 km of 942 irrigation perimeters. White dots indicate point estimates of multiway fixed effects regression model, with distance band, region, and birth cohort fixed effects; shaded regions indicate 95, 99, and 99.9% CIs. Percentages on the right indicate the proportion of the total sample size which is in each distance band. We include all clusters located within 10 km of any of the irrigated perimeters; in practice, there were no clusters located between 6 and 10 km away from any of the perimeters, as communities in this area are often reliant on river-based water access and thus located relatively close to the Niger and its tributaries. We collapse distance buffers into 2 km bands to ensure adequate sample sizes within each band.

general, these results are much more muted than those for pump-based irrigation and are rarely statistically distinguishable from zero.

Many children in nearby communities see substantial improvements in nutrition as a result of the pump-based irrigation installation (Fig. 4). For those children living closest to the irrigation (<4 km), child height-for-age is significantly improved by the introduction of irrigation. These effects are most pronounced among children born after the irrigation was completed, although even children who were already 1–4 years old when the irrigation was installed appear to have benefitted substantially. We find similar improvements in child weight-for-age in communities near active irrigation sites, indicating concomitant reductions in wasting. The frequency of children with low weight at birth (as reported by mothers during surveys) also appears to have been reduced by the irrigation improvements. The incidence rates of anemia, diarrhea, fever or cough, and all-cause child mortality appear not to have been significantly affected by the irrigation, although several of these are potentially limited by recall error during surveys.

At the same time, there appears to have been a decline in child nutrition among the outlying communities located farther from the newly constructed irrigation (constituting 16% of children in our sample). The treatment effect on height-for-age for those living 4–6 km from irrigation sites is consistently negative across all measures and for young children born before the irrigation's completion and in the several years thereafter. The same pattern holds for child wasting: worsening weight-for-age after the introduction of irrigation 4–6 km away. These declines could be due to shifts in labor and other resources toward the newly irrigated sites, leading to lower production in outlying areas. This interpretation was also echoed in FGDs with farmers participating in the irrigation scheme, as well as project staff. They regarded the movement of healthier individuals toward project sites in search of better economic prospects as a plausible side effect of the interventions. There is some evidence of increases in agricultural employment among men living in closer communities (2–4 km away from newly irrigated sites), partially offset by reductions in agricultural employment among men in communities 4–6 km away (although the survey samples used to detect these changes are relatively small). We do not observe differential changes in other household characteristics coinciding with the irrigation introduction in these outlying areas, indicating that the worse stunting and wasting rates are not likely due to shifts in population compositions.

Concentrating production on newly irrigated sites also appears to shift the occurrence of conflict events (Fig. 5). The likelihood of conflict events happening immediately around the perimeter (<1 km) declines substantially after the irrigation begins (by 10 percentage points). These events decline slightly postirrigation in the 1–5 km distance band, but actually increase in frequency at greater distances (5–10 km) following the completion of the new pump-based irrigation. Interviews with beneficiaries suggest that the rebels spare project sites as they ameliorate the living conditions for the population by whom they are supported or tolerated. The shift of violence to surrounding areas might be due to a strategic relocation of rebel activity or increasing frustration among the population that does not benefit from the nearby interventions.

Examining ecological impacts due the pump-based irrigation, visual interpretation of VHR satellite imagery showed a small extent of soil erosion at >60% of project clusters in the form of rill, gully, and stream channels, likely due to the presence of high subsurface water and the proximity to the Niger River. The erosion of a gully for example can be an indicator both of proximate erosion around the pumping and water channeling infrastructures and of broader soil erosion along the nearby river banks. Further, over 85% of the project site clusters showed signs of algal blooms at the edges of the Niger River (Fig. 6). Whether these gully erosions are due to excess irrigation or the flow of rainwater in the River is not clear through the VHR imagery analysis. A majority of gully and stream channel erosion around these projects is also due to the flow of water from the Niger River.

