Title

Local and distant impacts of water infrastructure on land use change in Africa.

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Abstract

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University of California, Berkeley

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The development of rural economies across the global south is often related to access to water and the development of water infrastructure. It has been argued that the drilling of wells and construction of new dams would unleash the agricultural potential of African nations that are exposed to seasonal water scarcity, strong interannual rainfall variability, and associated uncertainties in water availability. There are, however, some important environmental and social externalities that often remain overlooked, and whose impacts may be underestimated. The drilling of new wells has been reported to induce pastoralist communities to increase livestock density, often triggering overgrazing and land degradation, with important environmental impacts. For instance, overgrazing-induced loss of grass cover may allow for an increase in soil erosion and enhance the rate of dust emissions from denuded landscapes into the atmosphere with important impacts on local, regional, and global biogeochemical cycles. While this phenomenon is a known desertification pathway across subtropical Africa, its long-range impacts remain poorly understood. A region affected by overgrazing as a result the establishment of new boreholes and wells can be found in the Southern Kalahari (Southern Africa), where the loss in grass cover has been associated with the remobilization of linear dune systems. Here I use modeled pathways of air parcel trajectories starting from overgrazed regions of Southern Africa (as well as from other major dust sources in the Southern hemisphere) to investigate the potential impacts on the Southern Ocean. I found a positive relationship between ocean productivity and trajectory densities of dust emitted from Southern Africa.

Water infrastructure can also have a more local impact on land use and rural livelihoods. For instance, dam construction for agriculture or other uses, is often seen as a solution to the water scarcity problem in Africa, a continent affected by high levels of economic water scarcity and a strong untapped irrigation potential. While water security is often presented as the pathway to

poverty alleviation and invoked to justify large dam projects for irrigation, it is still unclear to what extent small holders will benefit from them. Are large dams built to the benefit of subsistence farmers or of large-scale commercial agriculture? Here I use remote sensing imagery in conjunction with advanced machine learning algorithms to map the irrigated areas (or 'command areas') that have appeared in the surroundings of 18 major dams built across the African continent between 2000 and 2015. I quantify the expansion of irrigation afforded by those dams, the associated changes in population density, forest cover, and farm size. I find that, while in the case of nine dams in the year 2000 there were no detectable farming patterns, in 2015 a substantial fraction of the command area (ranging between 8.5% and 96.7%) was taken by large-scale farms (i.e., parcels >200ha). Seven of the remaining 9 dams showed a significant increase in average farm size and number of farms between 2000 and 2015, with large-scale farming accounting for anywhere between 5.2% and 76.7% of the command area. Collectively, these results indicate that many recent dam projects in Africa are associated either with the establishment of large-scale farming or a transition from small-scale to mid-to-large scale agriculture. I analyze the value of water acquired by agribusiness investors by determining the value generated by irrigation through the enhancement of agricultural production in the command area of the same dams.

Contents

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Introduction

The construction of water infrastructure is often acclaimed as a possible pathway to the economic development of African rural economies (Hanjra et al., 2009) , while their socio-environmental externalities remain underestimated. The typical argument in favor of water infrastructure is that in semiarid agrarian systems both farmers and pastoralist communities depend on water for crops and livestock. Water is typically a major limiting factor for crops and livestock. Its intermittent and unreliable availability puts rural livelihoods at risk (Distefano and Kelly, 2017; Grey and Sadoff, 2007). The availability of affordable pumps has favored massive drilling of wells and boreholes, allowing farmers and ranchers to gain access to groundwater resources, a phenomenon that often led to aquifer depletion (e.g. Konikow, 2011).Likewise, the establishment of watering points by pastoralist communities, has allowed for an increase in stocking rates, often leading to overgrazing, loss in perennial grass cover, wind erosion, and dust emissions. Indeed, borehole drilling and the degradation of the surrounding land (or "piosphere") is a rather typical mechanism of desertification (Bhattachan et al., 2013) associated with the sedentarisation and concentration of grazing and trampling. A notable example is the case of the southern Kalahari, where the grazed area in the Kgalagadi district of southwest Botswana increased from 13 000 to 32 000 km^2 concurrently with an increase in the number of boreholes from eight to about 380 between 1950 and 1990s (Thomas and Twyman, 2004). The loss of perennial grasses in the overgrazed areas around these wells (Perkins and Thomas, 1993), likely contributed to dune mobilization (Thomas et al., 2005) and dust emissions (Bhattachan et al., 2013, 2012). The possible long-range impacts of land degradation remain poorly understood. It is often argued that dust emissions from degraded drylands could affect the biogeochemical cycles of downwind ecosystems via aeolian transport of mineral dust (e.g. Swap et al., 1992).In particular, the there is strong interest in the deposition of dust rich insoluble iron in the Southern Ocean because of the possible enhancement in ocean productivity that could result from such iron inputs. Indeed, iron is a limiting micronutrient in high-nutrient, low-chlorophyll waters of the Southern Ocean, and atmospheric dust from continental sources is one of the sources of bioavailable iron. Given the relatively few numbers of dust sources in the Southern Hemisphere, it is important to quantify the distribution of dust in the remote waters of the Southern Ocean and thus investigate ocean regions that likely depend on atmospheric dust for primary productivity (Ridgwell, 2002). In Chapter 1 I will investigate to what extent land degradation in this, and other regions of the southern hemisphere can contribute to iron fertilization in the Southern Ocean. Specifically, I will address the research question.

1. To what extent can dust from degraded areas of the Sothern Kalahari reach low-productivity areas in the Southern Ocean?
2. Can the existence of such low-productivity areas be explained by lack of mineral dust supply from terrestrial sources via aeolian transport?

To explore the geographic distribution of areas limited in the delivery of iron-rich atmospheric dust in the austral summer, I calculate forward trajectories from continental sources in the Southern Hemisphere between 2007 and 2015. A statistical comparison between trajectory patterns and maps of chlorophyll-a, an indicator of ocean productivity, shows a significant positive correlation in ocean areas between 45°S and 65°S, consistent with the dust deposition hypothesis.

Another major class of land use change associated with water infrastructure, results from the construction of irrigation dams, which typically induce more flooding of upstream areas, drying of the downstream channel, and the emergence of irrigated agriculture in adjacent and/or downstream regions. The construction of dams is a largely debated topic in sustainable development (WCD, 2000). Promoters argue that the development of water infrastructure and the availability of reservoirs to store water for irrigation and hydropower would favor the economic development of agrarian societies that strongly rely on farming as a major income source (Hanjra et al., 2009) and hydro-electric power for energy production . Opponents point to the destruction of ecosystems, loss of biodiversity and the inequitable distribution of the costs and benefits (WCD, 2000) of large dam projects. In Africa, numerous studies (e.g. Cole et al., 2014; Mulumba et al., 2012) point to the need for hydroelectric power development and associated dam construction to meet their clean energy mandates and the associated development goals. Other authors stress the negative impacts of dam construction on the environment and rural communities both in upstream locations that will be flooded by the reservoir, and in downstream areas that can lose access to vital water resources (Iimi, 2007; Pottinger, 2009). Indeed, dam construction is a mechanism of water appropriation by upstream actors and that may deprive downstream users often subsistence farmers, and pastoralist communities (Carr, 2017) It is commonly argued that dam construction for irrigation may be followed by land acquisitions by agribusiness corporations in areas abutting the reservoir or downstream from it because of their preferential access to water (Carr, 2017; Mehta et al., 2012), though conclusive evidence is often missing at the regional scale.

The current controversy about large-scale land acquisitions by foreign investors has raised questions regarding the world's future development and its impact especially in developing countries (Liversage, 2011).This controversy has opened important international discussions on how to improve land administration systems and investment in agriculture and infrastructure, so that the land rights and livelihoods of smallholder farmers, pastoralists and other vulnerable groups are protected (Pottinger, 2009). The need for water has been identified as an important driver of this global land rush (Dell'Angelo et al., 2018; Franco et al., 2013; Mehta et al., 2012; Rulli et al., 2013) resulting in the critically named phenomenon of "water grabbing", particularly for agricultural and hydro-electric power generation projects. Often related to the "land grabbing" syndrome - a phenomenon whereby multinational investment companies and countries lease prime land in developing countries for food and energy production (Rulli et al., 2013)- this process also implies injustice and power imbalance in the decision making of large scale water development projects. Water grabbing refers to when previous local water users – typically farmers – or ecosystems lose their water rights or are forced to share their limited water resources with powerful actors who take control and reallocate water allotments within a given area (Franco et al., 2013). The issue of "water grabbing" tends to be left out in discussions of large-scale land deals, although it can be a target and a driver of land acquisitions for agricultural uses (Mehta et al., 2012). In this dissertation, I develop an assessment of dam construction as a form of infrastructure development contributing to water grabbing.

Previous studies have investigated the impacts of dams on hydrological processes, ecosystems, and rural communities, relying on detailed field observations, case studies, and empirical data collection in specific locations with a scope ranging from the farm to the watershed scales. Here I focus on the recent construction of large irrigation dams across the entire African continent to identify some patterns and commonalities in the associated changes in land and water use using satellite data and hydrological analyses. Specifically, this dissertation addresses the following questions:

1. How do irrigation dams recently built in Africa (2000-2015) affect land use change in downstream areas? Do these new dams contribute to agricultural expansion, agricultural intensification (e.g., introduction of irrigation) or both? To what extent does new irrigated farmland emerge? Is it associated with deforestation and changes in population density? Who benefits from new irrigation dams? Smallholders or large-scale agribusinesses?

To address these research questions, I mapped the emergence of irrigated areas (also known as "command areas") in the zone adjacent to the dam, the change in forest cover and population density within the command area and shifts in farm size.

2. How does increase in production due to irrigation affect the value of production and effectiveness of the irrigation ventures?

After dam construction, access to irrigation water is expected to enhance the productivity of agricultural land within the command area, leading to an increase in revenues. I evaluated the increase in value generated by irrigation and used these estimates to determine the value of water to farmers cultivating the land within the command area, providing the first valuation of water appropriations by land investors.

3. How do riparian vegetation change in terms of buffer distance from the stream and distance away from the dam?

Dam construction is expected to affect the spatial extent and patterns of riparian vegetation in the reaches downstream from the dam. As these areas become drier, riparian vegetation cover is likely to shrink because of water stress. However, the opposite effect might also occur with the colonization of the riverbed by riparian vegetation because of the reduced exposure to flood disturbance. To evaluate these effects, I mapped changes in the extent and distribution of riparian forest vegetation downstream from the dam.

Table 1: Chapters in this dissertation

Chapter	Title
1	On the possible long-range impacts of dryland degradation from well over-drilling and overgrazing[1]
2	Are African irrigation dam projects for large scale agribusiness or small-scale farmers?
3	Value of water in the command areas of recent African dams.
4	Conclusions
	Appendix

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CHAPTER 1

On the possible long-range impacts of dryland degradation from well over-drilling and overgrazing

Reference: Tatlhego, M., Bhattachan, A., Okin, G. S., & D'Odorico, P. (2020). Mapping areas of the Southern Ocean where productivity likely depends on dust-delivered iron. Journal of Geophysical Research: Atmospheres, 125(3), e2019JD030926.

Introduction

Primary production in ocean ecosystems requires light and nutrients such as nitrogen and phosphorus to sustain the photosynthetic biochemical reactions. It also needs micronutrients such as soluble iron, understood to be a limiting factor for phytoplankton because of the critical role it plays in nitrogen fixation (Boyd et al., 2007; De Baar et al., 1995; Fung et al., 2000; Martin and Fitzwater, 1988; Okin et al., 2011). There is overwhelming evidence that in iron-deficient waters, phytoplankton bloom is constrained by nitrate reductase and the consequently limited production of chlorophyll-a (Martin et al., 1991; Martin and Gordon, 1988). This phenomenon has drawn the attention of many scientists who looked at the atmospheric and biogeochemical conditions conducive to soluble iron limitations in the ocean(e.g. Duce and Tindale, 1991; Fung et al., 2000; Martin and Fitzwater, 1988; Martin and Gordon, 1988; Okin et al., 2011), particularly in the Southern Ocean, which is known for having areas characterized by a very low productivity. Based on evidence from 12 iron addition experiments, Boyd et al. (2007) concluded that soluble iron supply limits production in one third of the world's oceans (in the Southern Hemisphere), by controlling phytoplankton blooms, which in turn affects other biogeochemical cycles (Jickells et al., 2005). The "iron hypothesis" (Martin et al., 1990) suggests that the relatively high atmospheric carbon dioxide concentrations during interglacial periods might be explained by the low deposition rates of iron-rich dust over parts of the world's oceans. In these instances, phytoplankton cannot synthesize the surplus of major nutrients that are present in the ocean water, thereby slowing down the vertical flow of carbon and oxygen known as the "biological pump"(Ridgwell, 2011). Because chlorophyll-a is a good proxy for ocean productivity, oceans that are high in nutrients but low in chlorophyll-a (HNLC)—like much of the Southern Ocean—are often low-productivity areas where photosynthesis is limited to the delivery of bioavailable iron transported by airborne dust or other mechanisms(Boyd et al., 2007; Duce and Tindale, 1991; Jickells et al., 2005; Mahowald et al., 2005). Some studies on iron sources to the Atlantic sector of the Southern Ocean suggest that upwelling of nutrient-rich water is the predominant source of bioavailable iron(Meskhidze et al., 2007), noting that aeolian dust requires acidic atmospheric conditions before it can become available for primary production, though, while airborne, desert dust undergoes chemical reactions that increase its soluble iron content(Bhattachan et al., 2016; Shi et al., 2012). Besides atmospheric dust, hydrothermal activity and sediment-derived iron may also be important sources of soluble iron in oceans (Tagliabue et al., 2010, 2009). In fact, Tagliabue et al. (2009) showed that riverine and coastal sediments have higher soluble iron content than their aeolian counterparts, which further dismissed the hypothesis that atmospheric dust is the most important source of soluble iron to the Southern Ocean. Sedimentary sources of iron typically undergo burial to enter the surface ocean production cycles later through upwelling and mixing (Sarmiento et al., 2004). Other mechanisms can involve the transport of iron-rich marine sediments by sea ice (Bhattachan et al., 2015). Most research on ocean productivity and dust deposition has historically concentrated on the Northern Hemisphere, where about 90% of the global dust sources are found (Ginoux et al., 2012; Goudie and Middleton, 2006). Dominant sources of global dust emissions are found along the so-called "dust belt" that includes arid regions of North Africa, the Arabian Peninsula, Central Asia, and North America (Goudie and Middleton, 2006; Prospero et al., 2002). Although satellite investigations (e.g. Prospero et al., 2002) have shown low dust activity in the Southern Hemisphere, vegetation loss resulting from the combination of climate change and land use could lead to increased dust activity in the region (Bhattachan et al., 2013, 2012; Bhattachan and D'odorico, 2014; Colazo and Buschiazzo, 2015; Gassó and Torres, 2019; Ginoux et al., 2012; McConnell et al., 2007; Thomas et al., 2005). Moderate Resolution Imaging Spectroradiometer (MODIS)-derived dust optical depth data show the existence of dust activity in the Etosha National Park of Namibia and the Makgadikgadi Pans of Botswana in Southern Africa (Ginoux et al., 2012). Other sources such as the Lake Eyre Basin in Australia, the Mar Chiquita of Argentina, and Patagonia are also important dust sources in the Southern Hemisphere (Ginoux et al., 2012; Goudie and Middleton, 2006; Prospero et al., 2002). Indeed, Australia and Patagonia are often recognized as major contributors to atmospheric dust that is then deposited in the Southern Ocean and Antarctica (Li et al., 2008). Recent efforts have mapped the pathways of airborne dust originating from known source regions in the Southern Hemisphere (e.g. Bhattachan et al., 2015, 2012; McGowan and Clark, 2008; Neff and Bertler, 2015; O'Loingsigh et al., 2017) but have not conclusively related dust transport to ocean productivity. In this study, we employ trajectory analyses to investigate regions of the Southern Ocean that are likely to remain limited in the supply of atmospheric dust. To achieve this goal, we utilize meteorological data and known natural and anthropogenic dust source points (Ginoux et al., 2012) to map the trajectory from each dust source. We then compare areas that are less likely to be in the dust trajectory footprint with low-ocean productivity areas reported by studies on phytoplankton productivity (Arrigo et al., 2008). We use this comparison to evaluate the extent to which the occurrence of low-productivity areas in the Southern Ocean can be explained by those that are removed from pathways of atmospheric dust transport originating from continental source regions during their main/principal dust-bearing seasons.

Methods

Dust Sources

The dust sources used in this study were selected from those identified by Ginoux et al. (2012), who provided a global map of major dust-emitting areas. Some of these major dust-emitting areas in Australia, Southern Africa, and South America are a focus of several regional studies (e.g. Bullard et al., 2008; Gassó and Torres, 2019; Vickery et al., 2013). In the Southern Hemisphere, dust emissions from Australia and South Africa dominantly occur between September and February, while in South America dust is emitted between December and

February (Ginoux et al., 2012). In this study, we calculate trajectories originating from each source in the course of the December-February season. Dust sources are classified as anthropogenic, hydrologic, and/or natural. The relative importance of these factors varies greatly for the three source regions considered here; for example, in some areas of Australia (anthropogenic) land use may contribute to more than 50% of the dust emissions (Ginoux et al., 2012), while in the other source regions its importance is generally smaller. Dust source points (geographical coordinates) were identified as the midpoints of 1° pixels that were completely active dust emitters (i.e., 100% of the surface was a dust source) on the dust source map taken from Ginoux et al. (2012). We used a selection criterion where only dust source areas covering a full 1° grid cell were chosen as potential initiation points (Table S1 in the supporting information), leading to a total of 54 sources (31 in Australia, 15 in Southern Africa, and 8 in South America).

Forward Trajectory Analyses

Forward trajectories from each potential dust source point were calculated using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess, 1998). The origin of each trajectory corresponds to the dust source points. Meteorological data utilized in this study were acquired from the National Oceanic Atmospheric Administration (NOAA) Atmospheric Resources Laboratory, from the Global Data Assimilation System (GDAS) one-degree archive (ftp://ftpprd.ncep.noaa.gov/pub/data/nccf/com/hysplit/prod/gdas/). Meteorological data used in this study span the period from December 2006 to December 2015. The model was initiated at 6 UTC for each source region, 500 m above ground level to calculate forward trajectories of 168 hr (7 days), every 6 hr per day throughout the dust season (December to February for South America, Southern Africa, and Australia) for every year between 2007 and 2015. The elevation used for the initialization is within the range of values used by other studies. McGowan and Clark (2008) ran the trajectory model for five different layers of the atmosphere and showed that highest concentration of the trajectories occurs in the air layer 1,000 m above the ground. Neff and Bertler (2015) initiated their trajectories at 100 m above ground to capture near-surface winds. Bhattachan et al. (2012) showed that the trajectories originating between 500 and 750 m from the Southern Kalahari did not yield significant difference between the spatial distribution of coordinates. Therefore, in this study the trajectories were initialized at 500 m. Likewise, the choice of the 7-day lifetime for airborne dust is justified by the values reported in the literature. A study across 15 general circulation models reported that the lifetime of dust ranges between 1.6 and 7.1 days (Huneeus et al., 2011); therefore, in this study we chose a maximum dust lifetime of 7 days, though other authors have used trajectory run lengths of 8 days (McGowan and Clark, 2008) or even 10 days (e.g. Neff and Bertler, 2015). Thus, we used a trajectory model to map the pathway that parcels of air would follow starting from each source area initiated every 6hr for 7 days. During atmospheric transport, the dust could be deposited via dry and wet deposition (Mahowald et al., 2005); however, the actual deposition processes are not explored in this study. Other studies have shown that the accuracy of HYSPLIT trajectories based on reanalysis data is robust and highly correlated with station measurements in the Southern Hemisphere (Neff and Bertler, 2015). HYSPLIT provides an opportunity to simulate the long-range transport of dust emitted by continental sources that are included in this study. In this study we do not establish a cause-effect relationship between dust emissions and chlorophyll-a concentration, but we simply create a probabilistic measure of how far the trajectories from major dust sources in the Southern Hemisphere can travel within the 7-day time frame and investigate the relationship existing between such a probabilistic measure of dust trajectories and ocean productivity.

The geographic locations of the pathway taken by each trajectory were then imported in the ArcGIS software (ESRI, Redlands, CA) and projected in World Geodetic System 1984 coordinate system to generate density plots of areas intersected by these dust trajectories. More specifically, for a 5° by 5° grid cell, the number of times a trajectory intersects that pixel was counted. To determine the probability that a pixel is located along the trajectory originating from a dust source, these counts were divided by the total duration, expressed as a multiple of 6-hr intervals (e.g., 4 intervals/day × number of days/years × 9 years). The results were presented as maps of probabilities of a 5° by 5° grid cell being intersected by trajectories in each run.

