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Assessing gaps in irrigated agricultural productivity through satellite earth observations—A case study of the Fergana Valley, Central Asia

Fabian Löw[a,b,*], Chandrashekhar Biradar[a], Elisabeth Fliemann[a], John P.A. Lamers[d], Christopher Conrad[c]

[a] International Centre for Agricultural Research in Dry Areas (ICARDA), Amman, Jordan
[b] MapTailor Geospatial Consulting, Bonn, Germany
[c] Department for Geography and Geology, University of Würzburg, Germany
[d] Center for Development Research (ZEF), Bonn, Germany

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ABSTRACT

Improving crop area and/or crop yields in agricultural regions is one of the foremost scientific challenges for the next decades. This is especially true in irrigated areas because sustainable intensification of irrigated crop production is virtually the sole means to enhance food supply and contribute to meeting food demands of a growing population. Yet, irrigated crop production worldwide is suffering from soil degradation and salinity, reduced soil fertility, and water scarcity rendering the performance of irrigation schemes often below potential. On the other hand, the scope for improving irrigated agricultural productivity remains obscure also due to the lack of spatial data on agricultural production (e.g. crop acreage and yield). To fill this gap, satellite earth observations and a replicable methodology were used to estimate crop yields at the field level for the period 2010/2014 in the Fergana Valley, Central Asia, to understand the response of agricultural productivity to factors related to the irrigation and drainage infrastructure and environment. The results showed that cropping pattern, i.e. the presence or absence of multi-annual crop rotations, and spatial diversity of crops had the most persistent effects on crop yields across observation years suggesting the need for introducing sustainable cropping systems. On the other hand, areas with a lower crop diversity or abundance of crop rotation tended to have lower crop yields, with differences of partly more than one t/ha yield. It is argued that factors related to the infrastructure, for example, the distance of farms to the next settlement or the density of roads, had a persistent effect on crop yield dynamics over time. The improvement potential of cotton and wheat yields were estimated at 5%, compared to crop yields of farms in the direct vicinity of settlements or roads. In this study it is highlighted how remotely sensed estimates of crop production in combination with geospatial technologies provide a unique perspective that, when combined with field surveys, can support planners to identify management priorities for improving regional production and/or reducing environmental impacts.

1. Introduction

Due to the surging need to meet the demands of a rapidly growing world population (Alexandratos and Bruinsma, 2012; Erb et al., 2013), a sustainable increase of crop production (yield) is among the major challenges (FAO, 2011). However, looming land scarcity often limits further agricultural expansion into natural ecosystems (Lambin et al., 2013; Lambin and Meyfroidt, 2011). Hence, sustainable intensification of crop production is virtually the sole means to enhance food supply (Foley et al., 2011; Wichelns and Oster, 2006), which has been recognized as the second sustainable development goal (SDG), underscoring that only sustainable food production systems should be ensured and resilient agricultural practices implemented as options to increase productivity and production (United Nations, 2016). However, current unsustainable land and water management practices, irrespective of scales, and spanning from farmer's decisions (e.g. furrow irrigation, application of fertilizer, etc.) to governmental rules (e.g. state order,

* Corresponding author at: International Centre for Agricultural Research in Dry Areas (ICARDA), Amman, Jordan.
E-mail address: fabian.loew@gmx.de (F. Löw).

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mono-culture, etc.) are still major hurdles for achieving productive potentials (Nellemann et al., 2009).

Irrigated crop production, which ranks among the most intensive cultivation practices (Salmon et al., 2015; Xiao et al., 2006), is worldwide threatened by a series of challenges including soil degradation (Gibbs and Salmon, 2015), reduced soil fertility, water scarcity (Tischbein et al., 2013), and diseases that in turn cause productivity decline (FAO, 2011). Also distorted macro economies, which, despite providing operating subsidies, render farming unprofitable that in turn results in repeated underinvestment over longer periods (Martius et al., 2012). Hence, considerable scope exist for improving agricultural productivity and inverse the on-going trend of losses in economic revenues, income, and agro-ecosystem services (FAO, 2013, 2011; Lobell, 2013; Lobell et al., 2010; Schierhorn et al., 2014). Particularly in (semi-) arid environments, spatially targeted means to improve production must be considered for irrigated agriculture because irrigated areas account for 16–20% of the total arable area and contribute to ca. 44% of total crop production (Alexandratos and Bruinsma, 2012).

Crop yield estimates are useful also for understanding the responds of crop productivity to managerial decisions and environmental factors, which require however information about the variability of yields at the field scale (Lobell, 2013). Satellite remote sensing can provide estimates of crop acreage and yields over larger regions (Johnson, 2014; Justice and Becker-Reshef, 2007; Lobell, 2013; Lobell et al., 2015). In combination with Geographical Information Systems (GIS), the potential for improving the information-base under irrigation management has been underscored (Anderson et al., 2011; Bastiaanssen and Bos, 1999; Lambin et al., 1993). Through a classification of satellite images in combination with crop yield models, archives of crop type maps allow for back-tracing and monitoring a score of themes including diversity and cropland-use intensity (Conrad et al., 2016a; Estel et al., 2016; Löw et al., 2015b; Martinez-Casasnovas et al., 2005), monitoring crop yield variability (Lobell, 2013; Lobell et al., 2009a) and detecting marginal lands (Fritsch et al., 2015). In turn, such information can guide decisions on sustainable agricultural production intensification (United Nations, 2016).

