INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
IFPRI

RESEARCH PROGRAM ON Policies, Institutions, and Markets
CGIAR
Led by IFPRI

IFPRI Discussion Paper 02081

December 2021

Climate Change, Agriculture, and Potential Crop Yields in Central Asia

Timothy S. Thomas

Kamiljon Akramov

Richard D. Robertson

Vijay Nazareth

Jarilkasin Ilyasov

Development Strategy and Governance Division
Environment and Production Technology Division

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

The International Food Policy Research Institute (IFPRI), a CGIAR Research Center established in 1975, provides research-based policy solutions to sustainably reduce poverty and end hunger and malnutrition. IFPRI's strategic research aims to foster a climate-resilient and sustainable food supply; promote healthy diets and nutrition for all; build inclusive and efficient markets, trade systems, and food industries; transform agricultural and rural economies; and strengthen institutions and governance. Gender is integrated in all the Institute's work. Partnerships, communications, capacity strengthening, and data and knowledge management are essential components to translate IFPRI's research from action to impact. The Institute's regional and country programs play a critical role in responding to demand for food policy research and in delivering holistic support for country-led development. IFPRI collaborates with partners around the world.

AUTHORS

Timothy S. Thomas (tim.thomas@cgiar.org) is a Research Fellow in the Environment and Production Technology Division of the International Food Policy Research Institute (IFPRI), Washington, DC.

Kamiljon Akramov (k.akramov@cgiar.org) is a Senior Research Fellow in IFPRI's Development Strategy and Governance Division, Washington, DC.

Richard D. Robertson (r.robertson@cgiar.org) is a Research Fellow in IFPRI's Environment and Production Technology Division, Washington, DC.

Vijay Nazareth (vijay@exetercapital.com) is Founder and Executive Director at the Center for Social Innovation, Fredrick, MD.

Jarilkasin Ilyasov (ilyasov@gmail.com) is an International Consultant at the Ministry of Investments and Foregin Trade of the Republic of Uzbekistan, Tashkent, Uzbekistan.

Notices

[1]IFPRI Discussion Papers contain preliminary material and research results and are circulated in order to stimulate discussion and critical comment. They have not been subject to a formal external review via IFPRI's Publications Review Committee. Any opinions stated herein are those of the author(s) and are not necessarily representative of or endorsed by IFPRI.

[2] The boundaries and names shown and the designations used on the map(s) herein do not imply official endorsement or acceptance by the International Food Policy Research Institute (IFPRI) or its partners and contributors.

[3]Copyright remains with the authors. The authors are free to proceed, without further IFPRI permission, to publish this paper, or any revised version of it, in outlets such as journals, books, and other publications.

Abstract

Agriculture in Central Asia is vulnerable to climate change due to rising aridity, declining availability of water resources for irrigation, and low adaptive capacity. We use climate data from CMIP5 with RCP8.5 for greenhouse gas emissions and the DSSAT crop model to investigate how yields of key crops in Central Asia will be affected by climate change. We distinguish changes in yields between spring and winter plantings, between irrigated and rainfed crops, and between crops grown with high and low amounts of fertilizer. The results suggest that countries (and areas within countries) that either have moderate summers or grow a number of crops in a relatively cold winter will benefit from climate change, while countries that grow many of the crops in the summer will experience losses.

Keywords: Central Asia, climate change, agriculture, crop modeling.

Acknowledgments

We thank the CGIAR Research Program on Policies, Institutions, and Markets led by IFPRI and the Ministry of Finance of the Russian Federation under IFPRI's Collaborative Research and Capacity Strengthening Program for Enhancing Agricultural Productivity and Food and Nutritional Security in Central Asia for financial support.

Competing Interests

The authors have no competing interests to declare.

Authors' Contributions

Timothy Thomas did most of the final modeling and writing for this article. Kamiljon Akramov wrote the section on Central Asian agriculture, contributed to the introduction and conclusion, and was responsible for the overall coordination of the project. Richard Robertson modeled the maize and potatoes and helped troubleshoot the modeling in the other crops. Vijay Nazareth contributed to early work with the cotton, wheat, and barley crop models. Jarilkasin Ilyasov produced the database of subnational information on spring vs. winter, irrigated vs. rainfed, and high input vs. low input on which the aggregations of crop model results are based.

Introduction

Agriculture is an important sector of the economy in Central Asia. In Uzbekistan, for example, agriculture accounts for 26 percent of the national GDP, and nearly 26 percent of the labor force is employed in agriculture. Tajikistan's numbers are similar for contribution to GDP, at almost 24 percent, but the reliance on agriculture for employment is much higher, at roughly 45 percent. For Kyrgyzstan, those numbers are 14 percent and 19 percent, respectively. For Kazakhstan, less than 5 percent of GDP is from agriculture, largely due to the importance of oil to its economy. Nonetheless, agriculture employs nearly 15 percent of its labor force, indicating that agriculture is a significant source of employment (World Bank 2021).

Agriculture is, by nature, highly dependent on both climate and weather, and the region has a far-ranging climate, with some parts having scorching hot summers, and others having wickedly cold winters. Most areas are entirely arid or semi-arid, while others receive healthy levels of precipitation. Figure 1 shows the mean annual precipitation for the period from 1960 to 1990 for Central Asia. We note a large portion of the southwestern sector has extremely low rainfall, with annual totals reaching only slightly more than 100 millimeters. The rainfall levels rise from south to north, but the average rainfall for all of Kazakhstan still only rises to around 250 millimeters per year. Higher rainfall levels are noted in much of the elevated areas of Kyrgyzstan and Tajikistan in particular, with levels reaching to around 1,000 millimeters in both places. Of the four countries, Tajikistan has the highest mean annual rainfall, at 543 millimeters, followed by Kyrgyzstan, at 411 millimeters.

Figure 2 shows the mean daily maximum temperature for the warmest month of the year. This map shows similar patterns to the rainfall map, with the highest temperatures in the southwest, and a general cooling pattern as one moves northward. It also shows cooler temperatures in the elevated areas of Tajikistan and Kyrgyzstan. These temperatures are important because the higher the temperature, the more agriculture is constrained. Parts of Tajikistan and Uzbekistan, for example, have mean daily maximum temperatures reaching around 38 degrees Celsius. It is also true that parts of Tajikistan and Kyrgyzstan do not typically reach above 10 degrees Celsius during the hottest month.

Figure 3 shows the mean daily minimum temperature for the coldest month of the year. This helps identify areas that may be too cold for winter crops. Here, we see that the northern areas get quite cold, down to nearly -24 degrees Celsius. The mountainous areas of Kyrgyzstan and Tajikistan, however, can reach even lower, around -29 degrees Celsius.

Climate change is already affecting agricultural productivity and will continue to affect it in the coming years. Policymakers need accurate quantitative assessments of the potential impact of climate change on various crops and regions so that they will be able to make the best-informed decisions and investments to help farmers and the entire sector adapt to the changes.

This paper uses biophysical models together with the climate models of the fifth phase of the Coupled Model Intercomparison Project (CMIP5) of the World Climate Research Programme to assess the potential impact of climate change on five key crops in Central Asia: wheat, barley, cotton, maize, and potatoes. Special care is taken to differentiate the effects of climate change on spring crops versus winter crops; rainfed crops versus irrigated crops; crops under high fertilizer rates versus lower fertilizer rates; and by location. The productivity of each relevant crop is assessed at a grid of locations roughly 9 kilometers apart.

While other studies have used crop models for Central Asia to examine the impact of climate change, most of those studies have focused on only a portion of the region and not all of them have focused on yields, both of which make the analyses difficult to include in national-level agricultural modeling. Valkama et al. (2020) use the ARMOSA crop model to evaluate changes in soil carbon under climate change, but only for a limited number of sites. Tian and Zhang (2020) study the irrigation water requirements for cotton and winter wheat for the whole region, but do not report yield changes due to climate change. Sutton, Srivastava, and Neumann (2013) used the AquaCrop model with CMIP3 climate models to compute yield changes for Uzbekistan for wheat, cotton, tomatoes, potatoes, apples, and alfalfa. Mitchell et al. (2017) used the DSSAT crop model to study the effect of climate change on cotton, rice, wheat, and tomatoes in Uzbekistan.

However, several older studies do similar work to what we present in this paper, though without the same control for crop management used here. Sommer et al. (2013) use the CropSyst model to compute changes to wheat yields in the Central Asia region using the older CMIP3 climate models. As part of the same analysis, Kato and Nkonya (2012) used DSSAT and CMIP3 to analyze cotton and potato yields under climate change. These were then used to calibrate the analysis done by Bobojonov and Aw-Hassan (2014).

Furthermore, embedded in several global analyses, there are spatially disaggregated crop modeling results that have informed the bioeconomic models (though the details are not clearly published at the national level), such as in Nelson et al. (2009) and Nelson et al. (2010). Other global crop modeling analyses have only displayed the results graphically (Müller and Robertson 2014) or have only reported the bioeconomic model results, but do not report the crop model results that informed the bioeconomic model. Others provided the data at a fine resolution (see Rosenzweig et al. 2014), but the downside to global crop modeling is that care is generally not taken to ensure national-level details are taken into consideration, such as multiple planting dates and region-appropriate crop varieties.

Even more studies have used crop models to examine the impact of climate and weather on various aspects of agriculture in Central Asia but did not endeavor to use the models to project the effect of future climate or have only used models to look for sensitivity analyses of temperature or precipitation changes. Ruan et al. (2020) use CropWat to study water stress in the Syr Darya Basin. Ibragimov et al. (2020) use CropSyst to look at the effect of a triple rotation on soil fertility in the Khorezm region of Uzbekistan. Guo et al. (2016) use the EPIC crop model to evaluate the risk of drought for maize, finding that Central Asia is among the highest maize drought risk in the world.

In addition to having value in its own right, the climate impact assessment on crops in this current article is used in related articles in this special issue that embed the changes presented here into a global bioeconomic model that assesses the greater economic impact of climate change on the agricultural sector in Central Asia.

We proceed as follows: in the next section we review the data used in this analysis. Then, we present a brief overview of agriculture in Central Asia, focused on the cropping sector. We then present the results of our crop model work and conclude with a summary and recommendations.

Data and Methodology

Climate models

Global climate models, which are also referred to as general circulation models (GCMs), are developed by climate scientists to determine how climate might change in response to greenhouse gas (GHG) accumulation in the upper atmosphere. The Climate Model Intercomparison Project is a globally recognized standard for proposing common experiments to climate modeling teams that can then be used to compare the effect of GHG emissions on climate. A new generation of experiments and models are produced every roughly 6 to 8 years. CMIP5 models were finalized in the 2011 to 2012 timeframe. For CMIP5, 61 models were developed and approved. The output from these models are often at a resolution of 40,000 square kilometers and much of the data is presented at monthly intervals.

In this paper, we used data at a roughly 80 square kilometer resolution. Downscaling the data can be very technical, and we therefore used data that was produced for the Agricultural Model Intercomparison and Improvement Project (AgMIP) Gridded Global Crop Model Intercomparison (GGCMI) project, which brought together global modeling teams to compare crop model results (Rosenzweig et al. 2014). Crop model-specific data that is not included in the original low-resolution GCMs, but which is essential for crop modeling and is included in the downscaled AgMIP-GGCMI data, are solar radiation and number of rainy days in each month. The AgMIP-GGCMI included five GCMs, though data for the fifth was available much later than the other four. Therefore, for this article, we used first four:

- GFDL-ESM2M, which was produced by the National Oceanographic and Atmosphere Administration General Fluid Dynamics Laboratory (GFDL) (Dunne et al. 2012, 2013);
- HadGEM2-ES, the Hadley Centre Global Environmental Model (HadGEM), from the Met Office Hadley Centre (Collins et al. 2011; Martin et al. 2011);
- IPSL-CM5A-LR, generated by Institut Pierre-Simon Laplace (IPSL) (Dufresne et al. 2013); and
- MIROC-ESM-CHEM (MIROC), from the Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo), and National Institute for Environmental Studies (Sakamoto et al. 2012).

These models were chosen by AgMIP-GGCMI, in part because they were thought to represent a good sample of the entire collection of GCMs produced for CMIP5.