Chlorophyll Mapping

Monthly chlorophyll-a concentrations were obtained from maps developed for the December–February season (austral summer) by the Ocean Ecology Laboratory of the NASA Goddard Space Flight Center for the years 2007–2015 (OBPG, 2016). These maps are based on remotely sensed data from the MODIS instrument aboard the Terra satellite, analyzed at monthly time steps at 9 km resolution (OBPG, 2016). A map of austral summer biological productivity for the Southern Ocean was created for the average December–February chlorophyll-a concentrations between 2007 and 2015 resampled at a 5° by 5° grid spatial scale.

Data Analyses

We statistically compared correlations (Spearman's correlation, ρ) between mapped distributions of dust trajectory densities and chlorophyll-a concentrations. We also used a nonparametric t-test to evaluate the occurrence of significant differences in average chlorophyll-a concentrations in areas with relatively low and high trajectory densities. The above analyses were carried out for different latitudinal belts. We determined the latitudinal bands as regions with high nutrient concentrations, for example, the upwelling zone between 65°S and 60°S and a downwelling zone between 50°S and 45°S (Laufkötter and Gruber, 2018; Sarmiento et al., 2004) Moreover, to evaluate the effect of the proximity to the coast of Antarctica, in some analyses we excluded a coastal belt of 100- and 1,000-km width. Although the dust season for Australia and Southern African sources is between September and February (Ginoux et al., 2012), we only use trajectories from December to February for all sources to compare the ocean biological productivity with dust trajectory densities.

Results

Dust trajectories for South America, Southern Africa, and Australia generally show a pattern that follows westerly winds, with decreasing densities away from each dust source (Figures 1a, 1c, 1e). All trajectories have a preferential pathway that extends east and southward and fades out with distance from the source region, with Australian trajectories reaching West Antarctica. There are also trajectories that do not complete the full cycle of 168 hr (23% of trajectories from

31 sources in Australia, 18% of trajectories from 8 sources in Southern Africa, and 17% of trajectories from 15 sources in South America). Trajectories from South America (Figure 1a) and Southern Africa (Figure 1c) also have pathways that extend in the north-west direction. In general, areas with the lowest occurrence probability of trajectories (i.e., lowest trajectory density) were in geographic locations distant and removed from the source areas.

We investigated the relationship existing between HNLC regions of the Southern Ocean (Figure 2) and trajectory density (Figure 1g) and found that areas with the lowest trajectory densities (i.e., probability of occurrence, $Pt \leq 0.05$) appear in regions south of the 65°S latitude. In this region, however, the chlorophyll-a concentration is often an order of magnitude higher than in low-chlorophyll-a regions of the Southern Ocean (i.e., areas shown in green in Figure 2). As a result, the chlorophyll-a concentration was on average significantly higher in areas with the lowest trajectory densities (i.e., small probability, Pt, of being intersected by trajectories originating in potential dust source regions; $Pt \leq 0.05$) than in the rest of the ocean areas south of the 45°S latitude. Coastal regions of Antarctica from 180°W to 135°W depict an average chlorophyll-a concentration of 0.5 mg/m3 (Figure 2) in a region of trajectory probabilities (Pt) below 0.05 (Figure 1).

The highest trajectory densities ($Pt \approx 1$) are found near and over land areas, especially close to the dust sources (Figure 1), except Antarctica. In comparison, only about 3.0 × 107 km2 exhibit >50% probability of receiving dust trajectories (Figure 3).
We ran statistical comparisons of chlorophyll-a concentrations within areas with the lowest trajectory density ($Pt \leq 0.05$) and the rest of the ocean domain (i.e., $Pt > 0.05$), south of the 45°S latitude, between the 45°S latitude and the 65°S latitude, and in all ocean areas south of the 65°S latitude. We carried out a t-test (Table 1) to compute mean differences between chlorophyll-a concentrations in regions of $Pt \leq 0.05$ and $Pt > 0.05$. Statistically significant differences (at the 95% confidence levels) only exist between latitudes 45°S and 65°S, and south of 45°S excluding the 1,000-km-wide coastal region of Antarctica (Figure 1), which tends to exhibit higher chlorophyll-a concentrations (Figure 2).
We employed a Spearman's correlation coefficient to determine the degree of association between trajectory probabilities (Pt) and chlorophyll-a concentrations. A positively significant relationship is shown to exist when regions of the Southern Ocean south of 45°S (Spearman's ρ = 0.16; p-value = <0.01) are considered, while the relationship is not statistically significant when regions south of 65°S (Spearman's $\rho = -0.01$; p-value = 0.86) are considered. Subregions that exclude the coastal regions of Antarctica exhibit a positive relationship between the probability of trajectories and chlorophyll-a concentrations (Table 1). Our results exhibit a statistically significant, positive association between the two variables (i.e., Pt and chlorophyll-a) at specific distances from the Antarctic coast. In fact, we found Spearman's correlations of ρ = 0.33, 0.49, and 0.26, (p-value < 0.01) in subregions of the Southern Ocean south of 45°S but at 100 km from the Antarctic coast, south of 45°S but at 1,000 km from the Antarctic coast, and between 45°S and 65°S, respectively.

Discussion

The goal of this study was to map regions of the Southern Ocean that would remain devoid of possible air parcel trajectories using a 9-year meteorological data set (GDAS1, 2007–2015)

(Figure 1). Although our study does not quantify dust deposition, we assume that deposition of dust rich in bioavailable iron occurs along the transport pathway. Moreover, because we focus on select, major dust sources, we do not account for other potential vectors of airborne bioavailable iron such as volcanic ash (e.g. Crespi-Abril et al., 2018; Duggen et al., 2007; Panebianco et al., 2017) from large but usually infrequent volcanic eruptions and combustion aerosols (e.g., Ito, 2015) or for emissions from cultivated land (Tegen et al., 2004; Tegen and Fung, 1995).

Our results (Figure 1) confirm previous conclusions (Bhattachan et al., 2012; Li et al., 2008; Neff and Bertler, 2015) that trajectory distributions from major Southern Hemisphere dust sources follow a southeastward path. A northwesterly pathway of trajectories originating in Southern Africa and Australia is also observed in our results, consistent with the Neff and Bertler (2015) study. All the other factors being equal (e.g., dust emission rates), our results are consistent with the study by Neff and Bertler (2015), showing that these Southern Africa and Australia sources deliver more trajectories to the Southern Ocean because of their geographic proximity and the consequently shorter transport distances (Figure 1e). The southwest Atlantic (i.e., the region between 30°W and 50°W, and south of 65°S) and some areas of Antarctica (e.g., the region
between 85°W and 180°W, and south of 70°S), exhibit the lowest probabilities of dust trajectories (Figure 1g), while the chlorophyll-a concentration map (Figure 2) and results from Moore et al. (2002) show that these regions have relatively high chlorophyll-a concentrations (0.3–3 mg/m3 chlorophyll-a) with respect to the southern Atlantic, Pacific, and Indian Oceans (0.1–1 mg/m3 chlorophyll-a). This result suggests that in this region of the Southern Ocean close to Antarctica aeolian dust is not a major source of bioavailable iron and that the relatively high productivity of the Southern Ocean is attributable to other sources of bioavailable iron in Antarctica, such as upwelling and ocean mixing (Martin et al., 1991, 1990; Sarmiento et al., 2004; Sedwick et al., 2000), sediment source inputs (Martin et al., 1991, 1990; Tagliabue et al., 2009; Wadley et al., 2014), and melting of sea ice (Atkins and Dunbar, 2009; Martin et al., 1990; McGillicuddy Jr et al., 2015). Utilizing remotely sensed sea surface temperature and chlorophyll-a data, Meskhidze et al. (2007) showed relatively low deposition in regions with elevated chlorophyll-a content in the Atlantic Ocean sector of the Southern Ocean, thus suggesting upwelling of cooler iron-rich waters as the main source of bioavailable iron. Our findings suggest that the main pathway of bioavailable iron supply to areas of Southern Ocean close to the Antarctica's coast is not associated with the atmospheric deposition of dust from terrestrial sources, suggesting that sediment from Antarctica and/or upwelling patterns (Sarmiento et al., 2004) can be important bioavailable iron sources. Indeed, the transport of iron-rich sediments from the Dry Valleys of Antarctica could potentially explain the relatively high ocean productivity at these latitudes (i.e., south of 65°S; Figure 2) (e.g., Arrigo & van Dijken, 2004; Bhattachan et al., 2015; Chewings et al., 2014). Because the transport of bioavailable iron in coastal sediments from Antarctica and Southern Ocean upwelling are not controlled by aeolian processes, we would not expect to find an association between HNLC and areas with a low probability of being intersected by trajectories from active dust emission sources. This explanation is consistent with the results in Table 1, which do not show higher ocean productivity in areas with lower trajectory densities close to Antarctica (either within a 1,000-km distance from the Antarctica coast or south of 65°S). Conversely, when the same analysis is repeated on the ocean south of 45°S but excluding the ocean areas relatively close to

Antarctica, we find that low-productivity areas (i.e., low HNLC) are associated with low trajectory densities, consistent with the dust deposition hypothesis. This is found when only areas that are more than 1,000 km away from the coast of Antarctica are considered (Table 1). In this case, low-productivity areas exhibit low trajectory density (Table 1), and an overall significant and positive correlation exists between trajectory density and chlorophyll-a concentration (Table 1). Similar results are found in the latitudinal band between 45°S and 65°S, which also excludes the southern region close to Antarctica (Tables 1 and 2). This latitudinal band coincides with the high-nutrient region of the Southern Ocean comprised between the upwelling zone at 60– 65°S and the subduction zone north of 45–50°S (e.g. Laufkötter and Gruber, 2018; Sarmiento et al., 2004) the chlorophyll-a concentration is on average smaller in areas with a low probability ($Pt < 0.05$) of being intersected by a trajectory (mean = 0.14; standard deviation = 0.03), compared to the rest of the domain in this latitudinal belt (mean = 0.25; standard deviation = 0.21). The subregion farthest from the Antarctic coast (i.e., between 45°S and 65°S) shows a positive and significant relationship between trajectory density and chlorophyll-a concentrations (Spearman's $\rho = 0.26$; p-value = <0.01).

These results show that dust-delivered iron is not a major contributor to ocean primary productivity close to the Antarctic coast and dust emitted from major continental sources in the Southern Hemisphere are perhaps not contributing to the observed biological activity near the Antarctic coast. Thus, other sources of bioavailable iron to the Southern Ocean such as coastal sediments, continental flows, and upwelling off Antarctica could explain the higher ocean productivity in areas close to Antarctica (e.g., the ocean region south of 65°S, with an area of roughly 107 km2). Aeolian transport of iron-rich dust from dust source areas across Australia, Southern Africa, and South America appears to be predominant away from the coast of Antarctica (e.g., between 45°S and 65°S, a region of the Southern Ocean with an area of roughly 5 × 107 km2), as reflected by the positive correlation between chlorophyll-a and the trajectory density.

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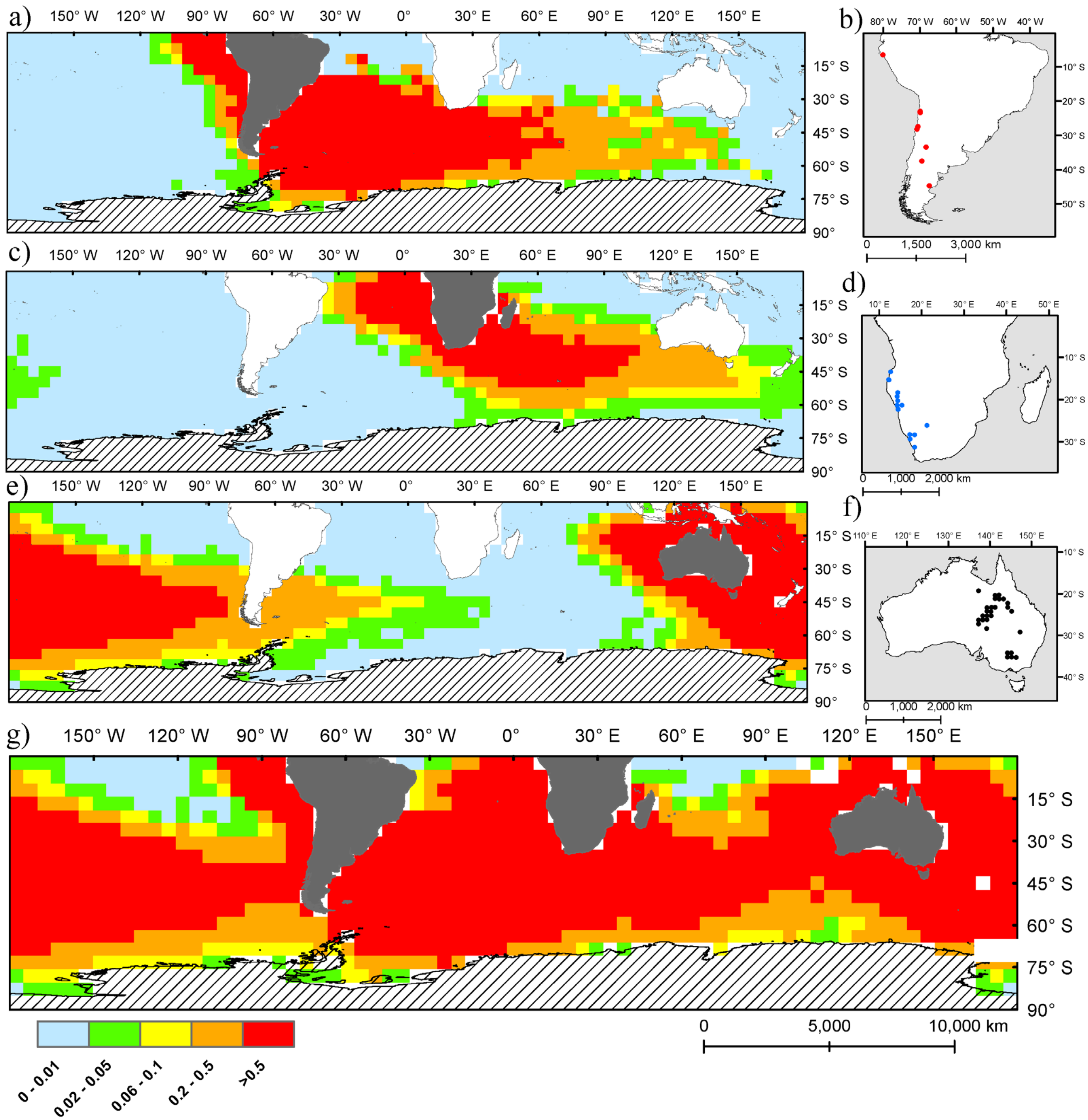
a)
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30° E
40° E
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1,000
2,000 km
e)
f)
110° E
120° E
130° E
140° E
150° E
g)
5,000
10,000 km
0 - 0.01
0.02 - 0.05
0.06 - 0.1
0.2 - 0.5
>0.5

Figure 1. Dust trajectories from (a, b) South America, (c, d) Southern Africa, (e, f) Australia, and (g) the combined Southern Hemispheric dust in probability density, P_t, of a 5° × 5° grid cell intersected by a trajectory originating from a dust source. For this figure, only trajectories that are south of the equator are shown.

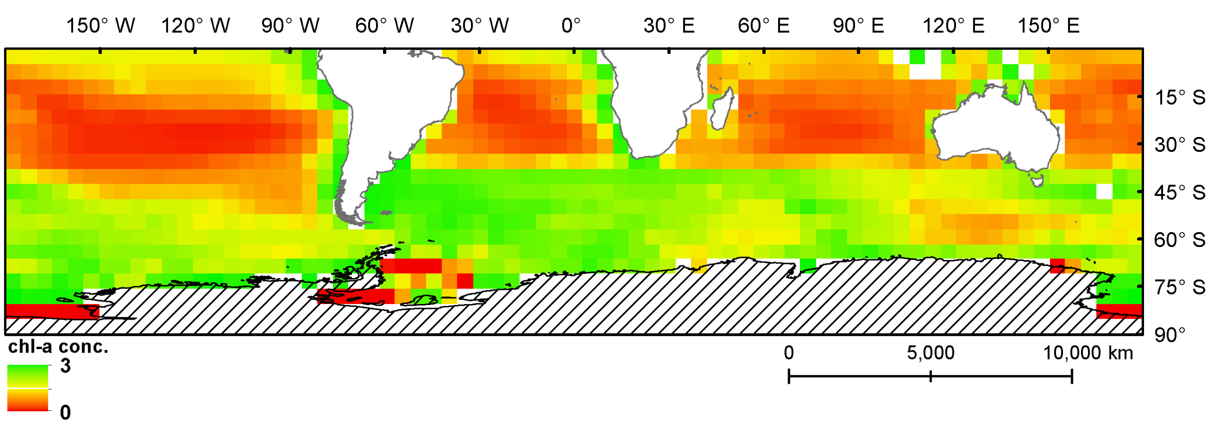

Figure 2. Average austral summer chlorophyll-a concentration (mg/m^3) derived from remotely sensed imagery from 2007 to 2015.

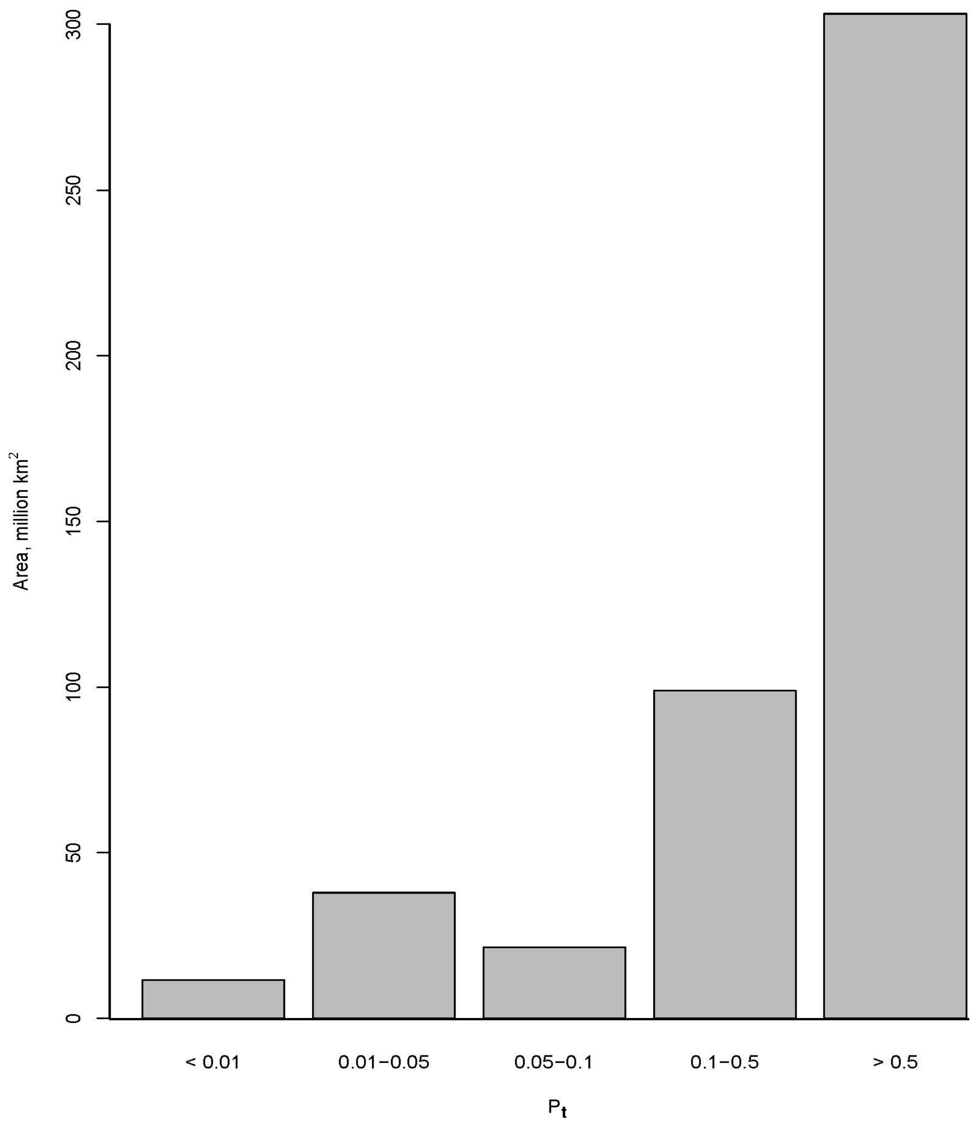

Figure 3. Areal coverage (million km^2) of the Southern Ocean (SO) with different trajectory densities (P_t).

Table 1Comparison Statistics (Mean ± Standard Deviation) of Chlorophyll-a Concentration (Figure 2) in Areas with the Lowest Trajectory Densities ($P_t \leq 0.05$) and the Rest of the Domain (i.e., $P_t > 0.05$). *Note*. Chlorophyll-a concentrations are expressed in mg/m^3. Mean comparisons are results of a paired *t*-test at the 95% con*fi*dence level.

