Global Environmental Change 50 (2018) 110–122

Contents lists available at ScienceDirect

Global Environmental Change

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

Global-scale patterns and determinants of cropping frequency in irrigation dam command areas

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ARTICLE INFO

Keywords:
Surface irrigation
Land use intensity
Cropping frequency
Fallow land
Water storage infrastructure
Boosted regression trees

ABSTRACT

A growing human population and shifting consumption patterns increase the pressure on agricultural production systems. Reservoir-based irrigation has boosted agricultural production through higher cropping frequencies, whereas the magnitude of this effect varies significantly across the globe. Technological, biophysical and socio-economic constraints often limit cropping frequency in the command areas of irrigation dams, yet the relationships with these factors remain poorly understood at the global scale. Here, we first determined the size and location of 1288 command areas of irrigation dams commissioned since 1985. Within these areas, we studied cropping frequency during the period of 2001–2012 using a global time series of land cover information. We further investigated potential biophysical, socio-economic and technological constraints for intensive cropping using a Boosted Regression Trees modeling framework. Our results showed that the largest extent of reservoir-irrigated croplands are located in India (5.9 Mha), Indonesia (1.5 Mha), China (1.4 Mha), Vietnam (0.9 Mha), Turkey (0.7 Mha), Iran (0.7 Mha), and Thailand (0.6 Mha). Globally, cropping frequencies in irrigation dam command areas were on average 16% higher compared to rainfed control areas, yet pronounced differences in the strength and direction of this effect were apparent across world regions. Technological properties of dams and irrigation systems were amongst the most important variables for explaining global-scale variation in cropping frequency. Specifically, we observed low cropping frequencies in smaller command areas ($< 10{,}000$ ha) and under long distance water allocation (> 20 km). The command areas of small reservoirs (storage capacity $< 7.9\ \mathrm{Mm}^3$) showed similar cropping frequencies compared to large reservoirs, yet with increased tolerance toward biophysical constraints. Our findings thus support arguments for future emphasis on de-centralized water storage facilities in order to reduce water losses and to improve access to irrigation water and infrastructure, thereby contributing to better meeting future agricultural production targets.

1. Introduction

Current population dynamics and shifting demands for agricultural produce increase the pressure on land-based production systems (Foley et al., 2011). Globally limited availability of fertile land will further require intensification of existing agricultural land (Tilman et al., 2011; Lambin and Meyfroidt, 2011). Irrigation is a key component in this context, currently boosting productivity on 24% of the world´s cultivated land (Portmann et al., 2010; Siebert and Döll, 2010a). Man-made reservoirs are vital for agricultural production, as they provide 40% of the global surface water extracted for irrigation (Biemans et al., 2011). Thereby, irrigation reservoirs provide the water needed to overcome periodic scarcity and allow for the decoupling of agricultural production from intra- and inter-annual precipitation variability (Benhin, 2008; Hillel et al., 2008; Lipton et al., 2003). The improved access to water allows for stabilizing and intensifying agricultural production systems (Domènech, 2015; Mueller et al., 2012; Siebert and Döll, 2010a) by minimizing undesired fallow periods and thus enabling more frequent cultivation (Gaur et al., 2008).

The benefits of irrigation reservoirs for agricultural production are frequently offset by technological, socio-economic and biophysical constraints of their location (hereafter collectively referred to as "*operational reality*"). On the technological side, extensive unlined canal schemes with high conveyance losses (Thakkar, 2000; World Bank,

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https://doi.org/10.1016/j.gloenvcha.2018.02.011
Received 2 June 2017; Received in revised form 31 January 2018; Accepted 25 February 2018

2007; Rohwer et al., 2007), sediment accumulation in reservoirs (Alahiane et al., 2016; Hu et al., 2009), or increasing competition between multiple water uses in the water-energy-food nexus interfere with irrigation water supply (Bonsch et al., 2015; Lacombe et al., 2014; Scott et al., 2007). Further, benefits for agricultural production vary across differently sized water storage infrastructures (Blanc and Strobl, 2014; WCD, 2000). Regarding socio-economic factors, market accessibility and population density co-determine irrigation suitability and agricultural intensity (Neumann et al., 2011). Further, inefficient administration of water distribution, or weak governance structures hamper the use of irrigation infrastructure in readily equipped schemes (Yami, 2015; Singh, 2016; Klümper et al., 2017). Biophysical limitations include unsuitable topography (Koluvek et al., 1993) and climate (Neumann et al., 2011; Iizumi and Ramankutty, 2015), or declining soil productivity under excessive irrigation (Gómez-Limón and Picazo-Tadeo, 2012; Singh, 2016).

While local to regional scale studies suggest that a reservoir's operational reality determines the intensity of agriculture in its command area, it remains unclear if case study insights are generalizable across larger geographic extents. A key reason for this knowledge gap is a scarcity of high-quality, spatial datasets on irrigation dam command areas. Several studies aimed at mapping irrigated lands globally (Salmon et al., 2015; Siebert et al., 2015), but the spatially explicit attribution of irrigated lands to dams has rarely been undertaken. First approaches associating changes in agricultural production with dams were based on aggregated areal units, such as administrative districts (Duflo and Pande, 2007), or watershed boundaries (Strobl and Strobl, 2011). These approaches represent only indirect approximations of command areas, and may be improved by considering dam- and location-specific parameters (e.g. reservoir storage capacity or topography). Such a refined dataset is required for better understanding the spatial distribution and properties of irrigation dam command areas (Strobl and Strobl, 2011).