CMIP5 experiments included five different representative concentration pathways (RCPs), which provide modelers with the pattern of emissions and accumulation of GHGs (Stocker et al. 2014). Among the RCPs, one is historical (no change), and the remaining four reveal the amount of “radiative forcing” they yield by 2100 (that is, the ability of the atmosphere to retain heat instead of radiating it back to space). RCP2.6, for example, has around 2.6 watts per meter squared in 2100. Of the remaining RCPs (RCP4.5, RCP6.0, and RCP8.5), RCP8.5 represents the highest amount of GHG accumulation modeled; it is also the one most used by researchers, and the one we elected to use. It might be thought of as producing an upper bound to climate change compared to the lower bound of the no climate change scenario.

Thus, it provides an upper bound on the amount of yield change that might happen. This allows us to focus more on the range across four different climate models within that scenario. Temperature differences between climate models are significant, with Kyrgyzstan, for example, having temperature changes from 2000 to 2050 ranging from 2.5 degrees to 5.4 degrees, depending on the model. These, in turn, lead to important differences in yield changes, with Kazakhstan's spring wheat ranging between 2000 and 2050 from a loss of 8.1 percent to a gain of 3.4 percent. IPCC shows that globally in 2050, the difference in temperature changes between RCP4.5 (a more modest emissions scenario) and RCP8.5 is 0.6 degrees (from 1.4 degrees to 2.0 degrees). This is much smaller than the changes for the region—but northern regions are known to have larger temperature changes projected. It might be better to think about the ratio of the changes: RCP4.5 is 70 percent of the change of RCP8.5. We, therefore, might expect that crop models using RCP4.5 might have yield impacts at roughly half of what RCP8.5 projects them to be, considering that the effect of temperature on yield is roughly quadratic.

Figure 4 shows the changes in annual precipitation projected between 2000 and 2050 under the four GCMs and assuming RCP8.5 (a high greenhouse gas emissions scenario). In the figure we see that Tajikistan, in particular, but also Uzbekistan and Kyrgyzstan, will become drier with climate change if three of the four models are correct. On the other hand, if HadGEM is correct, they will get wetter with climate change. The impact on Kazakhstan ranges from no change to positive change. Some of the gains in rainfall, however, might be offset by increased evaporation from higher temperatures.

Figure 5 shows changes in the mean daily maximum temperature of the warmest month. Since the Spring growing season encompasses the warmest month of the year, this is a good indicator of added stress on heat-sensitive crops. Table 1 aggregates the projected changes in climate at the national level. One of the most striking statistics in the table is the differences between climate models for changes in the mean daily maximum temperature for the warmest month for three of the four countries in the region. For example, the GFDL climate model projects that between 2000 and 2050, Kyrgyzstan will warm by 2.8˚C, while the HadGEM climate model tells us that it will be 5.9˚C. The other two models are more in line with the projections of HadGEM for the region, though HadGEM projects a higher increase than either of the other two.

On the other hand, the GFDL climate model projects an even greater increase in temperature than HadGEM for Tajikistan. Variation between climate models for temperature change is smallest there compared to the other three countries in the region. The maps for rising temperature in Figure 5 all indicate a general trend of less change in projected temperature the further north one goes.

DSSAT crop model

The Decision Support System for Agrotechnology Transfer (DSSAT) is a crop simulation software package consisting of multiple mathematical models (Jones et al. 2003). It is recognized as one of the most accurate models for biophysical analysis of crop growth. Some crops can be simulated in more than one model, which allows for alternatives in cases where one model might seem to perform poorly, and allows for comparison in the case where both (or all) perform reasonably.

For each roughly 80 square kilometer pixel (5 arc-minutes on each side), the models "grow" the crop in daily time increments using DSSAT's weather simulator and the monthly weather statistics that the GCMs provide. That is, given the monthly climate variables for any pixel, the weather simulates a plausible pattern of weather that could be drawn from the distribution that includes the climate parameters. In our analysis, the weather was simulated 80 different times (simulating 80 different years of weather based on the given climate parameters[1]) so that a meaningful average impact of climate on the crop could be calculated. The yields were computed for every pixel that MapSPAM (You et al. 2014) suggested contained more than 10 hectares of the crop.

The soil data used were adapted by Koo and Dimes (2010) from the Harmonized World Soil Data Base by Batjes et al. (2009). They were then further simplified into 27 types, each with high, medium, or low soil organic carbon; deep, medium, or shallow rooting depth; and a major component of sand, loam, or clay. When pixels had more than one soil type represented, the dominant type was used.

We not only calculated yields for each pixel but computed them over a window of possible planting dates, and over several different crop varieties, looking for the most optimal planting date and variety. Yield changes due to climate change were found by comparing the baseline yields (computed for the climate of 2000) with the yields based on the 2050 climate. In the 2050 climate, we restricted the variety to be the same as was grown in the baseline, but allowed the planting month to change, if it were optimal to do so.

We computed the average yield (computed over 80 different yield calculations from 80 years' worth of simulated weather data) for the baseline year 2000 to the average yield of each GCM computed over 80 years' worth of simulated weather data. Thus, whenever one statistic for climate change is presented, it will represent the median of the four GCMs used.

For barley and wheat, for every pixel where we ran DSSAT, we did so for the winter variety and the spring variety; rainfed and irrigated; and high fertilizer (which we set at 90 kilograms of nitrogen per hectare) and low fertilizer (which we set at 10 kilograms of nitrogen per hectare). We used national statistics to infer the proportion of each of the 8 possible combinations that were present in each pixel, along with the total hectares of the crop cultivated in the pixel, which we extracted from MapSPAM. We did the same for cotton, but only for high and low fertilizer levels, since essentially all cotton is planted in the spring and is irrigated.

The particular temperature range in Central Asia presented challenges for using the CERES wheat model inside DSSAT, which is the newer and therefore preferred model. In many locations where MapSPAM assured us that wheat grew, the CERES model told us that the harvest was a complete loss in more than half of the years. Since we did not trust this result and consulted with experts as to whether some kind of technical error was made in running the model and finding none, we reverted to the older model in DSSAT for wheat, the CROPSIM model. This eliminated the high failure rate and gave results that seemed much more reasonable.

Inside DSSAT, we used cultivars that were appropriate to the agroecozones of the region. We used three different varieties of barley, two different varieties of cotton, five different varieties of spring wheat (when we tried the CERES model), seven different varieties of winter wheat (when we tried the CERES model), two different varieties of winter wheat (CROPSIM) and one variety of spring wheat (CROPSIM). We also varied the planting date for spring crops from March to June, and the planting date for winter crops from September to November. We always chose the crop variety and planting month that gave the highest yield in each pixel in the baseline (year 2000), but in 2050, we kept the crop variety the same

---

[1] These were random simulations of weathers. The rule of thumb is to draw at least 30 different simulations so that the law of large numbers holds and that the mean of the results from the draws can be reliably said to represent the population of possible weathers under the given climate. We chose to use 80 to be more certain that mean was a very good representation of what the population mean would be.

as in 2000 while allowing the planting month to shift. These choices were somewhat philosophical, as we attempted to answer the question: What will the direct effect of climate change be on yields (before allowing for technological change to compensate and adapt)?

We also made the decision to not account for CO_2 fertilization, in part because of concerns as to whether the fertilization effect is known well enough over the long-term to model, and also because of the belief that any fertilization effect would be potentially offset by biotic stressors of plant pests and diseases which are expected to thrive in warmer temperatures, as well as the yield-reducing effect of ozone. De Pinto et al. (2020) review the literature regarding reasons to be skeptical about the yield-increasing potential of CO_2 fertilization.

While the detailed modeling is done at the pixel level, we also want to know the effect on average yields for each country. In order for us to be able to aggregate up to the national level, we have to make some kind of assumption as to the relative contribution of agriculture in each pixel. For that, we use MapSPAM (You et al. 2014) to tell us in which locations crops are grown, along with the concentration of the crop in a location, including the amount that is rainfed and the amount that is irrigated.

The MapSPAM data seemed to disagree with some national agricultural statistics on rainfed area and irrigated area, so we chose not to use this particular aspect of the data. Instead, we used the total area, and then used the national agricultural statistics to help assign which percent of the area of each cell for each crop should be attributed to each water regime by sub-national unit.

Central Asian Agriculture

Transition from the Soviet era

The agricultural sectors of Central Asian countries have experienced a sustained process of transition and reform since the early 1990s. These transformations led to new mixed structure of farm organization and produced new patterns in agricultural production. These countries shared a common legacy of collective agricultural production, which was sustained by a heavy reliance on subsidies, central planning and marketing networks.

The dissolution of the old state-led system severely disrupted the agricultural sector in the region. The absence of market institutions and the emergence of new national barriers posed additional obstacles for the marketing and supplying of goods and inputs. As a result, all countries experienced a sharp decline in output, including in agriculture, with widespread socioeconomic ramifications. It was under these conditions that initial reforms took place. The incomplete list of reforms embarked in 1990s included land reform, farm reorganization, irrigation and water management, price reform, and the development of market institutions (Rozelle and Swinnen 2004).

Land reform and farm reorganization

Land reform was one of the most far-reaching components of agricultural reform in the region (Lerman, Csaki and Feder 2004). During the Soviet era, all land was owned by the state and all agricultural land fell under the purview of state-run or state-supported collective farms. Households allowed land use rights grew crops for subsistence on small household plots, but full ownership rights with associated privileges were withheld.

While all governments in the region acknowledged the weaknesses of the collective farming system, they adopted different approaches to land reform and farm reorganization. The Central Asian countries demonstrated a more conservative approach in general than those in Central and Eastern Europe and the Caucasus, which moved quickly to allow private ownership rights, including the right to sell or transfer land. In the Kyrgyz Republic, which had nominally introduced private ownership in 1998, the government initially imposed a moratorium on land transactions to prevent landowners from selling their assets and gradually introduced full ownership rights (USAID 2005; Akramov and Omuraliev 2009). Kazakhstan gradually introduced the concept of private ownership of agricultural land more than a decade after independence (Petrick, Oshakbaev and Wandel 2014). Agricultural land in Tajikistan and Uzbekistan continues to be state-owned, while agricultural producers have somewhat limited long-term use rights.

Along with land reform, farm reorganization was another major undertaking by the countries in Central Asia during the early transition period. Farm reorganization in Central Asia resulted in the creation of various types of farm organizations ranging from smallholder family-led farms to large corporate enterprises. Overall, three general forms of farming units emerged throughout the region: agricultural enterprises, individual (private dehkan) farms, and household plots. Agricultural enterprises—which were variedly known as state farms, joint-stock companies, production cooperatives, or corporate farms, depending on the country—largely bore a resemblance to the old collective farms. Individual or private farms were direct beneficiaries of the breakup of collective farms: many farms of this type arose from collective land that was redistributed to households and individuals.

The growth of individual (private) farms drove the transformation of agriculture in Central Asia. The overarching patterns of farm restructuring, characterized by the rise of smallholders and the congruent decline of collective farming, were similar throughout the region. This held true even for land-abundant Kazakhstan, where large agricultural enterprises still retain a considerable presence. Over the years, policymakers have contended with the debate over whether farm sizes have become too small, for example in the Kyrgyz Republic (Akramov and Omuraliev 2009). Measures on farm size optimization and land consolidation such as in Uzbekistan appear to reflect concerns about land fragmentation.

The initial reforms in land and farm organization had a transformative effect on the rural landscape and agricultural production in Central Asia. Over the long term, land reform effectively re-distributed agricultural land from large enterprises to smaller private farms. In the Kyrgyz Republic, for example, land controlled by collective farms and large agricultural enterprises dropped dramatically from 93 percent of total cropland in 1990 to 26 percent in 2000 and less than 5 percent in the mid-2010s (Akramov and Omuraliev 2009; National Statistics Committee 2018; IFPRI, CAREC Institute, and ADB 2019). Currently, more than 300,000 individual farms with an average land size of 2.9 hectares, control about 82 percent of total cropland in the country. The remaining 13 percent of total cropland is occupied by more than 900,000 traditional household plots with an average size of 0.11 hectares per holding (Akramov and Omuraliev 2009 with updates).

In Tajikistan, land reform and farm reorganization started after the end of its civil war, which lasted from 1992 to 1997. The land reform was very slow until 2007. Between 2007 and 2012, more than 55 percent of all arable land use has been privatized in the form of lease farms, joint-stock companies, and dekhan farms (Lerman, 2012; Akramov and Shreedhar, 2012). Furthermore, the Program for Reforming the Agricultural Sector for 2012-2020 introduced additional agricultural land reforms. While the land is still the exclusive property of the state, legal entities and individuals have long-term land use rights, which allows the user to sell, donate, exchange, rent, pledge, and transfer it to another person in the form of inheritance. Currently, large agricultural enterprises occupy only 13 percent of arable land, compared to 21 percent under household plots, and 66 percent under private farms (Government of the Republic of Tajikistan 2012; Statistical Agency under the President of the Republic of Tajikistan 2019; IFPRI, CAREC Institute, and ADB 2019).

