Impact assessment of soil salinity on crop production in Uzbekistan and its global significance

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Impact assessment of soil salinity on crop production in Uzbekistan and its global significance

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ABSTRACT

Food security is threatened by the increasing food demand, competition for land and water resources, soil salinization, and curbing hazardous emissions. Currently, climate change is predicted to affect agricultural crop yields, which has been revealed by the statistical analysis of crop yield data. Studies have mapped and assessed soil salinity under climate change conditions, derived the relationship between soil salinity and groundwater patterns, and evaluated the impact of soil salinity on agricultural crop production worldwide. However, no investigation was focused on the dynamic cropland changes of Uzbekistan by soil salinity. The impact of fertilizer, herbicide, fungicide and insecticide applications on soil salinity is poorly understood not only in Uzbekistan but around the world. In addition, the impact of crop yield decline in Uzbekistan on other countries is not clear. To address above questions, nationwide cropland and soil salinity changes in Uzbekistan were monitored and mapped using the Google Earth engine platform for 2000–2020. It was found that the phosphorus-based mineral fertilizer contributed to soil salinity. However, no effect of other agrochemical applications on soil salinity was observed. Furthermore, the impact of soil salinity on crop production in Uzbekistan was sufficiently high, leading to rapid decline of the export rate of cotton and wheat. This rapid decline of export could jeopardize the economics of Bangladesh and food security of Afghanistan. Development of sustainable strategies for mitigating climatic variabilities and fertilizer management to reduce the severity of soil salinization in Uzbekistan is in urgent need.

1. Introduction

Soil salinity has drawn significant attention in agricultural practices owing to soil mineral deposition, which results in poor conditions of drainage (Eswar et al., 2021; Ma et al., 2018). Increased salt content of soil considerably affects the soil quality and agricultural productivity. Specifically, elevated soil salinity delays the crop growing seasons and eventually crop yields (J. Wang et al., 2018; Y. Wang et al., 2018). Soil salinity has become a significant concern of agricultural practices in Central Asia, which occupies 20% of the global saline and sodic agricultural lands (i.e., 211.7 million ha out of 1060.1 million ha). According to the Food and Agriculture Organization (FAO) report (2015), saline soils with extremely high salinity in Central Asia reach 91.5 million ha. Salt-affected soils in Central Asia are most rampant in the southern part of Kazakhstan, Uzbekistan, and Turkmenistan. Agricultural irrigation is the major cause of soil salinity in (semi-)arid region.

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Almost 20% of the total irrigated lands on Earth, outspread over 100 countries, are suffering from soil salinization. This figure is growing because of the unsustainable management of irrigation and climate change (Meena et al., 2019).

Global food security and corresponding increased food demand change the agrochemical inputs and compete for land-water resources, leading to land degradation and greenhouse gas emissions (Aggarwal et al., 2006; Hoogenboom, 2000). At the same time, climate change is predicted to progressively affect agricultural crop yields (Aggarwal et al., 2006), which have been evidenced by statistical analysis of the agricultural crop yields (Dhungana et al., 2006).

Climate change induced drought and increased evaporation deteriorate soil salinity (Hu and Lindo-Atichati, 2019). In irrigated agricultural fields, high soil surface temperature, poor irrigation and drainage (Singh et al., 2018), and altered rainfall patterns amass soluble salts in the active plant root zone. Moreover, highly mineralized groundwater from (un-)confined aquifers overburdened with irrigation water contributes to the topsoil salinization of the agricultural lands (Xie et al., 2020). Impacts of climate change on crop production including wheat, cotton and rice are becoming the core of scientific apprehension (Djanibekov and Finger, 2018; Kang et al., 2009; Perri et al., 2018). Nowadays, climate change is considered as one of the most influential drivers, negatively and increasingly affecting agricultural crop production. In the last decades, uncertainty regarding food production has been the continuous concerns (Khanom, 2016). Hence, there is an urgent need to develop climate adaptation strategies to combat the impacts on of climate change on crop yields.

Soil salinization is also influenced by soil fertilization (Rady, 2012). To reduce the negative effect of fertilization on soil quality, fertilizer characteristics, methods of applications, and fertilization scheduling, should be considered systematically together with the quality of irrigation water (R. Machado and Serralheiro, 2017). In addition, over-applications of mineral fertilizers should be avoided, and free of chloride, low-saline, and high purity fertilizers are highly recommended. In irrigated lands, agricultural crop nutritional requirements need to be carefully evaluated, taking the soil and irrigation water contribution into consideration. Prior to fertilizer applications, irrigation water should be assessed for the mineral content since irrigation water usually carries elevated levels of various minerals including nitrate, magnesium, calcium, boron, and sulfur. (Bacilio et al., 2016; Machado et al., 2008). Globally, many agricultural lands, especially the Central Asian agricultural lands have elevated contents of nitrogen in the top soil and groundwater owing to NO_3 leaching from fertilizer applications (Machado et al., 2008).

Organic farming has experienced a remarkable decline in several regions of the world due to the increased availability of mineral fertilizers, which plays a crucial role to accelerate crop production to cater for the growing world population (Ju et al., 2005). Notably, China utilizes excessive mineral fertilizers more than any other country, accounting for around 90% of the increase in mineral fertilizer use worldwide (Liu and Diamond, 2005; Farrell et al., 2014). Between 1980 and 2015, China has consumed six times more mineral fertilizers than the global average. Correspondingly, wheat yields had tripled throughout this period (i.e., 1980: wheat – 1.9 tons per ha and 2015: wheat – 5.4 tons per ha; Jiang et al., 2018; National Bureau of Statistics of China, 2016).

Increased land use and subsequent crop production significantly deteriorate the soil quality through repeatedly consuming the soil nutrients (Singh et al., 2016). In addition, increased crop production requires more fertilizer, herbicide and insecticide applications, leading to ecosystem pollution (Rose et al., 2018). Although insecticides contribute significantly to the agricultural production in the sense of maintaining global food security, fungicide applications contaminate the topsoil layer and cause soil deterioration and degradation. Potential soil contamination by insecticide and herbicide applications is high if insecticides and herbicides are continuously applied at elevated rates over time (Liebich et al., 2003).

Developed countries have ceased using unsustainable and hazardous agrochemicals such as pesticides in their agricultural sectors, and urge other countries to reduce the agrochemical use due to the health-related and environmental concerns (Colbach and Cordeau, 2018; Waggoner et al., 2013). However, weeds and insects are pondered to be the most important biotic constraints for agricultural crop production unless adequately controlled (Mézière et al., 2015; Milberg and Hallgren, 2004; Song et al., 2017).

Salt deposition in irrigated lands limits plant growth, slows and even reduces seed germination and persuades a substandard seedling establishment (Aydinoğlu et al., 2019; Farooq et al., 2017). As soil salinity declines, the plants can then take up water and nutrients. The first stage of plant salt response is a decrease in a plant growth rate, in line with a suite of changes in plant metabolism that is akin to those caused by plant water stress (Munns and Tester, 2008; Tomaz et al., 2020). This stress restricts the plant development, thus significantly and adversely affecting crop yields. In this study, nationwide cropland and soil salinity changes in Uzbekistan were monitored and mapped using the Google Earth engine platform for 2000–2020. The impact of soil salinity on crop productivity and local economy was analyzed.

2. Materials and methods

2.1. Study area

Uzbekistan is a land-locked country with typical dryland in Central Asia. It is located specifically in the Aral Sea Basin, sandwiched between the Amu Darya and the Syr Darya Rivers (Fig. 1). Uzbekistan occupies 447,400 km^2 and less than 43,000 km^2 is used for agriculture. It has a dozen of provinces and one autonomous republic. The landscape of Uzbekistan is dynamic from the west to the east with plain deserts, foothills, greater mountains, and large valleys. At any time of the year, extremely dry and mildly continental climate describes the geoposition of Uzbekistan, thus it is classified as an arid zone according to Sluijter et al. (2011). In fact, unique climate conditions, consisting of immensely cold winters, wet and cool falls, and dry, long and extremely summers, could only be observed in Uzbekistan (FAO, 2012). The main crops of Uzbekistan are winter wheat (*Triticum aestivum L.*) and cotton (*Gossypium hirsutum L.*). Crops are irrigated with the traditional irrigation method of furrow.

