

Rufin, Philippe; Peña-Guerrero, Mayra Daniela; Umirbekov, Atabek; Wei, Yanbing;
Müller, Daniel

Article — Published Version

Post-Soviet changes in cropping practices in the irrigated drylands of the Aral Sea basin

Environmental Research Letters

Provided in Cooperation with:

Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle (Saale)

Suggested Citation: Rufin, Philippe; Peña-Guerrero, Mayra Daniela; Umirbekov, Atabek; Wei, Yanbing; Müller, Daniel (2022) : Post-Soviet changes in cropping practices in the irrigated drylands of the Aral Sea basin, Environmental Research Letters, ISSN 1748-9326, IOP Publishing, Bristol, Vol. 17, Iss. 9, <https://doi.org/10.1088/1748-9326/ac8daa> , <https://iopscience.iop.org/article/10.1088/1748-9326/ac8daa>

This Version is available at:

<https://hdl.handle.net/10419/264382>

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ENVIRONMENTAL RESEARCH
LETTERS

LETTER

Post-Soviet changes in cropping practices in the irrigated drylands of the Aral Sea basin

OPEN ACCESS

RECEIVED
21 June 2022REVISED
25 August 2022ACCEPTED FOR PUBLICATION
30 August 2022PUBLISHED
12 September 2022

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Philippe Rufin^{1,2,*} , Mayra Daniela Peña-Guerrero^{2,3,6} , Atabek Umirbekov^{2,3,6} , Yanbing Wei^{3,4} and Daniel Müller^{2,3,5} ¹ Earth and Life Institute, Université Catholique de Louvain, Place Pasteur 3, 1348 Louvain-la-Neuve, Belgium² Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany³ Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Theodor-Lieser-Str. 2, 06120 Halle (Saale), Germany⁴ Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences (CAAS), 12 Zhongguancun South St., Beijing 100081, People's Republic of China⁵ Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany⁶ National Research University TIAME, 39 Kari Niyazov St., Tashkent 100000, Uzbekistan

* Author to whom any correspondence should be addressed.

E-mail: philippe.rufin@geo.hu-berlin.de**Keywords:** cropping frequency, crop production, land use intensity, irrigation, intensification, Landsat, Central AsiaSupplementary material for this article is available [online](#)**Abstract**

Water withdrawals for irrigated crop production constitute the largest source of freshwater consumption on Earth. Monitoring the dynamics of irrigated crop cultivation is crucial for tracking crop water consumption, particularly in water-scarce areas. We analyzed changes in water-dependent crop cultivation for 650 000 km² of Central Asian drylands, including the entire basin of the Amu Darya river, once the largest tributary to the Aral Sea before large-scale irrigation projects grossly reduced the amount of water reaching the river delta. We used Landsat time series to map overall cropland extent, dry season cropping, and cropping frequency in irrigated croplands annually from 1987 to 2019. We scrutinized the emblematic change processes of six localities to discern the underlying causes of these changes. Our unbiased area estimates reveal that between 1988 and 2019, irrigated dry season cropping declined by 1.34 million hectares (Mha), while wet season and double cropping increased by 0.64 Mha and 0.83 Mha, respectively. These results show that the overall extent of cropland in the region remained stable, while higher cropping frequency increased harvested area. The observed changes' overall effect on water resource use remains elusive: Following the collapse of the Soviet Union, declining dry season cultivation reduced crop water demand while, more recently, increasing cropping frequency raised water consumption. Our analysis provides the first fine-scale analysis of post-Soviet changes in cropping practices of the irrigated areas of Central Asia. Our maps are openly available and can support future assessments of land-system trajectories and, coupled with evapotranspiration estimates, changes in crop water consumption.

1. Introduction

The world's freshwater resources are under increasing pressure, mainly due to rising extractions for irrigated agriculture (Vörösmarty *et al* 2010). Agricultural consumption of irrigation water has been rising rapidly since the onset of the green revolution. Irrigated area increased from 102 million hectares (Mha) in 1950–306 Mha in 2005 (Siebert *et al* 2014) and

to 338 Mha in 2017 (FAO 2020). In 2017, irrigation was responsible for 71% of global freshwater consumption (World Bank 2021). Agriculture's high water demand can have severe consequences for local ecosystems and lead to ecosystem degradation, soil salinization, and soil erosion (Deng and Chen 2017, Jiang *et al* 2019). Meeting the rising demand for food, feed, fuel, and fiber amidst the growing scarcity of water resources will be a daunting task amidst the

supply-side challenges aggravated by land degradation and climate change.

Irrigation exacts a particularly heavy toll on water resources in arid and semi-arid areas where ground- and surface water resources are limited, and where crop production crucially depends on irrigation. Climate change amplifies water stress in crop production and increases water extraction due to more frequent and intense drought stress and higher plant evapotranspiration (Pokhrel *et al* 2021). Changes in the extent and timing of irrigated cultivation can affect freshwater availability, intensify water demand, and alter hydrological cycles (Singh 2015). Monitoring irrigated crop production on fine spatial and temporal scales is therefore indispensable for estimating crop water extraction, specifically in water-scarce regions.

Central Asia is a hotspot of climate change in which the rising consumption of irrigation water constitutes a salient challenge in light of decreasing water availability (Reyer *et al* 2017). Irrigated cropland in Central Asia increased from 2.5 Mha in 1910 to 7.4 Mha in 1990 (Micklin 2010). Expansion of irrigation mainly served to increase the production of cotton, a crop with high blue water consumption, to provide this ‘white gold’ to the Soviet Union (Abdullaev *et al* 2007, Aldaya *et al* 2010). After the collapse of the Soviet Union in 1991, irrigated agriculture remained a mainstay of the five newly independent Central Asian states. The extent of cotton cultivation contracted while less water-demanding wheat cultivation expanded, particularly in Uzbekistan and Turkmenistan (Kariyeva and van Leeuwen 2012, Beurs *et al* 2015). Unfortunately, official statistics on changes in cropping patterns are only available at the provincial level. Additionally, the quality of available statistical data is doubtful, as these data often represent planning figures more than a record of the actual situation (Edlinger *et al* 2012).