Although variability in crop yields on field level is an ubiquitous feature of agricultural landscapes, the gap between potential and actual yields often remain, even for the highest-yielding croplands (Lobell et al., 2005). Currently, many agricultural systems of the world have yields approaching only 70–80% of their yield potential (Lobell et al., 2009a). An improved understanding of the most limiting factors to yields is a precondition for reducing environmental impacts of agriculture practices such as e.g. the over-application of fertilizers, and identifying opportunities for improving productivity and hence farmers' income.

The irrigation systems of Central Asia are a prominent example for arid production systems highly exposed to production losses mainly caused by inefficient land and water use and on-going land degradation (Conrad et al., 2013a, 2016b; Glantz, 2005; Karimov and Niño-Zarazúa, 2014). The Fergana Valley in Uzbekistan is not only typical for the situation in Central Asia (Bichsel, 2009) but has a reputation of being among the most important agricultural areas in this region (Abdullaev et al., 2009b). It represents a large-scale cotton production system developed during the former Soviet Union epoch, with about 1.653 million ha (Mha) of irrigated land (SIC-ICWC, 2015). For around 70% of its population irrigated production is the cornerstone of their livelihoods whilst agriculture contributes to about 24% of the country's gross domestic product (Bichsel, 2009; Reddy, 2012). Whilst in other regions worldwide the application of GIS and remote sensing for supporting planning with information on crop production has been well-documented, this lacks for the irrigation areas in Central Asia such as in Fergana. Because agricultural diversification and intensification are important pillars in the theorem of sustainable agriculture, we assessed patterns of crop productivity and focused specially on the quantification and assessments of factors determining observed spatial patterns of crop yields using satellite remote sensing and regression modelling.

2. Study area

The Fergana Valley is located in the eastern part of the Aral Sea Basin, amid the Alatau Range in the North, the Tian Shan Mountains in the East and the Alay Mountains in the South (Fig. 1). Large tracts of the valley centre fall within the Republic of Uzbekistan, while the northern and eastern fringes are located in the Kyrgyz Republic. Smaller areas in the west and southwest belong to the Republic of Tajikistan. The climate is continental dry with 100–200 mm average annual precipitation. The average temperature ranges from −3.9 °C to 3.9 °C in January and from 20.2 °C to 34.7 °C in July (Munoz and Grieser, 2006). Future temperature increases are expected to be 1.5–2.5 °C (Lioubimtseva and Henebry, 2009) leading to a shift in runoff peaks from spring towards late winter seasons (Siegfried et al., 2012). The two major head flows of its main river Syrdarya, namely Naryn, Karadarya, and Tschirtschik, generate almost 70% of the entire valleys surface water (SIC-ICWC, 2015), which origins from the surrounding mountains and represents virtually the sole source for irrigation.

The Fergana Valley is one of the oldest and most intensely used irrigation systems in Central Asia (Bichsel, 2009). Despite its upstream location between the foothills of the Tian Shan Mountain, irrigated agriculture suffers from low field application efficiencies, groundwater salinization (Pereira et al., 2009; Reddy et al., 2013) and high river water salinities (Qadir et al., 2009). Even within the Fergana Valley, upstream-downstream disparities of water availability have been reported (Abdullaev et al., 2009b). Since the 1960s, cotton has been the main crop although successively supplemented by winter wheat after independence from the Soviet Union in 1991 (Abdullaev et al., 2009b). Whilst wheat yields stabilized around 5 t/ha between 1980 and 2000, cotton yields in the valley decreased from 4.6 t/ha (1980) to 2.9 t/ha (2000) (SIC-ICWC, 2015).

Fergana Valley is furthermore the most densely populated region in entire CA with more than 11 million inhabitants and densities up to 500 inhabitants per km^2 (FAO, 2013). The region's population is predicted to increase to twenty million over the next 40 years (United Nations, 2015), which will further increase the demand for food and water resources. Due to population growth, the availability of water in Uzbekistan already decreased from 2457 (1990) to 1837 m^3/yr per capita (2010) (FAO-UNESCO, 2013).

3. Datasets and preprocessing

3.1. Satellite data for crop classification and yield estimation

The analysis was based on multispectral Landsat-5 TM and RapidEye data over 2012–2014 (Table 1). The RapidEye system is a constellation of five identical satellites with a spectral range covering five channels (blue, green, red, red edge and near infrared), with a pixel size of 6.5 m (Tyc et al., 2005). Landsat-5 TM (30 m) comprises several channels including visible (blue, green, red), near infrared (NIR), and shortwave infrared (SWIR-1, SWIR-2) spectra, with a pixel size of 30 m. Thermal and pan-chromatic bands were not used.

Two pre-processing steps (geometric and atmospheric correction) ensured that the images were geographically adjusted and