As Uzbekistan progressively ceased to produce high-water demand crops such as cotton since 2017, degraded croplands for cotton production had been either abandoned or decommissioned from agricultural practices. We first mapped the actual croplands of Uzbekistan using the 2020 Google Earth Engine (GEE) data by scripting and visualizing the gained and loss croplands (Fig. 1). Since such cropland change maps were not available in Uzbekistan, these maps of this study served as a potential input to perform the soil salinity assessment only in croplands. Further perennial analysis of the cropland change is presented in the results section.

2.1.1. Climate change in Uzbekistan

One of the major contributions to the gross domestic product (GDP) of Uzbekistan is agriculture, predominately by winter wheat and cotton (Moyliev, 2021). Uzbekistan nowadays confronts paramount challenges with water scarcity, desertification of arable land, and increased and ongoing depletion of the Aral Sea ecosystem (Loodin, 2020). These challenges are inflamed by climatic stressors including more frequent and long droughts, increased air temperatures, reduced precipitation in corresponding seasons, and shift of the vegetation period due to the changes in climate patterns. This climate variability is anticipated to escalate in the near future, seriously and negatively affecting agricultural productivity and leading to the depletion of natural resources countrywide.

In Uzbekistan, there is no legislation specifically on climate change, and there are no general strategic guidelines. The agriculture is the

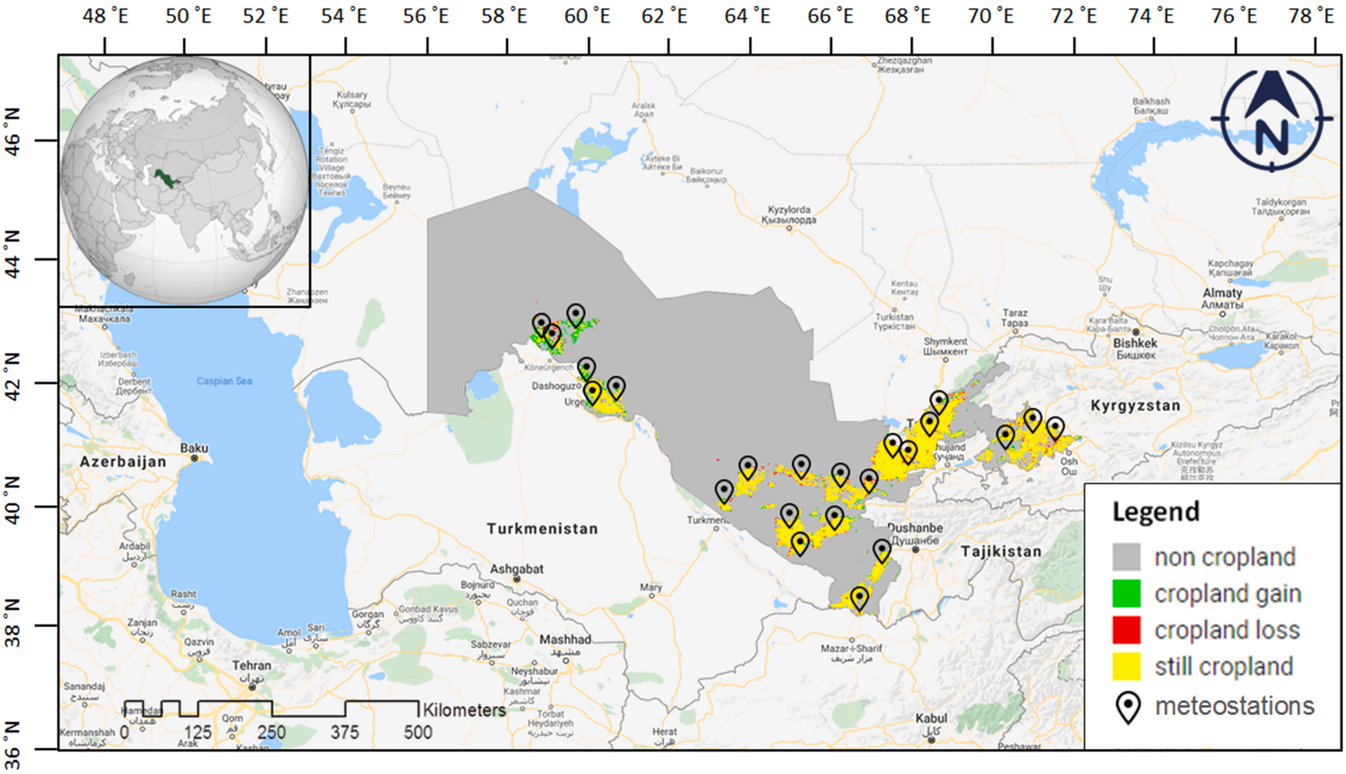

Fig. 1. Map of the study area: croplands and location of meteostations.

second predominant source of greenhouse gas (GHG) emissions in Uzbekistan after energy, releasing 42.9 million metric tons of carbon dioxide equivalent (MtCO2e) to the atmosphere (0.09% of global GHG emission) in 2019 (CAREC, 2020; USAID, 2021). Methane emissions from Uzbek agriculture increased by 98.2% in the recent decades, mainly by increased numbers of cattle and sheep (Sapkota et al., 2020). Above conditions drive springs and falls of Uzbekistan to become gradually warmer.

According to the perennial climatic observation data recorded in the indicated meteostations from 2000 to 2020 (Fig. 1) (Uzhydromet, 2021), the average air temperature of July (the peak summer time) exceeded + 28 °C, whereas in the peak winter time (January) it was nearly + 1 °C (Fig. 2). The average annual sum of precipitation was around 400 mm (Fig. 3). Therefore, the majority part of agricultural lands of Uzbekistan was irrigated. The vegetation period started from mid-spring (April) and terminated in mid-fall (October).

2.1.2. *Position of Uzbekistan*

Many studies have been carried out focusing on the assessment and mapping of soil salinity, the impact of climate variables on soil salinization, the relationship between soil salinity and other drivers, and the impact of soil salinity on crop production in Uzbekistan (Akramkhanov et al., 2011; Ivushkin et al., 2017a; Khasanov et al., 2022; Kulmatov et al., 2021a). Mapping and assessing soil salinity in Uzbekistan have mainly been performed using geographical information systems (GIS)

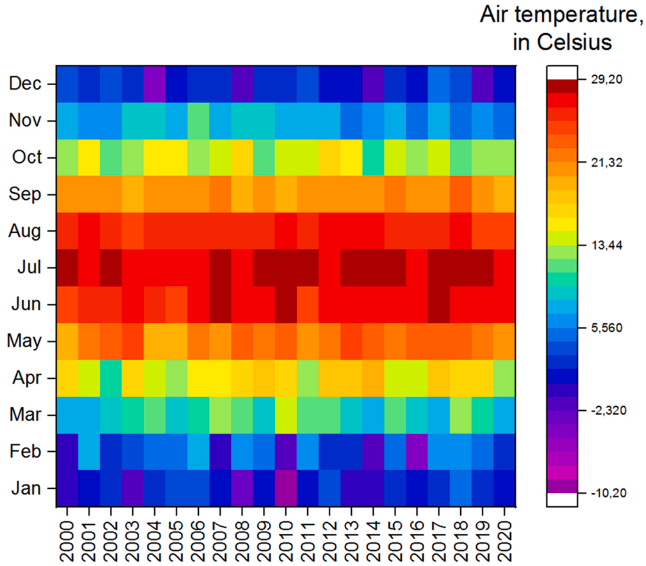

Fig. 2. Map of monthly average air temperature in Uzbekistan.

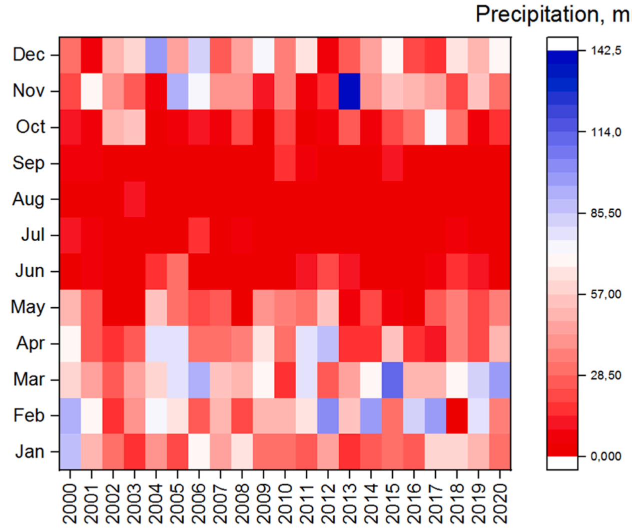

Fig. 3. Map of the monthly sum of precipitation in Uzbekistan.

and remote sensing. Ivushkin et al. (2017a) recently introduced satellite thermography as a novel approach to determine the plant salt response based on the canopy temperature. Using the interpolation methods, Eshchanov (2008), Ibrakhimov et al. (2011), Khasanov (2019), Kulmatov et al. (2021b), Platonov et al. (2015), Pulatov et al. (2020), and Sultanov (2018) employed normalized difference vegetation index (NDVI) as GIS tools to map soil salinity, which are then integrated with the field data to map and assess soil salinity with low errors.