In contrast to the Kyrgyz Republic and Tajikistan, large agricultural enterprises using leased state land and hired labor are still major actors in agricultural production in Kazakhstan, especially in its northern grain-producing regions (Petrick, Oshakbaev and Wandel 2014). Approximately 60 percent of arable land is cultivated by these enterprises, compared to 39 percent of arable land for private farms, and only 1 percent for household plots. In Uzbekistan, large agricultural clusters started to dominate the crop sector in recent years, while small private farms still produce nearly all livestock production.

Evolution of crop choices

Agricultural production and crop choices in the region have changed in favor of food and high-value commodities during the last two decades. In the past, the Kyrgyz Republic specialized in intensive livestock production, Tajikistan and Uzbekistan on cotton, and Kazakhstan grew mostly wheat. However, collapse in cross-border trade networks following the dissolution of the Soviet Union compelled national governments to focus on food security. This led to an expansion of wheat, potatoes, and vegetable crops in the Kyrgyz Republic, Tajikistan, and Uzbekistan. On the other hand, lands allocated for cotton and feed crops decreased concurrently. In more recent years, however, regional governments have taken a more expansive approach to food security: they not only prioritize self-sufficiency, but also value in terms of both nutrition and earnings. As regional trade links began to regenerate in the early 2000s, Kazakhstan has become an important source for cereals, reducing the need to grow wheat in the other countries.

In the Kyrgyz Republic, land allocated for wheat increased from 15 percent of the total sown area in 1990 to 42 percent in 2002. Horticulture likewise increased from a combined 8 percent of total land area to 12 percent in 2002. Feed crops and barley declined from 48 percent and 20 percent of the total sown area in 1990 to 20 percent and 6 percent in 2002, respectively (Akramov and Omuraliev 2009). Since that time, wheat in sown areas declined to 24 percent, as land was allocated for other crops instead and wheat availability became less of a concern due to improved international trade, mostly from Kazakhstan. Land allocated for barley and feed crops recovered somewhat during this time, increasing 27 and 14 percent, respectively. The share of horticulture continued to expand and reached 16 percent in 2015 (National Statistics Committee 2018).

Similarly, in Tajikistan, land allocated for food crops such as wheat, potatoes, and vegetables increased after initial reforms at the expense of cotton and feed crops. Cereals, mainly wheat, became the dominant crop in Tajikistan, planted on approximately 51 percent of arable land in the country, with wheat accounting for 41 percent of all land alone (Akramov and Shreedhar 2012). In 2016, grains continued to account for approximately 50 percent of arable land area. Although reduced in scale, cotton remains a major crop in Tajikistan, representing the second largest crop type with less than 20 percent of total land area. Land allocated for potatoes, melons, and vegetables account for a combined 15 percent of total sown area. Land area under fruit and vegetable production increased by 16 percent and 30 percent by 2011, respectively, compared to 2005 (Akramov and Shreedhar 2012). With a greater emphasis placed on growing food crops, the share of arable land allocated to feed crops declined significantly and occupied around 12 percent of arable land in 2016.

Likewise, land allocated for wheat increased in Uzbekistan at the expense of cotton and feed crops. During the 1990s and 2000s, land allocated for wheat and cotton ranged from 70 to 80 percent of total sown area. However, in the past decade, the government of Uzbekistan began to prioritize crop diversification, specifically by allocating more arable land to horticulture. As a result, land allocated for horticultural crops has been steadily increasing, and in 2016 reached almost 17 percent, representing a nearly 5 percentage-point increase from the early 2000s. A notable feature of agriculture in Uzbekistan and Tajikistan is the prevalence of double cropping on land allocated for wheat, with vegetables and feed crops often being grown as secondary crops. This has effectively increased the land area and production of vegetables and feed crops.

The government of Kazakhstan has also prioritized crop diversification in recent years. The Kazakh government's strategy has been primarily based on improving wheat production through a technology-driven increase in yield while expanding the area of forage crops and oilseeds. This strategy has encouraged agricultural producers to diversify their crop mix by planting less wheat and directing subsidies to feed and oilseed crops, such as sunflowers, flax, safflowers, rapeseed, and soybeans. The use of direct area-based subsidies has been one of the Kazakh government's most effective tools for implementing crop diversification strategies. Total oilseed sown area has tripled from around 700,000 hectares in 2006 to more than 2 million hectares in 2015. Crop diversification has also been driven by a growing livestock industry, which has generated additional demand for forage. Land allocated for feed crops increased from 2.3 million hectares in 2006 to nearly 3.7 million hectares in 2015, with a concurrent 20 percent reduction sown area for wheat. Although Kazakhstan is a land-abundant country with large areas of rainfed cropland in the north, agriculture in its southern regions more closely resembles practices found elsewhere in Central Asia (IFPRI, CAREC Institute, and ADB 2019).

Figure 6 illustrates trends in crop diversity in four Central Asian countries between 1990 and 2016, demonstrating a growing importance of horticulture in the region. The rise in land allocated for food crops in the 1990s reflected the desire of the governments in the region to ensure food self-sufficiency. In more recent years, however, higher-value horticulture crops in the Kyrgyz Republic, Tajikistan, and Uzbekistan are seeing an increase in production. In Kazakhstan, oilseeds have become more widely grown since 2010.

Changes in the distribution of arable land and livestock across farm types characterized a fundamental transformation in the Central Asian agricultural sector. In all countries, the share of the private sector, comprised of household and individual farms, in total agricultural production increased substantially. The private sector produces more than 95 percent of aggregate agricultural output in the Kyrgyz Republic and Uzbekistan, including almost 95 percent of crops and nearly all livestock output by the late 2000s (Akramov and Omuraliev 2009; IFPRI, CAREC Institute, and ADB 2019). While the production of staple crops, primarily cereals, deemed strategically important was the target of state intervention, horticulture and livestock have generally been left at the discretion of private and household farmers.

Changes in farm productivity

Data have generally demonstrated higher farm productivity in smallholder farms, owing to several possible factors including lower transaction and administrative costs, better governance, and efficiencies driven by individual crop choices. Unlike small farms, larger farms bear the costly administrative burdens of monitoring operations and enforcing labor discipline, which can offset their advantages from economies of scale (Lerman, Csaki and Feder 2004). The individualization of agriculture may have weakened these problems associated with collective agriculture, while simultaneously encouraging private incentives (Akramov and Omuraliev 2009). The changes in land use and farming structure led to high agricultural growth rates in the region. For example, in Tajikistan, agriculture grew by 6.4 percent per year during 2010–2019 (World Bank 2020).

While trends in land use, crop composition, and farm organization show important changes in the agricultural sector, changing labor and land productivity patterns are demonstrative of fundamental transformation within the sector itself (Timmer 2015). The combination of land and labor productivity captures the pace and extent of agricultural transformation and can be illustrated by a "Ruttan-a-gram," which measures the logarithm of productivity per hectare on its vertical axis and productivity per worker on its horizontal axis. This two-dimensional perspective provides the most general representation of the process of agricultural transformation (Hayami and Ruttan 1971).

Figure 7 shows the recent trends of agricultural productivity in Central Asia, which suggest some general patterns. The first is a severe reduction in both land and labor productivity in early 1990s. The second is a recovery in the late 1990s and early 2000s in both productivity indicators reversing the initial trend. The slope and length, indicating comparative trends across the two factors and the rate of change, respectively, of both lines differs significantly by country.

The point of reversal represents the start of recovery and appears to be similar across the various countries. The Kyrgyz Republic and Uzbekistan both experienced relatively early rebounds in land and labor productivity in the mid-1990s. However, the pace of productivity increases has been much faster in Uzbekistan than in the Kyrgyz Republic. Both land and labor productivity rebounded in Kazakhstan and Tajikistan in the late 1990s. One of the most striking features is the stagnation of land productivity growth in Kazakhstan. Yields per hectare grew very slowly between 1998 and 2014 and only in recent years has labor productivity recovered to pre-independence levels. The reorganization of farms, which was underway in the mid- to late 1990s in most of Central Asia, strongly influenced the flow of labor to and from the agricultural sector. In some countries, this period was marked by an influx of urban dwellers with little farming experience who entered agriculture after independence. Moreover, some countries experienced high rates of rural migration overseas, which were often not accounted for in official data. This can cloud the picture regarding labor productivity in agriculture.

Overall, land and labor productivity trends in Central Asian countries remain mixed. Thus, current government policies in the region aim to make up ground in terms of productivity with the rest of the world. Among the most common goals outlined in many of the national strategies is a desire to improve agricultural productivity through agricultural diversification, improvement of irrigation systems, targeted use of subsidies, and land policies.

Current situation

Table 2 shows the five leading crops from each country, based on harvested area. Note that wheat is first in every country. We can also see that barley is important to each country, ranking second in Kazakhstan and Kyrgyzstan, third in Tajikistan, and fourth in Uzbekistan. Regionally, however, cotton would easily rank third, even though it only made the top five in Tajikistan and Uzbekistan. Potatoes rank in the top five for two of the four countries. Oilseed crops and fruits, particularly apples and grapes, are also worthy of mention.

Figures 8 through 12 show the spatial distribution of cultivation of five of the most important crops for the region. These are from MapSPAM (You et al. 2014), which modeled the distribution of cultivation of each crop using a combination of satellite data, other geographic information, and subnational agricultural statistics. The legend shows the number of hectares in the pixel for each given crop. While MapSPAM is also able to distinguish location of irrigated crops from rainfed crops, the locational data seemed to be contradicted by national statistics in most of the countries. As a result, we opted to focus on the combined area of rainfed and irrigated crops.

Figure 8 shows that wheat is grown primarily in the north-central and south-central portions of the region, with some additional areas along the border with Russia in the northeast and northwest, as well as in the eastern portion of Kazakhstan. Figure 9 shows that barley tends to be grown in similar locations to wheat. Figures 11 and 12 show similar spatial patterns for growing maize and potatoes, though the relative density is much lower for both of those crops.

Cotton, on the other hand, is distinct from the other four crops just discussed, as Figure 10 shows. It is highly concentrated in the south-central part of the region, in eastern Uzbekistan and western Tajikistan.

Modeling Results

Wheat

Figure 13 combines the MapSPAM location information found in Figure 9 with national statistics on spring and winter wheat varieties to give an estimate of where spring wheat is grown. Using that information, together with information on the proportion of wheat that is irrigated and approximate fertilizer use, we used DSSAT to estimate yields in the climate around the year 2000, and then again to estimate the yields under four different climate models for 2050 using the RCP8.5 scenario.

Figure 14 shows pixel-level predictions of the impact of climate change on spring wheat by 2050, looking at the median across the four GCMs. We note that the highest yield losses appear to be in the most southern part of the region, especially in Tajikistan, and in areas along the north-central border with Russia. However, we also note a smattering of pixels with yield gains projected, particularly in much of the north-central part of Kazakhstan.

Table 3 shows the results for each country and climate model. In particular, we note that Tajikistan has the largest projected yield losses for spring wheat. This is in part because the growing area is already warm during the summer months, and climate change will make it much worse. We also note that the least affected country for spring wheat is Kazakhstan, in part because the major growing regions tend to have relatively cool summers, and the wheat is helped by some warming.

Note that there is variation between climate models, reflecting the differences in warming that each project. MIROC tends to be the least favorable toward spring wheat, and GFDL the most favorable. Figure 6, which shows projected temperature changes, helps us confirm the yield findings here.

Figure 15 is similar to Figure 13, in that it used both MapSPAM location information and national statistics to estimate where winter wheat is grown. Using that information, we modeled winter wheat yields for the climate around the year 2000, and for the four climate models for the year 2050. Unlike what we observed for spring wheat, much of the south-central part of the region will likely have higher winter wheat yields as a result of climate change (see Figure 16). It appears that the cold winters often limit the yields obtainable under the current climate, but with a slightly warmer climate, the crops will perform better. This observation, however, does not pertain to much of eastern Uzbekistan, which is projected to experience yield losses.