The visual analysis of VHR imagery suggests increased soil moisture at and around ~90% of the project clusters during the farming season (May to October) that, in some cases, continued to March of the next year. Before the irrigation interventions, many of these clusters were grassland and showed the presence of moisture only during the overflow of the Niger River, and high water in the

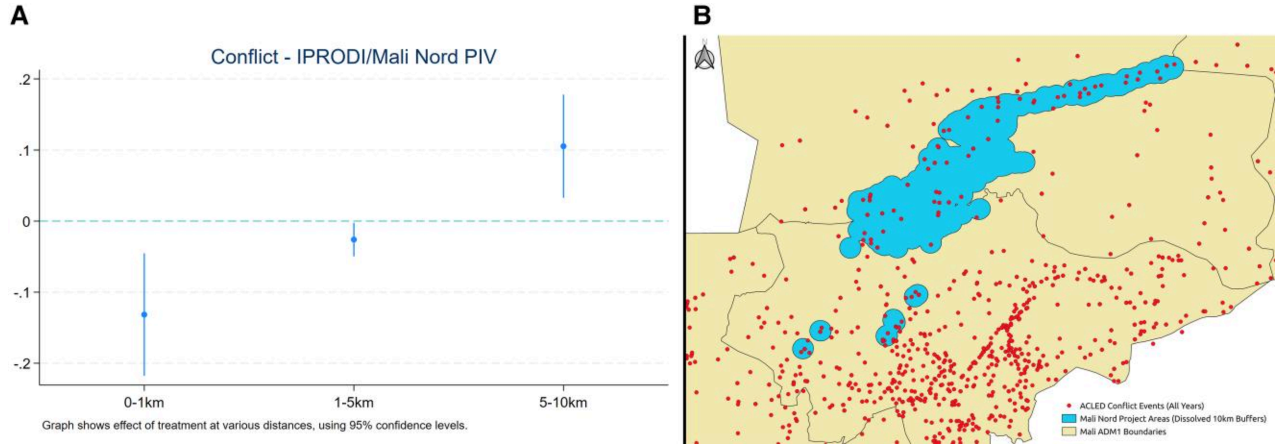

Fig. 5. A) Conflict reductions due to irrigation for locations closest to irrigation sites, offset by increases farther away and B) conflict events in Northern Mali 1997–2020. Sample of 70,650 observations, reflecting annual measurements of three distance bands around each of 942 irrigation perimeters. Dots indicate point estimates from multiway fixed effects regression model, with distance band and district-by-year fixed effects; vertical lines indicate 95% CIs.

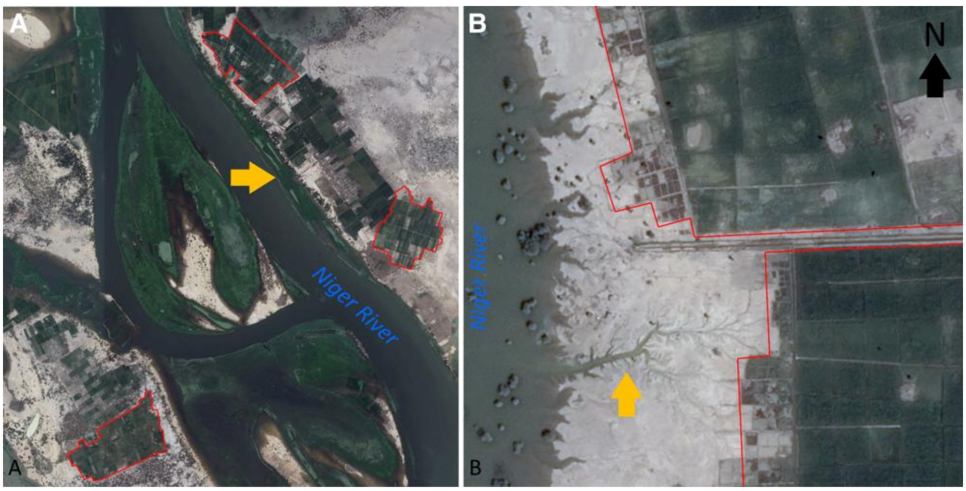

Fig. 6. A) Presence of algal bloom at the Niger riverbank (indicated by arrow) suggests leaching of nutrients and organic contents from farmland due to soil erosion and B) gully erosion (indicated by yellow arrow) formed by high flow of water from irrigation.