Region	Lowest trajectory density ($P_t \leq 0.05$)	Rest of the Southern Ocean ($P_t > 0.05$)	*p*-value
South of 45°S	0.39 ± 0.65	0.30 ± 0.28	0.49
South of 65°S	0.40 ± 0.76	0.32 ± 0.48	0.66
From 45°S to 65°S	0.14 ± 0.03	0.25 ± 0.21	<0.01
South of 45°S and at more than 1,000 km	0.17 ± 0.06	0.27 ± 0.25	<0.01
from the Antarctic coast South of 45°S and at more than 100 km from	1.44 ± 1.84	0.25 ± 0.25	0.37

Table 2: *Spearman's Correlations (p)* Between Trajectory Densities (P_t) and Chlorophyll-a Concentrations (mg/m^3) in Different Regions of the Southern Ocean *Note*. The test was based on a null hypothesis that correlation between trajectory densities (P_t) and chlorophyll-a concentrations is equal to 0.

Region	ρ	*p*-value
South of 45S	0.16	<0.01
South of 65S	-0.01	0.86
From 45°S to 65°S	0.26	<0.01
South of 45°S and at more than 1,000 km from the Antarctic coast	0.49	<0.01
South of 45°S and at more than 100 km from the Antarctic coast	0.33	<0.01

CHAPTER 2

Are African irrigation dam projects for large scale agribusiness or small-scale farmers?

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Introduction

Water availability is often viewed as a major factor constraining global food production and other economic activities under climate change and population growth (Deines et al., 2019; D'Odorico et al., 2018; Villani et al., 2018). Indeed, water security is crucial to poverty alleviation and economic development, particularly in marginalized rural communities that rely on agriculture (e.g. Doss *et al* 2014). Research from the last decade has emphasized how a sustainable development of agriculture should prevent further cropland expansion to avoid habitat destruction and associated biodiversity losses (Foley et al., 2011; Godfray et al., 2010). In other words, an environmentally sustainable increase in crop production should not expand the global farmland footprint but rely on the intensification of agriculture, which often requires bringing irrigation to those cultivated areas that are presently rainfed (Jägermeyr *et al* 2017, Rosa *et al* 2018). While irrigated agriculture is essential to sustaining growing trends in food production (Abdullah, 2006; Deines et al., 2019; Rosa et al., 2018) it often relies on limited water resources and claims the largest share of human water consumption worldwide (e.g. Nino *et al* 2016, D'Odorico *et al* 2018). To improve the use of limited freshwater resources available for irrigation, humankind has often relied on water storages, including groundwater stocks and surface water bodies, ranging from small farm-scale ponds to major reservoirs upstream from large dams (Van Der Zaag and Gupta, 2008). These storages retain water during the rainy or snowmelt seasons and allow for irrigation to enhance yields during the growing period. The need for reservoirs in irrigated agriculture is particularly strong in regions with semiarid or seasonally dry climates, particularly if the rainy season is not in sync with the growing season (e.g., "Mediterranean" climates) or if in the presence of adequate irrigation the temperature regime allows for double cropping by providing water to grow crops during the dry season (Ray and Foley, 2013). There is evidence that in many regions of the world - including Africa - the expansion of irrigation will require new seasonal water storages, a need that is expected to increase under climate change (Rosa et al., 2020). While aquifers offer a natural water storage for groundwater, runoff is most typically captured and retained in surface reservoirs upstream from dams and barrages.

It has often been argued that investments in major dam projects could trigger economic development and unleash the agricultural potential of regions where socioeconomic growth depends on crop production (Frenken, 2005; You et al., 2011). The case of the African continent is particularly emblematic because irrigation could be sustainably expanded to vast tracts of rainfed land across the continent, thus increasing crop production by 100% without causing groundwater depletion or loss of environmental flows (Rosa et al., 2018). Indeed, Africa has a great irrigation potential as only 6% of its cultivated land is irrigated, mostly in the north of the continent (You et al., 2011). As the African population increases, there a growing need for increased crop production through intensified agriculture, which often requires irrigation, in addition to other inputs

(Binswanger-Mkhize and Savastano, 2017). The development of irrigation, however, requires investments in equipment and infrastructure, including water storages, that small-scale farmers in the developing world may be unable to afford (Rulli and D'Odorico, 2013; Wichelns and Oster, 2006). Therefore, it has often been argued that foreign investors could step in and provide the resources needed to bring the technology to "modernize" agriculture in Africa and develop irrigation infrastructure, including dams (Chakrabarti and Da Silva, 2012; Schiffman, 2013; von Braun and Meinzen-Dick, 2009).

Interestingly, while large dam projects are often out of the reach of marginalized rural communities, economic development and poverty alleviation are typically invoked to justify such projects (Scudder, 2012; You et al., 2011) instead of exploring smaller scale alternatives such as in-farm storages and detention ponds, which have only recently been included in the rural development discourse (Blanc and Strobl, 2014; Burney et al., 2013; Strobl and Strobl, 2011; Van Der Zaag and Gupta, 2008; Wisser et al., 2010). Big dam projects have been at the center of heated debates about their socio-environmental costs and benefits, whether they are indeed a necessary and sufficient condition for the economic development in countries relying on agriculture, and who will benefit from these large reservoirs: Local communities or agribusinesses? Smallholders or large-scale commercial farming (Woodhouse, 2012)?

Recent years have seen an increasing number of large scale land acquisitions, a phenomenon also known as the "global land rush", whereby agribusinesses and large transnational corporations lease large tracts of prime agricultural land in developing countries to conduct commercial agriculture (Cotula *et al* 2009, Deininger *et al* 2011, Mehta *et al* 2012, Dell'Angelo *et al* 2018, Rulli *et al* 2013, Franco *et al* 2013). With water often at the center of these investments, this process has also been referred to as "water grabbing" when the development of irrigation in the land acquired by large scale land investors occurs at the expenses of water availability to local communities (Dell'Angelo et al., 2018; Mehta et al., 2012; Rulli and D'Odorico, 2013). Are large irrigation dams built to the benefit of local farmers or large-scale land investors and water "grabbers" (Bues, 2011; Carr, 2017; Woodhouse, 2012).

Critical social research as well as the environmental science literature point to major social, environmental, and economic impacts of large dam construction, including migrations and resettlements of local communities that depend on floodplain agriculture both upstream and downstream from dammed rivers (Eguavoen and Tesfai, 2012); transition from small-scale subsistence farming to large scale agribusinesses and associated losses of rural livelihoods (Carr, 2017; Collier, 2008; Eguavoen and Tesfai, 2012); disruption of hydrologic regimes, aquatic habitat, ecosystem function, and consequent biodiversity losses (Altieri, 2009; Siegmund-Schultze et al., 2018); and inequitable distribution of costs and benefits of large dam projects (Carr, 2017; Collier, 2008; Eguavoen and Tesfai, 2012; Schoneveld et al., 2010; WCD, 2000). Overall local communities remain often affected by the negative impacts on land access, economic activities, livelihoods, and human health (Kibret et al., 2016), including infant mortality (Mettetal, 2019). On the other hand, proponents of dam construction point to improved food productivity and availability (Ngom et al., 2016; Yildiz et al., 2016), the economic development of local communities through increased employment (Kidane et al., 2014) improved food quality and quantity (Collier, 2008), and the introduction of diversified farming systems in regions that were previously dependent on only pastoral or other forms of non-arable farming (Kidane et al., 2014). Therefore, an outstanding question in the growing debate on large dam projects for irrigation remains whether, after dam construction, local small-scale farmers actually use water from the upstream reservoir to irrigate their land and whether they are rather displaced by large-scale

commercial farming, likely as a result of the new nearby infrastructure that makes their land preferential target for large scale land acquisitions, as already reported in the case of other infrastructure such as roadways (Grandia, 2013).
These questions are difficult to address because of the lack of data and methods to investigate the socio-environmental impacts of dam construction. Access to records of land use, concessions, permits and licenses is often difficult, as well as documenting drivers of eviction, relocation or resettlement of local communities (D'Odorico and Rulli, 2014). Socioeconomic responses to dam construction likely depend on where the land is located because upstream and downstream cropped areas are expected to be impacted differently. In fact, while upstream areas seldom change in crop productivity (except for the areas that are flooded by the reservoir), the response of downstream regions depends on the proximity to the dam (Strobl and Strobl, 2011). Therefore, here we focus on active command areas, defined as the areas irrigated using water from the dam. Such areas are here determined as the newly irrigated areas appearing in the surroundings of the dam after its commissioning. Unlike global studies that have mapped irrigated areas at coarse scales (e.g. Siebert *et al* 2015, Thenkabail *et al* 2009, Nagaraj *et al* 2021) here we use Landsat imagery (30m) to map irrigated areas during crop growing periods at the local scale. We propose methods based on the application of machine learning algorithms as an alternative to hydrologic calculations proposed by Rufin et al. (2018) for those regions where detailed hydrologic data are not available.

We concentrated on a collection of georeferenced irrigation dams in Africa built in the years after 2000, when the recent land rush took place in Africa and other regions of the world (Rulli et al., 2013). We investigate the evolution of farm sizes and actual command areas and quantify the environmental and human impacts.

Study Areas

We focused on African dams built after year 2000, a period that has seen a rise in large scale land investments globally (Rulli et al. 2013). We used the georeferenced dam registry from the Food and Agriculture Organization (FAO). This selection (Table A1) was based on the year our study period ended, 2015, and on when the dam started to operate. We concentrated only on dams for irrigation use as denoted in the AQUASTAT dam list; dams denoted as planned or lacking an opening date were not included. Dams for hydropower generation or other non-agricultural and mixed uses were not included. These criteria led to a list of 18 dams in 7 countries in total (Figure 1, Table A1, supplementary materials). A point shapefile of these dams was created and exported to Google Earth Engine (GEE), a cloud-based platform that includes a rich library of remote-sensing and other geospatial datasets along with several sophisticated tools for geospatial and remote sensing data analysis in JavaScript API environment. Image processing methods is described in the following section and a roadmap is shown in Figure A1 in the Supplementary Materials.

Data and Methods

In addition to the data described in Section 2, MODIS Terra Land Surface Temperature collection (Wan, Zhengming et al., 2015) was used to investigate temperature changes in study areas over the 2000-2015 time period (Table A2 in Supplementary materials), and the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et al., 2015) used to infer mean precipitation based on daily data in all dams (Table A2). Interestingly, there were only minimal interannual temperature changes through the study period. Similarly, precipitation data were extracted, to evaluate whether changes in greenness (NDVI) in the command areas were contributed by changes in precipitation. A Mann-Whitney test of mean comparison was computed to compare the mean precipitation in the period leading to 2000 and to 2015 for mean in land surface temperatures and precipitation (Table A2).

Image Processing

GEE enables high-performance and quick remote sensing analyses (Gorelick et al., 2017). Using the newest, cloud free images from Landsat 8 Operational Land Imager (OLI), a rectangular area of interest that fully contained a watershed delineated using the dam as the outlet point, was drawn to include all the immediate irrigated areas, and all upstream inundated areas. On GEE, Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007) 30m elevation imagery was used for the delineation of the upstream watershed and the downstream floodplains. The rectangular delineation size was guided by the delineated watershed boundary.

Ground truth data was previously collected in two of the dams of interest in South Africa and Ethiopia (total of four) in 2015 the rest of the training points used were determined visually using very high-resolution imagery on Google Earth Pro. On Google Earth Pro, training data was acquired by setting the time slider to the year of interest and using land cover classes within the command area of interest previously identified, and later exported to ArcGIS as KML files. Further conversion of these into shapefile formats that can be used as training data was also done on ArcGIS 10.7. Training data was collected for both years (i.e., 2000 and 2015) to help differentiate land cover classes that did not exist in 2000, especially the existence of irrigation. Careful delineation of training data for year 2000 was done based on careful choice of clearly discernable features to not mislabel some classes

Careful delineation of training data for year 2000 was done based on careful choice of clearly discernable features to not mislabel some classes.

. However, even though this task was a carefully performed, in cases where no clear classification was possible because vegetation types were mixed, or changed among sparse shrubs, mixed tree-shrubs-grass plains, and sparse non-photosynthetic vegetation on bare ground, we labeled the class based on the one that looked dominant. This classification, however, did not affect our results, as the focus of this study is on irrigated croplands.

To understand the difference in spectral signatures of these irrigated areas and other land cover classes, we ran a spectral band chart for each feature- known cultivated areas showed higher NDVI and SWIR values, however irrigated areas showed even higher NDVI as compared to their rainfed counterparts. Irrigated areas are expected to have lower surface temperature than the adjacent non-irrigated areas because a greater fraction of the incoming solar irradiance is spent in evapotranspiration (i.e., it is turned into latent heat fluxes) (e.g. Droogers and Bastiaanssen 2002). Therefore, a correspondingly smaller fraction of the incoming solar energy is available to increase the sensible heat of the soil surface (Sacks et al., 2009). This was in accordance with past work designed to identify irrigated croplands (Wu and De Pauw, 2011).

Due to the multi temporal nature of the 30m Landsat data that covers our study period, Landsat 5 Thematic Mapper (TM) data were used for the year 2000, Landsat 8 data were used for the year

2015. Our criteria for image selection accounted for crop seasonality, based on FAO's crop calendars for each country (http://www.fao.org/agriculture/seed/cropcalendar/welcome.do). The occurrence and timing of multiple growing seasons was detected by looking at the temporal variability of crop vigor based on the NDVI signal. Specifically, we used all images available for each area of interest and assumed that multiple spikes in NDVI depicted multiple growth periods (Figure 2a(i)).

Imagery classification and command area mapping

Our classification goal was to identify land cover classes and, subsequently, land use in years 2000 and 2015 as two snapshots representative of land use conditions existing before and after dam construction, respectively. In a pilot study based on known irrigated areas in Bergrivier and Injaka dams (South Africa), and Tendaho and Amerti dams (Ethiopia), actual ground truth data was collected and spectral plots of bands of the different classes were computed to determine what bands were the most important in identifying these land cover classes. Further identification of training points was aided by visually identifying features on Google Earth Pro and locating them on actual Landsat imagery.

A random forest classifier was then employed to classify imagery in the years 2000 and 2015, for the period identified as the crop growing seasons only. Classifications were carried out on a case-by-case process due to the differing crop growth seasons in different regions. Random forest classifier was chosen because it showed better accuracy results as compared to the classification and regression trees (CART), on the GEE platform. Guided by our research questions and image resolution, 30m, we chose the following land cover classes; water, buildings, rainfed agriculture, irrigated agriculture, riparian vegetation, bare areas, woody vegetation, grass, and fallowed regions. Data was split 70/30 for training and validation. To avoid overfitting, mean absolute error was used with different maximum leaf nodes of 5, 50, 200, 500 and the best tree size was chosen as one with the least mean absolute error (200). This model was then saved and used on python to classify the rest of the imagery.

Command area determination was mostly based on irrigated land cover classes and their proximity to the dam and/or canals that extend from a dam, aided by visual examination of Google Earth Pro imagery. Likewise, the areas irrigated prior to the construction of the dam were determined using imagery from 2000 adopting the same methods as for 2015. In GEE, changes in land cover and land use in the command areas as well as in the flooded areas upstream from the dam were investigated. To that end forest cover in 2000, and forest loss per year between 2000 and 2015 where quantified using the Hansen Global Forest Cover dataset (Hansen et al., 2013). During initial data exploration, we plotted spectral bands for the different land cover classes identified (Figure A2(ii)), NIR and SWIR1 bands showed to be the most important in identifying cultivated areas, and although the SWIR1 signature did not vary much for irrigated and rainfed land cover classes, the random forest classifier proved to be able to identify this difference.

Similarly, human population in 2000 and 2015 was extracted from the Global Human Settlement Layers, Population Grid (GHSL) dataset (European Commission et al., 2015) for both the command areas and the upstream flooded areas.

Farm size determination

Using the resampled land cover classes for irrigated and rainfed farming, combined with NDVI thresholds for the two forms of farming in the two years, a canny edge detection algorithm (Ali and Clausi, 2001) was used to determine farm edges and, consequently farm sizes, using pre-determined median NDVI values, with a minimum NDVI threshold of ≥0.3 in 2000, to include both rainfed and irrigated farms, and ≥0.5 in 2015 to only assess farms influenced by irrigation. We ran post edge detection cleaning to remove areas with riparian vegetation stands in clear cases where they were delineated together with farm parcels (Figure A3). Using the 200ha cutoff for large scale farms (Land Matrix, 2017), we classified the land parcels in the command area as large- or small-scale farms. We also looked at the entire farm size distribution as shown in the results section. Assessing farm sizes based on 30 m Landsat pixels prevents features smaller than 30 m from showing in our analyses. In other words, our results can be impacted by the minimum mapping unit in the estimation of farm edges and consequently farm sizes. This means that, farms that are close together could be easily consolidated as one, and plots within a farm that are far from each other could be taken to be individual farms. Because of these limitation in the resolution of the farm size assessment, the results of our analysis are here used to evaluate a general trend in land parcel size change rather than an accurate high-resolution estimate of farm size.

Data Analyses

Proportions of command areas in 2000 and 2015 were computed to determine how much of the 2015 command area was irrigated in 2000, if any. Computation of hectarage of forest cover in 2000 and forest summed loss per year were computed in each dam command area, and in flooded areas upstream of the dam. We expressed these results in terms of percentages to communicate changes in 2000 and 2015 for irrigated areas and forest loss.

Mean farm size comparison between 2000 and 2015 using was computed for each dam the significance of mean size differences was tested using the Mann-Whitney test. We also investigated the presence of large-scale farms using 200 ha as the threshold for large scale farms (Land Matrix, 2017). Changes in the mean size of large-scale farms between the two years was determined only for command areas in which large-scale farms were existent in 2000.

Results

Our image classification results show high overall accuracies (>90%) in areas of low to no woody crops such as grapevines and orchards. Regions with fruit trees and grapevines show overall accuracies above 80%; the lower accuracy is due to difficulties in distinguishing irrigated tree plantations from green riparian areas (Table 5). We provide the shapefiles of the command areas and dam points shared here https://doi.org/10.6084/m9.figshare.14745456 (see Supplementary Materials).

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As expected, most cases included in this study exhibit an expansion of irrigation after the construction of the dam with the appearance of command areas that by far exceed in size the pre-existing irrigated areas (Table 1) as shown in Figure 2 for two illustrative cases. In 10 of these dams there was almost no irrigation before the construction of the dam (though these areas were often cultivated with rainfed farming), while in the other 9 cases less than 50% of the command areas was irrigated in the year 2000, mostly in the form of floodplain irrigation. Kissir and Brezina dams of algeria show no sign of irrigation implementation (Table 1). Overall, these results show how, as expected, dams lead to the emergence of new irrigated areas, known as "command areas" (Rufin et al., 2018). To evaluate the impact these new or expanded irrigation projects have on the environment and local communities, we look at changes in forest cover, population density, the number of farms and their size. Our results do not show any discernable dependence of increase in command area with factors such as dam height, expected dam capacities or any other dam physical properties, suggesting that other factors related to the implementation of irrigation matter more. Our analysis of precipitation shows no major changes between the period leading to 2000 and 2015 (Table A2) that could have confounded the mapping of the command areas by mixing the effects of irrigation on land surface attributes to those of precipitation.

Between 2000 and 2015 population density increased in all command areas except three (Injaka and Steelpoort, South Africa and Koga, Ethiopia) (Figure 4). Such a population increase can be the result of spillovers of large-scale land investments to local farmers through contract farming and employment opportunities associated with the adoption of intensive methods of farming (Kleemann and Thiele's, 2015). Alternatively, it could be an effect of the relocation of people from the areas upstream from the dam that are now flooded by the reservoir (Table 2) to downstream areas, possibly seeking employment opportunities in the new irrigated farms. Compared with the average population growth reported in these countries (all <2%, World Development Indicators, The World Bank), command areas are hotspots of population growth (>5%).

Changes in forest cover are modest (<1%) in all command areas. Moreover, some of these areas did not exhibit any forest cover and/or loss at all. While changes in tree cover are negligible, command areas exhibit important changes in land use. In addition to the expansion of irrigation (Figure 2(i & ii), Table 1), we observed a change in farm size, with evidence of an overall transition from small-scale subsistence farming to large scale commercial agriculture (Table 3). Results of the non-parametric Mann Whitney U-test comparison of mean farm size (μ_A) between year 2000 and 2015 show a statistically significant difference (except for Steelpoort (South Africa) with an increase in mean farm size during the study period. In the case of 9 dams there were no detectable farming patterns in 2000 and therefore we reported a zero average farm size. Overall, the number, *n*, of farms has dramatically increased after the construction of these dams, except for the case of Injaka, where it slightly decreased, because of a process of consolidation and merging of land parcels. The increase in mean farm size, number of farms (Table 3), and overall irrigated areas (Table 1) indicate that not only has farming expanded within the command areas (i.e., the total farmed area, $\mu_A \times n$, has increased) but also that many new farms have appeared and that they are of bigger in size (hence the increase in μ_A).Thus, mid- to large- scale farming is benefiting from new irrigation opportunities emerging in areas that were either only partly used for agriculture or not farmed at all prior to the construction of the dam.