Remote sensing provides independent monitoring data to capture the agricultural dynamics of large areas at a fine spatial and high temporal resolution. The rapid improvement of hardware, algorithms, and data availability offers unprecedented opportunities for mapping agricultural systems, including the production of crop-type maps on national to continental scales (d’Andrimont *et al* 2021, Blickensdörfer *et al* 2022). Historic reconstructions of crop types, however, are hampered by a lack of ground data for the past and the varying availability of satellite data due to changing sensor constellations and acquisition plans. One solution is the analysis of intra-annual time series of satellite images to identify cropping practices based on the timing and frequency of cultivation, e.g. during the wet season, the dry season, or both (Bégué *et al* 2018). This reduces the need for ground-based crop-type reference data (Rufin *et al* 2021a) while enabling insight into the dynamics of land use intensity and crop water use (Conrad *et al* 2016).

Here, we use Landsat time series to provide a spatially and temporally detailed characterization of changes in the cropping practices of the Amu Darya and parts of the Syr Darya basins. We pursue three objectives: First, we map changes in cropland extent, dry season cropping, and cropping frequency for every year from 1987 to 2019. Second, we characterize the change trajectories of cropping practices at the national and regional scales. Third, we investigate typical change processes and highlight their underlying drivers for six exemplary sites. Overall, our research provides the first long-term assessment of changes in cropping practices in this understudied region. All resulting maps are openly available for further use at <https://doi.org/10.5281/zenodo.6957722>.

2. Methods

2.1. Study area

Our study area covers 650 000 km² of Central Asian drylands (figure 1). We include the entire Amu Darya basin (535 000 km²) and parts of the Syr Darya basin. The study area is characterized by an arid climate with hot, dry summers and cold winters. Crop cultivation almost exclusively depends on irrigation. The Amu Darya was the largest tributary to the Aral Sea before large-scale irrigation projects were initiated during the Soviet period, particularly since the 1960s (Micklin 2014). At present, almost all crop production in the study area relies on surface water irrigation (FAO 2012, White *et al* 2014).

The growing period in the study area can be divided into two cropping seasons: the wet season and the dry season. Wet season crops (mainly winter wheat) reach maturity between April and July and dry season crops (mainly cotton) are harvested between August and October. Winter wheat consumes less blue water because its growing season stretches from autumn, through winter to spring, when precipitation is higher and evapotranspiration lower. Cotton, in contrast, is grown over the hot, dry summer period and thus has a substantially higher water demand compared to that of winter wheat (Khaydar *et al* 2021).

Overall, our study area covers nine provinces in Uzbekistan, three in Tajikistan, and two in Turkmenistan (figure 1). We excluded areas above elevations of 2000 m because most crop production and almost all irrigated agriculture is concentrated at lower altitudes.

2.2. Workflow

Our workflow (figure 2) relies on the Google Earth Engine cloud-computing platform and Quantum GIS (QGIS) for map production. We used Python and R for local post-processing and validation. We generated seasonal time series metrics from available Landsat surface reflectance images of the study area for each year from 1987 to 2019. Training and validation