stream channels due to the flow of water from the River. Soil moisture on a subset of project clusters has increased throughout the year after the irrigation interventions, but this was not the case for a majority of clusters, including many for which the shallow riverbanks of the Niger River and normal rainy seasons contribute to ongoing nearby moisture. Our complementary statistical analyses indicate no meaningful changes in water or vegetation indices along the river banks that coincide with the onset of irrigation. Similarly, we find no impacts on either of these indices along 50- and 100-m buffers immediately outside the irrigated perimeters.

At the same time, we do not observe broader changes in infrastructure development accompanying the irrigation interventions. Visual interpretation of VHR images of project clusters did not show the relocation or development of infrastructure other than related to irrigation interventions, such as dirt roads and a few minor canals.

Taken together, we observe some limited ecological impacts around perimeters that appear to be in line with those expected for irrigation systems at this scale.

Discussion

Our results are in line with the few extant studies of small-scale irrigation efforts in conflict-affected settings: we observe NDVI increases during the growing season of 32% relative to counterfactual levels, similar to those found in Afghanistan (4). The gains we observe from small-scale irrigation are also comparable to those found for large-scale dam-based irrigation elsewhere in Africa and India (10, 26). Finally, our estimates on nutritional benefits from small-scale irrigation comport with previous findings on the improvements in nutritional intake and diversity from solar-powered drip irrigation and market gardens in Benin (30–32) and other small-scale irrigation in Mali (33).

At the same time, the introduction of irrigation also shifts the geographic distribution of farm production and thereby creates net gains for some communities and losses for others, here observable in terms of nutritional, employment, and conflict outcomes. This is not unique to the particular setting we study, as large dam-based irrigation impacts also vary extensively (10, 26). Addressing these distributional concerns should continue to be a priority for policymakers considering irrigation investments as a means to fortify community resilience to climate conditions and adhering to the sustainable development goal principle of do no harm.

Finally, while we were able to examine many of the most likely types of ecological impacts due to the newly installed irrigation, future research should further investigate additional potential impacts that may occur in other contexts. In some settings, irrigation can induce other forms of pernicious soil damage like iron toxicity, waterlogging, accumulation of organic acids from crop residues, decreases in pH, and toxicity at shallow depths in the root zone. Combining HR remote sensing with in situ measures of such phenomena could provide important evidence at sufficient scales to estimate these potential impacts of small-scale irrigation investments.

Materials and methods

Sample of irrigation sites

We designed our sample around the sequential set of irrigation activities supported by the government of Germany and its partners in northern Mali from 1999 to 2020. In total, there are 942 project sites in Mali's northern Inner Delta. Seven hundred and ninety-two of these projects are classified as pump-based irrigation, and 150 are flooded areas ("mares"). We obtained data on georeferenced perimeters for each of these sites which were collected during implementation and construction of the irrigation, as well as the year of irrigation completion for each site.

Impacts on remotely sensed agricultural production

To estimate the effect of project completion on agricultural production, we use a panel dataset at the polygon-year unit of analysis consisting of measures of water availability (NDWI) and agricultural production (NDVI) from 1986 to 2021 obtained via GEE using Landsat imagery. We use the staggered variation in the timing of irrigation completion to draw comparisons between those observations in which the polygon is already irrigated (treatment) and those that are not yet irrigated (control). We use a difference-in-difference methodology estimated via TWFE that adjusts for the unobserved factors specific to each polygon and common shocks happening in each region and year.

Impacts on child nutrition and health

The effects on child nutrition and health utilized data collected from five Demographic and Health Survey rounds in Mali between 1995 and 2018. Child nutrition metrics are derived from anthropometric measures of child stunting, wasting, and body mass. We also utilize reported measures of low birth weight, childhood illness, and child mortality. DHS households were selected based on cluster locations that were within 6 km of project sites and grouped into three distance bands from the nearest project site: 0–2, 2–4, and 4–6 km.