Table 4 helps quantify the gains and losses for winter wheat under climate change, with very large gains in Kazakhstan and Kyrgyzstan. Most of the wheat grown in Kazakhstan is spring wheat, however, so such a large boost only modestly raises the overall projection for wheat productivity in Kazakhstan. Kyrgyzstan, on the other hand, has more than 60 percent of its wheat area cultivated in the winter, so the positive value will be more strongly reflected in gains to climate change in its total wheat production.

Winter wheat in Tajikistan is projected to increase under climate change, and the decline projected for Uzbekistan is modest, and reflects a general consensus among the different climate models. There is much more variation between the models for Kazakhstan and Kyrgyzstan.

Given these findings, it appears that except for Uzbekistan, there may be some advantage in expanding winter wheat cultivation, and possibly cutting back on spring wheat cultivation. The latter is only appropriate if it becomes no longer economically viable to cultivate spring wheat in certain areas. Otherwise, even with some reduction of the spring wheat yield, it still may prove to be more profitable than cultivating other crops in the spring. However, given the large projected temperature changes, all countries should carefully consider the possibility of expanding cultivation into areas not currently cultivated due to the cold.

Barley

We see in Figure 17 areas where spring barley is cultivated, based on MapSPAM and national agricultural statistics. These locations appear to be similar to areas where spring wheat is cultivated, except that barley area will generally be much less than wheat area. Figure 18 shows the direct climate effect modeled by DSSAT. Again, the pattern appears to be similar to those found for spring wheat—which, since the crops are similar, makes sense.

Table 5 shows the expected direct effects of climate change on spring barley. The patterns are similar to those for spring wheat, except that the median losses are around 70 to 80 percent higher (as a percent change) for all but Tajikistan. Tajikistan will have a lower percentage of loss from climate change for spring barley compared to spring wheat. Temperature seems to again be the primary culprit, with the hotter climate models leading to greater yield losses.

Figure 19 shows what we believe to be the distribution of winter barley, based on MapSPAM and agricultural statistics. Winter barley appears to be grown primarily in the south-central part of the region, though some is grown Uzbekistan south of the Aral Sea and in eastern Kazakhstan.

Figure 20 shows that much of the winter barley grown in Uzbekistan and southern Tajikistan will do worse under climate change, but there are also places in both countries where it will do better. Most winter barley areas in Kyrgyzstan and Kazakhstan show that climate change will enhance productivity. Table 6 shows us that the gains and losses in Tajikistan and Uzbekistan will just about cancel each other out: Uzbekistan will have a 0.7 percent improvement, and Tajikistan a 2.8 percent decline. Kyrgyzstan and Kazakhstan, on the other hand, will have sizable improvements, at 14 and 20 percent, respectively. However, there is such a small percentage of barley grown in the winter in those two countries that unless there is a shift to grow more in the winter, the increase will not affect total production of barley very much.

Cotton

We have already seen where cotton is grown from the earlier MapSPAM figure. Figure 21 shows us that much of the cotton area in Uzbekistan is projected to have slightly lower yields under climate change, though there are also some areas with some gains, as well. We see mixed results for the impact of climate change on cotton in Kazakhstan and Tajikistan—some areas improving and others declining. In the end, Table 7 helps us sort out whether the gains or losses come out ahead. We see that Uzbekistan will average a decline in cotton productivity of around 5 percent, while Tajikistan and Kazakhstan will experience small gains of 0.7 and 2.1 percent. While Kyrgyzstan seems to be the country with the largest percentage gain of over 6 percent, its cotton area is very small, and the productivity increase will have very little impact.

Summary for 5 major crops

Table 8 produces a summary of the impact of climate change on wheat, barley, and cotton presented in the preceding section. It also presents results from a separate DSSAT analysis that was done with coarser spatial resolution (half degree) for maize and potatoes. We note that for these two crops, climate change will prove quite beneficial for Kyrgyzstan, yet harmful for the other three countries. Maize in Uzbekistan is expected to decline in productivity by 22 percent due to climate change, while Kazakhstan is projected to have a decline in potato productivity of just under 18 percent.

The evidence suggests that climate change is expected to significantly lower global crop yields between 2000 and 2050, including maize and potatoes (Nelson et al., 2010). Our DSSAT analysis in this study shows that productivity declines for maize in Central Asia due to climate change will be less than what is anticipated for the rest of the world. Furthermore, potato productivity decline is similar to or only slightly higher in Central Asia than in the rest of the world.

When viewed in terms of productivity changes around the globe, what initially appeared to be a pessimistic projection for Central Asian agriculture might be considered a neutral or more optimistic outcome. That is, when global supply and demand are considered, what will likely be higher maize and potato prices might create an opportunity in Central Asia to expand production due to its relative strength (at least for maize). It should also signal to policy makers that investment in finding or developing maize and potato varieties that are more suitable to a warmer climate could be one that benefits farmers and the agriculture sector greatly.

Conclusions

In this study, we allow farmers to shift planting dates in response to climate change. However, while farmers are also likely to switch varieties to ones better suited to future climate, we decided to keep the variety constant for the following reasons. First, the varieties within the DSSAT crop model are often limited. Second, by changing the variety, we would remove some of the measurable incentives for RCPclimate. Third, there is an exogenous rate of technical change inside the IMPACT economic model, which uses the DSSAT results, and in some sense, this exogenous change reflects changes in the cultivar. Therefore, our estimates are likely to slightly overstate yield reductions due to climate change.

Furthermore, our analysis was limited to the effect of changes in averages of climate variables on productivity of key annual crops. While climate change is likely to increase the variability of rainfall and temperature, the weather generator inside DSSAT that we used assumes a fixed variation. That means that we did not account for any changes in drought or flooding on yields.

Because this article focused on the impact on key annual crops, we ignored perennial crops that are important for the region like apples, grapes, and other fruits. We also ignored vegetables that are important to the region such as tomatoes and annual fruits like watermelons. DSSAT does not model fruit crops and is limited in the number of vegetable crops it can model. Finally, we failed to address the impact of climate change on livestock, which is an important component of agriculture in the region.

What we accomplished in this article is nonetheless important and potentially very helpful in preparing the agricultural sector for climate change. We began with a summary of the changes in the agricultural systems in the region from the Soviet era coupled with a brief overview of the state of agricultural production in Central Asia (focusing on key crops). We also reviewed some of the latest climate models to show the potential changes farmers will face by 2050 and discovered that Central Asia is projected to experience greater climate shocks than most regions, primarily through temperature changes.

We used the climate data and applied it to the question of how yields of key crops will be affected by climate change. Without any changes in where crops are currently grown, we anticipate that Kyrgyzstan will likely benefit from climate change—at least in 4 out of 5 crops analyzed in this article. Kazakhstan will experience generally modest losses—though losses to potatoes could be of concern. On the other hand, both Tajikistan and Uzbekistan will likely face higher losses—with at least Tajikistan’s cotton breaking even.

The general principle that seems to be revealed here is that countries (and areas within countries) that either have moderate summers or grow a number of crops in a relatively cold winter will benefit from climate change, while countries that grow many of the crops in the summer—and where the summer is already hot—will experience losses.

Several policy implications emerge from these findings. First, there appear to be opportunities for growing more winter crops, and therefore there may need to be more mechanisms established to promote their growth, including making farmers aware of the possibility and making sure that seeds and fertilizers are available to farmers. More research may be needed to be done to investigate efficiencies that might be found in crop rotations (as well as challenges that this might present).

Second, there may be an opportunity to shift some of the farming to areas that in the past might have been too cool for optimally farming summer crops, but with climate change, might become ideal. Shifting farming areas entails a number of supporting initiatives, including incentives for farmers to relocate, possibly developing irrigation for those areas, and ensuring farmers have access to input markets and markets for selling their harvests.

Third, reduction in yields in some places due to climate change suggest that new investment in research and development of new seeds or production techniques might be required. This research can take advantage of some of the research done in international research institutes or perhaps be done in conjunction with institutes such as CIMMYT and its sister CGIAR organizations. Such research might be focused on developing heat and drought tolerant varieties but could also include finding appropriate water and nutrient conserving technologies, which might include no-till or low-till agriculture.

Fourth, means of communicating new research and ideas to farmers need to be developed and enhanced. In addition to traditional extension, innovative use of radio, television, the internet, and mobile phones could save on money and reach more farmers. The FAO has a website for sharing ideas and best practices for this kind of advisory services (http://www.fao.org/e-agriculture/). One innovative idea involved farmers in India using the cameras on the mobile phones to send pictures to agronomists to get advice on plant care (Ceballos et al. 2018).

Other ideas to be considered include searching for different crops that would be productive under climate change; in cases where sub-optimal fertilizers are currently used, efforts to get farmers to increase their use (including advocacy, pricing, and ensuring availability) could more than compensate for climate change losses; and investigating the use of winter cover crops to increase soil organic matter and to enhance nitrogen in the soil for the spring crops.

References

Akramov, K., and G. Shreedhar. 2012. “Economic development, external shocks, and food security in Tajikistan”, IFPRI Discussion Paper 1163. Washington, DC: International Food Policy Research Institute.

Akramov, K., and N. Omuraliev. 2009. “Institutional change, rural services, and agricultural performance in Kyrgyzstan”, IFPRI Discussion Paper 00904. Washington, DC: International Food Policy Research Institute.

Batjes, N., K. Dijkshoorn, V. van Engelen, et al. 2009. *Harmonized World Soil Database*. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Bobojonov, Ihtiyor and Aden Aw-Hassan. 2014. “Impacts of climate change on farm income security in central Asia: an integrated modeling approach”, *Agric. Ecosyst. Environ.* **188**:245–255.

Ceballos, Francisco Tim Foster, Koen Hufkens, Arun Jadhav, Samyuktha Kannan, and Berber Kramer. 2018. “SEEING IS BELIEVING: Using Crop Pictures in Personalized Advisory Services”. Project Note. Washington: IFPRI.

Collins, W. J., et al. 2011. "Development and Evaluation of an Earth-System Model—HadGEM2." *Geoscientific Model Development* 4: 1051–1075.

De Pinto A, Cenacchi N, Kwon H-Y, Koo J, Dunston S. 2020. “Climate smart agriculture and global food-crop production”, *PLoS ONE* 15(4): e0231764. https://doi.org/10.1371/journal.pone.0231764

Dufresne, J. L., et al. 2013. "Climate Change Projections Using the IPSL-CM5 Earth System Model: From CMIP3 to CMIP5." *Climate Dynamics* 40: 2123–2165.

Dunne, J. P., et al. 2012. "GFDL’s ESM2 Global Coupled Climate-Carbon Earth System Models Part I: Physical Formulation and Baseline Simulation Characteristics." *Journal of Climate* 25: 6646–6665.

Dunne, J. P., et al. 2013. "GFDL’s ESM2 Global Coupled Climate-Carbon Earth System Models. Part II: Eitzinger, A., Läderach, P., Sonder, K., Schmidt, A., Sain, G., Beebe, S., … Nowak, A. (2012). Tortillas en el Comal: Los Sistemas de Maíz y Fríjol de América Central y el Cambio Climático. CIAT Políticas en Síntesis. Cali, Colombia. Retrieved from https://ciat.cgiar.org/wp-content/uploads/2012/12/politica_sintesis6_tortillas_en_comal.pdf

FAO (Food and Agriculture Organization of the United Nations). 2021. FAOSTAT Statistical Database.

Government of the Republic of Tajikistan. 2012. Program for reforming the agricultural sector of the Republic of Tajikistan for 2012-2020. Dushanbe.

Guo, Hao, Xingming Zhang, Fang Lian, Yuan Gao, Degen Lin, and Jing’ai Wang. 2016. “Drought Risk Assessment Based on Vulnerability Surfaces: A Case Study of Maize”, *Sustainability* 8(8).

Hayami, Y., and V. Ruttan. 1971. “Induced innovation in agricultural development”, Discussion Paper No. 3. Minneapolis: University of Minnesota.

Hijmans, R. J., S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis. 2005. “Very High Resolution Interpolated Climate Surfaces for Global Land Areas.” *International Journal of Climatology* 25: 1965–1978. www.worldclim.org.

IFPRI, CAREC Institute, and ADB. 2019. “Agricultural Development in Central Asian Regional Economic Cooperation (CAREC) Member Countries: Review of Trends, Challenges, and Opportunities. Research Report. Manila, Philippines: Asian Development Bank.

Ibragimov, N., Y. Djumaniyazova, J. Khaitbaeva, S. Babadjanova, J. Ruzimov, A. Akramkhanov, and J. Lamers. 2020. “Simulating Crop Productivity in a Triple Rotation in the Semi-arid Area of the Aral Sea Basin”, *International Journal of Plant Production* 14(2):273-285.