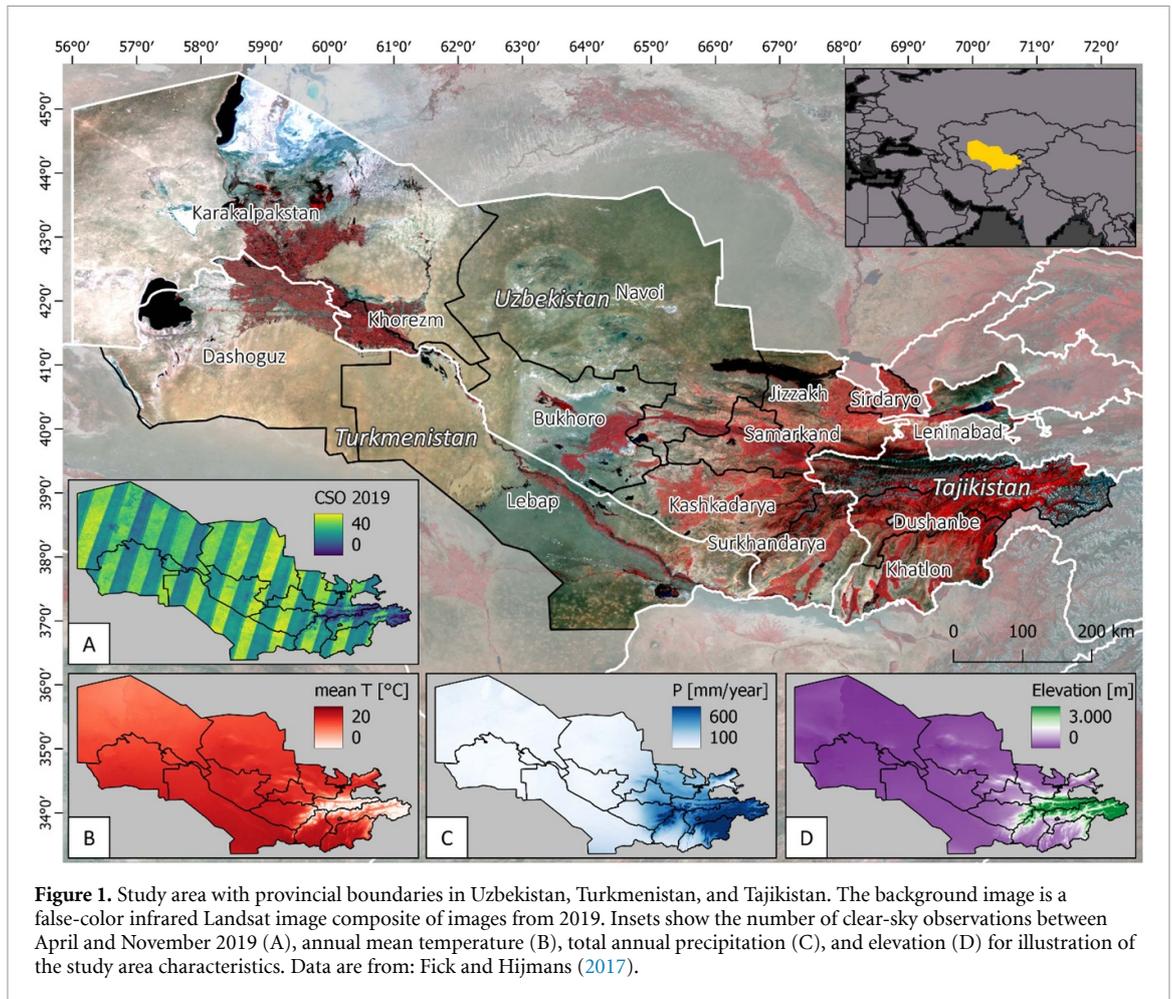


Figure 1. Study area with provincial boundaries in Uzbekistan, Turkmenistan, and Tajikistan. The background image is a false-color infrared Landsat image composite of images from 2019. Insets show the number of clear-sky observations between April and November 2019 (A), annual mean temperature (B), total annual precipitation (C), and elevation (D) for illustration of the study area characteristics. Data are from: Fick and Hijmans (2017).

data for the target class catalog (table 1) were generated based on Google Earth Engine and the GEE Time Series Viewer plugin for QGIS (Rufin *et al* 2021b). We used a random forest classification model (Breiman 2001) to produce annual maps of cropping practices. We limited our analyses to regions that were used for dry season cropping for at least 5% (two years in most cases) of the study period. We validated the maps with state-of-the-art techniques for estimating accuracy and area (Olofsson *et al* 2014, Stehman 2014). We achieved a median overall accuracy of 91.4% across the study period. We derived class-wise error-adjusted area estimates from the reference sample to track the overall changes in class area independently of the maps.

We spatially aggregated the annual categorical maps to derive time series of continuous land use metrics at the 3 km grid-cell level. These metrics were (a) the percentage of cropland (including wet season cropping, dry season cropping, and double cropping), (b) proportion of dry season cropping (including double cropping and fodder crops) relative to overall cropland in percent, and (c) cropping frequency, represented by the average number of harvests on the cropland in each grid cell. Wet season cropping and dry season cropping produce

one harvest, while double cropping (including fodder crops) produces two harvests. Cropping frequency thus ranges from 1 (all cropland is harvested once) to 2 (all cropland is harvested twice). Our data thereby allows deriving the extent of annual cropland and annual harvested area, which exceeds the cropland area by the amount of areas harvested twice per year, i.e. double-cropped areas.

The annual time series of the three land use metrics were used to (a) assess country-level change trajectories; (b) create a spatially explicit map of overall change patterns, using autoregressive linear models; and (c) describe typical land use change processes in the region, based on official reports, statistics, scientific literature, and expert knowledge. All methods are described in detail in the supplementary material.

3. Results

3.1. Post-Soviet changes in cropping practices

Our error-adjusted area estimates provide insight into the overall patterns of change in the study period (figure 3). Wet season cropping reached a low point of 0.33 Mha (± 0.11 Mha) in 1989, increased to 1.12 Mha (± 0.2 Mha) by 2000, and subsequently changed little. The total area of wet season crops amounted to