As mean air temperature rises and precipitation decreases in Uzbekistan, salt-affected cropland areas are proportionally extending. By investigating the impact of climatic factors and other drivers on soil salinity in Uzbekistan, Forkutsa et al. (2009), Kulmatov et al. (2020), and Hamidov et al. (2020) revealed the significant relationship between climate parameters and soil salinity. Kulmatov et al. (2020), Kulmatov et al. (2021a), and Khasanov et al. (2022) recently further disseminated the influence and acceleration of soil salinity by climatic variation, surface and ground water, and groundwater table. The results were statistically analyzed with significant correlations, which served as an early warming for the central government to take the mitigation actions in agriculture.

Platonov et al. (2015); Begdullayeva et al. (2007); Bobojonov et al. (2013); Bezborodov et al. (2010), and Egamberdieva et al. (2007) examined the plant salt response in a typical saline land of Uzbekistan. According to these studies, overall soil salinity was perceived as a wicked soil threat. While soil salinity reduced the national agricultural crop production, it negatively affected the soil microbial community and soil quality. The government was urged to cease traditional agricultural practices and restore the drainage systems.

As discerned from the above, no investigation was focused on the change of cropland in Uzbekistan due to land degradation. Furthermore, overall salinity map of Uzbekistan and nationwide soil salinity trends are unavailable to gain insight into the actual picture of the country in terms of salty soils. In addition, fertilizer and other agrochemical application data are scarce not only in Uzbekistan but worldwide. Correspondingly, no data are available regarding the decline of crop yields in Uzbekistan and other countries as a result of increased soil salinity. Considering above, the objects of this research are to: (1) project the dynamics of cropland change in Uzbekistan using remote sensing data; (2) assess soil salinity of croplands and derive the relationships of soil salinity with the driving factors; (3) evaluate the accuracy of the Google Earth Engine data; (4) analyze mineral fertilizer consumption, agrochemical use, and crop yields; and, (5) estimate the impact of agricultural collapse in Uzbekistan on food security at the national level and on the affiliated trading countries.

2.2. Data acquisition

20 satellite images (2000–2020) per analysis were used in this research for the spatial analyses of cropland change and soil salinization. The sensor of the satellite images was Moderate Resolution Imaging Spectroradiometer (MODIS). The temporal resolution of the sensor varied between one to two days and covered 250 × 250 m per pixel (for further information, see LAADS DAAC).

The ground truth tabular data of cropland change and salt-affected irrigated lands at a provincial level were derived from the governmental organizations such as the subsidiaries of the Ministry of Agriculture (2021), the Ministry of Water Resources (2021), and the Cadaster Agency of Uzbekistan (2021). The actual ground data of cropland change were derived from the provincial subsidiaries of the Ministry of Water Resources, which were embargoed by this governmental organization to present to the global audience. For this reason, these official data were only served to conduct the accuracy assessment of the GEE results. Howbeit, the cropland change analysis through the GEE platform was represented in this research. Twenty-year climate data of air temperature and precipitation were obtained from 23 stations across the irrigated lands, appertaining to the Center of Hydrometeorological Service of Uzbekistan (Uzhydromet, 2021). Other raw data including mineral fertilizer applications, agrochemical (i.e., herbicide, fungicide and insecticide) use, and crop yields (i.e., cotton and winter wheat) were acquired from the Provincial Hydro-Land Reclamation Expeditions under the subsidiary of the Ministry of Water Resources of Uzbekistan (2021).

Trade data of the export rates of agricultural crops were collected by consecutively reviewing the economic database of Tashkent State University of Economics, Uzbekistan. These data were validated by the world's leading international trade data visualization tool – The Observatory of Economic Complexity (OEC) (2021) managed by international organizations such as World Bank. Data of demography were obtained from the most reliable internet source – Worldometers (2021). To gain a better insight into the data acquisition, the information of all the types of data was integrated in a single table (Table 1).

2.3. Google Earth Engine platform

The GEE is a cloud platform for storing and processing spatial datasets to analyze and make ultimate decisions (Mutanga and Kumar, 2019). Google Earth with stored spatial datasets from different sensors was connected to the cloud engine. The current data archive, in line with satellite sensors, is composed of Geographic Information Systems-based vector datasets, demographic, digital elevation models, social, climate, and weather data layers.

The front-end of GEE provides a suitable environment for interactive data and algorithm development. Academics, independent researchers, individuals, and governments may now exploit this large archive of data for change detection, mapping patterns, and quantifying resources on the Earth's surface. However, the GEE requires sufficient knowledge of scripting in Java language (Fuentes et al., 2020). The large computational capacities of the latest computers or software are not required. Subsequently, resource-poor researchers can conduct analysis using GEE. In this study, the GEE platform was chosen because it was time-effective and resource-saving (Amani et al., 2020).

In Uzbekistan, there is no open-access data on the spatial and temporal change in the national cropland area. Thus, using the GEE platform will enable interested individuals to gain insight into the cropland change dynamics over time. In this research, all the satellite data of

Table 1
Information on the existing data of Uzbekistan.

Data type	Temporal scale	Spatial scale	Source
MODIS images	2000–2020	Uzbekistan	Google Earth Engine
Cropland change	2000–2020	Uzbekistan	Ministry of Agriculture (2021); Cadaster Agency of Uzbekistan (2021); Ministry of Water Resources (2021)
Soil salinity	2000–2010, 2012–2020	Irrigated land of Uzbekistan	Ministry of Agriculture (2021); Ministry of Water Resources (2021)
Climate data	2000–2020	Uzbekistan	Center of Hydrometeorological Service of Uzbekistan (2021)
Mineral fertilizer application	2000–2020	Irrigated land of Uzbekistan	Ministry of Agriculture (2021)
Chemicals use	2000–2020	Irrigated land of Uzbekistan	Ministry of Agriculture (2021)
Crop yield	2000–2008, 2011–2017, 2019, 2020	Irrigated land of Uzbekistan	Ministry of Agriculture (2021)
Export rate	2000–2020	Uzbekistan, worldwide	Observatory of Economic Complexity (2021)
Demography	2000–2020	Uzbekistan	Worldometers (2021)

Uzbekistan were stored in the GEE platform and cropland change was mapped using the MODIS Land Cover dataset.

2.4. Soil salinity assessment

In this study, we employed two frequently used vegetation condition indices (NDVI and enhanced vegetation index [EVI]) generated with MODIS data (Huete et al., 1999):

$$NDVI = NIR - RED / NIR + RED \tag{1}$$

$$EVI = G \times (NIR\text{-}RED) / (NIR + C_1 \times RED - C_2 \times BLUE + L) \tag{2}$$

where, NIR, RED, and BLUE - MODIS sensed reflectance in near-infrared, red, and blue wavelengths, respectively; G – gain factor, equals to 2.5; and $C_1 = 6$, $C_2 = 7.5$, and $L = 1$. The NDVI is a widely accepted and commonly utilized index of vegetation, although it is vulnerable by changes in soil or particle reflectance, as well as saturation from plant biomass. The EVI was subsequently developed to address some of these drawbacks by providing a more comprehensive measure of canopy change (Huete et al., 2002). The MODIS product MOD13A2 was used to calculate both NDVI and EVI in this study.

For the nationwide soil salinity assessment of the croplands, satellite images of post-April and mid-August were used. This was based on the fact that wheat and cotton reached their maximum biomass (max. NDVI and EVI) in the end of April and in the middle of August, respectively. Post-April and mid-August were thus the ideal periods to track soil salinity as evidenced by many studies (Ivushkin et al., 2017b, 2018).