Indeed, in the command areas of Talo, in Mali, Tendaho and Koga in Ethiopia, and Zitemba, Taksebt, Fontaine, El Agrem in Algeria, and Hassan in Morocco there was no recognizable sign or farming prior to dam construction but these areas exhibit the establishment of large-scale farms (i.e., farms greater than 200ha) until 2015. Altogether large-scale farms account for a substantial fraction of the command area (ranging between 8.5% and 96.7%), (Table 3). Command areas of

Egypt, Fontaine and Steelpoort do not show any emergence of large-scale farms at all. Of the command areas that were partly cultivated prior to dam construction (and where farms greater than 200 ha existed in 2000), four show an increase in the area occupied by large scale farms between 2000 and 2015 (Amerti, Injaka, Kessem, Merowe), three show a decrease (Bergrivier, Injaka, and Taskebt), while Steelpoort shows no sign of large farms either in 2000 or 2015. Interestingly, the number of these very large farms is only a small percentage (<0.25%) of the total number of farms, even though their total area is a substantial fraction of the command area, which suggests that these farms have very big areas (Table 3).

Because the threshold of 200 ha commonly used to characterize large scale farming (e.g., Land Matrix, 2020), is somewhat arbitrary, we also considered the entire distribution of farm size (Table 4). The case of Bergrivier is an exception to the general pattern of increase in the area occupied by large farms between 2000 and 2015 since it is shown to have been built upstream of previously irrigated areas. In fact, in this case there is an increase both in the small (<1ha) and mid-sized (10-50 ha) farms while the area of bigger farms (>50ha) dropped to zero between 2000 and 2015. In Injaka and Taskebt, the farm size distribution has not dramatically changed, though in Injaka there has been a slight increase both in small (<1 ha) and small to mid-sized farms (1-10ha) at the expenses of bigger farms. Of note is again the case of Steelpoort, where the area occupied by small farms has increased from 7.5% to 47.2% the total area of mid-sized farms (10-50 ha) has decreased from 79.8% to 34.7%, indicating that this dam project was realized to the benefit of smallholders. Interestingly, the farm sizes detected by our analysis are consistent with the values reported by the FAO (Lowder et al., 2016) family farming platform dataset.

Discussion and conclusions

The current controversy about large-scale land acquisitions by foreign investors has raised questions regarding the world's future development and the associated impacts especially on developing countries (de Schutter, 2011; Liversage, 2011; Robertson and Pinstrup-Andersen, 2010). This debate has opened important international discussions on how to improve land administration systems and investment in agriculture and infrastructure, so that the land rights and livelihoods of smallholder farmers, pastoralists and other vulnerable groups are protected (de Schutter, 2011). Liversage (2010) notes that, in our attempt to understand the impacts of foreign investment and development trajectories of poor communities, we should not divert our attention from the influence of local administration systems and the positive influence that foreign investment might have on an area of interest. As with large transnational land deals, the construction of dams has been viewed as the result of non-democratic decision making (Franco et al., 2013), resulting in what is critically known as 'water grabbing' (Dell'Angelo et al., 2018; Mehta et al., 2012; Rulli et al., 2013). This term refers to a condition in which local populations or ecosystems lose their rights (either formal or informal) to use water or are forced to share it with powerful, self-interested actors who take control of water resources in that specific area (Franco et al., 2013). Often forgotten in the debate on large-scale land deals, water can be a major target and driver of land investments (Mehta et al., 2012). Similarly, our results demonstrate how the construction of new dams for irrigation can favor large-scale farming in the areas that will benefit from the improved access to irrigation water, thereby contributing to a transition from small-scale subsistence farming to large-scale commercial agriculture. The construction of dams has often been a controversial approach to the sustainable development of agriculture (Scudder, 2012; WCD, 2000). Proponents of dams invoke the social and economic benefits provided by these infrastructures, including irrigation, hydro-electric power generation, water supply and other uses (Cole et al., 2014; Mulumba et al., 2012; Taliotis et al., 2014), while opponents remind us of how dams are responsible for the destruction of ecosystems and biodiversity and that the costs and benefits of dam projects are often inequitably distributed (WCD, 2000).

Our results show that irrigated areas increased by >55% in the command area of dams that showed signs of irrigation in 2000, while in the command areas that showed no irrigation in 2000 the irrigated area increased from 0 to a maximum of ~ 9000ha in 15 years (Table 2). We need to stress that this does not depict the actual rate of command area growth since the dams studied here were built in different years between 2000 and 2015, and their ages ranged between 3-14 years. It is of utmost importance to note that implementation of dam and irrigation projects does not follow a defined timeline which can be used to infer how much or when irrigation projects will be completed, therefore we find expansion of command areas to be variable in different dams.

Interestingly, we find that, while less than 2% of the farms are greater than 200ha, in many cases they claim a substantial fraction of the command area (Tables 4 and 5). Overall, large dam projects tend to favor the establishment of large to midsized farms, though some exceptions exist (e.g., Steelpoort, and – to some extent – Bergrivier). This outcome can also be explained by cases such as that of Talo dam, Mali, which was initially meant to allocate small scale and medium scale farms to rural communities (Meierotto, 2009), while our results show more than 96% of the irrigated area belongs to large scale farms (even though the number of large farms accounted for less than 1% of the total number of farms) (Table 4).

Overall, in most command areas the mean farm sizes in 2000 and 2015 were significantly different (Table 4) supporting the hypothesis of a transition to larger scale farming. According to the AQUSTAT dam lists (http://www.fao.org/aquastat/en/databases/dams) 53 dams have been planned for future construction in Africa for agriculture. The methods and analyses developed in this manuscript can be used to monitor changes in cultivation, farming practices (including irrigation) and land tenure in the areas downstream from those dams and investigate the possible impacts on local communities and rural livelihoods. Specifically, it will be important to evaluate the extent to which the construction of these water infrastructures will contribute to the expansion or the intensification of agriculture (or both), dispossession of local farmers, fishing and pastoralist communities.

Table 1. Command areas, forest cover and percentage loss, and population counts in 2000 and 2015. At the time of data acquisition, the new dam in Egypt was only identified by geographic location and no name, hence the reason we called it 'Egypt'.

Country	Dam	2015 Command area (ha)	Command area fraction irrigated in 2000 (%)	Command area 2000 tree cover (ha)	Total forest loss in command area 2000-2015 (ha)		Population count	
					(ha)	(%)	2000	2015
Ethiopia	Amerti	4878.6	24.01	14093.2	99.5	0.70	1069	1736
Algeria	Beni Haroun	20983.2	1.8	60.0	31.7	52.8	5439	5685
Algeria	Brezina	0	0	0	0	0	~	~

South Africa	Bergrivier	1737.3	100	27.9	12.4	44.4	2337	3608
South Africa	Ceres- K	10982.2	69.9	0	0	-	33269	52886
Egypt	Egypt	1176.7	0	0	0	-	-	-
Algeria	El Agrem	1158.7	0	58.5	35.05	59.9	2345	2492
Algeria	Fontaine	1514.8	0	13.3	35.1	0.26	5512	6862
Morocco	Hassan	1656.1	0	206.9	0.3	>100	4129	4889
South Africa	Injaka	5987.5	100	3271.0	2604.3	80	806	84
Ethiopia	Kessem	16823.9	41.6	159.0	67.3	42.3	361	2429
Algeria	Kissir	0	0	69.7	5.58	0.08	1735	3554
Ethiopia	Koga	7268.4	0	510.6	1.2	≈0	20923	9416
Sudan	Merowe	32810.5	90.1	0	0	-	0	0
South Africa	Steelpoort	138.6	69.9	0	0	-	32	26
Algeria	Taksebt	7365.4	49.2	6027.9	0.15	≈0	8682	9977
Mali	Talo	9337.9	0	2071.7	13.6	0.7	32	188
Ethiopia	Tendaho	4056.2	0	0.6	1.0	>100	6	189
Algeria	Zitemba	6798.0	0	3.9	0.65	16.7	29025	34024

Table 2: Characteristics of areas flooded by the reservoirs.

Country	**Dam**	**Forest loss in flooded area (ha)**	**Population in 2000**
Ethiopia	Amerti	3.18	333
Algeria	Beni-H	15.71	11951
South Africa	Bergrievier	205.74	0
Algeria	Brezina	0	0
South Africa	Ceres-K	0	0
Egypt	Egypt	0	0
Algeria	ElAgrem	23.89	268
Algeria	Fontaine	0	23
South Africa	Injaka	50.56	83
Ethiopia	Kessem	0.79	766
Algeria	Kissir	30.8	11
Ethiopia	Koga	1.85	0
Sudan	Merowe	0	0
Morocco	Hassan	0	0

South Africa	Steelpoort	2.42	18
Algeria	Taksebt	18.59	3154
Mali	Talo	0.19	65
Ethiopia	Tendaho	0.26	0
Algeria	Zitemba	9.38	11

Table 3. Average farm size (μ_A), number of farms, and extent of large farms (i.e., greater than 200ha) in the command areas in 2000 and 2015. The asterisk (*) denotes statistically different mean farm sizes between 2000 and 2015 (p-value<0.001), while "ns" refers to mean values that are not statistically significant.

Country	Dam	Mean Farm Area μ_A (ha)		Number of Farms, *n*		Fraction of land taken by farms > 200 ha (%)		Fraction of farms >200 ha (%)		Mean area of farms>200ha
		2000	2015	2000	2015	2000	2015	2000	2015	
Ethiopia	Amerti	0.7	3.0*	19560	36256	16.0	19.9	0.01	0.04	3145.8
Algeria	Beni	1.2	3.1*	3875	21509	0	5.2	0	0.02	2791.1
Algeria	Brezina	0.0	0.0	0	0	0	0.0	0.0	0.0	0.0
South Africa	Bergrivier	1.5	16.5*	2097	2433	47.0	0	0.2	0	2015.7
South Africa	Ceres	0	2.1*	0	6259	0	16.3	0	0.1	634.4
Egypt	Egypt	0	1.1*	0	416	0	0	0	0	0
Algeria	El Agrem	0	2.2*	0	1469	0	22.1	0	0.1	1135.7
Algeria	Fontaine	0	0.7*	0	2123	0	0	0	0	0
Algeria	Hassan	0	2.9*	0	580	0	0	0	0	0
South Africa	Injaka	3.0	4.7*	3963	3384	28.0	23.2	0.1	0.01	1083.6
Ethiopia	Kessem	2.6	2.7*	11133	14823	25.4	52.0	0.04	0.25	2208.5
Algeria	Kissir	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ethiopia	Koga	0	2.3	0	4995	0	33.1	0	0.1	1072.2

Sudan	Merowe	4.6	8.3*	6222	19524	68.0	76.7	0.32	0.2	2805.2
South Africa	Steelpoort	0.3	1.2 ns	82	474	0.0	0.0	0.0	0.0	0.0
Algeria	Taksebt	2.6	6.3*	4450	7477	17.6	7.1	0.04	0.3	3141.3
Mali	Talo	0	38.2	0	297	0	96.7	0	0.4	5526.7
Ethiopia	Tendaho	0	1.3	0	6369	0	8.5	0	0.02	1458.9
Algeria	Zitemba	0	2.5	0	5871	0	14.7	0	0.07	1133.1

Table 4. Farm size distribution in the command areas, expressed as % of the total command area in 2015, Brezina is left out of this list for not having discernable irrigated farms in both years.

%A→ Dam	<1 ha 2000	2015	1- 10 ha 2000	2015	10-50 ha 2000	2015	50- 100 ha 2000	2015	> 100 ha 2000	2015
Amerti	35.2	21.5	21.4	16.5	15.4	16.9	4.9	12.2	23.1	32.9
Beni Haroun		16.7		30.5		28.9		9.9		13.9
Bergrivier	6.6	24.2	11.2	52.9	13.5	22.9	7.3	0	61.4	0
Ceres		11.4		22.4		30.9		9.9		25.4
Egypt		17.3		54.7		27.9		0		0
El Agrem		18.2		23.6		23.8		12.3		22.1
Fontaine		23.3		34.8		26.3		7.8		7.8
Hassan		6.6		20.6		45.9		12.1		14.6
Injaka	7.9	8.9	13.3	18.7	27.3	27.6	8.5	6.1	43.0	38.7
Kessem	21.3	11.8	19.0	12.2	17.7	12.5	6.4	4.4	35.5	59.1
Kissir	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Koga	0	11.9	0	19.6	0	16.2	0	7.2	0	45.0
Merowe	3.9	5.2	6.9	6.7	10.3	4.7	4.8	2.1	74.1	81.3
Steelpoort	7.5	47.2	12.8	18.1	79.8	34.7	0.0	0.0	0.0	0.0
Taksebt	20.5	16.5	24.9	27.9	21.6	22.7	6.8	12.3	26.2	20.5
Talo		0.4		0.7		1.0		1.0		96.8
Tendaho		21.1		21.7		24.5		16.8		16.0
Zitemba		14.2		28.5		26.5		11.2		19.7

Table 5. **Summary of overall accuracies and numbers of training points per region/country per year. Note that South African points are reported separately for the Cape and North-East regions because they differ in climates and types of crops.**

Country	Year	Overall Accuracy (%)	Number of points	
			Total	Irrigated
Algeria	2000	89	10499	1051
	2015	86	14127	2131
Egypt	2000	94	500	0
	2015	98	7731	2460
Ethiopia	2000	98	6234	1917
	2015	94	11229	3413
Morocco	2000	92	500	0
	2015	91	10227	450
Mali	2000	98	400	0
	2015	96	4662	3201
South Africa (Cape)	2000	89	12312	4739
	2015	91	15283	2789
Sudan	2000	95	3014	500
	2015	98	4307	632
South Africa (NE)	2000	91	7347	1583
	2015	94	12453	3903

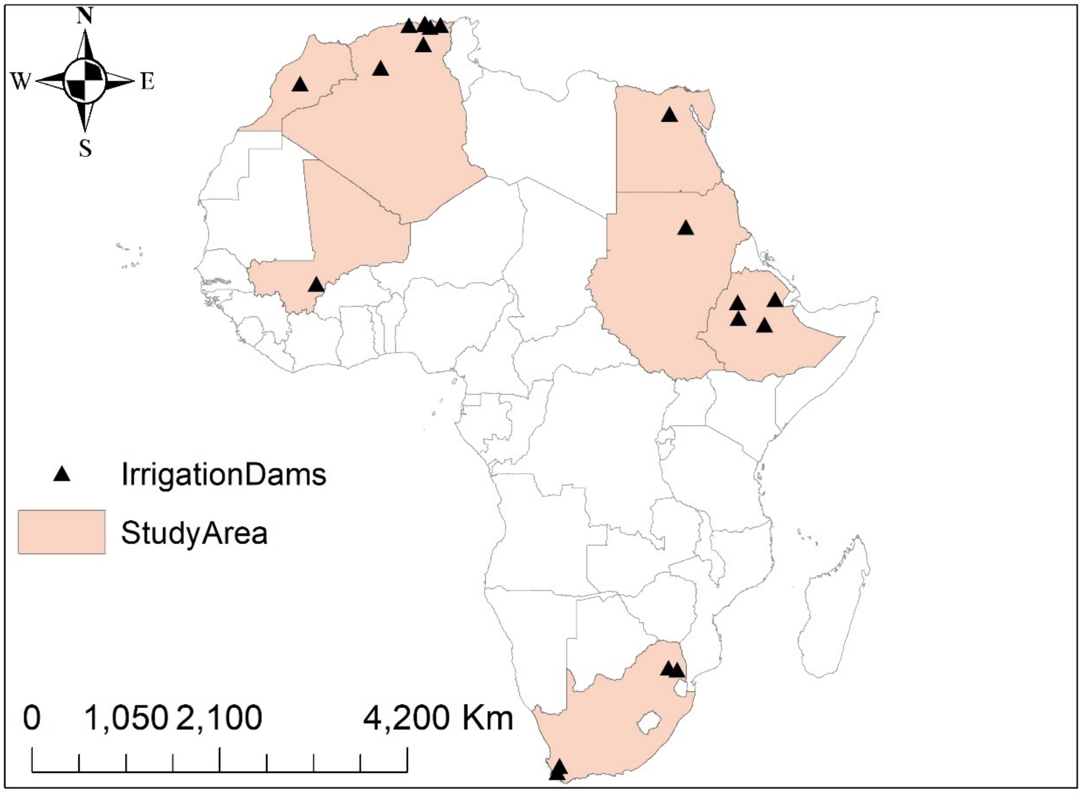

Figure 1. Map showing dams chosen or this study and the countries they are in. Dams were spread over multiple climate settings.

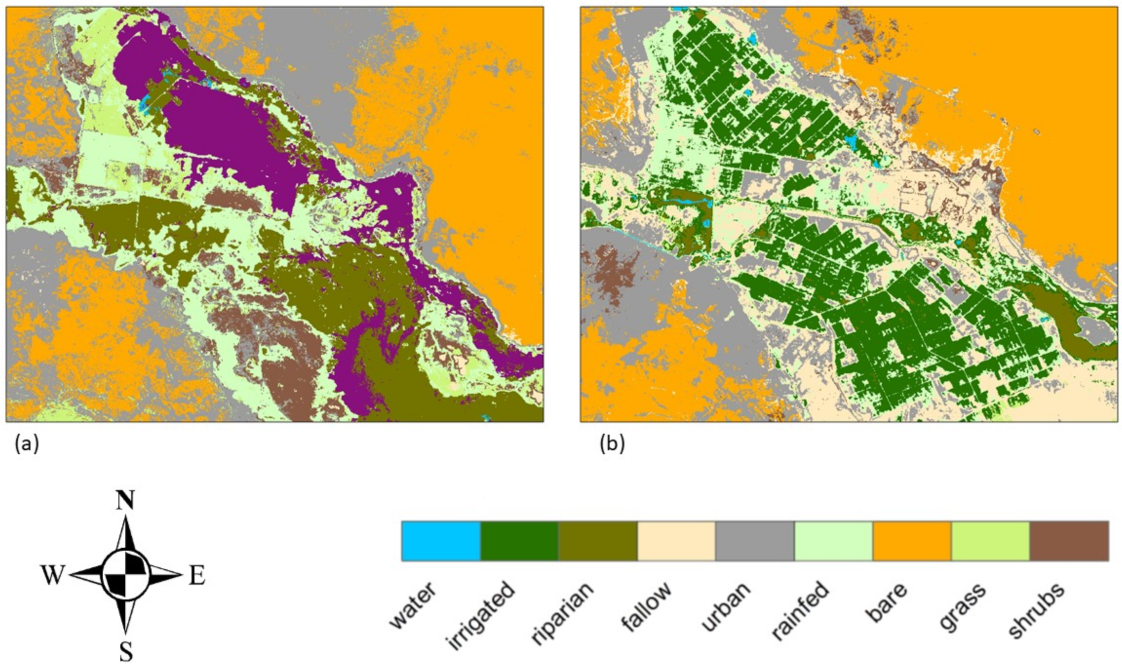

Figure 2(i): Classified crop growth season image composites of Tendaho irrigation dam in 2000 (a) and 2015 (b), which is before and after dam construction and eventual opening. The purple class (not on legend) in the 2000 image depicts post flooding area along the Awash River floodplain.

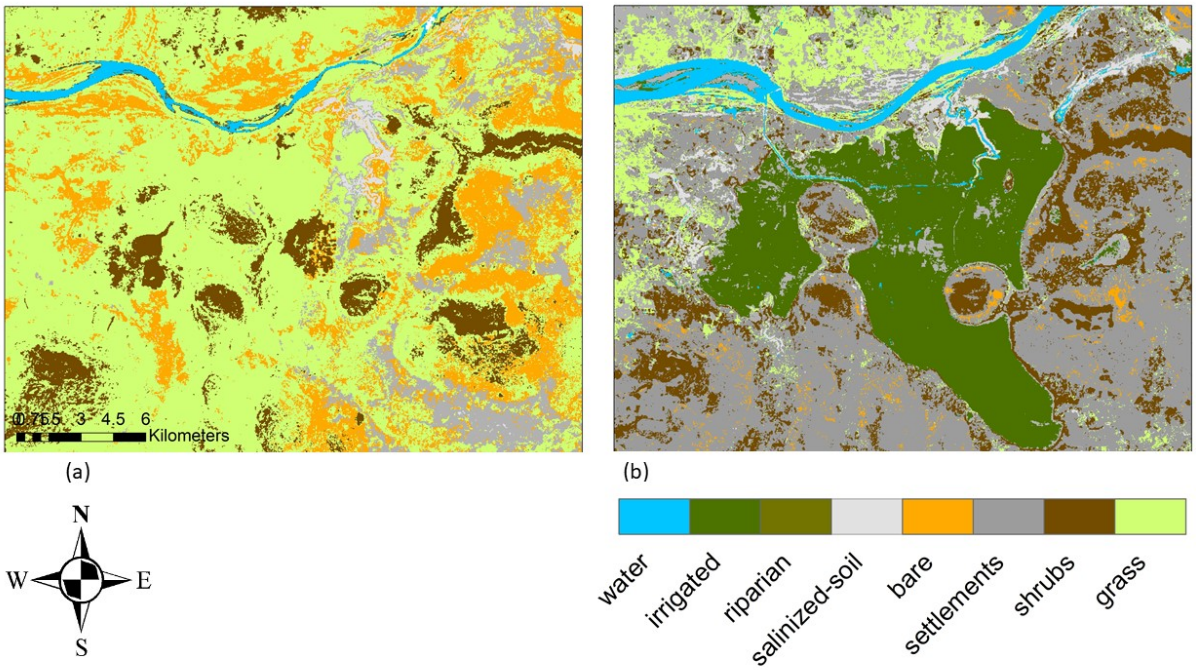

Figure 2(ii): Classified crop growth season image composites of Talo irrigation dam in 2000 (a) and 2015 (b), before and after dam construction and eventual opening, respectively.