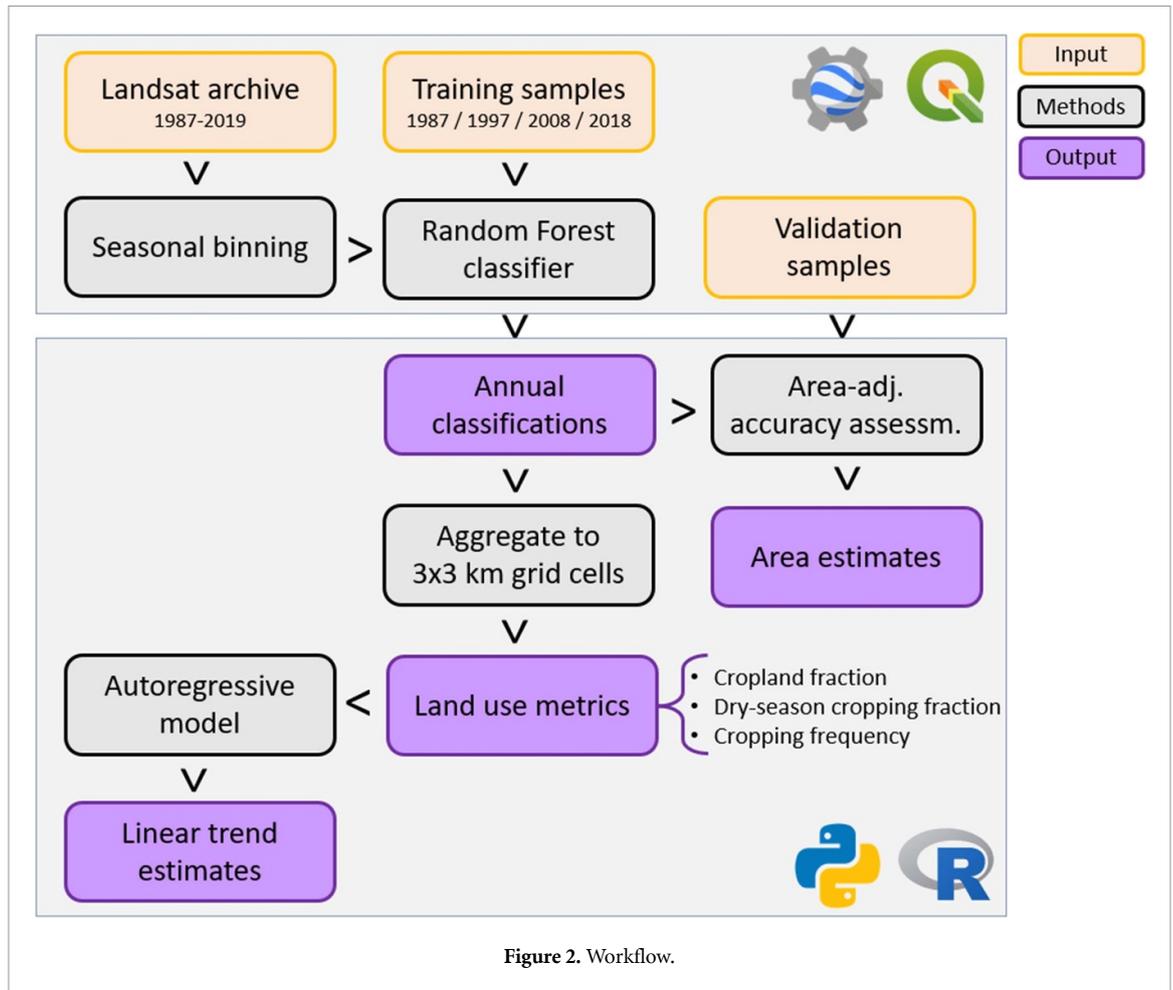


Figure 2. Workflow.

Table 1. Target class catalog.

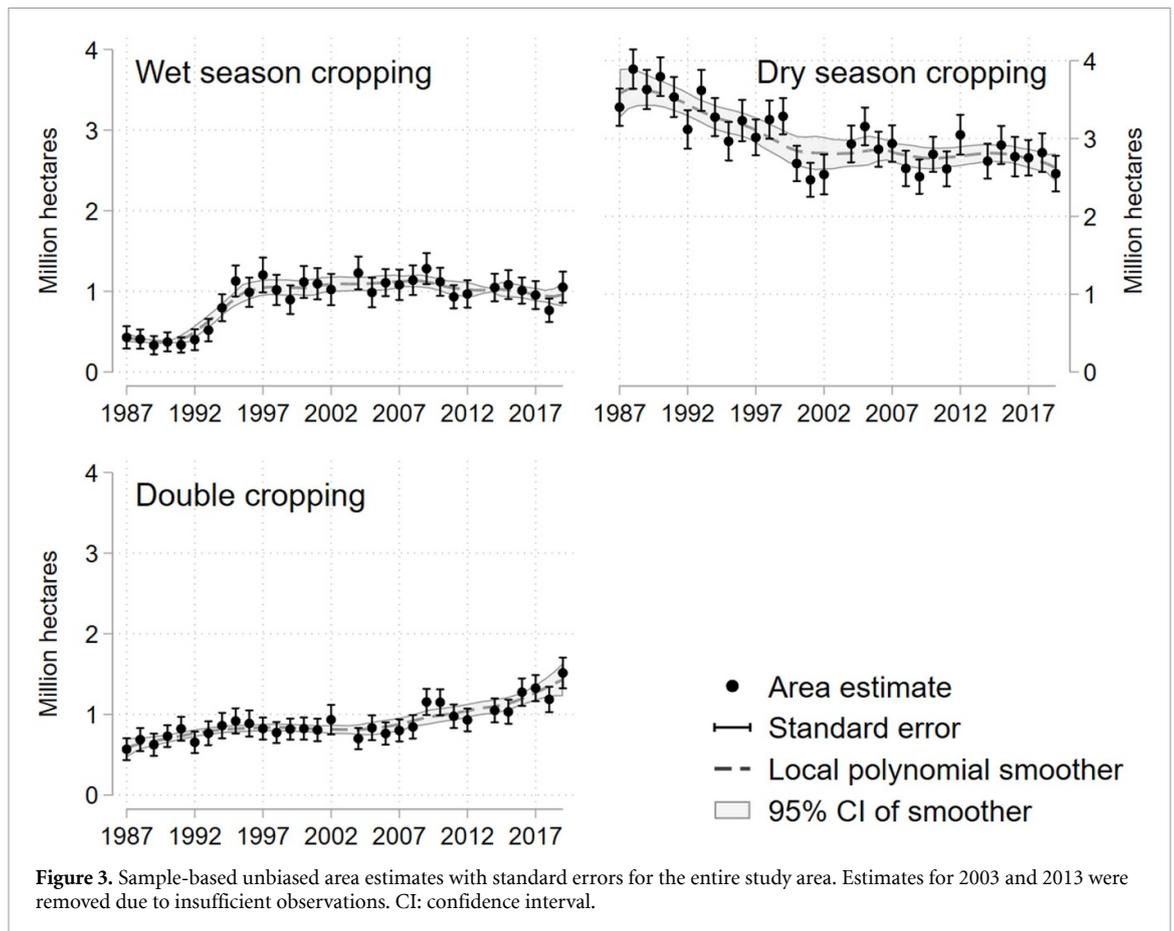
Class name	Description
Wet season cropping	Irrigated or rain-fed crops planted in winter or early spring and harvested before mid-June (mostly winter wheat).
Dry season cropping	Irrigated summer crops (mostly cotton but also rice and vegetables) that are harvested in the second half of the year.
Double cropping	Two cultivation cycles with two harvests per year; can also include irrigated fodder crops (mostly alfalfa) with multiple harvests.
Non-cropland	Vegetated lands (woody vegetation in forests, shrublands, orchards, and tree plantations and herbaceous vegetation in wetlands, fallows, and unmanaged grasslands) and unvegetated lands (rock, settlements, sand, and surface water).