Jones, J., G. Hoogenboom, C. Porter, K. Boote, W. Batchelor, L. Hunt, P. Wilkens, et al. 2003. “The DSSAT Cropping System Model.” *European Journal of Agronomy* 18(3–4): 235–265.

Kato, E., Nkonya, E., 2012. “The Economics of Adaptation to Climate Change in Central Asia”, Adaptation to Climate Change in Central Asia and People’s Republic of China Project Research *Report*. IFPRI, Washington, DC.

Koo, J., and J. Dimes. 2010. *HC27 Generic Soil Profile Database, Version 1*. Washington, DC: International Food Policy Research Institute.

Lerman, Z., C. Csaki, and G. Feder. 2004. *Agriculture in Transition: Land Policies and Evolving Farm Structures in Post-Soviet Countries*. Lanham: Lexington Books.

Martin, G. M., et al. 2011. "The HadGEM2 Family of Met Office Unified Model Climate Configurations", *Geophysical Model Development* 4: 723–757.

Mitchell, Donna, Ryan B. Williams, Darren Hudson, and Phillip Johnson. 2017. “A Monte Carlo analysis on the impact of climate change on future crop choice and water use in Uzbekistan”, *Food Security* **9**(4):697-709.

Müller, Christoph and Richard D. Robertson. 2014. “Projecting future crop productivity for global economic modeling”, *Agricultural Economics* 45:37-50.

National Statistics Committee of the Kyrgyz Republic. 2018. Statistical dynamic tables on agriculture. Online database, available at http://stat.kg/ru/statistics/selskoe-hozyajstvo/.

Nelson, G., Rosegrant, M., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S.,Zhu, T., Sulser, T., Ringler, C., Msangi, S., You, L., 2010. *Food Security, Farming and Climate Change to 2050: Scenarios, Results, Policy Options.* IFPRI, Washington, DC.

Nelson, G.C., Rosegrant, M.W., Koo, J., Robertson, R., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., Magalhaes, M., Valmonte-Santos, R., Ewing, M., Lee, D., 2009*. Climate Change. Impact on Agriculture and Costs of Adaptation*. International Food Policy Research Institute, Washington, DC.

O’Neill, B.C., Carter, T.R., Ebi, K.L., Edmonds, J., Hallegatte, S., Kemp-Benedict, E., Kriegler, E., Mearns, L., Moss, R., Riahi, K., van Ruijven, B., van Vuuren, D. 2012. Meeting Report of the Workshop on The Nature and Use of New Socioeconomic Pathways for Climate Change Research, Boulder, CO, November 2-4, 2011. Available at: http://www.isp.ucar.edu/socioeconomic-pathways.

Petrick, M., D. Oshakbaev, and J. Wandel. 2014. "Kazakhstan's wheat, beef and dairy sectors: an assessment of their development constraints and recent policy responses", *Kazakhstan's Economic Strategy: Halfway to 2030*. Philadelphia.

Rosenzweig, C., J. Elliott, D. Deryng, A. C. Ruane, C. Müller, A. Arneth, K. J. Boote, C. Folberth, M. Glotter, N. Khabarov, K. Neumann, F. Piontek, T. A. M. Pugh, E. Schmid, E. Stehfest, H. Yang, and J. W. Jones. 2014. "Assessing Agricultural Risks of Climate Change in the 21st Century in a Global Gridded Crop Model Intercomparison." *Proceedings of the National Academy of Sciences*, doi:10.1073/pnas.1222463110.

Rozelle, S., and J. Swinnen. 2004. "Success and failure of reform: insights from the transition of agriculture", *Journal of Economic Literature* 404-456.

Ruan, Hongwei, Jingjie Yu, Ping Wang, and Tianye Wang. 2020. “Increased crop water requirements have exacerbated water stress in the arid transboundary rivers of Central Asia”, *Science of the Total Environment* 713 (April).

Sakamoto, T., Y. Komuro, T. Nishimura, M.Ishii, H. Tatebe, H. Shiogama, A. Hasegawa, et al. 2012. “MIROC4h: A New High-Resolution Atmosphere–Ocean Coupled General Circulation Model.” *Journal of Meteorology Society of Japan* 90(3): 325–359.

Sommer, R., Glazirin, M., Yuldashev, T., Otarov, A., Ibraeva, M., Martynova, L., Bekenov, M., Kholov, B., Ibragimov, N., Kobilov, R., Karaev, S., Sultonov, M., Khasanova, F., Esanbekov, M., Mavlyanov, D., Isaev, S., Abdurahimov, S., Ikramov, R., Shezdyukova, L., de Pauw, E. 2013. “Impact of climate change on wheat productivity in Central Asia”, *Agric. Ecosyst. Environ.* 178:78–99.

Statistical Agency under the President of the Republic of Tajikistan. 2019. Regions of Tajikistan: Statistical Yearbook. Dushanbe.

Stocker, T.F., D. Qin, G.-K. Plattner, L.V. Alexander, S.K. Allen, N.L. Bindoff, F.-M. Bréon, J.A. Church, U. Cubasch, S. Emori, P. Forster, P. Friedlingstein, N. Gillett, J.M. Gregory, D.L. Hartmann, E. Jansen, B. Kirtman, R. Knutti, K. Krishna Kumar, P. Lemke, J. Marotzke, V. Masson-Delmotte, G.A. Meehl, I.I. Mokhov, S. Piao, V. Ramaswamy, D. Randall, M. Rhein, M. Rojas, C. Sabine, D. Shindell, L.D. Talley, D.G. Vaughan and S.-P. Xie, 2013: Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sutton, W.R., Srivastava, J.P., Neumann, J.E., 2013. *Looking Beyond the Horizon. In: How Climate Change Impacts and Adaptation Responses will Reshape Agriculture in Eastern Europe and Central Asia*. The World Bank, Washington DC.

Tian, Jing and Yongqiang Zhang. 2020. “Detecting changes in irrigation water requirement in Central Asia under CO2 fertilization and land use changes”, *Journal of Hydrology* 583 (April).

Timmer, P. 2015. "Managing structural transformation: a political economy approach." WIDER Annual Lecture 18. Helsinki.

USAID. 2005. Land tenure and property rights assessment for Kyrgyzstan. Washington, DC: USAID.

Valkama, Elena, Gulya Kunypiyaeva, Rauan Zhapayev, Muratbek Karabayev, Erbol Zhusupbekov, Alessia Perego, Calogero Schillaci, Dario Sacco, Barara Moretti, Carlo Grignani, and Marco Acutis. 2020. “Can conservation agriculture increase soil carbon sequestration? A modelling approach”, *Geoderma* 369 (June).

World Bank. 2020. Tajikistan agrifood sector and public expenditure review. Washington, D.C.

World Bank. 2021. World Development Indicators. Washington: The World Bank. Accessed on December 7, 2021.

You, L., S. Wood, U. Wood–Sichra, W. Wu. 2014. “Generating Global Crop Distribution Maps: From Census to Grid.” *Agricultural Systems* 127 (May): 53–60.

Tables for "The Biophysical Effect of Climate Change on Crops in Central Asia"

Table 1. Climate statistics for circa 2000 and for 2050

	2000	Change, 2000-2050			
Country	Base	GFDL	Had-GEM	IPSL	MIROC
	Mean daily maximum temperature of the warmest month				
Kazakhstan	29.8	2.0	5.0	3.9	4.6
Kyrgyzstan	21.2	2.8	5.9	4.9	5.5
Tajikistan	22.3	5.8	5.2	4.5	4.6
Uzbekistan	34.9	2.7	4.9	4.4	4.7
	Mean daily minimum temperature of the coldest month				
Kazakhstan	-17.0	3.2	5.3	3.8	5.0
Kyrgyzstan	-19.8	2.5	3.8	3.8	5.4
Tajikistan	-15.8	2.4	4.3	4.1	5.4
Uzbekistan	-7.5	1.8	4.4	2.5	2.8
	Annual rainfall, mm				
Kazakhstan	241	26	18	4	25
Kyrgyzstan	411	-7	18	-47	8
Tajikistan	543	19	59	-65	-17
Uzbekistan	187	-13	25	-23	-19
	Rainfall, wettest 3 consecutive months, mm				
Kazakhstan	88	18	4	2	6
Kyrgyzstan	183	2	2	-15	-1
Tajikistan	252	6	31	-18	-1
Uzbekistan	86	-6	19	-9	-11
	Rainfall, driest 3 consecutive months, mm				
Kazakhstan	35	1	0	-2	3
Kyrgyzstan	40	-3	-5	-11	-1
Tajikistan	28	2	-6	-13	0
Uzbekistan	7	-2	-3	-3	-1

***Source:** Author's calculations, based on WorldClim 1.4 (Hijmans et al. 2005) for the climate of 1960 to 1900; and on data from Mueller and Robertson (2014).*

Table 2. Five main crops from each country, ranked by harvested area, average 2018 to 2020

Country	Crop	Hectares harvested	Tons produced	Yield, tons per hectare
Kazakhstan	Wheat	11,569,365	13,217,902	1.14
Kazakhstan	Barley	2,740,872	3,820,198	1.40
Kazakhstan	Linseed	1,221,482	999,675	0.82
Kazakhstan	Sunflower seed	804,925	843,557	1.05
Kazakhstan	Safflower seed	285,819	213,559	0.75
Kyrgyzstan	Wheat	246,809	615,398	2.49
Kyrgyzstan	Barley	204,821	468,459	2.28
Kyrgyzstan	Maize	105,445	706,250	6.70
Kyrgyzstan	Potatoes	79,983	1,382,524	17.29
Kyrgyzstan	Sunflower seed	11,845	15,401	1.31
Tajikistan	Wheat	262,636	820,623	3.12
Tajikistan	Seed cotton	189,899	368,239	1.94
Tajikistan	Barley	71,535	138,352	1.94
Tajikistan	Potatoes	49,570	981,801	19.83
Tajikistan	Apples	43,656	236,380	5.41
Uzbekistan	Wheat	1,324,574	5,887,355	4.44
Uzbekistan	Seed cotton	1,072,224	2,680,419	2.51
Uzbekistan	Grapes	103,708	1,600,011	15.43
Uzbekistan	Apples	102,164	1,134,269	11.13
Uzbekistan	Barley	97,024	135,598	1.39

Source: *FAOSTAT (FAO 2021)*

Notes: *Columns reflect averages for 2018 to 2020*

Table 3. Summary of yield change for spring wheat, 2000-2050

Country	Harvested area, 2005 (hectares)	GFDL	HadGEM	IPSL	MIROC	Median
Kazakhstan	10,944,376	2.5	3.4	-8.1	-7.3	-2.4
Kyrgyzstan	148,576	-2.0	-5.2	-4.2	-9.2	-4.7
Tajikistan	74,787	-8.0	-16.9	-13.5	-17.0	-15.2
Uzbekistan	72,389	-10.1	-9.6	-9.1	-12.5	-9.8

***Source**: Authors.*

Table 4. Summary of yield change for winter wheat, 2000-2050

Country	Harvested area, 2005 (hectares)	GFDL	HadGEM	IPSL	MIROC	Median
Kazakhstan	883,456	42.4	109.7	59.9	117.2	84.8
Kyrgyzstan	258,811	32.5	51.0	42.6	68.2	46.8
Tajikistan	243,870	7.4	7.3	2.1	-1.0	4.7
Uzbekistan	1,375,391	-4.3	-7.7	-7.0	-9.7	-7.4

***Source**: Authors.*

Table 5. Summary of yield change for spring barley, 2000-2050

Country	Harvested area, 2005 (hectares)	GFDL	HadGEM	IPSL	MIROC	Median
Kazakhstan	1,584,575	5.6	-1.8	-9.7	-7.0	-4.4
Kyrgyzstan	95,204	-4.2	-9.5	-7.6	-11.4	-8.5
Tajikistan	28,338	-3.1	-14.1	-9.6	-12.8	-11.2
Uzbekistan	3,438	-12.3	-16.4	-17.7	-22.5	-17.0

***Source**: Authors.*

Table 6. Summary of yield change for winter barley, 2000-2050

Country	Harvested area, 2005 (hectares)	GFDL	HadGEM	IPSL	MIROC	Median
Kazakhstan	4,764	20.8	19.4	6.1	31.5	20.1
Kyrgyzstan	6,057	6.0	9.7	19.1	27.6	14.4
Tajikistan	13,156	4.1	-3.7	-1.8	-5.9	-2.8
Uzbekistan	65,329	4.2	1.1	0.2	-3.3	0.7