Mapping soil salinity of croplands in Uzbekistan was carried out by extracting the cropland areas and applying the MOD13A2-based vegetation index with an $NDVI > 0.3$ according to Ivushkin et al. (2017a). With this NDVI threshold, vegetated areas were withdrawn from non-vegetated cropland pixels. Afterward, a 20-year cropland change map and 20-year soil salinity map of Uzbekistan were created. These maps were then converted into numerical values in hectares and validated with the actual ground data. By comparing the remotely sensed data with the actual data, the potential accuracy of maps was calculated. A comparison between the GEE-based and in-situ methods was performed according to the output of root mean square error (RMSE), which was then used to assess the model performance throughout the cross-validation method. The predictions with the lowest RMSE were the most accurate.

2.5. Data analysis

Basic statistics were conducted for the visualization and analysis of data of mineral fertilizer applications, agrochemical use, and crop yields using the Statistical Package for the Social Sciences (SPSS) statistics software v25 (IBM Corp, 2017). Using the same software, the analysis of variance (ANOVA) with *F* values in contrast was conducted to evaluate the performance of different factors (i.e., mineral fertilizer applications, agrochemical use, crop yields, salt-affected areas, precipitation, and air temperature). All the other numeric data visualizations were performed using the Origin (2018) program. Pearson's correlation was used to validate the patterns and display the interlinkage and inter-dependence of these factors. These correlation coefficients were calculated and visualized using the RStudio Team (2017).

3. Results and discussion

3.1. Cropland change in Uzbekistan

The GEE-based cropland change in Uzbekistan was obtained through querying in Java for the years of 2000–2020 (Fig. 4). According to this figure, there was no significant change in the entire irrigated lands countrywide. Despite minor oscillations in between, the total croplands were extended by 4,000 ha within the years of 2000–2020 (Fig. 4A). However, there was an upward trend for cropland loss where decommissioned cropland areas were almost quadrupled, increasing from 100,000 ha in 2000–400,000 ha in 2020 (Fig. 4B). Massive land owning had been started from 2000 (280,000 ha) to 2005 (364,000 ha), occupying around extra 84,000 ha (Fig. 4C). This land owning process peaked in mid-2010 s (440,000 ha), and experienced a significant drop by roughly 335,000 ha in 2020. A considerable reduction characterized the change of still cropland areas during the 20 years. Specifically, still cropland areas underwent a reduction of 300,000 ha, from around 3.8 million ha in 2000–3.5 million ha in 2020 (Fig. 4D). This was attributed to the change of croplands to residential areas, settlements, and city roads.

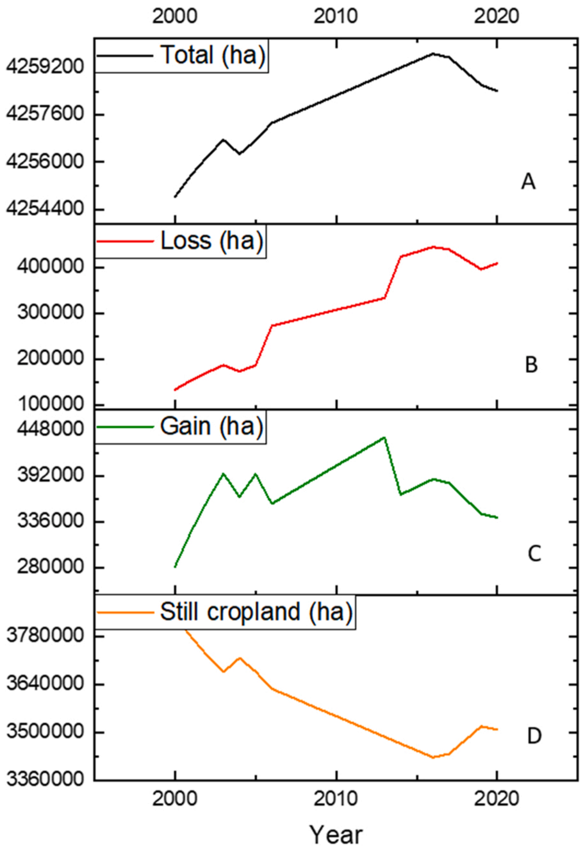

Fig. 4. Cropland change in Uzbekistan within 2000–2020.

The GEE cropland change maps of Uzbekistan had an accuracy of about 81.3% with $p < 0.01$. RMSE accounted for 1.04. The GEE platform was assumed reliable to monitor the cropland change with each method having 20% of error for cropland change monitoring based on the 80% of affinity. This must be considered in countrywide land management.

Uzbekistan is considered as a typical dryland, which suffers from soil threats according to Rodríguez Eugenio (2021). Soil salinization frequently occurs due to the predominant applications of unsustainable and outdated furrow irrigation with highly-mineralized surface water under non-functional conditions of the existing drainage system. Mineral and inorganic fertilizers are commonly used in the croplands to increase crop yields. In the meantime, immoderate filtrate and runoff may contaminate the environment when coming from the irrigation canals and reservoirs. Croplands have thus been decommissioned from agricultural use in the country. Corresponding to the decommissioning of cropland areas, land owning has vastly occurred within the years of 2000–2020. Several national policies have been developed, targeting to safe land owning. For instance, remote croplands were used for the construction of huge water dams, filled by the transboundary rivers – the Amu Darya and the Syr Darya, and their tributaries. Numerous policies have also been forged to ensure safe irrigation with continuously regulated mineralization of surface and ground water. As water resources are scarce in Uzbekistan due to its geolocation, the enforcement of these policies goes beyond in agriculture.

3.2. Soil salinity map of Uzbekistan

Salinization of irrigated lands is the main reason for the decrease in crop yields, which negatively affects the food security of the countries of Central Asia, especially Uzbekistan. Once multiple time series of cropland change maps were created, they were used to identify and extract the cropland areas at the country level. Soil salinity was then mapped in croplands by calculating the NDVI and EVI over the MODIS images captured in April and August, the potential months in which the biomass of cotton reached its maximum. Our spatial analysis confirmed the reduced biomass. The reduction of cotton biomass was attributed to the degraded soils, especially saline soils of croplands under water stress. The soil salinity maps are presented in Fig. 5.

Severely saline cropland areas had been extended over the years (Fig. 5). No stress was observed in the experimental years in the eastern part of the country with non-dominated saline areas. In the central part of Uzbekistan with significant agricultural practices, soils of the croplands were moderately and strongly salted during 2000–2015. However, these patterns abruptly changed within the last five years. The main reason of the increased land reclamation was the shift from traditional agriculture to sustainable agriculture by restricting the planting of high-water demand crops in this part of the country. The reclamation status of the soils in the western part of the country had been exacerbated over time and severely saline soils were common in the croplands in 2020. As shown in Fig. 1, the massive share of land owning was in this region and the owning process delivered river water to the croplands. The only available river water was from the Amu Darya River, whose inflow experienced a sharp reduction, causing the river water to become severely mineralized and polluted (Liu et al., 2021). Furrow irrigation with this mineralized river water led to severe soil salinity in this region.

Notwithstanding some increases in the non-saline cropland areas in the 2005 s, the cropland areas rapidly shrank by almost 150,000 ha from 550,000 ha in 2005–400,000 ha in 2020. Aligning with non-saline croplands, weakly saline (Cl^- - 0.01–0.03 mEq/L) areas also experienced a sudden decrease by around 200,000 ha. Regarding the moderately saline (Cl^- - 0.031–0.07 mEq/L) croplands, the nadir was recorded in 2005 at about 1.91 million ha, followed by some fluctuations and peaked at 2.03 million ha after a decade in 2015. At the end of the experimental years, moderate saline croplands had a slight reduction by 40,000 ha. There was only an upward trend for severely saline croplands ($Cl^- > 0.07$ mEq/L) at this stage. These areas have been gradually extending from 450,000 ha in the beginning to 750,000 ha at the end of the experimental years.

To assess the accuracy of the GEE-based data, an accuracy assessment of the GEE results was performed, which was conducted by partitioning the country into provinces and comparing with the actual ground data provided by the Ministry of Agriculture (2021) and the official national reports by the Cadaster Agency of Uzbekistan (2021). The accuracy of the GEE-based results was 74.1% with $p < 0.01$ and the RMSE was approximately 0.64.