1.05 Mha (± 0.19 Mha) in 2019. Dry season cropping is the most extensive of the mapped categories, with a maximum of 3.89 Mha (± 0.25 Mha) in 1988. We observed gradual declines thereafter, particularly during the 1990s. In 2001, dry season cultivation reached its minimum of 2.54 Mha (± 0.26 Mha). In 2019, dry season crops covered 2.55 Mha (± 0.23 Mha). Dry season crops exhibit substantially more variation in the error-adjusted estimates than do wet season crops and double cropping. Double cropping occupied 1.51 Mha (± 0.19 Mha) in 2019, up from only 0.57 Mha (± 0.14 Mha) in 1987. The expansion of double cropping was particularly rapid after 2000.

Overall, the higher cropping frequency resulted in an increase in the harvested area across the study region during the observation period, while cropland extent remained stable (supplementary material, figures S5 and S6).

3.2. Country-level change trajectories

We assessed the annual distributions (median and interquartile range) of the land use metrics at the country level (figure 4). Overall, cropland percentages in all countries experienced a slight decrease until the 2000s. While the decrease continued in Tajikistan, the proportion of cropland slightly increased after



2000 in Turkmenistan and Uzbekistan. The percentage of dry season cropping decreased most drastically in Uzbekistan, from 95% before the collapse of the Soviet Union to 60% in 2001. Volatile patterns in dry season cropping were observed in Tajikistan. Cropland percentages remained stable in Turkmenistan and slightly increased in Uzbekistan. Cropping frequency was low overall, decreasing in the 1990s but increasing after 2010 in Tajikistan and especially in Uzbekistan.

Linear trend estimates from an autoregressive model reveal the spatial patterns of the overall change processes for each metric (figure 5). Hotspots of cropland expansion occurred, e.g. in the outer limits of irrigation districts in Turkmenistan, while cropland contracted in the surrounding areas of the downstream reaches of the Amu Darya. Increases in dry season cropping were observed in a few small regions, while negative trends dominated large parts of all three countries. Local hotspots of increasing cropping frequency were observed in Samarkand, while decreases were visible in Jizzakh, Khatlon, and Dushanbe.

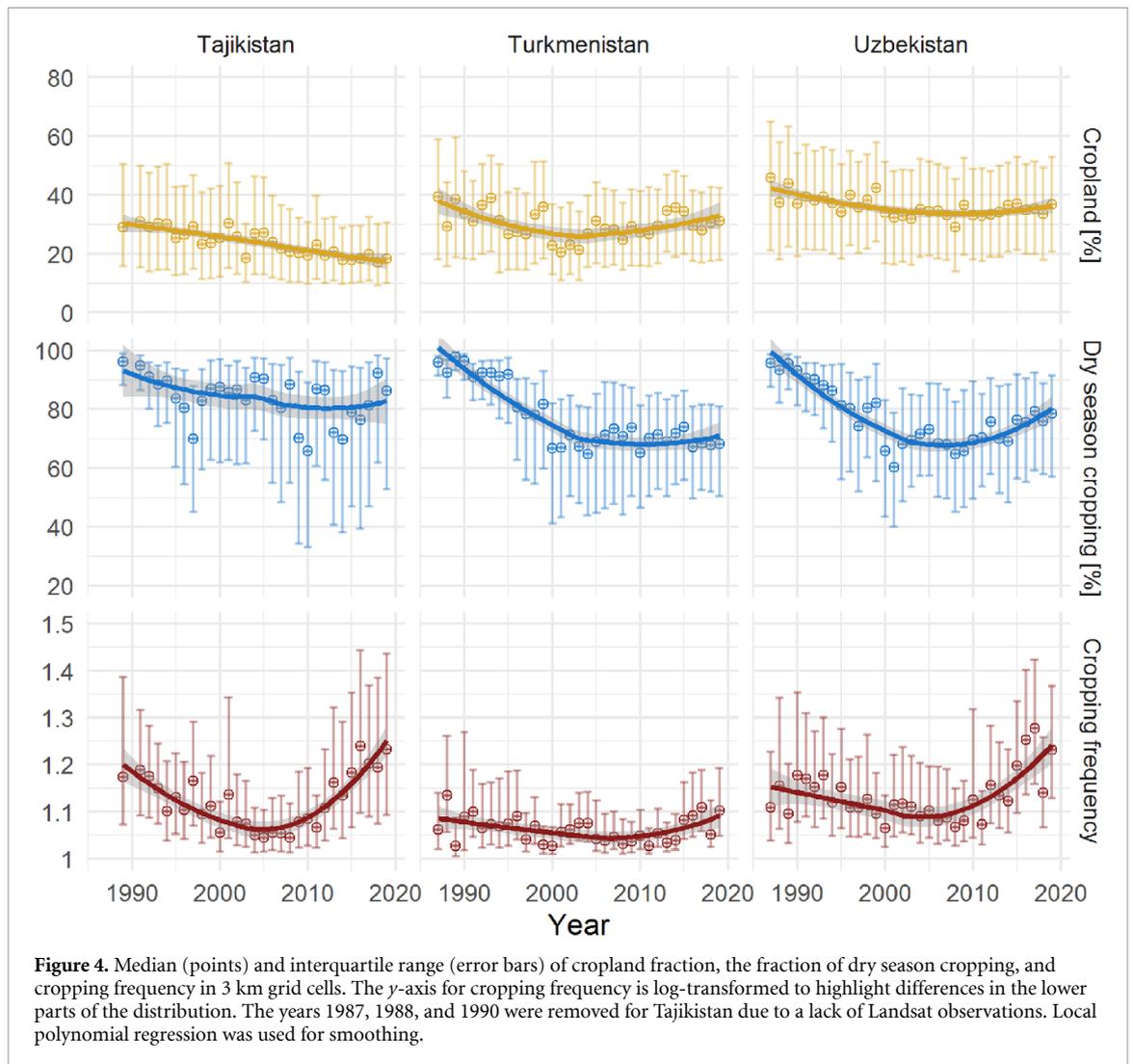
3.3. Local change processes

We consciously selected six 3 km-by-3 km sites that provide emblematic examples, which we use to explicate the underlying change processes. These sites encompass examples of changes in cropland

extent (i.e. substantial expansion and contraction), an increase and decrease in dry season cropping, and cropping frequency (figure 5 indicates the locations of sites A–F, and figure 6 presents the sites in detail).