***Source**: Authors.*

Table 7. Summary of yield change for cotton, 2000-2050

Country	Harvested area, 2005 (hectares)	GFDL	HadGEM	IPSL	MIROC	Median
Kazakhstan	216,735	4.9	-0.1	2.6	1.6	2.1
Kyrgyzstan	45,690	6.6	1.1	6.0	6.9	6.3
Tajikistan	281,988	1.6	-3.7	0.1	1.2	0.7
Uzbekistan	1,445,796	-0.9	-7.0	-5.1	-4.5	-4.8

***Source**: Authors.*

Table 8. Summary of Results from Biophysical Modeling, 2000-2050

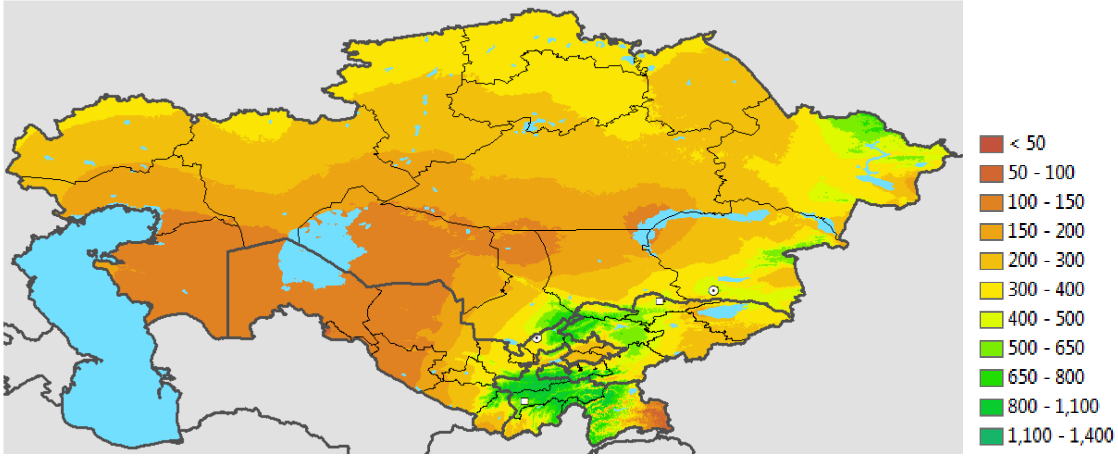
	Cotton		Barley		Wheat	
Country	**Harvested area, 2000**	**Climate effect on yields (%), 2000-2050**	**Harvested area, 2000**	**Climate effect on yields (%), 2000-2050**	**Harvested area, 2000**	**Climate effect on yields (%), 2000-2050**
Kazakhstan	216,735	2.1	1,589,339	-4.3	11,827,832	-1.3
Kyrgyzstan	45,690	6.3	101,261	-7.7	407,387	15.9
Tajikistan	281,988	0.7	41,494	-8.6	318,656	-10.5
Uzbekistan	1,445,796	-4.8	68,768	-0.2	1,447,780	-10.2

	Maize		Potatoes	
Country	**Harvested area, 2000**	**Climate effect on yields (%), 2000-2050**	**Harvested area, 2000**	**Climate effect on yields (%), 2000-2050**
Kazakhstan	98,252	-6.1	161,938	-17.7
Kyrgyzstan	70,582	34.7	70,644	30.7
Tajikistan	33,143	-16.0	28,667	-12.8
Uzbekistan	33,675	-22.4	44,676	-13.9

Source*: Authors.*

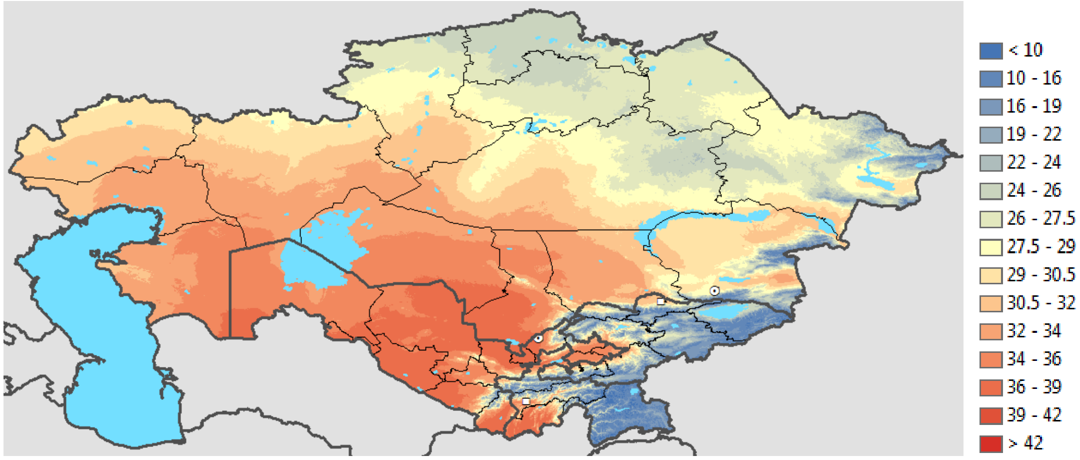
Figures for "The Biophysical Effect of Climate Change on Crops in Central Asia"

Figure 1. Mean annual precipitation, 1960-1990



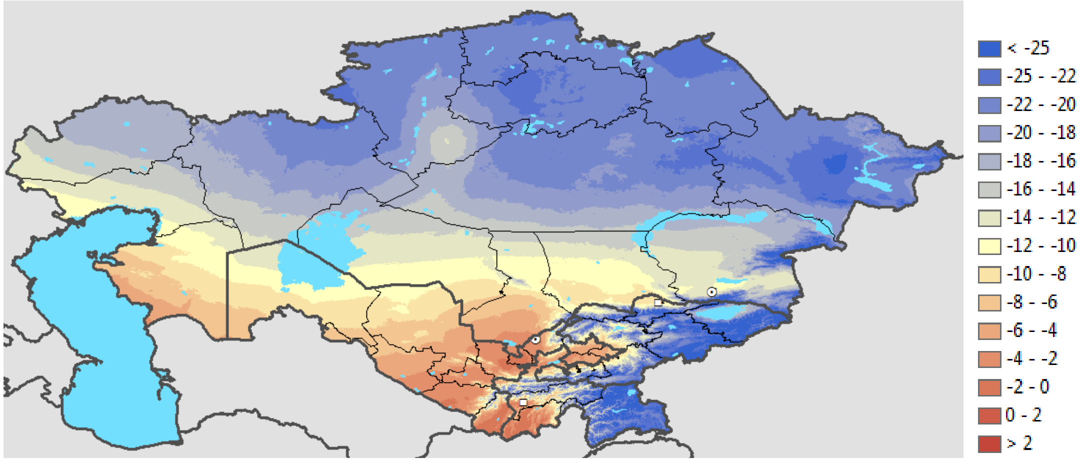
Source*: WorldClim version 1.4 (Hijmans et al. 2005).*

Figure 2. Mean daily maximum temperature for the warmest month, 1960-1990



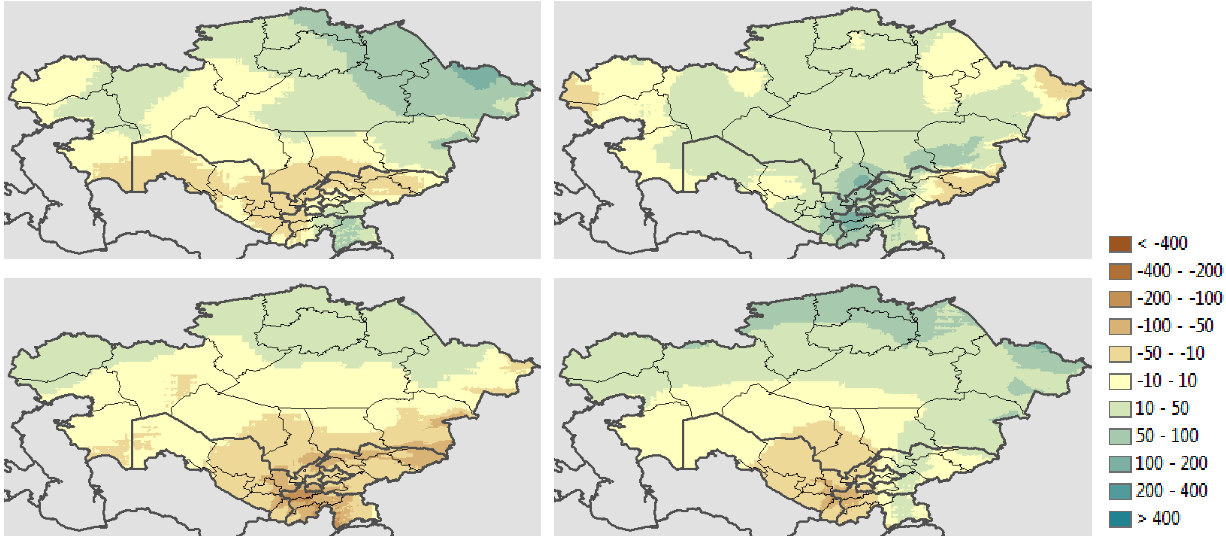
Source*: WorldClim version 1.4 (Hijmans et al. 2005).*

Figure 3. Mean daily minimum temperature for the coldest month, 1960-1990



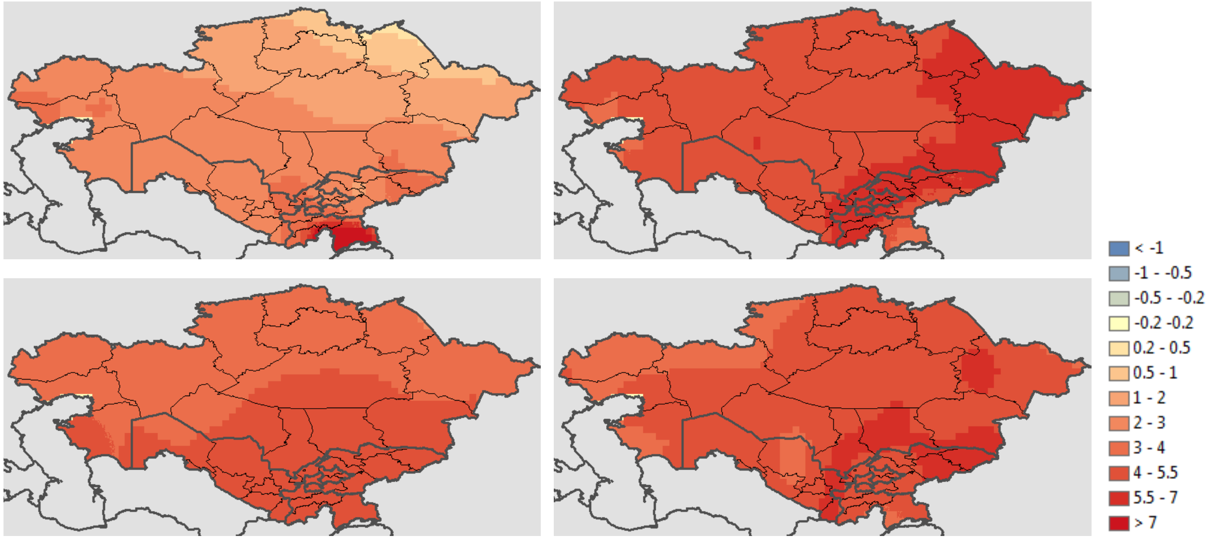
Source: *WorldClim version 1.4 (Hijmans et al. 2005).*

Figure 4. Change in Precipitation, 2000-2050



Source: *Authors based on Müller and Robertson (2014).*
Notes: *All GCMs (climate models) are from the AR5, RCP8.5. Top left, GFDL; top right, HadGEM; bottom left, IPSL; bottom right, MIROC. Values are for annual changes.*

Figure 5. Change in Mean Daily Maximum Temperature of the Warmest Month, 2000-2050



Source: *Authors based on Müller and Robertson (2014).*
Notes: *All GCMs (climate models) are from the AR5, RCP8.5. Top left, GFDL; top right, HadGEM; bottom left, IPSL; bottom right, MIROC. Values are for annual changes.*