As the DHS survey is cross-sectional, each individual is observed only once. Some individuals are observed before the nearest project to them is completed (controls) and some are observed after the nearest project is completed (treatments). We implement a TWFE strategy—incorporating region, time, and distance-band fixed effects—to calculate the treatment effects on each outcome measure at each of the three distance bands.

Impacts on conflict incidence

To assess conflict around the irrigation project sites, we utilize data from the ACLED dataset which contains nearly 5,000 events between 1997 and 2022. Event data were refined into six groups of actors which include state actors, external actors, jihadist groups, militias, other named organizations, and all others. We utilize a panel dataset of all irrigated perimeter locations which includes irrigation completion as well as ACLED conflict counts within three distance bands surrounding project locations: 0–1, 1–5, and 5–10 km.

The unit of observation within this dataset is at the irrigated perimeter-by-year-by-distance band, and each perimeter is observed every year, both before (controls) and after the onset of irrigation (treatments). We implement a TWFE strategy to calculate the treatment effect on conflict in each of the three distance bands, and estimate the treatment effect on conflict in two ways. First, we estimate the effect on all conflict events reported in ACLED. Second, we estimate the effect on conflict events that do not involve state actors.

Ecological impacts

Thirty-three perimeters first irrigated between 2015 and 2018 across eight clusters were selected for the assessment of ecological impacts using VHR (<1 m) and HR (3 m) satellite imagery. At least one scene of VHR imagery was available before, during, and after implementation for each perimeter, while HR imagery was more frequently available for exploring seasonality. Each of the selected clusters contains three or more irrigation project sites and provides an opportunity for visual analysis of a combination of soil erosion, soil moisture, land conversion to development, and crop diversity. We utilized elements of visual interpretation (e.g. tone, shape, pattern, association, etc.) to identify impacts within each selected project site cluster. We complemented this visual interpretation of VHR imagery with statistical analysis of water and vegetation indices derived from medium-resolution imagery for this sample of 33 perimeters. We calculated NDWI and NDVI along the nearest river banks for these perimeters, as well as for 50- and 100-m buffers immediately beyond the perimeters. We implemented TWFE models to assess whether the onset of irrigation in these perimeters led to nearby changes in soil moisture and vegetation.

Notes

[a] The project interventions we study aimed to be "conflict-sensible" by minimizing the risk of conflict (particularly land conflict). This was supposed to take place via a program advisory board (Comité Consultatif), consisting of traditional representatives of the Tuareg, Songhrai, Fulbe, and other ethnic groups, which decides unanimously on the locations of new irrigation perimeters situated in northern Mali. Moreover, all groups of farmers that applied for an irrigation project in their village were required to facilitate a peace agreement of all stakeholders in the village, in order to avoid land conflicts (1). Other project components focused on increasing interactions and dialogue between different ethnic groups and/or conflict parties through activities in advisory boards or user committees.

[b] See Duflo and Pande (26) on how the effects of irrigation on rural poverty can be a paradox. The intervention may decrease water availability for other users, particularly downstream from project locations (and also for other sectors). In the supplementary analysis, we find no evidence of negative downstream "spillover" effects in this context.

[c] The projects guard against erosion by creating stone contour walls and planting trees and hedges (23).

Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

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Author Contributions

S.G., K.S., and M.W. prepared the geospatial data on program locations, satellite measures, and survey data. R.S. and M.W. prepared and analyzed the survey data. A.B. and K.S. analyzed the satellite-derived measures and imagery. S.T. interpreted the satellite-derived measures using contextual knowledge. M.R. and M.N. provided the knowledge of project implementation and analysis design. A.B., S.G., R.S., K.S., and S.T. prepared the manuscript.

Data Availability

The data on irrigation interventions is available from AidData upon reasonable request. Data on conflict events, NDVI, NDWI, and household survey data are publicly available from the cited sources. Commercial satellite imagery can be purchased from Planet using https://www.planet.com/contact-sales/.

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