Site A depicts the increase in cropland extent and frequency of the dry season crop in the Dashoguz province of Turkmenistan. In the 2000s, Turkmenistan constructed water channels to divert drainage water from Dashoguz to the controversial artificial Golden Age Lake (Stone 2008). The cropland increase in this site arises from the newly developed irrigated areas adjacent to these drainage channels. This site stands in contrast to the overall decline in cropland in the province, likely caused by salinization and land degradation (UN 2013). Site B illustrates a decrease in cropland in the Khatlon province, Tajikistan. In the 2000s, this region saw high cropland abandonment rates, due to the deterioration of irrigation facilities and land degradation (Bann *et al* 2012, World Bank 2020).

Site C is located in the upstream area of the Karshi channel, which delivers water from the Amu Darya to the Karshi oasis in Uzbekistan. The observed increase in dry season cropping reflects the newly established irrigated cropland in the vicinity of the channel. Sites D and E are situated in the upstream region of the Kashkadarya and Zarafshan rivers, both former tributaries to the Amu Darya in Uzbekistan. Both sites experienced a significant decline in cotton cultivation



during the previous three decades (Uzcomstat 2020). As a result, dry season cropping decreased significantly throughout this period. Note that in sites D and E, dry season cropping percentages increased in more recent years because of the increases in double cropping, which is included in the dry season cropping figure.

In site E, the switch from cotton to winter wheat facilitated the cultivation of a second crop; hence, cropping frequency increased. From the 1990s up to 2007, former collective farms in Uzbekistan were transformed into individual farms, providing farmers the independence to produce and privately sell crops that were not subject to government quotas, unlike cotton and wheat. Policies that removed state quotas from cotton cultivation positioned wheat as the leading strategic crop in Uzbekistan's agricultural policy (Abdullaev 2009, MacDonald 2012). As part of the state farm optimization programs, quotas for cotton cultivation were abolished for individual farms between 2006 and 2015, particularly in the Samarkand province. Winter wheat was the preferred alternative for farmers, as it allowed the cultivation

of a second crop in the dry season and contributed to the diversification of agriculture, including vegetable production. Site F, in the Syrdarya province in Uzbekistan, experienced a decline in cropping frequency from 1988 until the mid-2000s and a slight rebound thereafter. The declining cropping frequency was likely due to the rising groundwater table and accompanying mineralization in the upper soil layers, which caused the salinization of 95% of the province's irrigated lands (Kulmatov *et al* 2021, Khasanov *et al* 2022).

4. Discussion

We have characterized the dynamics of crop cultivation in the irrigated drylands of the Aral Sea basin at annual time steps from 1987 to 2019. Our findings reveal how the institutional reforms in response to the collapse of socialism in 1991 initiated a shift away from cotton, mainly toward winter wheat. In the early 1990s, wheat production plummeted, causing local wheat prices to increase and leading, in Uzbekistan