The results of this study were consistent with those of recent similar studies carried out by local and international scientists. Ibrakhimov et al. (2011); Kulmatov et al. (2021b); Nouri et al. (2018); Pulatov et al. (2020), and Sultanov et al. (2018) conducted studies in Uzbekistan and Australia to assess soil salinity using the interpolation methods. They proved that the potential of the interpolation methods was reliable when the actual ground data were available. Furthermore, they had similar mapping accuracy and RMSE errors, based on which they claimed the interpolation methods had the capabilities to map soil salinity. In this study, we confirm that the GEE platform has the possibility to map soil salinity using the NDVI and EVI on MODIS images at a greater spatial scale.

3.3. Mineral fertilizers, chemicals and crop yield

Uzbekistan replies on two main agricultural crops, winter wheat and cotton, to ensure national and international food security. In this

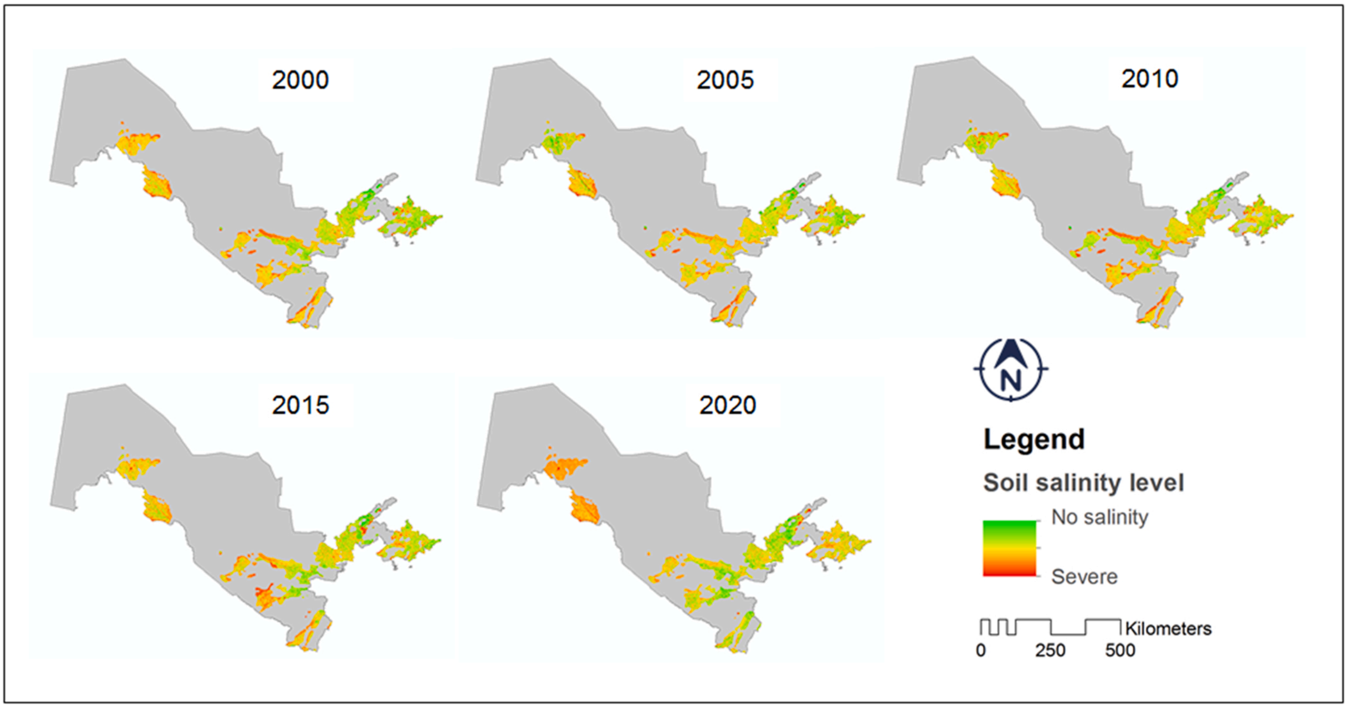

Fig. 5. Soil salinity map of croplands of Uzbekistan (to obtain quantitative data from the soil salinity maps created by the GEE platform, the type of raster was altered from continuous to discrete. The output was displayed in Fig. 6 as a graph).

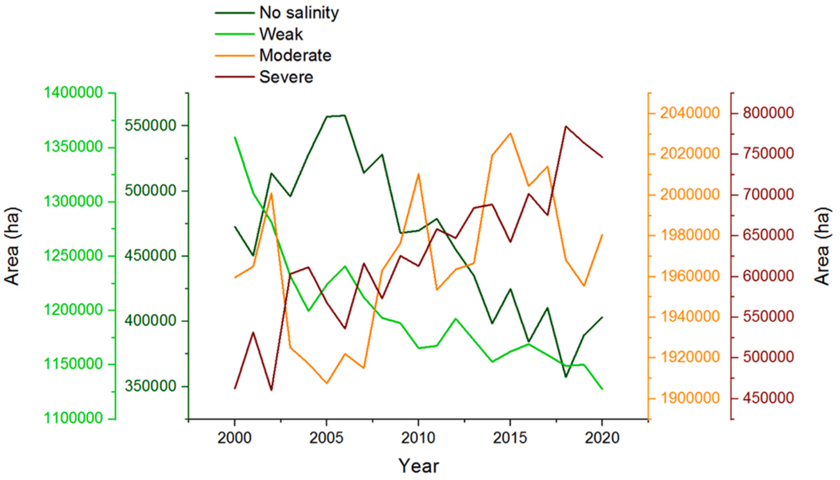

Fig. 6. Non-saline and salt-affected croplands of Uzbekistan over 2000–2020.

research, application rates of nitrogen (N), phosphorus (P), potassium (K) and agrochemicals such as fungicide, herbicide and insecticide for cotton and wheat were considered. Moreover, to evaluate the impact of their applications on the crop yields, crop yield data were included in the analysis of this study. As a result, 20-year tabular data were statistically analyzed to corroborate whether the average application rate goes beyond the world average one (Jiang et al., 2018; Rady, 2012; Yasuor et al., 2020).

For mineral fertilizer applications, the average application rate of K was about 10 kg/ha in both cotton and wheat fields. The P application rate, on the other hand, was moderately compact – 100 kg/ha for cotton and 70–100 kg/ha for wheat on average. The annual recorded data of N application rate were relatively loose and were hard to interpret in both cotton and wheat fields. Specifically, the average application rate can vary from 500 to 550 kg/ha for cotton and 450–480 kg/ha for wheat. According to The World Bank Group (2018), the average fertilizer consumption in Uzbekistan was 252 kg/ha, nearly double of the world average. However, our data revealed that the annual fertilizer consumption was around 600 kg/ha, exceeding the World Bank statistics. Furthermore, CAREC (2020) indicated that the fertilizer application in Uzbekistan contributed 8 MtCO2e to the global GHG emissions. The excessive fertilizer consumption in the agricultural sector of Uzbekistan requires proper optimization.

Despite numerous countries have already prohibited utilizing agrochemicals in agriculture, Uzbekistan has its own position to gradually cease unsustainable chemicals through promoting “green” techniques such as phyto-melioration. The agrochemical consumption of the agriculture in Uzbekistan is illustrated in Fig. 8.

Owing to the potential systematic errors of the consumption rate, the agrochemical applications were plotted in boxes (Fig. 8). The data in the second quartile are closer to the average agrochemical consumption. As shown in the figure, the average application rate of fungicide was roughly 530,000 L (300 mL/ha – the governmental standard of Uzbekistan), followed by herbicide – 310,000 L (60 mL/ha), and insecticide – 150,000 L (100 mL/ha). These data are higher than the world average (De et al., 2014) and mitigation measures are required to reduce the agrochemical consumption. Agrochemical consumption reduction might also prevent the acceleration of heavy metal accumulation in the croplands that could become another serious problem with soil salinization.

According to the UNDP (2021), Uzbekistan is the second-largest cotton exporter and fifth largest cotton producer in the world. Therefore, any change in the cotton production in Uzbekistan by soil threats will have a footprint on the global trade. Additionally, Uzbekistan is one of the main raw wheat suppliers of the neighboring countries in Central Asia and the former USSR countries. Tracking the yields of these two main crops is important for the well-being of the country. 20-year data were analyzed to identify the average cotton and wheat yields per ha in Uzbekistan (Fig. 9).