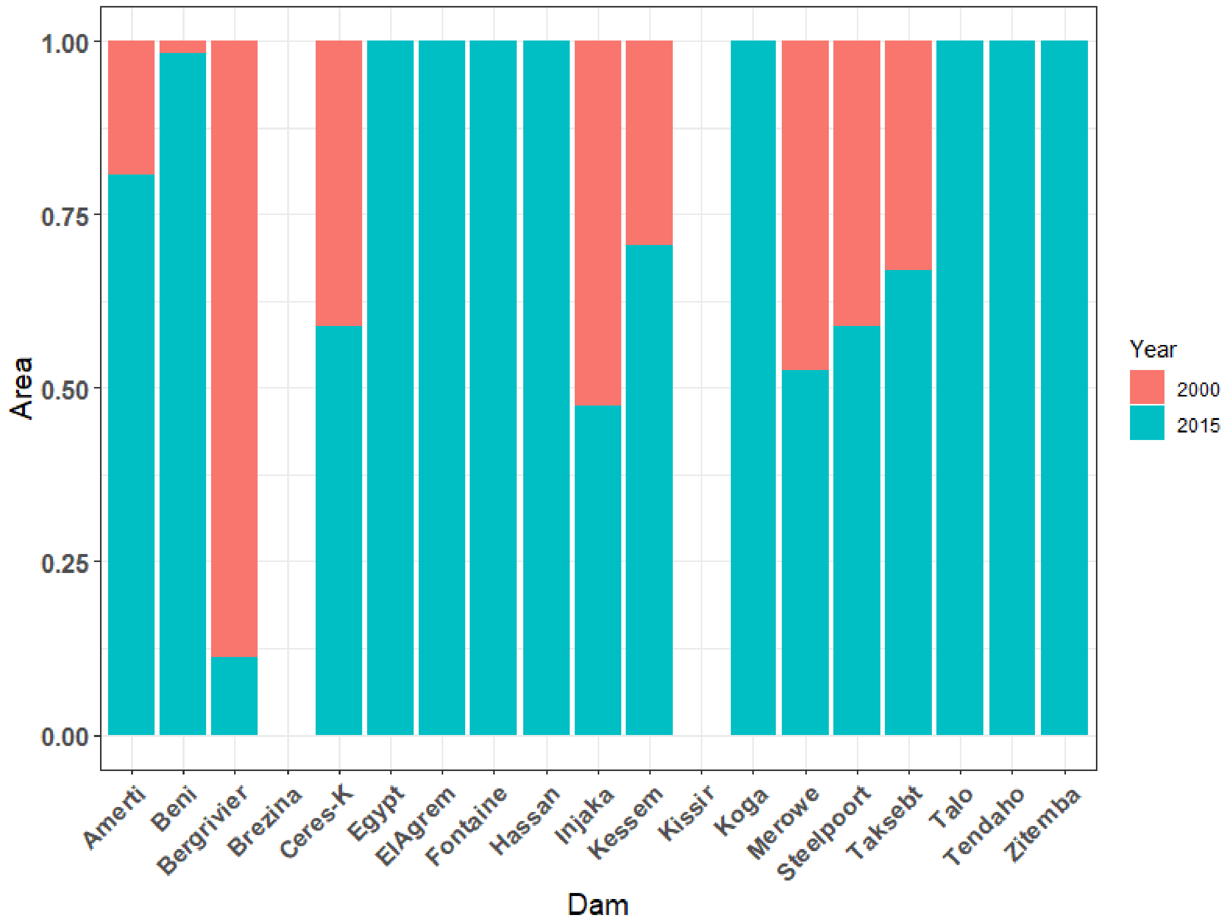

Figure 3. Proportions of the 2015 command areas that were irrigated (in red) and in 2000 in the case of the eighteen African dams included in this study. Kissir and Brezina dams in Algeria did not show any irrigated cultivation in 2000 and 2015.

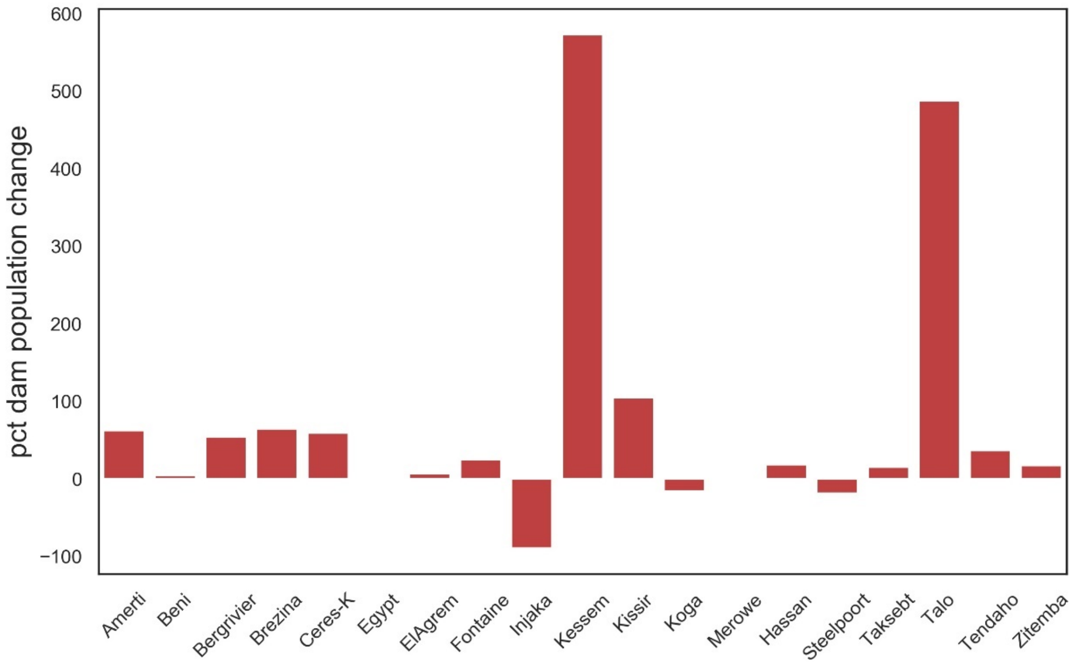

Figure 4: Human population changes within the dam command areas as percentage of the 2000 population. All command areas show an increase in human population except for Koga, Ethiopia, Injaka and Steelpoort, South Africa.

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CHAPTER 3

Value of water in different African command areas
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Introduction

The pressure on water resources for agricultural use is increasing globally, especially in water-limited environments, as a result of growing populations, increasing affluence, and the consequent need for food and agricultural products (Falkenmark and Rockstrom, 2006; D'Odorico et al., 2018). As the major contributor to human water consumption, agriculture accounts for about 85% of societal water needs. A scarce and essential resource, water is a major factor constraining crop production and an important determinant for investments in agriculture, which often aim at securing access to water resources for irrigation (Mehta et al., 2012).

Water used by agriculture is too bulky to be transported over long distances and is typically used locally to sustain the production of crops that are then either consumed in the region or placed on national and global markets (Allen, 1998; Hoekstra and Chapagain, 2011). Thus, water appropriation by agribusiness corporations typically occurs through the acquisition of land rights (e.g., land acquisitions, long-term leases, or land concessions) in areas with good access to adjacent streams, underlying aquifers, or other existing water bodies (Rulli et al., 2013; Dell'Angelo et al., 2018). Alternatively, water appropriations may occur directly through the acquisition of water rights and water entitlements (in areas where such rights exist and can be traded separately from land rights), or through the construction of dams and the associated water storage in reservoirs for a variety of uses, including irrigation (Hanjra et al., 2009; Mehta et al., 2012; Duvail et al., 2012). Reservoirs allow for the storage of water from wet seasons and its use in dry seasons, providing a more reliable and predictable supply as well as opportunities for extending cultivation to drier months of the year.

The zones irrigated with water from such reservoirs are often known as "command areas" (e.g., Rufin et al., 2018). Recent research has mapped the emergence or expansion of command areas in the proximity of major irrigation dams in Africa, typically downstream from them (Tatlhego et al., in rev). Interestingly, it has been found that the command areas of dams built in the African continent in the last two decades for agricultural use have been targeted by large scale land investors (Tatlhego & D'Odorico, *in rev*.), suggesting that large dams are often built more to the benefit of large-scale commercial farming than smallholders or subsistence agriculture (Tatlhego and D'Odorico, in rev.). In this context it remains unclear to what extent crop production can be enhanced by access to water stored in the reservoir upstream from these new dams. What is the value generated by irrigation in the new command areas? Answering this question would allow for an estimate of the 'shadow price' of water acquired by agribusiness corporations and local farmers operating in the command area and provide an estimate valuation of the increase in farmland value resulting from access to water (e.g., Young and Loomis, 2014). The value of water, however, is difficult to determine as it is often affected by subjective perceptions of what is scarce, particularly because water is extremely variable in its geographical occurrences and availability (Hanemann, 2006).

Understanding the value of water, crop and irrigation water requirements is needed to fully appreciate the benefits farmers get from having access to irrigation water in the command area and, helps evaluate the economic benefits brought about by investments in dam and irrigation infrastructure, and in turn, helps improve crop productivity and water use efficiencies (Kifle and Gebretsadikan, 2016). In water limited environments, water can be easily considered a scarce, valuable economic resource (Tewabe and Dessie, 2020) and the construction of dams is often invoked as an investment that would allow for a more reliable water supply (Gray and Sadoff, 2007), though recent studies on "green infrastructure" indicate more sustainable and equitable approaches to irrigation water management (Palmer et al., 2015; Ross and Hasnain, 2017). Indeed, the construction of the new African dams has been shown to have preferentially occurred to the benefit of large-scale farming rather than small-holders (Tatlhego & D'Odorico, *in rev*) , suggesting that agribusinesses are gaining control over precious water resources. What type of economic gains can result from irrigated farming within these command areas? In this study, we attempt a quantitative assessment of the value generated by water and the increase in land value under suitable crop scenarios.

Methods

This study focuses on 18 dams (Table 1) built in Africa for agriculture after 2000 according to the FAO-AQUASTAT database (FAO, 2016). Irrigated (or 'command') areas (Table 1) were identified in a previous study using land use classification (Tatlhego and D'Odorico, *in review*). Command area delineations were identified as those that showed irrigation in 2015. Their polygon boundaries were used to extract maximum (irrigated) crop yields ($Y_{I,i}$, expressed in hg/ha) from the Global Agro-Ecological Zoning version 4 data base (GAEZ, 2021) for every crop, i, suitable to that area (Table S1). In the case of banana, date, melon, and sesame, we used 2016 yields from the FAO (FAOSTAT, 2021). The GAEZ database provides crop yields that need to be adjusted to be consistent with the FAO values. The conversion factors, q, provided by GAEZ (2021) are reported in Table S1. FAO food prices at the farm gate were used to determine the value generated by water in agriculture as explained below (http://www.fao.org/faostat/en/#data/PP).

Using the WATNEEDS crop water model (Chiarelli et al. 2020), we determined green water (i.e., rainwater) consumption (GWC_i, See Table S2) and the irrigation water requirements (IWR_i), which is the irrigation (or "blue") water required by each suitable crop, i, to attain maximum yields during their growth season (Table S3). The maximum crop yields ($Y_{I,i}$) provided by GAEZ (2021) are attained in irrigated conditions. Assuming a linear scaling of yields with water consumption (i.e., evapotranspiration), the corresponding rainfed yields ($Y_{R,i}$) were determined as (Dorenbos and Kassam, 1979)

$$Y_{R,i} = Y_{I,i}\left(1 - k_{y,i}\left(1 - \frac{\mathrm{GWC}_i}{GWC_i + IWR_i}\right)\right) \qquad Eq.\ 1$$

where $k_{y,i}$ is a crop-specific constant of proportionality, expressing the linear dependence of yields on crop water use. Values of $k_{y,i}$ were taken from (Smith and Steduto, 2012) and in those few cases in which they were not available they were assumed to be equal to 1. Values of $k_{y,I}$ can be defined as proportion of crop water use compared to the reference crop. Thus, the increase in crop yield (in t/ha) induced by irrigation is *Eq. 2* (Table S4).

$$\Delta Y = YI,i - YR,i \qquad Eq.2$$

For each command area, we used crop statistics data to compare rainfed and irrigated production and ascertain the change in production that could be attributed to irrigation. Using farm gate FAO crop prices (Table S5), $P_{i,c}$ for crop *i* in country *c* (in \$/t), the value, v_i, (in US\$) generated by the irrigation of that crop was calculated as (D'Odorico et al., 2020)

$$v_i = \Delta Y_i \, P_{i,c} \, A_i \qquad Eq.\ 3$$

with *Eq. 2* being the irrigation-induced increase in the yield (t/ha) of crop *i* cultivated within an area, A_i, of the command area, and the subscript *c* referring to the country in which the command area is located. The amount, V_i (m^3), of water needed for the irrigation of crop *i* was then calculated as the product of its irrigation water requirement, IWR_i (m^3/ha= 0.1 mm, calculated with the WATNEED MODEL) by its area A_i, divided by the efficiency e_i,

$$V_i = \frac{IWR_i}{e_i} A_i\,, \qquad Eq.\ 4$$

where the efficiency, e_i, of the irrigation system used for crop, *i*, is the ratio between the amounts of irrigation water evapotranspired ("consumed") by the crop and the applied water (e.g., Sauer et al., 2009). We accounted for the efficiency of irrigation because farmers typically must account for water withdrawals rather than water consumption. The value of water (*wv*) used for the irrigation of crop *i* in each command area is then determined as the ratio (US\$/m^3)

$$wv_i = \frac{v_i}{V_i} = \frac{e_i\,\Delta Y_i\,P_{i,c}}{IWR_i}. \qquad Eq.\ 5$$

We used efficiency values (Table S6) equal to 0.60 and 0.64 (0.25 and 0.30) for sprinkler (surface) irrigation in North Africa and Sub-Saharan Africa, respectively (Sauer et al., 2009) and assumed that farmers adopt the irrigation techniques (i.e., sprinkler vs surface) that maximize yields in the GAEZ (2021) database. Irrigation efficiency is fraction of the water volume provided through irrigation that is actually used by the plant. The remaining fraction (i.e., 1-e) contributes to soil drainage or surface runoff. Sprinkler irrigation method sprinkles water around towards plants thus saving water as compared to surface irrigation which basically floods the planted surfaces and using way more water than needed. For crops whose yields were taken from FAOSTAT we assumed that farmers practice sprinkler irrigation because in most cases we are looking at newly established irrigated agriculture in areas undergoing major investments in irrigation infrastructure, including the construction of dams or barrages.

Similarly, the crop-specific value generated by irrigation water per unit area (*va*, in US$/ha) is

$$va_i = \Delta Y_i \, P_{i,c} \qquad Eq.\ 6$$

We calculate these values for all crops suitable to the command area (Tables 2 and S7).

Command area boundaries were delineated as the median extent of irrigated cropland in 2015 using Landsat 30 m pixels (Tatlhego and D'Odorico, in rev) while the crop yield data (GAEZ, 2021) were at the coarser resolution of 10 km pixels (Yu et al., 2020). The lack of spatially-explicit data on actual crop distribution across Africa impedes the estimate of the value generated by irrigation in crop production within the command areas. Therefore, in these analyses we considered a few suitable scenarios (Table 3). Specifically, we assumed (a) that the entire command area is cultivated with all the crops that are suitable to that area, with all crops having the same crop-specific area A_i; (b) that farmers choose to cultivate the entire command area with the crops that generate the highest revenue per amount of water expenditure, or (c) per cultivated area; we also consider the scenario (d) in which the five most cultivated crops in the country (base on FAOSTAT data for 2016) are planted in the command area (provided that they are suitable to that area), with all crops having the same area A_i. For each of these scenarios we then calculated the average value of water both in US$/m3 and US$/ha (Table 3)

Results

This study determined the shadow price of water stored in relatively new African reservoirs as the value generated by irrigation water in the command area under a variety of crop scenarios (Table 2 & Table 3). Such values are found to range from less than ten cents of US dollar per cubic meter for most staple crops to more than one dollar for 'cash' crops such as dates or other fruits, consistent with the results from other regions of the world (D'Odorico et al., 2020). Similarly, the revenues generated by irrigation per unit command area, strongly vary across crop types, ranging from few hundred dollars per hectare per year for most staple crops, to more than ten thousand US$/ha/y for dates in Algeria (Tables 3 and S7). These results show how the use of water and land for low-value crops often leads to a suboptimal use of water resources and arable land, though other factors – including food security – must come into play in the selection of the crops planted by farmers. In the case of dates, bananas or other plantations, production is perennial (i.e., the same plants remain productive for multiple years) and these multi-year investments can be at risk under severe drought, as it happened in recent years to almond plantations in California. Conversely, some annual crops (e.g., cereals) can be combined to have more than one harvest/year. Known as "multicropping", this practice achieves higher land productivities, thereby partly reducing the productivity gap existing with fruit plantations.

The average total volume of water used in the command area – calculated as the average IWR (Table S3) for all crops times the command area (Table 1) – is found to be consistently smaller than the reservoir capacity (Table 1), likely because (1) important evaporative losses from the reservoir are not accounted for; (2) these reservoirs might have multi-year management goals (i.e., they are used to transfer water from wet to dry years instead of just from wet to dry seasons); (3) some areas are used for multi-cropping; and (4) the command areas of these newly built dams are likely still undergoing expansion as new farms are established in the surrounding areas. Factors such as the time needed for reservoir fill-up, age of the dam, and implementation of irrigation projects may explain how irrigation projects develop and unfold over time.

Table 1. List of dams included in this study and the main properties of their reservoirs and command areas.

Dam	Country	Year of Completion	Storage Capacity	Command area	Average Irrigation Water Requirement (IWR) for all crops	Annual Average Irrigation Water Volume
			(Mm^3)	(ha)	(m^3/ha)	(Mm^3)
Beni Haroun	Algeria	2003	96	20983.2	3795	79.6
Brezina	Algeria	2001	122.5	0	7417	0
El Agrem	Algeria	2002	32.5	1158.7	3842	4.45
Fontaine des Gazelles	Algeria	2000	55	1514.8	6777	10.3
Kissir	Algeria	2009	68	0	3843	0
Taksebt	Algeria	2001	175	7365.4	4114	30.3
Zit Emba	Algeria	2001	120	6798.0	3930	26.7
Amerti	Ethiopia	2012		4878.6	2183	10.6
Koga	Ethiopia	2012	83.1	7268.4	2136	15.5
Tendaho Irrigation dam	Ethiopia	2009	1860	4056.2	7044	28.6
Berg River Dam	South Africa	2009	130	1737.3	5219	9.1
Cere Koekwdouw	South Africa	2001	17.2	10982.2	5650	62.0
Injaka	South Africa	2001	125.03	5987.5	3091	18.5
Steelport Pumped Stor.	South Africa	2013	347.44	138.6	3965	0.5
Talo	Mali	2006	180	9337.9	5511	51.5

Hassan	Morocco	2005	31	1656.1	6781	11.2
Merowe	Sudan	2009	12500	32810.5	5786	189.8

Table 2: Crop-specific water values ($/m^3) for recently built African irrigation dams. In Boldface: the value of the 5 most cultivated crops in the country if they are suitable to that location.