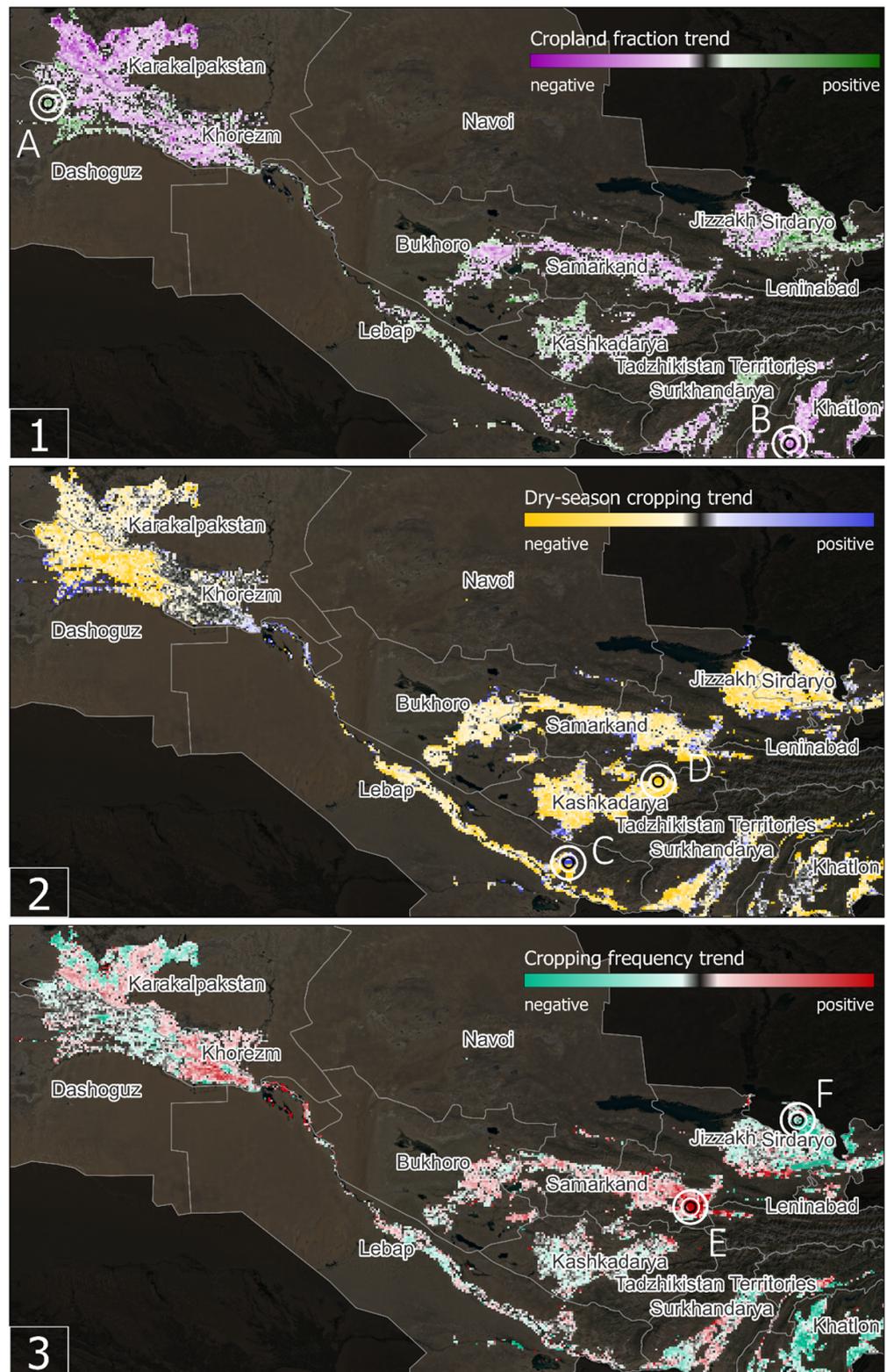
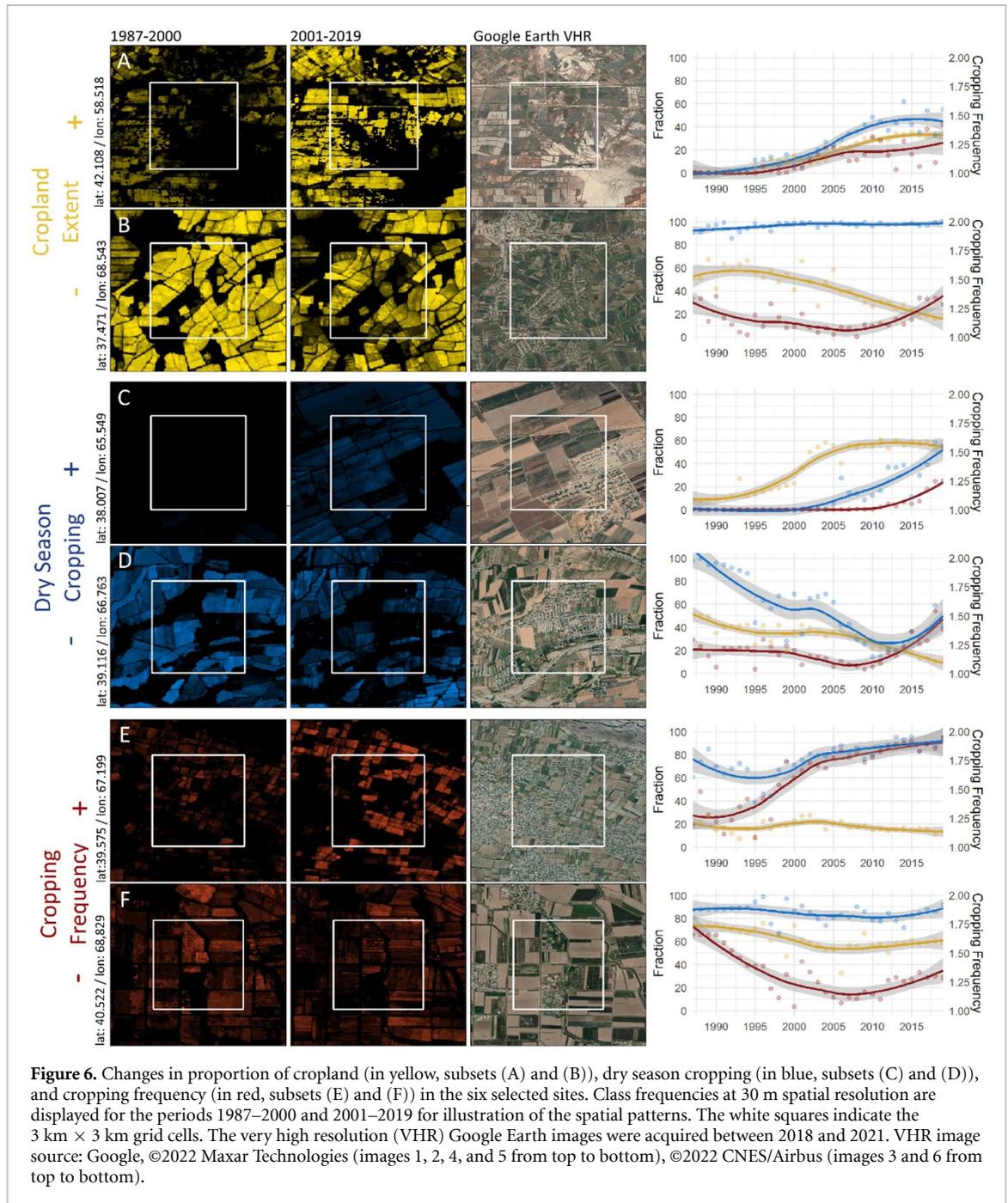


Figure 5. Linear regression time trend estimates of cropland fraction (1), dry season cropping fraction (2), and cropping frequency (3). Letters A to F refer to the sample locations in figure 6 and the names refer to the provinces.

and Turkmenistan, to the introduction of wheat self-sufficiency policies to meet domestic demand (Lerman *et al* 2016, Lombardozzi and Djanibekov 2021). As a result, the cultivation of winter wheat in Uzbekistan and Turkmenistan expanded by 1.4 Mha

between 1992 and 2019, whereas cotton cultivation declined by 0.6 Mha (FAO 2020).