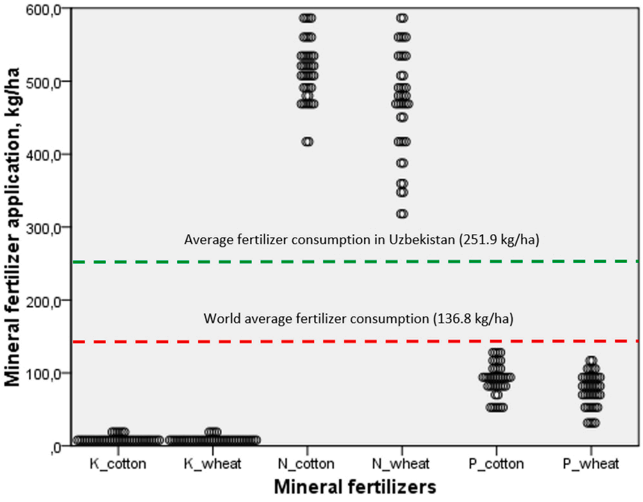

Fig. 7. Mineral fertilizer consumption in Uzbekistan.

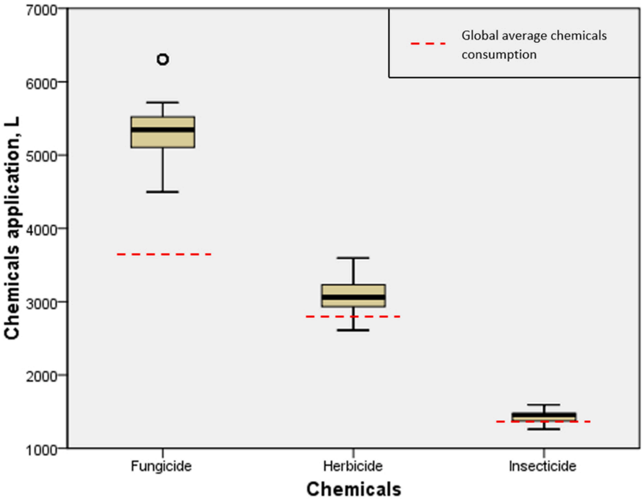

Fig. 8. Chemicals consumption in the agriculture of Uzbekistan (in ’00).

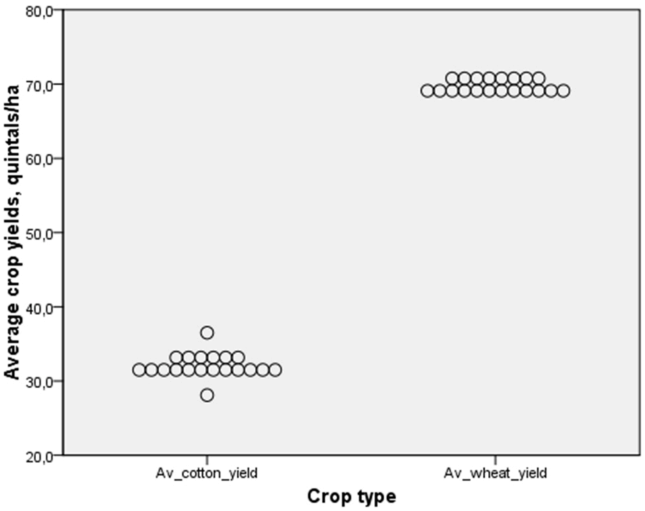

Fig. 9. Average crop yield in Uzbekistan between 2000 and 2020.

The average cotton yields are 32–34 quintals per ha, which is fairly dynamic. The average yields of wheat range from 68 to 71 quintals per ha. Crop yields are the most important factor and the core of this study since their values ensure national and international food security. Hence, the effect of other factors on crop yields were measured and shown in the next sections.

3.4. Relationship between crop yield, soil salinity, and other factors

Recently, correlation between soil salinity, groundwater table and groundwater mineralization was identified in Uzbekistan (Khasanov et al., 2022). According to Khasanov et al. (2022), a strong relationship between soil salinization, rising groundwater table and increasing groundwater mineralization was derived. This provided clear evidence that soil salinization was driven by groundwater.

Cotton yields had a moderate relationship with the N application rate (> 0.6) and precipitation in winter (> 0.5) (Fig. 10). N applications provided the required nutrients for cotton growth (Macdonald et al., 2021) and the atmospheric precipitation in winter increased the soil moisture, creating an ideal condition for cotton growing. On the other hand, there was no significant correlation of wheat yields with any other recognized factors.

A positive and remarkable correlation was identified between soil salinity and the P application rate (> 0.75). This was new to Uzbekistan and yet not observed heretofore. As shown in the “corrplot”, the N application rate could reduce the severity of soil salinization (> 0.6) and precipitation in winter also helped slow down the soil salinization processes in Uzbekistan (> 0.6). Engrossingly, the effect of agrochemicals was not evidentially detected and there was no direct effect of agrochemicals neither on crop yields nor on soil salinization. The correlation of heavy metal accumulation in croplands of Uzbekistan as a consequence of mineral fertilizer and agrochemical applications with soil salinization and crop yields was not included in this study.

Once the relationship between all the considered factors was determined in this study, the statistical significance of the correlation was characterized, which is summarized in the ANOVA table (Table 2) to validate above predictors according to the *F* values.

The ANOVA test showed that the relationship between the average cotton crop yields and factors such as fertilizer consumption, insecticide applications, climatic factors and soil salinity was validated to be statistically significant. This validation statistically confirmed that these factors were the main predictors of cotton yields. For the average wheat yields, air temperature and precipitation in summer had a lower *F* value, but, sufficient to become the predictors according to the significance.

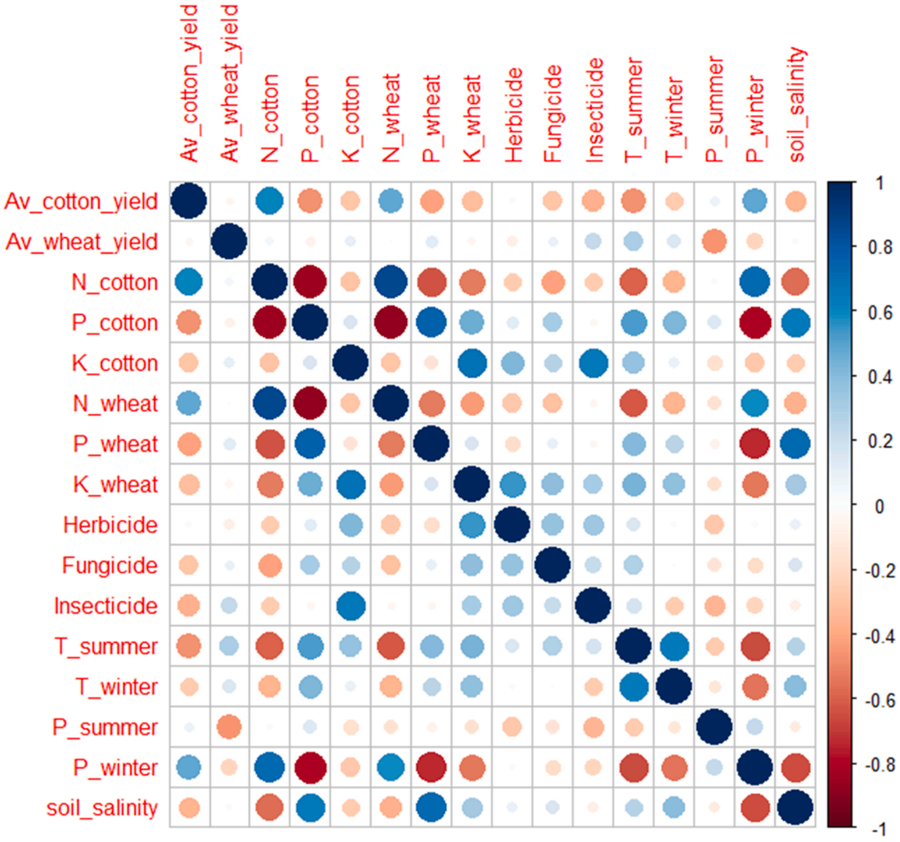

Fig. 10. Correlation plot of crop yield, mineral fertilizer and chemical application, climate factors and soil salinity.

Table 2
F values of ANOVA tests between crop yield and fertilizer and chemicals application, soil salinity, and climate factors for Uzbekistan.