Dam	Wheat	Maize	Rice	Barley	Millet	Sorghum	Soybean	Potatoes	Sugar cane	Sugar beet	Ground nut	Cotton fiber	Banana	Sun-flower	Sesame	Olive	Melon seed	Almond	Dates
	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)	(US$/m^3)
Beni H.	**0.072**	0.042	0.018	**0.032**	0.028	0.046	0.072	**0.171**	-	0.021	0.013	0.004	0.054			**0.018**			**1.323**
Brezina	**0.043**	0.029	0.010	**0.020**	0.018	0.037	0.040	**0.080**	-	0.010	0.024	0.003	0.043			**0.015**			**1.066**
El Agrem									-				0.053						**1.348**
F. Gazelles	**0.056**	0.033	0.013	**0.022**	0.016	0.049	0.046	**0.102**	0.061	0.011	0.032	0.005	0.047						**1.112**
Kissir									-				0.053						**1.348**
Takserbt	**0.070**	0.046	0.019	**0.032**	0.030	0.049	0.075	**0.164**	-	0.019	0.045	0.006	0.054						
Zit Emba	**0.064**	0.046	0.019	**0.029**	0.029	0.049	0.074	**0.158**	-	0.018	0.045	0.006	0.052						**1.284**
Amerti	-	-	0.028	-	-	-	0.021	0.125	-				0.031						
Koga	-	-	0.029	-	-	-	0.022	0.146	-				0.032						
Tendaho		**0.013**	0.007			**0.016**	0.010		0.028		0.021	0.002	0.021						
Berg River	**0.012**	**0.017**	0.023	0.011	0.017	0.012	**0.012**	0.071	**0.017**	0.008	0.012	0.001	0.055	**0.017**					
Cere K.	**0.014**	**0.017**	0.021	0.012	0.016	0.013	**0.012**	0.077	**-**	0.010			0.053	**0.042**					
Injaka	**0.014**	**0.027**	0.023		0.030	0.020	**0.021**	0.048	**0.011**		0.028	0.001	0.060	**0.014**					
Steelport	**0.019**	**0.013**	0.022		0.038	0.015	**0.027**	0.177	**0.025**		0.034	0.002	0.059	**0.013**					
Talo	0.002	**0.028**	**0.012**			**0.019**	0.008		0.076		0.026	**0.004**	0.040						
Hassan	**0.033**	**0.035**	0.017	**0.027**	0.022	0.045	0.021	0.083	0.086	0.015	0.039	0.005	0.071			**0.016**		**0.010**	
Merowe	0.055	0.163	0.007			**0.126**	0.152		0.299		**0.220**	0.001			**0.041**		**0.015**		

Table 3: Water values (US$/m^3) and added value of irrigation (US$/ha) for recently-built African irrigation dams according to a variety of cross scenarios (a) the command area is cultivated with all the crops that are suitable its location with each crop having the same specific area; (b) only the crop with the highest water (US$/m^3) value is cultivated; (c) only the crop with the maximum economic land productivity (US$/ha) is cultivated; and (d) only the top 5 most cultivated crops in the country are cultivated (provided that they are suitable to the command area).

Dam	(a) Average Water Value (all suitable crops)	(b) Highest Water Value	Crop with Highest Water Value	(c) Water Value with the crop attaining the max increase in economic productivity	Crop attaining the max increase in revenue	(d) Average Water Value for the 5 most common crops in the country	Max increase in economic land productivity	Average increase in economic land productivity
	(US$/m3)	(US$/m3)		(US$/m3)		(US$/m3)	(US$/ha)	(US$/ha)
Beni Haroun	0.231	2.205	Dates	2.205	Dates	0.536	11356	1126
Brezina	0.173	1.777	Dates	1.777	Dates	0.406	20277	1787
El Agrem	1.167	2.246	Dates	2.246	Dates	2.246	10805	5738
F. des Gazelles	0.194	1.854	Dates	1.854	Dates	0.538	20172	1874
Kissir	1.167	2.246	Dates	2.246	Dates	2.246	10805	5738
Takserbt	0.089	0.273	Potatoes	0.273	Potatoes	0.075	1365	378
Zit Emba	0.245	2.140	Dates	2.140	Dates	0.640	12242	1291
Amerti	0.093	0.196	Potatoes	0.196	Potatoes	-	741	303
Koga	0.102	0.228	Potatoes	0.228	Potatoes	-	857	330
Tendaho	0.025	0.044	Sugarcane	0.044	Sugarcane	-	578	227
Berg River	0.059	0.236	Potatoes	0.236	Potatoes	0.044	1270	339
Cere Koekwdouw	0.071	0.257	Potatoes	0.257	Potatoes	0.051	1526	442
Injaka	0.051	0.159	Potatoes	0.094	Banana	0.032	694	137
Steelport	0.063	0.276	Potatoes	0.062	Banana	0.036	827	198
Talo	0.041	0.119	Sugarcane	0.119	Sugarcane	0.031	1121	282
Hassan	0.064	0.143	Sugarcane	0.118	Banana	0.048	1546	501
Merowe	0.170	0.468	Sugarcane	0.468	Sugarcane	0.157	1155	305
Mean	0.236	0.875	-	0.857	-	0.506	5726	1235

Discussion and Conclusions

Water is an essential and scarce resource that has no substitutes. As such, it is often treated as an economic commodity, and is increasingly becoming the target of agribusiness investors, through land acquisitions, water markets, and financialization of water resources (Baumann et al., 1998; Chong and Sunding, 2006; ICWE, 1992; Schmidt and Matthews, 2018). Proponents of the view of water as a private commodity argue that, by creating property rights on water and allowing water to be traded for profit, we can prevent that this precious resource is wasted and ensure that it is placed at its most valuable (i.e., profitable) use (Savenije and Zaag, 2002; Debaere and Li, 2020). The commodification of water, however, has been challenged by those who view it as a common good, a shared legacy, or a human right (Shiva, 2002; 2019; Johnson et al., 2016; Mehta et al., 2012; Opel, 2008). To date, most water resources around the world are not treated as a private good that is exchanged in water markets because most countries do not recognize tradeable property rights on water (Richter, 2016). Rather, water resources are acquired through rights on land with good access to water because of the presence of shallow aquifers, adjacency to streams and other water bodies, or the development of water infrastructures such as dams that allow for a more reliable, predictable, and regular supply of water for irrigation.

The construction of new dams allows for the emergence of new irrigated ("command") areas in their vicinity and the consequent intensification of agriculture with higher yields and revenues. Through the construction of a dam and the management of the water stored in its reservoir a consortium of farmers can ensure a physical appropriation of water for irrigation. In such conditions, it is also possible to envision the emergence of trading of water entitlements among farmers or the acquisition of water from a hypothetical irrigation district managing the reservoir. Such exchanges require a good knowledge of the value generated by irrigation water through the increase in crop production in irrigated areas. In other words, it is important to understand how much irrigation water is worth to farmers. This study estimated the value generated by irrigation water in the command areas and the associated increase in land value, thus giving a better way to evaluate how important irrigation ventures are in developing countries. Evaluating these can be used as important tool by decision and policy makers on whether a particular country region should embark on these developments.

Our analysis is based on an estimate of the "shadow" price of water through the evaluation of the increase in agricultural output and its value at the farm gate (D'Odorico et al., 2020). The rationale underlying this method of water valuation is that farmers bear similar costs to sustain rainfed and irrigated production (same land and seeds, and about the same labor and other inputs) and the costs of management and operation of irrigation systems are expected to be negligible with respect to the revenues generated by irrigation (D'Odorico et al., 2020). If irrigation is carried out sustainably (i.e., without depleting groundwater stocks or environmental flows (Rosa et al., 2018)), the environmental costs and future costs of irrigation can also be neglected and the added value of irrigation can be directly determined from the increase in production (D'Odorico et al., 2020). Such an increase is what motivates land investors to secure rights on land parcels within the command area of irrigation dams, making such areas a preferential target for land acquisitions (Tatlhego and D'Odorico, in rev.).

As expected, the results of this analysis show a strong dependency of the added value of irrigation on crop type (Table 2). Of course, farmers' decision to plant staple or cash crops will depend on several factors that are not accounted for in this study, including the different inputs required by various crops, their cost, and the associated risks: economies of scale, farmers' investment capacity, access to credit, technology, expertise, and markets for the placement of their products. It will also depend on the 'farming system' – conceived as the combination of means of production, expertise, land stewardship, ways of life, and rural livelihoods – and on whether it focuses on self-subsistence or profit-generating agribusiness. These and other factors may explain why farmers might choose to plant crops that generate lower revenues rather than profit-maximizing crops per unit area (Table 3, (c) scenario); or why they may attain relatively low water productivities per unit volume with respect to productivity-maximizing crops (Table 3, (b) scenario). Interestingly, these two scenarios tend to coincide in the sense that in most cases the crops that maximize water productivity (i.e., revenue generated per unit volume, in $/m3) are the same crops that maximize economic yields (i.e., revenue generated per unit area, in $/ha) with only few exceptions (Table 3). In other words, while farmers may in general decide to optimize either financial? or water productivity - depending on their relative scarcity - in this case the two strategies are met by planting the same crops (Table 3).

These analyses provide a first valuation of the ecosystem services provided by water used for irrigation and of the increased income that access to water would provide to farmers and agribusiness investors. These results can also be utilized for simple economic analyses to determine to what extent the cost of the dam and associated infrastructure would be justified by the increase in crop production, though the environmental and social impacts of dams would also need to be accounted for.

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Conclusion

In this dissertation I sought to investigate consequences that follow strategies taken by Africans in achieving water security in water limited environments, be it for small-scale subsistence agriculture and/or agrarian business ventures. I employ model computations to assess distant effects of dust plains created as the result of desertification and/or other processes that lead to loss of vegetation cover. I start out by mapping out areas of the Southern Ocean that lack bioavailable iron which has previously been found to be a constituent of atmospheric dust. Using modeled pathways of air parcel trajectories starting from dust source areas in South America, Southern Africa and Australia, and corresponding average chlorophyll-a concentrations in the Southern Ocean. My findings suggest that dust sources within the southern half of Africa have high deposits towards the southeast part of the continent and experience reduction with distances from the land mass. These findings also suggest that African desertification contributes significantly high amounts of dust to the Southern Ocean in comparison to South America. I also employed remote sensing image analyses to investigate newer methods of water resource development, specifically dam constructions for irrigation purposes. This analysis showed an increase in areas irrigated downstream from dams, but also showed that a significant portion of these was taken by few large-scale farms, which I designated as commercial.

Essential to these findings is the deduction of whether the water development strategies studied showed any efficiency and/or sustainability. Forest loss, upstream flooding and consequent waterlogging, and the downstream replacement of riparian vegetation by irrigated croplands are shown as the major ecosystem changes that follow irrigation dam constructions. I further investigated how human communities react to dam constructions by computing population changes in command areas and upstream areas. Human populations show general displacement in upstream regions and some increase in command areas.

To add to the demonstrated ecosystem and population changes, these findings suggest newer questions that could be used by future environmental impact assessment practitioners on what they could consider when making decisions on zoning water development developments. These results also have the potential to inform the science community on the extent of impacts of potential dam projects, to prepare not only for local influences but distant ones too.

Analyses in this dissertation provide a first valuation of the ecosystem services provided by water used for irrigation and of the increased income that access to water would provide to farmers and agribusiness investors. These results can also be utilized for simple economic analyses to determine to what extent the cost of the dam and associated infrastructure would be justified by the increase in crop production, though the environmental and social impacts of dams would also need to be accounted for. Armed with this knowledge, decision and policy makers could use the findings of this dissertation and the methods to forecast the future of planned dam developments and help with water use allocation.

Appendix

The files used to write this article are saved on this link https://doi.org/10.6084/m9.figshare.14745456

- The ‘MosaicandClassficationScript.txt’ holds the script used in Google Earth Engine (GEE) to make a composite of a growing period for a specific region. The script also contains how to build a Random Forest Classifier, Classify the image, and calculate the accuracy of the classifier.
- The ‘chartForestLossScript.txt’ charts forest loss per year in command areas, using the Hansen Global Forest cover dataset in GEE.
- The ‘populationCountScript.txt’ extracts population count from the Global Human Settlement Layer and sums it for 2000 and 2015, for one command area at a time.
- The ‘DamsPost2000.zip’ contains a point shapefile of the dams used in this study.
- ‘AfricanIrrigatedAreas.zip’ contains the final merged shapefile of irrigated regions in study dams, the command areas in 2015.
- ‘AfricanDamFloodedAreas.zip’ contains the shapefile of upstream inundated regions after dam construction.
- The figures listed here depict (and are referenced) in the methods section in the main manuscript.

Introduction

This supplement contains supporting information for methodology and results, especially the ones that were not outputs from our main objectives but rather supported the process of acquiring the intended results. Figures included in this are mostly intended to show examples of outcomes, accompanied by data files included in the above-mentioned repository, and comparisons of weather/climate variables to help determine whether these had an impact on changes in dam command areas.

Table A1. Summary of the dams considered in this study and of their characteristics

Dam	Coordinates	Capacity Mm^3	Height, m	Country	End of construction/ commissioning	Flooded Area (max reservoir area)
Amerti	9.79; 37.27	0.04	28	Ethiopia	2012	2438.5
Beni-Haroun	36.52; 6.26	96	120	Algeria	2003	3547.4
Bergrivier	-33.9;19.06	130	62	South Africa	2007	468.6
Brezina		122.5		Algeria	2001	40.7
Ceres-K	-33.36;19.28	17.2	64	South Africa	2001	452.4
Egypt	29.18; 30.39	1195	-	Egypt		1140.9
El Agrem	36.76; 5.79	32.5	60	Algeria	2002	35.9
Fontaine	35.12; 5.58	55	42	Algeria	2000	186.6
Hassan	31.81; -6.82	31		Morocco	2005	242.4
Injaka	-24.89; 31.09	125.03	51	South Africa	2001	717.8
Kessem	9.15; 39.89		90	Ethiopia	2015	2262.687
Kissir		68	56	Algeria	2009	24.3
Koga	11.39; 37.18	83.1	20	Ethiopia	2012	1297.5
Merowe	18.72; 31.99	12500	67	Sudan	2009	31216.5
Steelpoort	-24.73; 30.22	347.4	71	South Africa	2013	1007.2
Taksebt	36.68; 4.12	175	-	Algeria	2001	1566.7
Talo	13.22; -5.2	180	5	Mali	2006	481.3
Tendaho	11.69; 40.96	1860	53	Ethiopia	2009	995.1
Zitemba	36.52; 6.26	120	-	Algeria	2001	7015.9

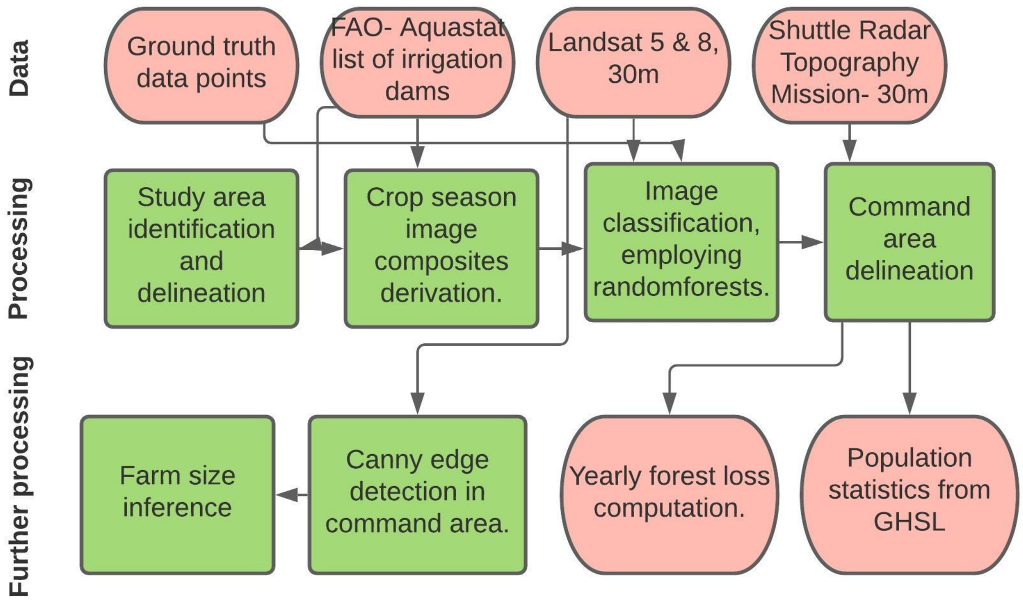

Figure A1: Summary of methods workflow. The green boxes denote actions where primary computations were carried out while peach colored boxes denote data extraction of secondary data.

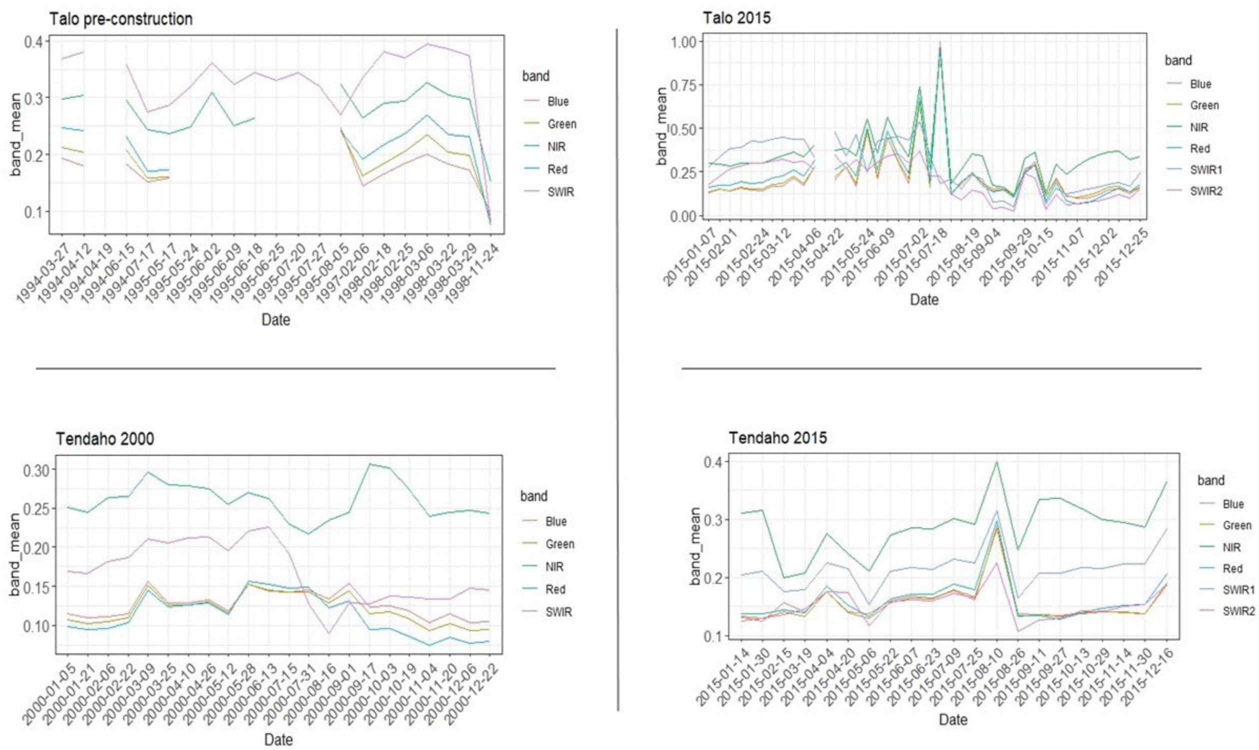

Figure A2 (i): One-year plot of band spectra centered at dam command areas before construction (2000) and after construction (2015). These results were used to determine frequency of cultivation using expected plant spectra as indicator. These plots were also used to confirm cropping season as suggested by FAO Aquastat crop calendars; cropping seasons are those that show elevated NIR values that coincide with plant rigor.