Agricultural intensification (i.e. increasing production output on agricultural land) is commonly achieved via increasing inputs, such as water, labor or fertilizer, or via an optimized land management that leads to a more efficient use of the same input resources (Erb et al., 2013). A common mechanism for increasing the output of cropland is to increase the frequency of cultivation, or cropping frequency, for instance via the introduction of multiple cropping cycles (Iizumi and Ramankutty, 2015) or by minimizing fallow years (Boserup, 1965; Estel et al., 2016). In the year 2000, 28% of the world´s croplands were fallow (Siebert et al., 2010b), indicating a vast potential for agricultural intensification. Specifically in areas where access to water is critical for successful crop cultivation, insufficient irrigation water supply is causing undesired fallow periods (Gaur et al., 2008), which translate into lower cropping frequencies through a variety of processes (Evans and Sadler, 2008). At the command area level, altered irrigation water distribution to reduce the number of water users is a common measure for adapting to insufficient water availability (Bouman et al., 2007; Perry and Narayanamurthy, 1998). At the farm level, fallowing can be performed to spatially optimize irrigation distribution (i.e. temporarily or permanently retiring land from production to allocate the remaining water to a smaller area), or to preserve soil moisture for upcoming cultivation cycles (Evans and Sadler, 2008; Debaeke and Aboudrare, 2004; Kahil et al., 2015). Additionally, long-term irrigation mismanagement and lack of drainage systems can deteriorate soil productivity, ultimately leading to temporary or permanent land abandonment (Evans and Sadler, 2008; Qadir et al., 2014; Wood et al., 2000).

In the light of increasing demands for food, feed, fuel, and fiber, the further exploitation of reservoir-based irrigation is part of the option space for increasing the productivity of cropping systems (Manikowski and Strapasson, 2016; van Ittersum et al., 2016; You et al., 2011). Assessing the scope of these productivity increases requires investigating the cropping frequency in reservoir-based irrigation schemes and its spatial determinants on a global scale. Specifically, identifying technological limitations for agricultural production will help to better target infrastructure investment. Delays and failures to meet cropping intensity targets are prevalent for large dams and thus potentially relate to infrastructure size (WCD, 2000). Since the causes of such variations remain weakly understood, a comparative analysis of cropping frequency determinants in command areas of large versus small reservoirs is needed to disentangle the underlying processes.

Here, we first approximated the command areas of a global sample of irrigation dams and assessed cropping frequencies therein. We then investigated the effects of the technological, biophysical, and socio-economic properties of irrigation dam command areas on cropping frequency using Boosted Regression Trees. Specifically, we addressed the following research questions:

1 What are the spatial patterns of irrigation dam command areas at the global scale and cropping frequencies therein?
2 How do the technological, socio-economic and biophysical properties of command areas determine cropping frequency in command areas?
3 Which command area properties are related to low cropping frequencies and how do these differ for smaller and larger reservoirs, respectively?

2. Material and methods

2.1. Command area allocation

We collected data on geolocations of single-purpose and multi-purpose irrigation dams from the GRanD and AQUASTAT databases (Lehner et al., 2011; FAO, 2015), while restricting our analyses to dams commissioned since 1985 (n = 1626). We fused the two databases, since GRanD comprised highly detailed data on geolocation and dam attributes, while AQUASTAT included dams not represented in GRanD. As a large fraction of the AQUASTAT entries missed information on geolocation, we used available data on dam and river name, closest city, and administrative unit to locate these missing entries in Google Maps (n = 596). Existing coordinates were checked and corrected, if necessary (n = 412). After fusion with the GRanD database and duplicate removal, the database comprised a total of 1370 irrigation dams in 71 countries worldwide (Fig. 1).

A globally concise definition of command area size and location is challenging, since regional biophysical, technological, and socio-economic factors co-determine conveyance and irrigation efficiencies (Daccache et al., 2014; Jägermeyr et al., 2015; Rohwer et al., 2007), and thus regulate the extent of land that can be irrigated given a quantity of water. To account for these differences, we calculated country-level ratios between total area of cropland irrigated with surface water [ha] and total reservoir storage capacity [Mm^3]. We used the global map of irrigated areas (Siebert et al. 2013) to derive national surface-water irrigated land extent, and AQUASTAT statistics (FAO, 2015) to extract the national reservoir storage capacity in the year 2005 or the most proximate year for which data was available. The resulting ratio represented the potential area that can be irrigated given a unit of water [ha/Mm^3] in a given country. Assuming that reservoir storage capacity is a primary determinant of command area size (Strobl and Strobl, 2011), we multiplied the storage capacity of each dam [Mm^3] with the country-specific ratio to estimate the command area size [ha] for each dam. Finally, we compared the resulting estimates with reported command area sizes (n = 266) gathered from independent national databases, reports, and the World Register of Dams (Supplementary Material, Table S1; see Fig. 4 and Table S2 for results).

We spatially allocated the estimated command area extent for each dam, accounting for parameters representing: irrigated cropland abundance (P1), topography (P2), watershed structures (P3), reservoir size (P4), national borders (P5), and distance to the dam (P6) (Fig. 2a–f). To understand the sensitivity of the allocation, we tested 24