	Average cotton yield		Average wheat yield	
	F value	Significance	*F* value	Significance
N (cotton)	52.7	< 0.01	N/A	N/A
P (cotton)	40.4	< 0.01	N/A	N/A
K (cotton)	16.5	< 0.01	N/A	N/A
N (wheat)	N/A	N/A	1.7	0.14
P (wheat)	N/A	N/A	2.3	0.08
K (wheat)	N/A	N/A	0.9	0.53
Herbicide	0.8	0.28	1.6	0.21
Fungicide	6.4	0.17	1.1	0.36
Insecticide	17.2	< 0.01	4.1	0.03
Summer *T*	38.1	< 0.01	16.6	< 0.01
Winter *T*	8.9	0.41	7.2	0.10
Summer *P*	1.7	0.46	15.9	< 0.01
Winter *P*	20.3	< 0.01	2.8	0.29
Soil salinity	15.5	< 0.01	0.1	0.88

3.5. *Global impact of Uzbek cotton export*

As Uzbekistan is one of the largest cotton exporters, in the capital city of Tashkent, there are several companies and owning headquarters serving as trading partners with their countries of origin, which are listed below (Jurewicz and Shlyapochnik, 2018):

1. Paul Reinhart AG (Switzerland)
2. Cargill Cotton (UK)
3. Louis Dreyfus (Belgium)
4. Ecom Agroindustrial Corp. Ltd. (Switzerland)
5. Pexus Cotton Limited (UK)
6. Devcot S.A. (France)
7. Sicle Cotton Ltd. (Switzerland)
8. ICT Co. Ltd. (UK)
9. Daewoo International (Korea)
10. Cottonex Anstalt (Liechtenstein)
11. Olam International (Singapore)
12. Central Cotton (UK)
13. Xin Jiang Nongken (China)

Above companies export cotton from Uzbekistan to the designated areas in the world. The contribution of these companies to the national GDP of Uzbekistan in terms of the agricultural sector is remarkable. As shown in Fig. 11, cotton lint export is averagely over 500 million USD and 800 metric tons during 2000–2020 (Jurewicz and Shlyapochnik, 2018; OEC, 2021; Trading Economics, 2021).

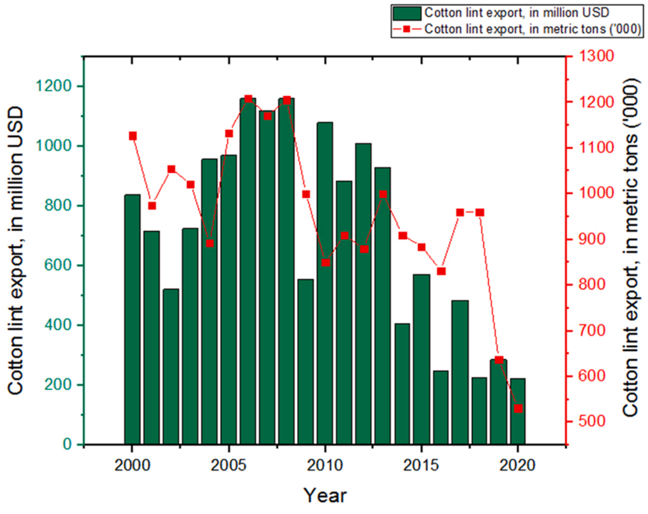

Fig. 11. Uzbek cotton export rate over 2000–2020.

Cotton export revenue had been steeply dropped over 20 years, starting with around 820 million USD in 2000 (1.12 million metric tons [Mt]), peaking in 2006 and 2008 at 1.150 billion USD (1.2 million Mt)), reaching its nadir at 210 million USD in 2020 (550,000 Mt).

It should be noted that owing to concerns of food security and insufficient water for irrigation, the cotton fields steeply decreased, and replaced by the grain fields after 2016.

After the shift toward sustainable agriculture by restricting high-water demand crop production such as cotton in 2017, the export rates significantly decreased. However, the average cotton yields per hectare was kept unchanged. This means that the unchanged amount of cotton yields per hectare can still be obtained while the cotton fields are being shrunk over time due to soil degradation and the deficiency of water resources. This might have negative footprint in the global cotton trade in partnering with the countries illustrated in Fig. 12 (OEC, 2021).

Uzbekistan is the main and integral cotton supplier of Bangladesh, which imports 39% of Uzbek cotton (Fig. 12). As the main cotton importer of Uzbekistan, the import share of Bangladesh became higher, reaching around 50–60% because of the considerable reduction in the cotton outputs of Uzbekistan in the recent years. The textile industry of Bangladesh constitutes approximately half of the national GDP. Thus, even a negligible change could be potentially reflected by the national GDP of Bangladesh (Fibre2Fashion, 2021; Jurewicz and Shlyapochnik, 2018). Therefore, the results of this paper could serve an early warning for Bangladeshi to prepare for the potential risk resulted from the decrease in Uzbek cotton outputs.

Uzbekistan is also the third largest cotton supplier to China, anteceded by the United States and India. Uzbekistan, on average, exports 28% of cotton to China (Fibre2Fashion, 2021). Since China is deemed as the largest cotton importer, consumer, and producer in the world, either a positive or a negative change in Uzbek cotton output could barely have an impact on the Chinese GDP.

Uzbekistan is the fifth largest cotton supplier to Turkey, exporting 8% of the total Uzbek cotton. Since the textile industry of Turkey contributes around 10% to the national GDP, Turkey is the second largest cotton lint importer of Uzbekistan, right after Russia (Jurewicz and Shlyapochnik, 2018). The significant change or drop in Uzbek cotton export might affect the textile industry of Turkey.

Although the national share of Uzbek cotton export is only 6% for Russia, which is sufficiently low compared to the above countries, Uzbekistan is the largest cotton lint supplier of Russia. Uzbekistan nowadays provides about 60% of the total lint imports of Russia (Fibre2Fashion, 2021; Jurewicz and Shlyapochnik, 2018). A percentage drop on Uzbek cotton export could become problematic for the textile industry of Russia.

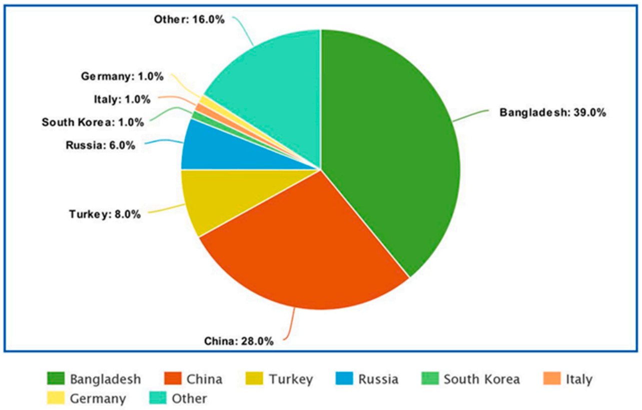

Fig. 12. Main cotton trading partners of Uzbekistan (% of the total Uzbek cotton export).

Uzbekistan is the primary cotton supplier to Germany and Italy despite a negligible portion in the national cotton trade share. Based on the quality of Uzbek cotton, these countries mainly utilize the cotton for medicinal purpose. This market share could be jeopardized as cotton fields are reduced in Uzbekistan with reference to decommissioning the highly salt-affected croplands. Thus, cotton import of these countries might be under risk. Lastly, South Korea is steeply restricting the cotton import from Uzbekistan since Brazilian cotton is more sustainable in concurrence (Jurewicz and Shlyapochnik, 2018).

Evidentially, as cotton exports are declining and croplands are being withdrawn from agricultural uses owing to soil salinization and traditional agricultural practices, Uzbekistan may suffer serious decreases in the contribution of the agricultural sector to the national GDP. This could lead the above-listed cotton enterprises to terminate their activity in Uzbekistan. Being proactive, Uzbekistan has started nationwide agricultural advocacy to promote vegetable and fruit production, sustaining the national food security.

3.6. Global impact of Uzbek wheat export

Exports of wheat from Uzbekistan have been executed by singing the agreement between two countries (Lombardozzi and Djanibekov, 2021; Sherzod et al., 2018). As can be seen from Fig. 13 (OEC, 2021; Trading Economics, 2021; Tridge, 2021), wheat exports in Uzbekistan are considerably low, comparing with cotton exports. For a couple of years, Uzbekistan did not export any wheat at all. However, in 2004 and in 2017, wheat exports culminated by 48 million USD (600,000 Mt) and 52 million USD (650,000 Mt), respectively. In the recent years, Uzbekistan has supplied 200,000 Mt of wheat for different prices.