Locally, the observed changes in cropping practices exhibit strong spatial heterogeneity, conditioned by local irrigation potential and management



decisions. Our findings suggest that water availability and the functionality of irrigation and drainage facilities are among the major determinants of changes in cropland use and intensity. Land degradation, often attributable to drainage infrastructure's poor performance or to excessive surface irrigation (causing waterlogging and the use of saline water for irrigation), arguably contributed to the contraction of dry season cropping (Qadir *et al* 2009).

The shift in cropping patterns had mixed implications for water use in the region. The shift from cotton to winter wheat alleviated pressure on water resources, because winter wheat requires about half the amount of water that cotton does (Khaydar *et al* 2021). The shift to winter wheat permitted farmers

to plant a second crop with a shorter growing season after the wheat harvest in early summer (Platonov *et al* 2014). Double cropping requires additional irrigation water, as the second crop matures during the dry season when crop water requirements are high (Khaydar *et al* 2021). In such cases, the net effect on water consumption of declining cotton production and increased double cropping is unclear and should be the topic of further research.

Crop-type maps would permit further disentangling the nuances of water use in the region. However, reference data on crop types are difficult to obtain (Bégué *et al* 2018), particularly for large areas and the past. Recently, a ground-based crop-type dataset was made available for parts of the study

region and period, which we harmonized with our class catalog, and included in our training database (Remelgado *et al* 2020). While satellite image time series enabled crop-type mapping locally, e.g. in the Fergana Valley (Löv *et al* 2018), mapping crop types across larger regions would require broader spatial and temporal data coverage. In this study, we mapped historic changes in cropping practices by classifying distinct crop growing cycles discerned from intra-annual satellite image time series. This methodology contributes essential data about land and water use intensity in dryland regions and allows for fine-scale examinations of the determinants of land use change (Conrad *et al* 2016, Rufin *et al* 2019, 2021a).

Our study presents novel insights on changing cropping practices over a large area in a transnational setting. We cover 650 000 km² annually over more than three decades. We believe our data provide a new benchmark for filling current knowledge gaps in the region (Conrad *et al* 2020). Our study makes use of the full Landsat archive, but the mapping was challenging for years with low image availability. Low observation density can compromise detection accuracies and induce higher variability in the features derived from the image time series (Dara *et al* 2018). Here, the southeastern parts of the study area were particularly affected in the years 1987–1991, 2003, and 2013.

The use of global classification models facilitates large-area mapping over long time spans (Griffiths *et al* 2018, Senf *et al* 2020). We trained our model with data from multiple years with different sensor constellations and observation densities, which produced accurate maps throughout the study period. Moreover, we removed uncertain predictions in times and regions with insufficient observation density and we excluded false classifications of some seasonally flooded wetland areas. The aggressive masking and subsequent trend calculations further reduced the effect of data scarcity in the 1990s, which had been previously documented for Central Asia (Dara *et al* 2018). Despite some remaining class-specific uncertainties, our maps have high overall accuracy, and the map-based and sample-based area estimates and change trajectories align well with the local remote sensing results and statistics documented in the literature.

Globally, the surface area of many endorheic lakes is shrinking, a process in which irrigated agriculture plays a key role (Wang *et al* 2018, Wine and Laronne 2020). The Aral Sea is a paradigmatic example of the destiny of a terminal lake that shrank due to a grossly reduced water inflow caused by excessive water extraction for agriculture. Providing monitoring data that permits pinpointing the causes of the lake's shrinkage to upstream land use is an important step to inform land use policies to better manage water use (AghaKouchak *et al* 2015). We highlight cropping frequency as an essential metric revealing changes in water consumption that

otherwise remain hidden in conventional cropland area-based estimates. Our study provides a ready-to-use method for deriving the long-term change trajectories of cropping practices across large areas without requiring extensive ground datasets or processing infrastructure.

5. Conclusion

Mapping cropland dynamics on fine spatial and temporal scales provide pertinent input for monitoring crop-water consumption and informing land use planning and investment in irrigation. We assessed the changes in cropping practices of 650 000 km² of drylands upstream of the Aral Sea over a period of 33 years. Our methods rely on openly available Landsat satellite data, circumventing the need for *in-situ* reference data collection, and can thus be used to study long-term changes in the cropping practices of other irrigated semi-arid or arid regions. Our work contributes knowledge and data in support of fine-scale assessments of large areas in transnational settings, which can allow to attribute water consumption to its underlying causes.

Increasing the efficiency of agricultural water resource use constitutes a grand challenge for the world's dryland areas amidst a rising demand for agricultural products while climate change and land degradation compromise water resource availability in the future. Assessing the spatiotemporal dynamics of crop water use and the underlying processes that give rise to these dynamics should be a top research priority, particularly in water-scarce regions. Our results indicate a reduction of crop water consumption in some areas, due to the shift away from water-intensive cotton cultivation to less water-intensive winter wheat; however, water consumption potentially increased in more recent years, due to the increased cropping frequency. Changes in overall crop water consumption since the collapse of the Soviet Union in 1991 remain elusive and should be subject to further research.

Data availability statement

The data that support the findings of this study are openly available at the following DOI: [10.5281/zenodo.6957722](https://doi.org/10.5281/zenodo.6957722).

Acknowledgments

We are very grateful to Andrey Dara, Christopher Krause, and Tillman Schmitz for their help in collecting the training and validation data and for additional intellectual input. We acknowledge funding from the Volkswagen Foundation within the SUSADICA Project (grant number: 96264) and the FRS-FNRS (grant number: T.0154.21).

ORCID iDs

Philippe Rufin  <https://orcid.org/0000-0001-8919-1058>

Mayra Daniela Peña-Guerrero  <https://orcid.org/0000-0001-8974-2956>

Atabek Umirbekov  <https://orcid.org/0000-0001-5567-2574>

Yanbing Wei  <https://orcid.org/0000-0002-5802-5361>

Daniel Müller  <https://orcid.org/0000-0001-8988-0718>

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