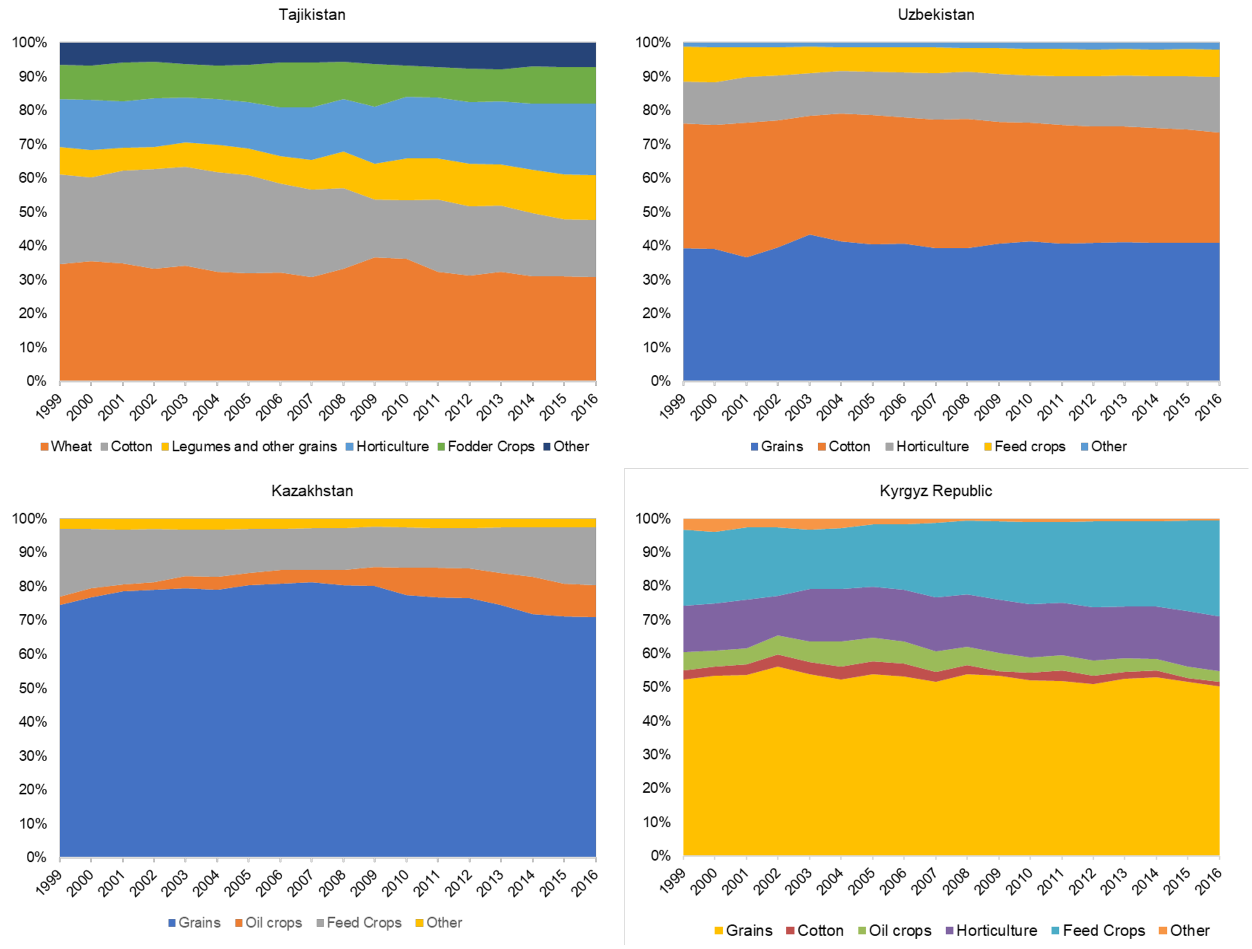
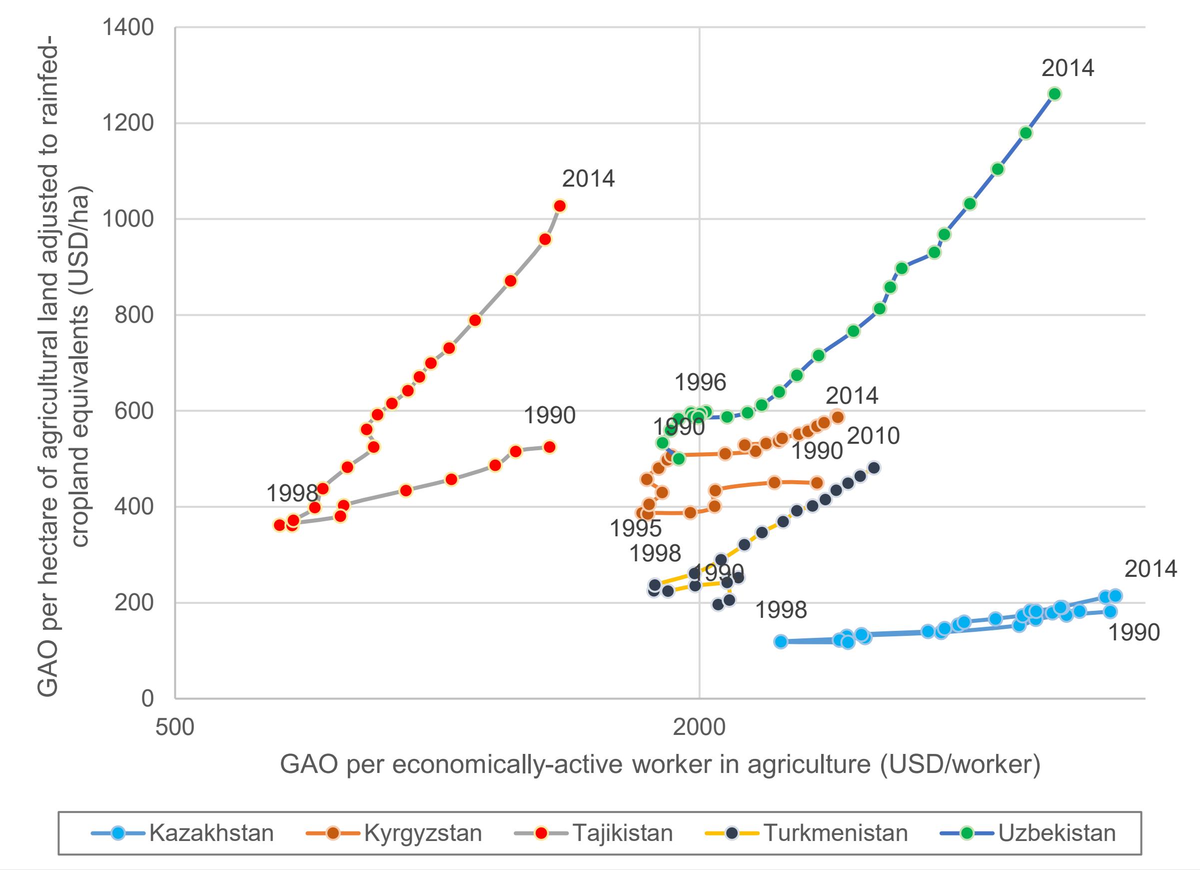


Figure 6. Crop diversity in Central Asia, share of total harvested area, 1999-2016

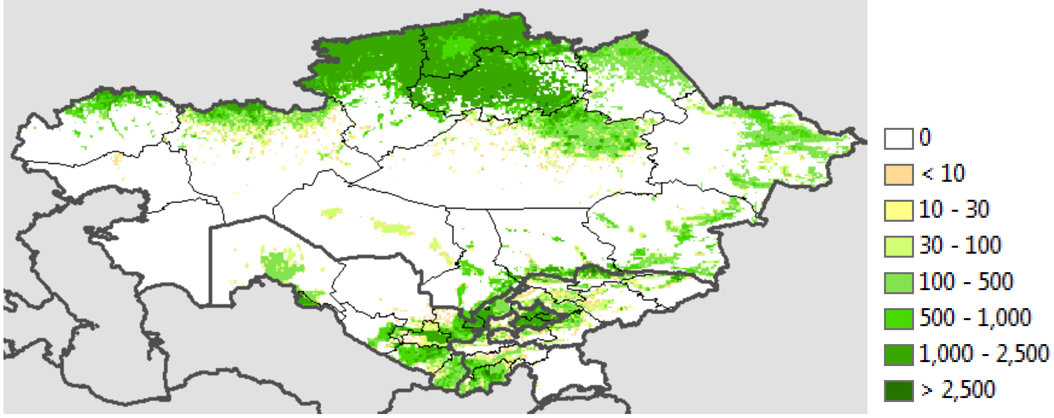
Source: *Authors' depiction using data from national statistical agencies of respective countries.*

Figure 7. Land and labor productivity in Central Asian agriculture, 1990-2014



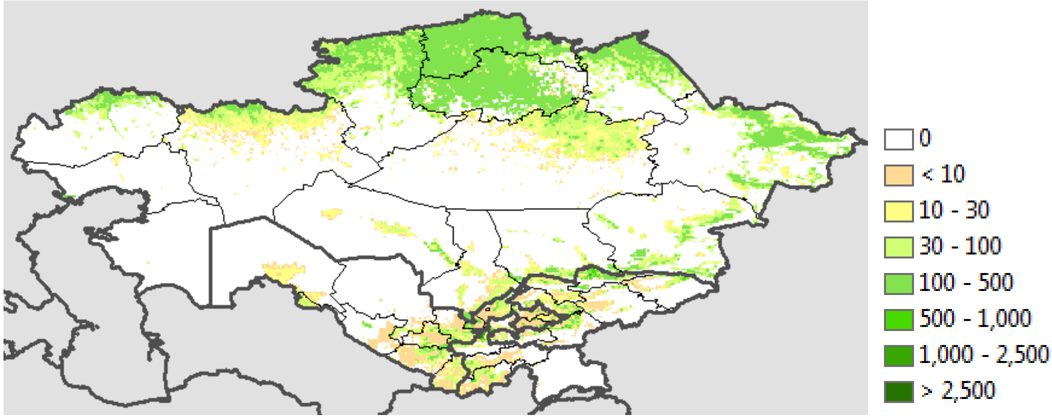
Source: *Authors' depiction using data from FAO and national statistical agencies.*
Note: *GAO stands for Gross Agricultural Output.*

Figure 8. Distribution of wheat cultivation (hectares per pixel), circa 2005



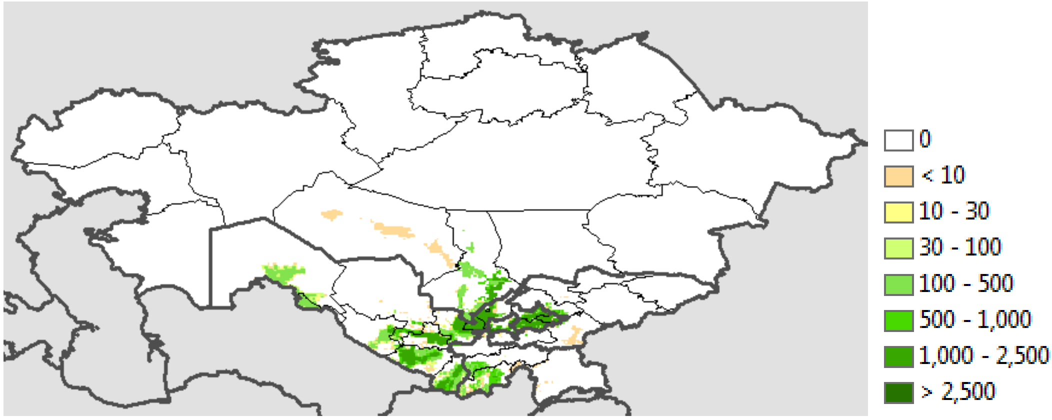
Source: *SPAM 2005 (You et al. 2014).*
Note: *A pixel has roughly 6,600 hectares at 40 degrees north and around 5,500 hectares at 50 degrees north.*