According to OEC (2021), Uzbekistan mainly supplies Afghanistan with 37.7% of the national wheat export share (Fig. 14). This share has markedly risen since 2016 when the risk of famine increased dramatically in Afghanistan. To ensure food security in Afghanistan, Uzbekistan sold almost all of the wheat outputs to this country. An unexpected shrinkage of the wheat lands in Uzbekistan could beget serious consequences and impacts on the well-being of the Afghan population.

Iran (31.3%) and Azerbaijan (23.6%) were the main importers of Uzbek wheat in the middle of the experimental years. Because of the cheaper price in regards to the quality of wheat, these countries found that this was an optimal way to ensure the national food source. However, the quality of Uzbek wheat has decreased with reference to the worse reclamation status of croplands. Alike Georgia, Kyrgyz Republic, and Tajikistan have restricted the wheat import from Uzbekistan due to the quality. These countries are then importing wheat from Kazakhstan (OEC, 2021; Trading Economics, 2021; Tridge, 2021).

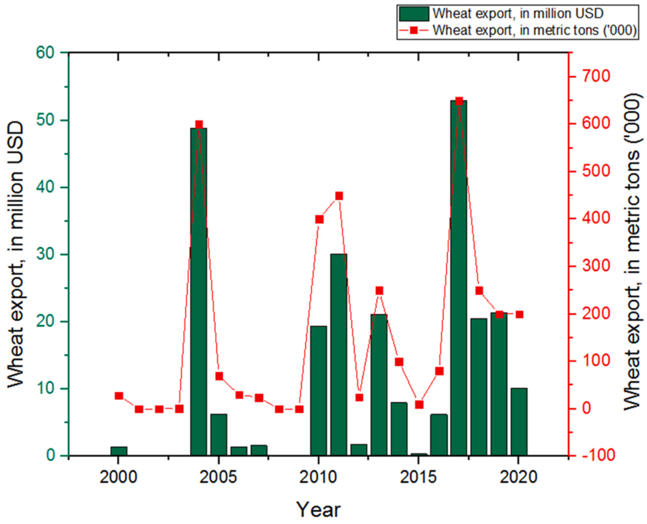

Fig. 13. Uzbek wheat export rate over 2000–2020.

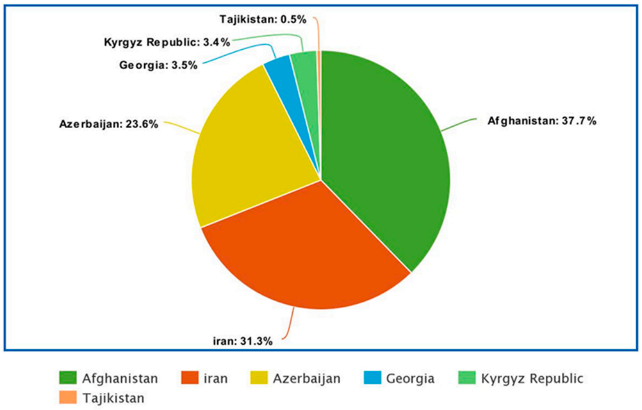

Fig. 14. Main wheat trading partners of Uzbekistan (% of the total Uzbek wheat export).

Wheat production in Uzbekistan, as one of the primary food sources, could facilitate the tense food supply in Afghanistan. Proper management of croplands in Uzbekistan may protect these two nations in terms of food security.

3.7. The role of Uzbek demography

Increasing population could also be one of the potential drivers for the decline in exports (Mamo, 2019). The demography of Uzbekistan reveals a rising trend (Fig. 15) (Worldometers, 2021). In 2000, population of Uzbekistan was nearly 24.5 million in 2000. Thanks to the arithmetical progressive growth, the population was around 33.5 million in 2020, 9 million growth over 20 years. To reduce the unemployment rate in Uzbekistan, a number of cotton yarn processing enterprises under international cooperation were established. Instead of exporting cotton lint, Uzbekistan started trading textile which was deemed more beneficial. The same occurred for the wheat production. Growing population could potentially limit the export and pressurize consuming. To maintain the balance between consuming and export, sustainable land management and practices should be prioritized in Uzbekistan. This can be achieved by adapting the most successful practices that have been successfully implemented in the Netherlands and the United States.

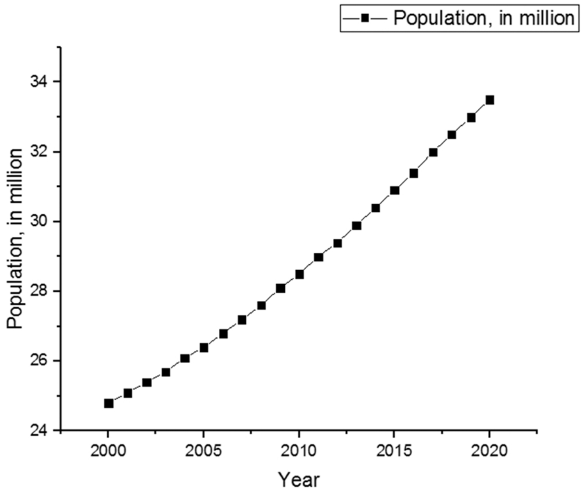

Fig. 15. Demographics of Uzbekistan over 2000–2020.

4. Conclusions

Through our study, it is possible to detect and track the cropland changes and irrigated soil salinity of Uzbekistan by the GEE approach with higher accuracy and lower RMSE. This experiment revealed the advances of the GEE platform to facilitate the proactive decision-making over agricultural practices. Aligning with this, the GEE-based approach could replace the conventional method of agricultural monitoring processes that considered a remarkable limitation in the evaluation of food security in Uzbekistan. Moreover, as the non-saline and weakly saline cropland areas gradually decreased in Uzbekistan, the severely salt-affected areas have rapidly increased within 2000–2020. We assume that this is an exceptionally unpleasant environmental signal that urgently demands nationwide sustainable agricultural practices to reduce the impact of potential environmental risks on other nations.

Crop production needs an increased input of water and mineral fertilizers, potentially increasing the severity of soil salinity. However, through the data analysis on the mineral fertilizer consumption, we identified that Uzbekistan consumed the increased amount of fertilizers comparing with the global average to harvest the stable crop yields from irrigated lands. In this research, the effect of P applications on the salt-affected cropland expansion was also discovered. Therefore, fertilization management needs to consider the potential effects of salinity on cotton and wheat growth and soil salinity. Promoting fertigation in Uzbekistan could increase mineral fertilizer use efficiency without unexpected increases in soil salinity. On the other hand, the implementation of biofertilizers has the potentials to enhance agricultural crop salt tolerance and eliminate soil salinization.

No effect was observed for the applications of herbicides, insecticides and fungicides on either crop yields or soil salinity. This might pose to further scrutinize the effects of agrochemical applications on heavy metal accumulation in the topsoil, and subsequent impact on crop production.

According to this study, cotton export of Uzbekistan has a significant and direct impact on the national GDP of Bangladesh. Nonetheless, Uzbek wheat endures the national food security of Afghanistan in the recent years. This means that other nations could suffer economic difficulties and shortages when Uzbekistan reduces its crop production due to soil salinity. Therefore, it is necessary to develop different sustainable scenarios and strategies for mitigating potential climatic variabilities and fertilizer management to reduce the severity of soil salinization. This can be achieved based on big data analysis and by promoting machine learning in the agricultural sector of Uzbekistan.

Ethics approval

Not applicable.

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CRediT authorship contribution statement

Rashid Kulmatov and Fadong Li - Conceptualization and Supervision; Fadong Li, Rashid Kulmatov, Sayidjakhon Khasanov, Andre van Amstel - Methodology; Sayidjakhon Khasanov and Harm Bartholomeus – Software, Validation; Sayidjakhon Khasanov - Formal analysis, Data curation; Sayidjakhon Khasanov and Andre van Amstel - Writing – original draft preparation; Sayidjakhon Khasanov and Ilhomjon Aslanov – Visualization; Sayidjakhon Khasanov and Nabijon Holov - Investigation; Komolitdin Sultonov - Resources; Sayidjakhon Khasanov - Data curation; Sayidjakhon Khasanov, Rashid Kulmatov, Fadong Li, Andre van Amstel, Harm Bartholomeus, Ilhomjon Aslanov, Komotdin Sultonov, Nabijon Holov, Hongguang Liu, and Gang Chen - Writing – review & editing; Fadong Li - Project administration. The authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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Competing interests

The authors declare no conflict of interest.

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