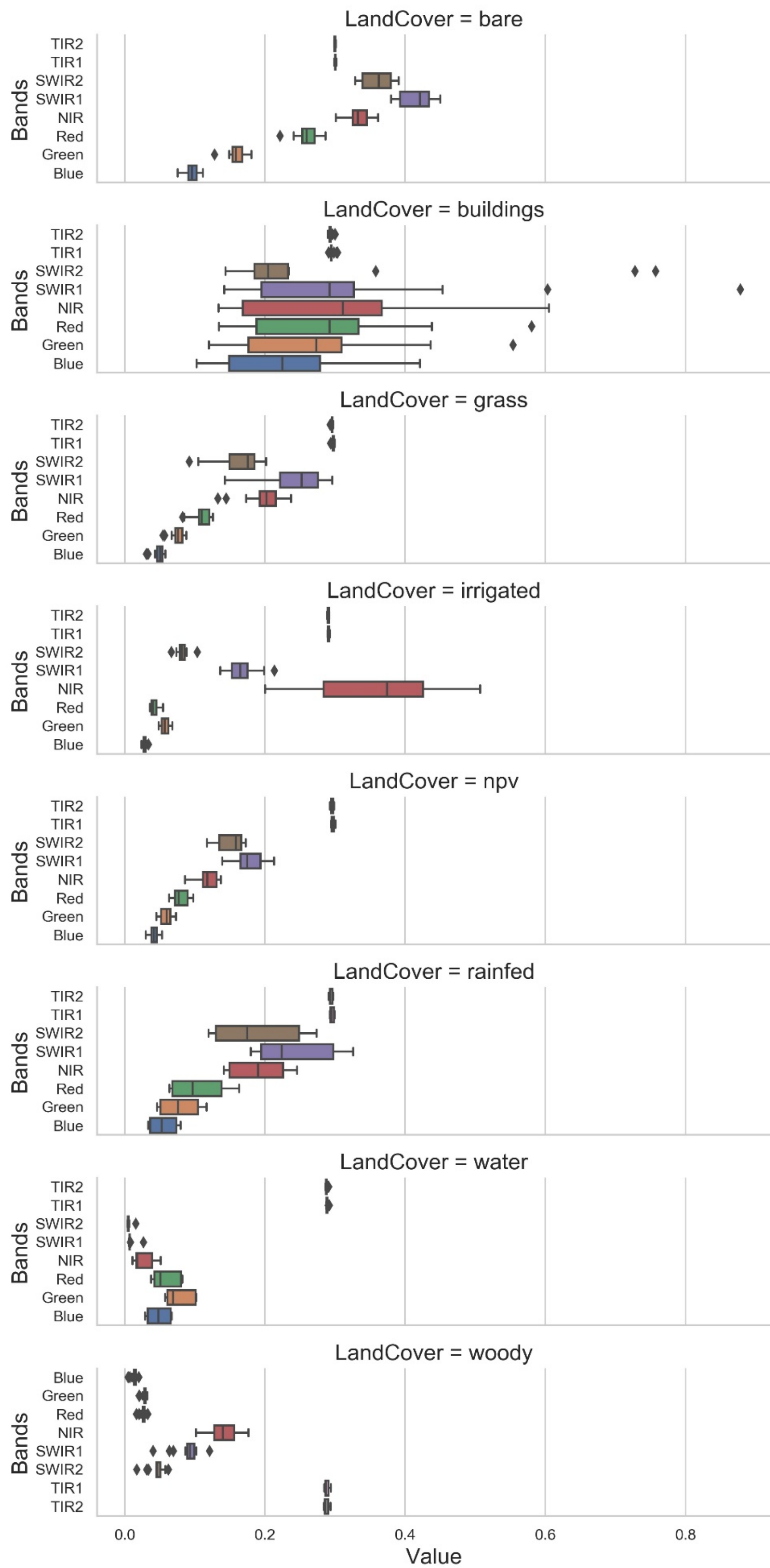
LandCover = bare
LandCover = buildings
LandCover = grass
LandCover = irrigated
LandCover = npv
LandCover = rainfed
LandCover = water
LandCover = woody
Bands
TIR2
TIR1
SWIR2
SWIR1
NIR
Red
Green
Blue
0.0
0.2
0.4
0.6
0.8
Value

Figure A2(ii): Feature band signature exploration used with initial ground truthing data, the NIR and SWIR1 bands are the most distinctive bands for irrigated cultivated land away from other features, while the variance in the SWIR1 band between the rainfed and irrigated is very minimal. Our random forest classifier showed that it was able to detect differences despite the minimal differences in variance between the two cultivated classes.

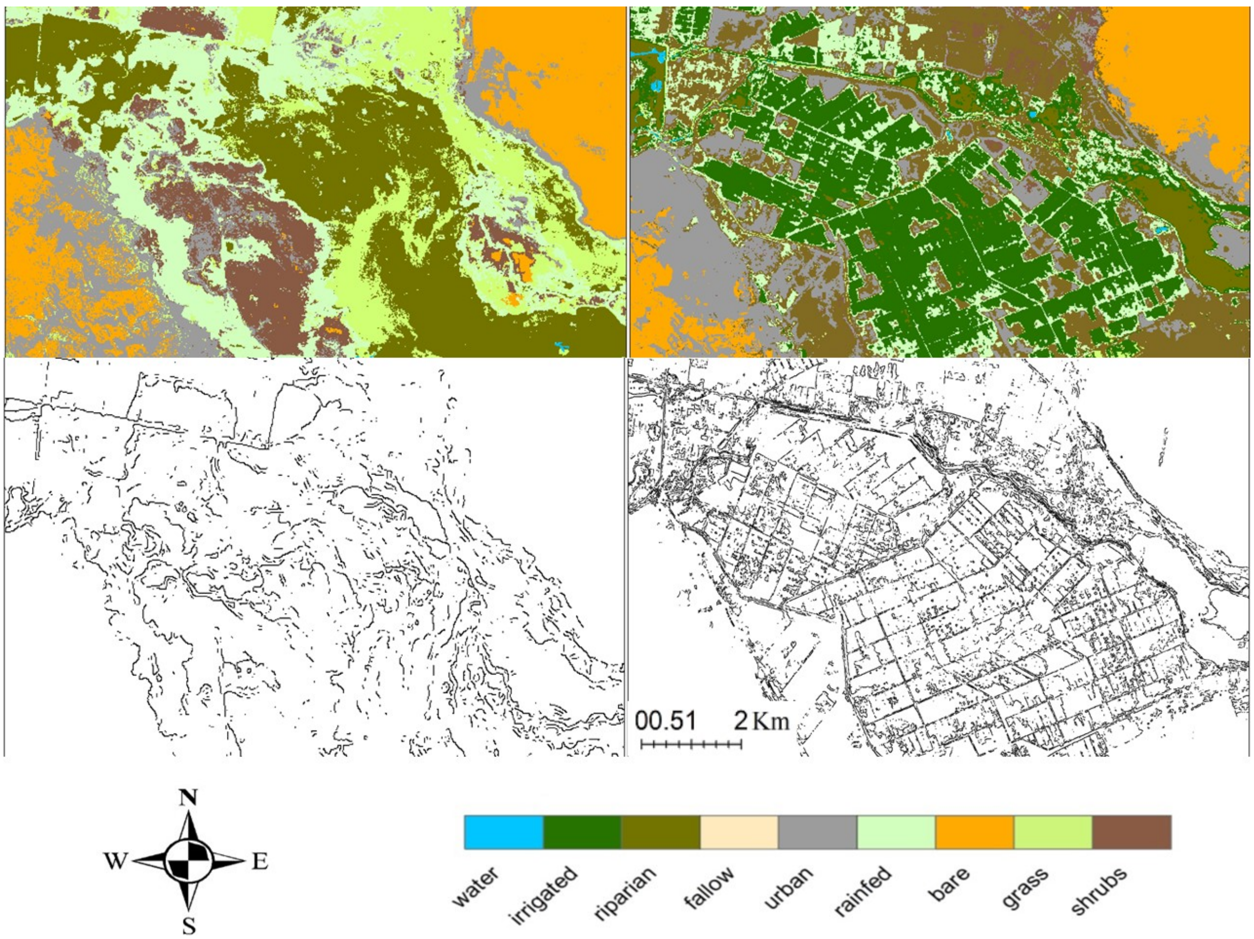

Figure A3: Examples of 2000 and 2015 classified images of Tendaho dam, Ethiopia, and the resultant canny edge detection results at NDVI threshold of 0.3 used to infer farm sizes in both years.

Table A2: Comparisons of mean precipitation in the years leading to 2000 (1995-2000) and 2015 (2010-2015). Rainfall data were extracted from The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes (Funk et al., 2015) These data were used to decipher how climate varied over the period of our study, and see if these were in a way able to explain the results we encountered. These results suggest no statistical significance that

precipitation differed in 2000 and 2015 ($p > 0.05$). Mean land surface temperature comparisons from 2000 and 2015 are also presented and are based on data extracted from MODIS Land Surface temperature and emissivity dataset (Wan, Zhengming et al., 2015)

Dam	µ Precipitation 2000 (mm)	µ Precipitation 2015 (mm)	p-value precipitation	µ LST 2000 °C	µ LST 2015 °C	p-value surface temperature
Amerti	4.03	2.8	>0.05	25.9	27.5	>0.05
Beni	1.62	1.9	>0.05	30.6	25.4	>0.05
Bergrivier	1.4	1.7	>0.05	22.4	23.8	>0.05
Brezina	0.4	0.5	<0.05	34.3	29.8	>0.05
Ceres	0.9	1.02	>0.05	24.3	26.4	>0.05
Egypt	0.00	0.00	>0.05	36.9	34.7	>0.05
ElAgrem	1.4	1.6	>0.05	26.1	23.6	>0.05
Fontaine	0.5	0.5	>0.05	34.4	30.5	>0.05
Hassan	1.02	0.9	>0.05	32.8	27.9	>0.05
Injaka	5.04	2.5	>0.05	24.3	26.9	>0.05
Kessem	1.3	0.8	>0.05	39.1	41.3	>0.05
Kissir	1.4	1.6	>0.05	23.0	20.7	>0.05
Koga	3.9	3.5	>0.05	31.5	31.6	>0.05
Merowe	0.00	0.03	>0.05	41.9	38.6	>0.05
Steel	2.6	1.6	>0.05	26.9	30.1	>0.05
Taksebt	1.7	2.1	>0.05	29.7	24.3	>0.05
Talo	1.8	2.2	>0.05	36.4	34.3	>0.05
Tendaho	0.7	0.4	>0.05	42.5	42.8	>0.05

Table A3: Sample descriptive statistics of NDVI trends from before dam building, to 2015. These show the observed trend of increase in plant rigor in the different dams. While we note the increase of greenness with time, it is also worth noting that some years in between show very low NDVI values, leading to an assumption of yearly available cultivated/irrigated land. Landsat image collections that spanned the delineated command areas were used to extract these data.

Dam	year	mean NDVI	min NDVI	max NDVI	std
Amerti	2000	0.3	0.3	0.4	0.1
Amerti	2001	0.2	0.2	0.2	
Amerti	2008	0.4	0.4	0.5	0.1
Amerti	2009	0.4	0.3	0.5	0.1
Amerti	2010	0.3	0.3	0.4	0.1
Amerti	2011	0.4	0.1	0.5	0.1
Amerti	2013	0.4	0.2	0.6	0.1
Amerti	2014	0.4	0.2	0.5	0.1
Amerti	2015	0.4	0.2	0.6	0.1

Amerti	2016	0.4	0.1	0.6	0.1
Amerti	2017	0.3	0.2	0.3	0.1
Beni	2001	0.2	0.2	0.2	
Beni	2002	0.2	0.2	0.2	0
Beni	2003	0.2	0.1	0.2	0.1
Beni	2006	0.1	0	0.1	0
Beni	2007	0.3	0.1	0.5	0.1
Beni	2009	0.3	0.1	0.4	0.1
Beni	2010	0.3	0	0.5	0.1
Beni	2011	0.3	0.2	0.6	0.1
Beni	2013	0.3	0	0.5	0.2
Beni	2014	0.2	0	0.4	0.1
Beni	2015	0.3	0.1	0.5	0.1
Beni	2016	0.3	0	0.6	0.2
Beni	2017	0.3	0.1	0.5	0.2
Berg	2013	0.3	0	0.4	0.1
Berg	2014	0.4	0.1	0.4	0.1
Berg	2015	0.3	0	0.4	0.1
Berg	2016	0.3	0	0.4	0.1
Berg	2017	0.3	0.1	0.4	0.1
Bergrivier	2000	0.2	0	0.4	0.1
Bergrivier	2001	0.2	0	0.4	0.2
Bergrivier	2003	0.4	0.4	0.4	0
Bergrivier	2004	0.3	0	0.4	0.2
Bergrivier	2005	0.3	0	0.4	0.2
Bergrivier	2006	0.2	0	0.4	0.1
Bergrivier	2007	0.3	0.2	0.4	0.1
Bergrivier	2008	0.2	0.2	0.2	
Bergrivier	2009	0.3	0.1	0.4	0.2
Bergrivier	2010	0.3	0.2	0.3	0.1
Bergrivier	2011	0.3	0.2	0.3	0
Ceres	2000	0.2	0	0.4	0.1
Ceres	2001	0.2	0	0.4	0.2
Ceres	2003	0.2	0.2	0.2	0
Ceres	2004	0.3	0.2	0.4	0.1
Ceres	2005	0.2	0.1	0.4	0.1
Ceres	2006	0.3	0.1	0.4	0.1
Ceres	2007	0.3	0.2	0.4	0.1
Ceres	2008	0.3	0.2	0.4	0.1
Ceres	2009	0.3	0.3	0.3	0
Ceres	2010	0.3	0.3	0.3	0
Ceres	2011	0.2	0.2	0.2	0
Ceres	2013	0.3	0.1	0.5	0.1
Ceres	2014	0.3	0.2	0.4	0.1
Ceres	2015	0.3	0	0.4	0.1

Ceres	2016	0.3	0	0.4	0.1
Ceres	2017	0.2	0.2	0.3	0.1
Egypt	2002	0.1	0.1	0.1	0
Egypt	2003	0.1	0.1	0.1	0
Egypt	2013	0.1	0.1	0.1	0
Egypt	2014	0.1	0.1	0.1	0
Egypt	2015	0.1	0	0.1	0
Egypt	2016	0.1	0.1	0.1	0
Egypt	2017	0.1	0.1	0.1	0
ElAgrem	2001	0.3	0.3	0.3	
ElAgrem	2002	0.4	0.4	0.4	
ElAgrem	2003	0.3	0.1	0.5	0.2
ElAgrem	2006	0.1	0	0.3	0.2
ElAgrem	2007	0.4	0.2	0.5	0.1
ElAgrem	2009	0.4	0.1	0.5	0.1
ElAgrem	2010	0.4	0	0.6	0.2
ElAgrem	2011	0.5	0.3	0.6	0.1
ElAgrem	2013	0.4	0	0.5	0.2
ElAgrem	2014	0.2	0	0.5	0.2
ElAgrem	2015	0.4	0	0.6	0.2
ElAgrem	2016	0.3	0	0.6	0.2
ElAgrem	2017	0.2	0	0.6	0.2
Fontaine	2001	0.1	0.1	0.1	
Fontaine	2002	0.1	0.1	0.1	
Fontaine	2003	0.1	0	0.1	0
Fontaine	2006	0.1	0	0.1	0
Fontaine	2007	0.1	0.1	0.1	0
Fontaine	2009	0.1	0.1	0.1	0
Fontaine	2010	0.1	0	0.1	0
Fontaine	2011	0.1	0	0.1	0
Fontaine	2013	0.1	0.1	0.1	0
Fontaine	2014	0.1	0	0.1	0
Fontaine	2015	0.1	0.1	0.1	0
Fontaine	2016	0.1	0	0.1	0
Fontaine	2017	0.1	0.1	0.1	0
Hassan	2001	0.1	0.1	0.1	
Hassan	2002	0.3	0.2	0.3	0.1
Hassan	2003	0.2	0.1	0.2	0
Hassan	2006	0.2	0.1	0.3	0.1
Hassan	2007	0.2	0.1	0.3	0.1
Hassan	2009	0.2	0.1	0.2	0.1
Hassan	2010	0.2	0.1	0.3	0.1
Hassan	2011	0.2	0.2	0.4	0
Hassan	2013	0.2	0.1	0.3	0.1
Hassan	2014	0.2	0	0.3	0.1

Hassan	2015	0.3	0.2	0.4	0
Hassan	2016	0.2	0	0.3	0.1
Hassan	2017	0.3	0.2	0.4	0.1
Injaka	2000	0.5	0.1	0.6	0.1
Injaka	2001	0.4	0.1	0.6	0.2
Injaka	2003	0.1	0.1	0.1	0
Injaka	2004	0.5	0.2	0.6	0.1
Injaka	2005	0.3	0.2	0.4	0.1
Injaka	2006	0.4	0.1	0.6	0.2
Injaka	2007	0.4	0.1	0.6	0.2
Injaka	2008	0.4	0.1	0.6	0.2
Injaka	2009	0.4	0.1	0.6	0.2
Injaka	2010	0.6	0.5	0.6	0.1
Injaka	2011	0.6	0.5	0.6	0.1
Injaka	2013	0.3	0.1	0.6	0.2
Injaka	2014	0.4	0	0.6	0.2
Injaka	2015	0.3	0	0.6	0.2
Injaka	2016	0.4	0	0.6	0.2
Injaka	2017	0.4	0.2	0.6	0.2
Kissir	2001	0.3	0.3	0.3	
Kissir	2002	0.5	0.5	0.5	
Kissir	2003	0.3	0.1	0.6	0.2
Kissir	2006	0.2	0	0.5	0.3
Kissir	2007	0.5	0.3	0.6	0.1
Kissir	2009	0.4	0.2	0.6	0.1
Kissir	2010	0.4	0	0.6	0.2
Kissir	2011	0.5	0.4	0.5	0.1
Kissir	2013	0.4	0	0.6	0.2
Kissir	2014	0.2	0	0.5	0.2
Kissir	2015	0.4	0	0.6	0.2
Kissir	2016	0.4	0	0.5	0.2
Kissir	2017	0.3	0	0.6	0.2
Koga	2000	0.3	0.2	0.5	0.1
Koga	2001	0.2	0.2	0.2	
Koga	2008	0.4	0.4	0.4	0
Koga	2009	0.3	0.2	0.3	0.1
Koga	2010	0.3	0.1	0.5	0.2
Koga	2011	0.4	0.2	0.6	0.1
Koga	2013	0.3	0.1	0.6	0.2
Koga	2014	0.3	0	0.6	0.2
Koga	2015	0.4	0.2	0.6	0.1
Koga	2016	0.4	0.2	0.6	0.1
Koga	2017	0.3	0.3	0.3	0
Merowe	2000	0.1	0	0.1	0
Merowe	2008	0.1	0.1	0.1	0

Merowe	2009	0.1	0.1	0.1	
Merowe	2011	0	-0.1	0.1	0.1
Merowe	2013	-0.1	-0.2	0.1	0.1
Merowe	2014	0	-0.1	0.1	0.1
Merowe	2015	0	-0.2	0	0.1
Merowe	2016	-0.1	-0.2	0.1	0.1
Merowe	2017	-0.1	-0.1	0	0
Steelpoort	2000	0.3	0.2	0.4	0.1
Steelpoort	2001	0.2	0.1	0.2	0.1
Steelpoort	2003	0	0	0	
Steelpoort	2004	0.3	0.2	0.5	0.1
Steelpoort	2005	0.2	0	0.2	0.1
Steelpoort	2006	0.3	0.1	0.4	0.1
Steelpoort	2007	0.2	0.1	0.3	0.1
Steelpoort	2008	0.3	0.1	0.4	0.1
Steelpoort	2009	0.3	0.3	0.4	0
Steelpoort	2010	0.5	0.5	0.5	
Steelpoort	2011	0.3	0.3	0.3	
Steelpoort	2013	0.3	0.1	0.4	0.1
Steelpoort	2014	0.3	0.1	0.5	0.1
Steelpoort	2015	0.2	0	0.5	0.1
Steelpoort	2016	0.3	0.2	0.5	0.1
Steelpoort	2017	0.3	0.1	0.5	0.2
Taksebt	2002	0.2	0.1	0.3	0.1
Taksebt	2003	0.3	0.1	0.3	0.1
Taksebt	2006	0.3	0.3	0.3	0
Taksebt	2007	0.3	0.1	0.5	0.1
Taksebt	2009	0.3	0.1	0.5	0.1
Taksebt	2010	0.4	0.1	0.6	0.1
Taksebt	2011	0.4	0	0.6	0.1
Taksebt	2013	0.4	0	0.6	0.1
Taksebt	2014	0.3	0	0.5	0.2
Taksebt	2015	0.3	0	0.6	0.1
Taksebt	2016	0.3	0	0.6	0.2
Taksebt	2017	0.4	0	0.6	0.2
Talo	2006	0.2	0.2	0.3	0
Talo	2007	0.2	0.1	0.3	0.1
Talo	2009	0.2	0.1	0.3	0.1
Talo	2010	0.2	0.1	0.3	0.1
Talo	2011	0.2	0.1	0.3	0.1
Talo	2013	0.3	0.1	0.4	0.1
Talo	2014	0.2	0.1	0.3	0.1
Talo	2015	0.2	0.1	0.4	0.1
Talo	2016	0.2	0.1	0.4	0.1
Talo	2017	0.2	0.2	0.2	0

Tendaho	2000	0.1	0	0.1	0
Tendaho	2008	0.1	0.1	0.1	0
Tendaho	2009	0.1	0.1	0.1	0
Tendaho	2010	0.1	0.1	0.1	0
Tendaho	2011	0.1	0	0.1	0
Tendaho	2013	0.1	0.1	0.2	0
Tendaho	2014	0.1	0.1	0.2	0
Tendaho	2015	0.1	0	0.2	0
Tendaho	2016	0.1	0.1	0.2	0
Tendaho	2017	0.1	0.1	0.1	0

Table S1. Maximum yields YI from the GAEZ (in black) or FAOSTAT (in red). The last row provides the conversion factor from GAEZ to FAO yield values (from GAEZ, 2021).

Dam	Country	Climatic region	Wheat	Maize	Rice	Barley	Millet	Sorghum	Soybean beans	Potatoe, sweetpotatoe	Sugarcane	Sugarbeets	Groundnuts	Cotton/fiber	Banana	Sunflower	Sesame	Olives	Melonseed	Almonds	Dates
			(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)	(hg/ha)
Beni Haroun	Algeria	3	9039	13599	10385	8386	6918	8931	5741	17339		10976	1081	726	5835	5065		1350			64831
Brezina	Algeria	3	6898	11743	6571	6608	5430	8696	3996	9953		6239	2392	758	5835	3844		1466			64831
El Agrem	Algeria	3													5835						64831
Fontaine	Algeria	3	8135	12147	8113	6776	4652	10425	4261	11826	6498	6664	2917	978	5835	2956					64831
Kissir	Algeria	3													5835						64831
Takserbt	Algeria	3	8837	14404	10589	8353	7297	9459	5858	16202		9892	3653	1086	5835	5310		1580			64831
Zit Emba	Algeria	3	8661	14695	10776	8068	7203	9662	5905	15972		9655	3712	1146	5835	5390		1983			64831
Amerti	Ethiopia	1	7324	9264	10310		4857	5398	3884	13632					**6854**	4870					
Koga	Ethiopia	1	7701	10456	9835		6607	5676	4115	16007					**6854**	4974					
Tendaho	Ethiopia	1		6336	5201			5286	2266		5728		1655	689	**6854**	1833					
Berg River	South Africa	3	8580	15279	11478	8413	7552	10552	6193	16855	9588	9801	3380	1236	**7312**	5587		2392			
Cere	South Africa	3	9650	15506	10877	9125	7627	11307	6431	19422		12084			**7312**	5672		2484			
Injaka	South Africa	2	5064	9300	9047		5168	6997	4228	9303	12311		3022	906	**7312**	4215					
Steelport	South Africa	2	7092	9520	8496		6485	5168	5281	16002	13030		3589	1260	**7312**	4922					
Talo	Mali	1	1666	10315	8070			8030	4040		9549		2734	1005	**5832**	2699					
Hassan	Morocco	3	8500	14843	10452	7924	7145	9895	5715	15449	10656	9695	3483	1211	**6644**	5281		2575		6296	
Merowe	Sudan	1	2338	7713	566			5981	2998		6448		2307	56		2858	2758		1605		
Gaez--> FAO conversion factors			*0.875*	*0.87*	*0.875*	*0.885*	*0.9*	*0.88*	*0.9*	*0.275*	*0.1*	*0.14*	*0.67*	*0.35*	*0.25*	*0.9*	*1*	*0.22*	*1*	*1*	*1*

Table S2: **Green Water Consumption (GWC) calculated for each crop and every location with the WATNEEDS model (Chiarelli et al., 2020)**

Dam	Country	Climatic Region	Wheat	Maize	Rice	Barley	Millet	Sorghum	Soybean beans	Potatoes, sweetpotatoe	Sugarcane	Sugarbeets	Ground nuts	Cotton/ fiber	Banana	Sunflower	Sesame	Olives	Melonseed	Almonds	Dates
			(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)		(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)
Beni Haroun	Algeria	3	349	443	867	031	##########	313	##########	##########	##########	###########	461	270	##########	960	120	##########	##########	##########	##########
Brezina	Algeria	3	133	93	84	115	80	47	37	82	##########	56	82	006	##########	00	90	##########	20	##########	##########
El Agrem	Algeria	3	219	471	629	097	##########	169	##########	##########	##########	###########	276	938	##########	920	100	##########	##########	##########	##########

Fontaine des Gazelles	Algeria	3	215	86	27	304	72	95	59	50	######### #	######### ##	04	20	######### #	00	60	######### #	######### #	######### #	######### #
Kissir	Algeria	3	286	446	651	093	######### #	163	######### #	######### #	######### #	######### ##	270	979	######### #	920	100	######### #	######### #	######### #	######### #
Takserbt	Algeria	3	296	437	774	987	######### #	281	######### #	######### #	######### #	######### ##	337	242	######### #						
Zit Emba	Algeria	3	611	449	009	224	######### #	351	######### #	######### #	######### #	######### ##	497	354	######### #	110	880	######### #	######### #	######### #	######### #
Amerti	Ethiopia	1	566	479	318	425	######### #	363	######### #	96	######### #	######### ##	181	725	######### #						
Koga	Ethiopia	1	341	251	117	202	######### #	148	######### #	65	######### #	######### ##	352	567	######### #						
Tendaho Irrigation dam	Ethiopia	1	037	955	009	949	######### #	949	69	45	######### #	######### ##	062	895	######### #						
Berg River Dam	South Africa	3	224	475	334	751	######### #	927	######### #	######### #	######### #	######### ##	247	798	######### #	290	180	######### #	######### #	######### #	######### #
Cere Koekwdouw	South Africa	3	256	215	133	156	######### #	512	######### #	######### #	######### #	######### ##	067	278	######### #	980	860	######### #	######### #	######### #	######### #
Injaka	South Africa	2	630	961	859	293	######### #	137	######### #	######### #	######### #	######### ##	352	959	######### #	410	130	######### #	######### #	######### #	######### #
Steelport Pumped Stor.	South Africa	2	182	258	326	042	######### #	405	######### #	######### #	######### #	######### ##	770	926	######### #	160	020	######### #	######### #	######### #	######### #
Talo	Mali	1	850	530	730	112	######### #	202	08	16	######### #	######### ##	79	448	######### #						
Hassan	Morocco	3	352	921	982	648	######### #	923	######### #	34	######### #	######### ##	37	687	######### #	850	030	######### #	######### #	######### #	######### #
Merowe	Sudan	1		46	46	46	46	46			46			46	46			10	0	10	00

Table S3: **Irrigation Water Requirement (IWR) calculated for each crop and every location with the WATNEEDS model (Chiarelli et al., 2020)**

Dam	Country	Climatic Region	Wheat	Maize	Rice	Barley	Millet	Sorghum	Soybean beans	Potatoe, sweetpotatoe	Sugarcane	Sugarbeets	Groundnuts	Cotton/fiber	Banana	Sunflower	Sesame	Olives	Melonseed	Almonds	Dates	Average IWR for all crops
			(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)		(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)	(m^3/ha)
Beni Haroun	Algeria	3	216	5003	6939	24	4084	2979	4849	5151	5117	6066	4237	2404	7195	20	3220	2960	2240	4250	5150	3795
Brezina	Algeria	3	3347	8533	9723	4125	7499	4583	7887	7253	11652	9459	6182	4584	13863	1660	5740	7890	6140	9390	11410	7417
El Agrem	Algeria	3	460	4980	7244	69	4065	3156	4809	5104	5497	6158	4464	2792	7578	20	3120	2790	1910	3970	4810	3842
Fontaine des Gazelles	Algeria	3	2870	7677	9144	3493	6714	4270	7067	6625	10379	8573	5771	4386	12415	1500	5420	7440	5210	8920	10880	6777
Kissir	Algeria	3	394	5005	7223	73	4090	3162	4848	5132	5505	6173	4470	2751	7566	20	3120	2790	1910	3970	4810	3843
Taksebt	Algeria	3	277	4838	6904	52	3940	2989	4601	5006	4951	6061	4310	2403	7157							4114
Zit Emba	Algeria	3	198	4986	6927	56	4127	3028	4968	5135	5118	6063	4275	2523	7343	20	3530	3380	2540	4740	5720	3930
Amerti	Ethiopia	1	0	0	356	0	0	0	3895	3782	4338	4642	4687	360	6325							2183
Koga	Ethiopia	1	0	0	307	0	0	0	3883	3754	4156	4660	4618	317	6076							2136
Tendaho Irrigation dam	Ethiopia	1	4856	4697	7086	4658	4029	4468	5531	5127	13229	9211	6044	6618	16013							7044
Berg River Dam	South Africa	3	1799	5203	7947	2083	4680	4933	6047	5376	8084	6025	5312	6934	11115	2290	3180	5250	1780	5490	5630	5219
Cere Koekwdouw	South Africa	3	2756	5876	8705	2671	5292	5687	6678	5946	9978	7015	5886	8050	12415	1980	2860	4590	1580	4690	4700	5650
Injaka	South Africa	2	3903	525	2533	4053	235	662	1154	1448	5233	2766	1041	1923	7369	4410	1130	5930	2210	5800	6410	3091
Steelport Pumped Stor.	South Africa	2	4624	1161	2962	4572	732	1358	1764	1838	6909	3547	1558	2883	8898	5160	2020	7400	2590	6970	8390	3965
Talo	Mali	1	7673	301	2050	1083	4093	4618	5169	5698	9414	9818	5656	3634	12435							5511
Hassan	Morocco	3	2478	5637	7474	2943	7059	5337	7507	7372	10719	8842	7325	4413	13052	1080	6010	7140	4760	8720	10980	6781
Merowe	Sudan	1	1292	1022	1393	1058	913	984	684	776	2468	1660	781	1477	2887	7580	9550	18670	10750	20710	25280	5786

Table S4. Irrigation-enabled increase in crop yield, $\Delta Y = Y_I - Y_R$

Dam	**Country**	**Climatic Region**	**Wheat**	**Maize**	**Rice**	**Barley**	**Millet**	**Sorghum**	**Soybean beans**	**Potatoe, Sweetpotatoe**	**Sugarcane**	**Sugarbeets**	**Groundnuts**	**Cotton/fiber**	**Banana**	**Sunflower**	**Sesame**	**Olives**	**Melonseed**	**Almonds**	**Dates**
			(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)	(t/ha)
Beni Haroun	Algeria	3	0.055	0.914	0.818	0.005	0.430	0.620	0.413	1.423		0.790	0.080	0.037	0.340	0.005		0.050			3.069
Brezina	Algeria	3	0.515	1.086	0.597	0.520	0.498	0.762	0.374	0.933		0.567	0.212	0.062	0.524	0.249		0.116			5.479
El Agrem	Algeria	3													0.354						2.920
Fontaine des Gazelles	Algeria	3	0.572	1.089	0.752	0.493	0.412	0.934	0.385	1.092	0.556	0.595	0.264	0.084	0.511	0.185					5.451

Kissir	Algeria	3													0.353						2.920
Takserbt	Algeria	3	0.068	0.958	0.842	0.011	0.447	0.662	0.408	1.325		0.723	0.279	0.056	0.342						
Zit Emba	Algeria	3	0.045	0.986	0.835	0.011	0.452	0.668	0.435	1.312		0.690	0.275	0.059	0.338	0.005		0.081			3.308
Amerti	Ethiopia	1			0.079				0.299	1.102					0.337						
Koga	Ethiopia	1			0.068				0.315	1.274					0.327						
Tendaho Irrigation dam	Ethiopia	1		0.447	0.405			0.368	0.209		0.460		0.141	0.048	0.570						
Berg River Dam	South Africa	3	0.256	1.190	0.983	0.300	0.581	0.759	0.514	1.374	0.567	0.630	0.274	0.088	0.507	0.279		0.120			
Cere Koekwdouw	South Africa	3	0.442	1.285	0.962	0.418	0.625	0.893	0.555	1.651		0.881			0.549	0.284		0.124			
Injaka	South Africa	2	0.303	0.089	0.310		0.025	0.080	0.082	0.249	0.516		0.058	0.022	0.368	0.211					
Steelport Pumped Stor.	South Africa	2	0.482	0.204	0.345		0.097	0.122	0.159	0.550	0.711		0.105	0.047	0.439	0.246					
Talo	Mali	1	0.134	0.064	0.244			0.637	0.388		0.591		0.256	0.052	0.408						
Hassan	Morocco	3	0.436	1.107	0.826	0.417	0.578	0.727	0.481	1.371	0.808	0.826	0.309	0.088	0.525	0.195		0.170		0.442	
Merowe	Sudan	1	0.234	0.675	0.051			0.521	0.300		0.609		0.231	0.005		0.286	0.276		0.160		

Table S5: **Country-specific crop prices (*P*) at farm gate for the year 2016 (FAOSTAT, 2021)**

Dam	Country	Climatic Region	Wheat	Maize	Rice	Barley	Millet	Sorghum	Soybean beans	Potatoe, Sweetpotatoe	Sugarcane	Sugarbeets	Groundnuts	Cotton/fiber	Banana	Sunflower	Sesame	Olives	Melonseed	Almonds	Dates
			(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)	(US$/t)
Beni Haroun	Algeria	3	411.2	335.4	547.5	228.4	400.5	326.6	1270.1	283.3	189.7	37.8	778.4	339.3	474.5			230.8			3700.6
Brezina	Algeria	3	411.2	335.4	547.5	228.4	400.5	326.6	1270.1	283.3	189.7	37.8	778.4	339.3	474.5			230.8			3700.6
El Agrem	Algeria	3	411.2	335.4	547.5	228.4	400.5	326.6	1270.1	283.3	189.7	37.8	778.4	339.3	474.5			230.8			3700.6
Fontaine des Gazelles	Algeria	3	411.2	335.4	547.5	228.4	400.5	326.6	1270.1	283.3	189.7	37.8	778.4	339.3	474.5			230.8			3700.6
Kissir	Algeria	3	411.2	335.4	547.5	228.4	400.5	326.6	1270.1	283.3	189.7	37.8	778.4	339.3	474.5			230.8			3700.6
Takserbt	Algeria	3	411.2	335.4	547.5	228.4	400.5	326.6	1270.1	283.3	189.7	37.8	778.4	339.3	474.5						3700.6
Zit Emba	Algeria	3	411.2	335.4	547.5	228.4	400.5	326.6	1270.1	283.3	189.7	37.8	778.4	339.3	474.5						3700.6
Amerti	Ethiopia	1	394.4	186.8	375.0	347.4	291.3	262.8	386.1	185.0	125.6	37.8	934.6	339.3	229.2						
Koga	Ethiopia	1	394.4	186.8	375.0	347.4	291.3	262.8	386.1	185.0	125.6	37.8	934.6	339.3	229.2						
Tendaho Irrigation dam	Ethiopia	1	394.4	186.8	375.0	347.4	291.3	262.8	386.1	185.0	125.6	37.8	934.6	339.3	229.2	412.2					
Berg River Dam	South Africa	3	251.9	219.0	547.5	227.9	400.5	233.5	421.3	254.1	38.3	37.8	525.0	126.6	471.0	412.2					
Cere Koekwdouw	South Africa	3	251.9	219.0	547.5	227.9	400.5	233.5	421.3	254.1	38.3	37.8	525.0	126.6	471.0	412.2					

Injaka	South Africa	2	251.9	219.0	547.5	227.9	400.5	233.5	421.3	254.1	38.3	37.8	525.0	126.6	471.0	412.2					
Steelport Pumped Stor.	South Africa	2	251.9	219.0	547.5	227.9	400.5	233.5	421.3	254.1	38.3	37.8	525.0	126.6	471.0	412.2					
Talo	Mali	1	415.1	175.5	291.9	568.7	216	187.3	149.4	784.7	189.7	37.8	610.9	339.3	474.5						
Hassan	Morocco	3	272.2	258.0	547.5	283.5	400.5	489.4	487.0	203.9	189.7	37.8	1043.1	339.3	736.2			600.6		301.7	
Merowe	Sudan	1	415.1	335.4	547.5	568.7	400.5	326.6	487.0	517.9	189.7	37.8	778.4	339.3	474.5		2214.6		1566.3		

Table S6 - Crop specific efficiency (e) of irrigation

Dam	**Country**	**Climatic Region**	**Wheat**	**Maize**	**Rice**	**Barley**	**Millet**	**Sorghum**	**Soybean beans**	**Potatoe, Sweetpotatoe**	**Sugarcane**	**Sugarbeets**	**Groundnuts**	**Cotton/fiber**	**Banana**	**Sunflower**	**Sesame**	**Olives**	**Melonseed**	**Almonds**	**Dates**	tomatoes	pulses	coffee
Beni Haroun	Algeria	3	0.6	0.6	0.25	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.25	0.6	0.6		0.25			0.6	0.6	0.25	0.6
Brezina	Algeria	3	0.6	0.6	0.25	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.25	0.6	0.6		0.25			0.6	0.6	0.25	0.6
El Agrem	Algeria	3	0.6	0.6	0.25	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.25	0.6	0.6		0.6			0.6	0.6	0.6	0.6
Fontaine des Gazelles	Algeria	3	0.6	0.6	0.25	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.25	0.6	0.6		0.6			0.6	0.6	0.25	0.6
Kissir	Algeria	3	0.6	0.6	0.25	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.25	0.6	0.6		0.6			0.6	0.6	0.6	0.6
Takserbt	Algeria	3	0.6	0.6	0.25	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.25	0.6	0.6		0.25			0.6	0.6	0.25	0.6
Zit Emba	Algeria	3	0.6	0.6	0.25	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.25	0.6	0.6		0.25			0.6	0.6	0.25	0.6
Amerti	Ethiopia	1	0.64	0.64	0.3	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64		0.64			0.64	0.64	0.3	0.64
Koga	Ethiopia	1	0.64	0.64	0.3	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64		0.64			0.64	0.64	0.64	0.64
Tendaho Irrigation dam	Ethiopia	1	0.64	0.64	0.3	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.3	0.64	0.64		0.64			0.64	0.64	0.64	0.64
Berg River Dam	South Africa	3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.64	0.3	0.3	0.3	0.64	0.3		0.3			0.64	0.3	0.64	0.64
Cere Koekwdouw	South Africa	3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.64	0.3	0.64	0.64	0.64	0.3		0.3			0.64	0.3	0.64	0.64
Injaka	South Africa	2	0.64	0.64	0.3	0.64	0.64	0.64	0.64	0.3	0.3	0.64	0.64	0.3	0.64	0.3		0.64			0.64	0.3	0.64	0.3
Steelport Pumped Stor.	South Africa	2	0.64	0.3	0.3	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.3	0.64	0.64		0.64			0.64	0.64	0.3	0.64
Talo	Mali	1	0.3	0.64	0.3	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.3	0.64	0.64		0.64			0.64	0.64	0.64	0.64
Hassan	Morocco	3	0.6	0.6	0.25	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.25	0.6	0.6		0.25		0.64	0.64	0.6	0.25	0.6
Merowe	Sudan	1	0.64	0.64	0.3	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.3	0.64	0.64	0.64	0.64	0.64		0.64	0.64	0.64	0.64

Table S7 - Crop specific crop value generated by irrigation (in $/ha). Columns x, y, and z show Mean Value (top 5 crops cultivated in the country, if suitable for the area), Average of all crops suitable to the area, and Crop with Max irrigation added value, respectively.

Dam	Country	Climatic Region	Wheat	Maize	Rice	Barley	Millet	Sorghum	Soybean beans	Potatoe, Sweetpotatoe	Sugarcane	Sugar beets	Groundnuts	Cotton/ fiber	Banana	Sunflower	Sesame	Olives	Melon seed	Almonds	Dates	x	y	z
			($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)
Beni Haroun	Algeria	3	25.684	352.251	512.013	1.286	191.253	230.090	582.744	1466.383		213.410	93.390	36.203	645.281			52.468			**11356.204**	2580.405	1125.619	11356.204
Brezina	Algeria	3	242.182	418.693	373.371	134.260	221.533	282.831	527.959	961.401		152.992	246.705	60.259	995.387			122.078			**20277.142**	4347.413	1786.914	20277.142
El Agrem	Algeria	3													671.062						**10805.097**	10805.097	5738.080	10805.097
Fontaine des Gazelles	Algeria	3	268.626	419.821	470.241	127.342	183.215	346.681	542.993	1124.933	1054.236	160.618	306.792	81.438	970.049						**20172.024**	5423.231	1873.501	20172.024
Kissir	Algeria	3													670.008						**10805.097**	10805.097	5737.553	10805.097
Takserbt	Algeria	3	32.179	369.268	527.093	2.783	198.952	245.702	575.561	**1364.508**		195.084	323.893	54.463	648.637							280.906	378.177	1364.508
Zit Emba	Algeria	3	21.142	379.936	522.654	2.740	201.305	247.938	613.601	1351.385		186.192	319.429	57.466	641.953						**12241.800**	3404.267	1291.349	12241.800
Amerti	Ethiopia	1			33.652				128.478	**741.412**					309.011							33.652	303.138	741.412
Koga	Ethiopia	1			29.224				135.118	**856.726**					299.916							29.224	330.246	856.726
Tendaho Irrigation dam	Ethiopia	1		96.057	173.669			109.919	89.614		**578.128**		196.359	46.465	522.801							102.988	226.626	578.128
Berg River Dam	South Africa	3	73.772	299.660	614.986	77.338	258.654	201.344	240.456	**1269.793**	216.993	170.190	214.491	31.855	955.154	127.942						191.765	339.474	1269.793
Cere Koekwdouw	South Africa	3	127.358	323.459	602.243	107.724	278.059	237.015	259.919	**1525.737**		237.943			1034.217	129.889						210.156	442.142	1525.737
Injaka	South Africa	2	87.093	22.399	193.981		10.948	21.185	38.487	229.794	197.495		45.693	7.995	**694.094**	96.524						88.400	137.141	694.094
Steelport Pumped Stor.	South Africa	2	138.713	51.349	216.065		43.365	32.319	74.466	507.762	272.326		82.226	16.825	**827.205**	112.714						129.914	197.945	827.205
Talo	Mali	1	63.684	12.969	81.411			135.606	64.476		**1121.265**		233.618	49.995	773.843							69.995	281.874	1121.265

Hassan	Morocco	3	135.654	328.297	516.903	133.621	257.318	404.554	260.533	1016.603	1532.620	222.965	480.763	84.930	**1546.447**			463.030		133.363		238.793	501.173	1546.447
Merowe	Sudan	1	110.893	260.097	32.049			193.244	162.223		**1154.704**		268.023	4.939			610.787		250.924			330.744	304.788	1154.704