Figure 9. Distribution of barley cultivation (hectares per pixel), circa 2005



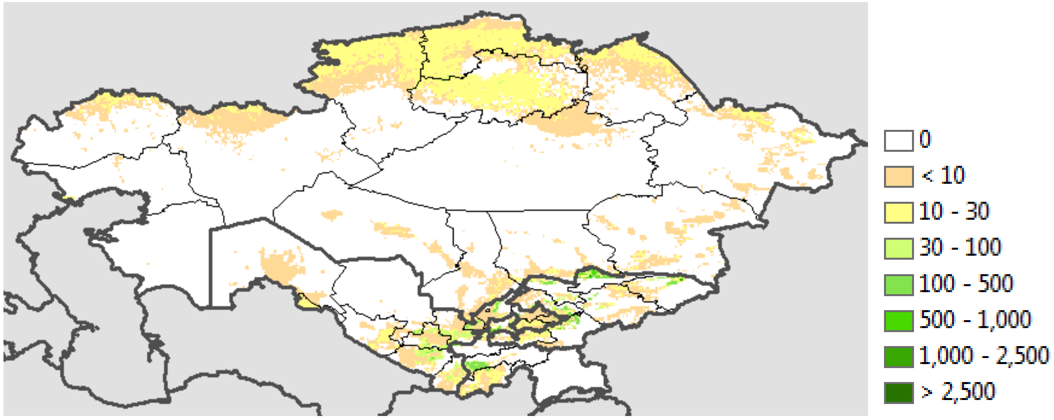
***Source**: SPAM 2005 (You et al. 2014).*
***Note**: A pixel has roughly 6,600 hectares at 40 degrees north and around 5,500 hectares at 50 degrees north.*

Figure 10. Distribution of cotton cultivation (hectares per pixel), circa 2005



***Source**: SPAM 2005 (You et al. 2014).*
***Note**: A pixel has roughly 6,600 hectares at 40 degrees north and around 5,500 hectares at 50 degrees north.*

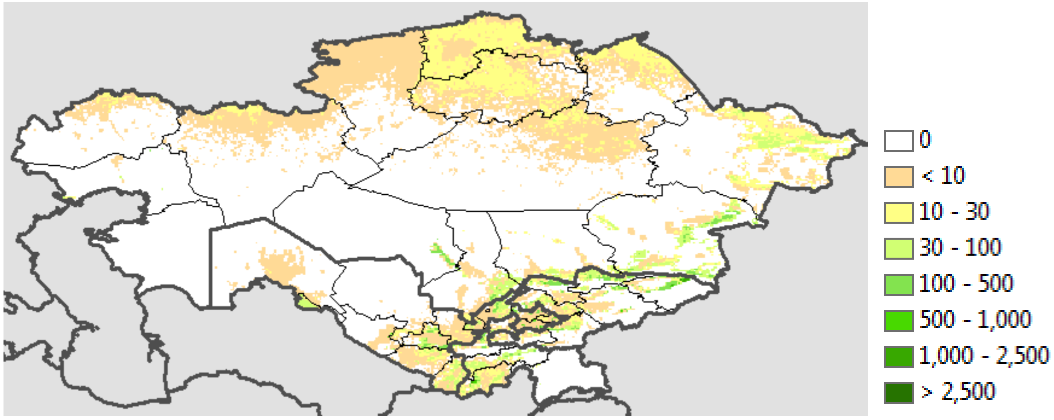
Figure 11. Distribution of maize cultivation (hectares per pixel), circa 2005



Source: *SPAM 2005 (You et al. 2014).*

Note: *A pixel has roughly 6,600 hectares at 40 degrees north and around 5,500 hectares at 50 degrees north.*

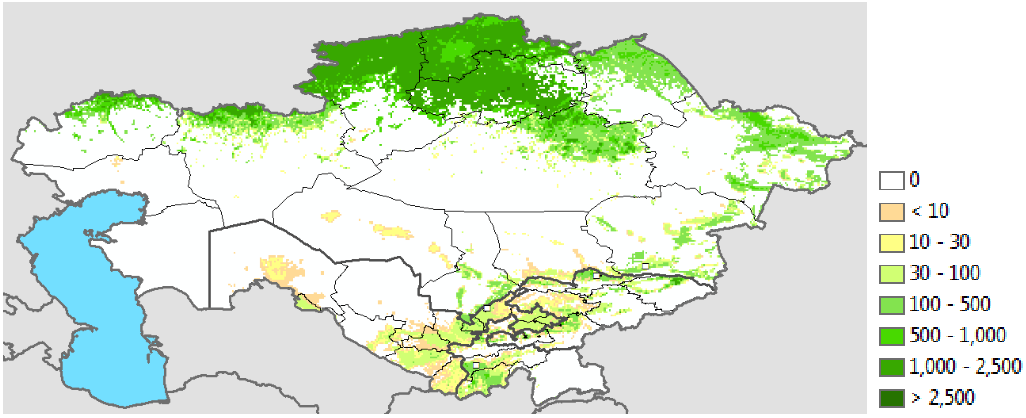
Figure 12. Distribution of potato cultivation (hectares per pixel), circa 2005



Source: *SPAM 2005 (You et al. 2014).*

Note: *A pixel has roughly 6,600 hectares at 40 degrees north and around 5,500 hectares at 50 degrees north.*

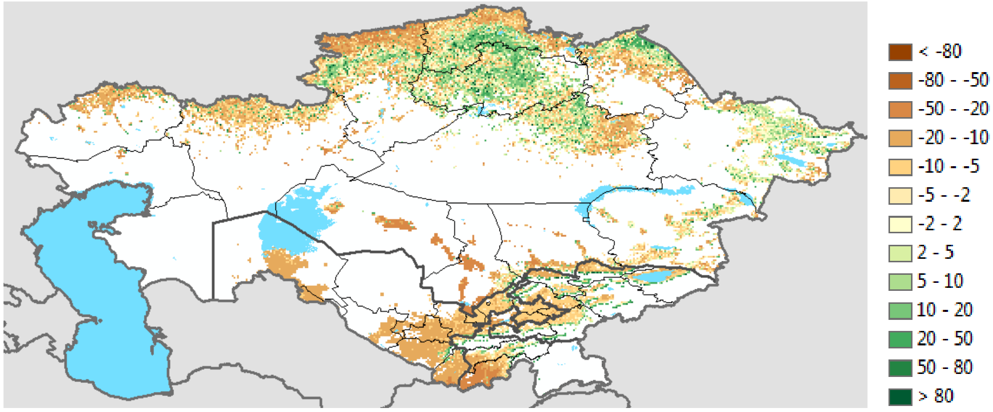
Figure 13. Hectares of spring wheat harvested (hectares per pixel)



Source*: Authors' depiction using SPAM 2005 (You et al. 2014) and national statistical data.*

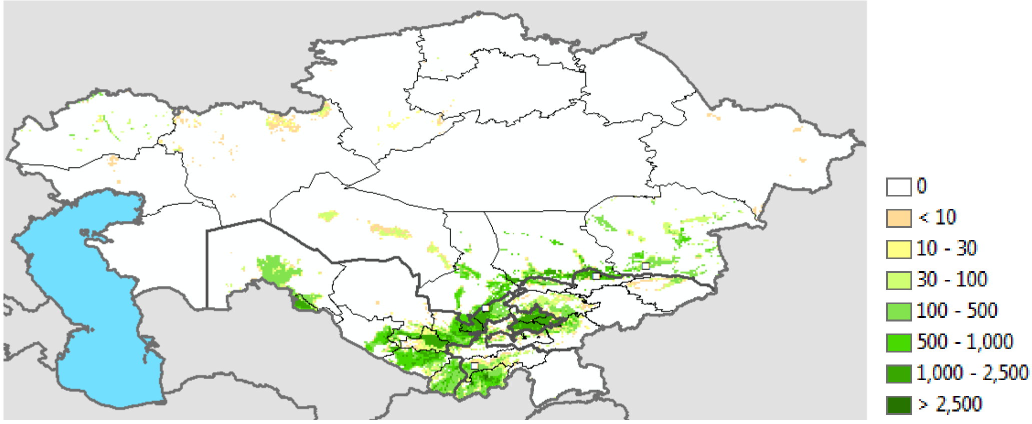
Note: *A pixel has roughly 6,600 hectares at 40 degrees north and around 5,500 hectares at 50 degrees north.*

Figure 14. Percent yield change, spring wheat, 2000-2050



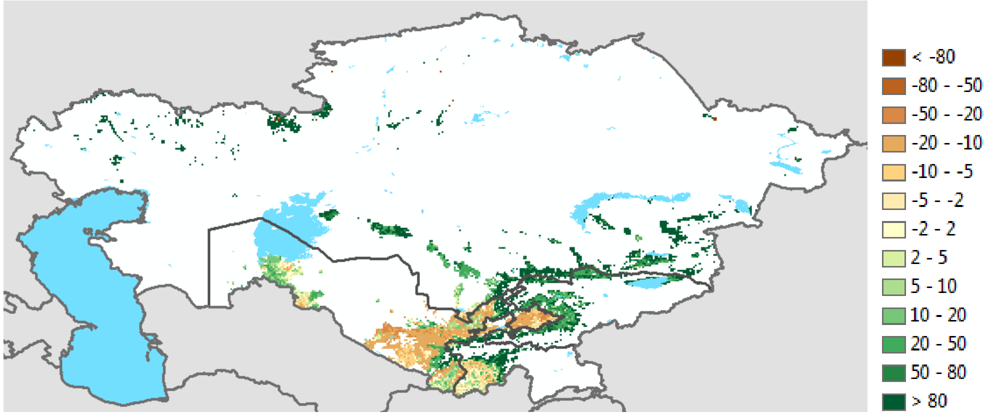
Source: *Authors' depiction using modeling results*

Figure 15. Hectares of winter wheat harvested



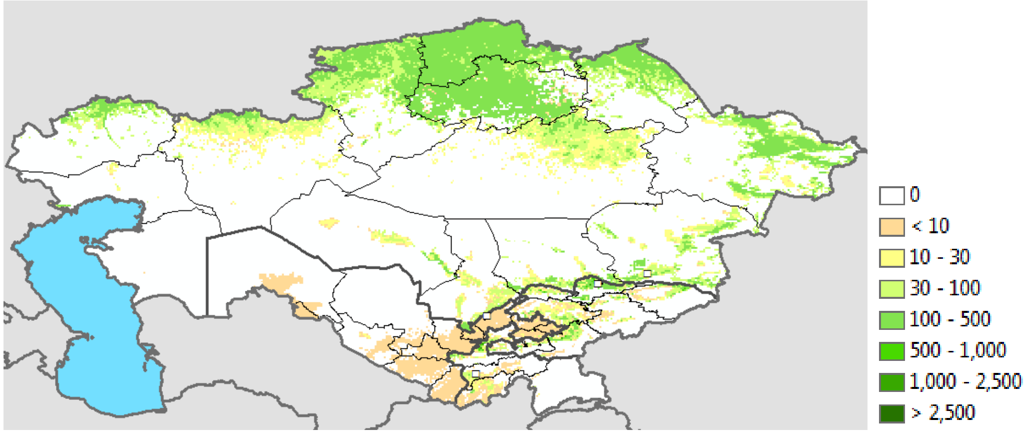
Source: *Authors' depiction using SPAM 2005 (You et al. 2014) and national statistical data.*
Note: *A pixel has roughly 6,600 hectares at 40 degrees north and around 5,500 hectares at 50 degrees north.*

Figure 16. Percent yield change, winter wheat, 2000-2050



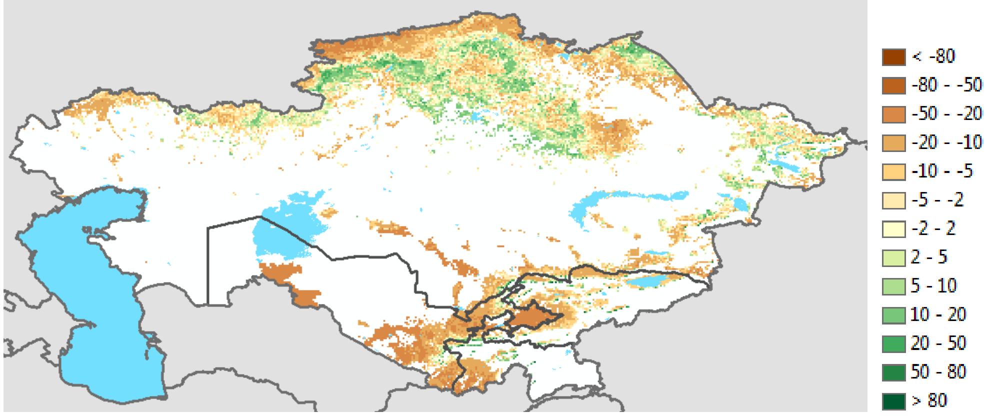
Source: Authors' depiction using modeling results

Figure 17. Hectares of spring barley harvested



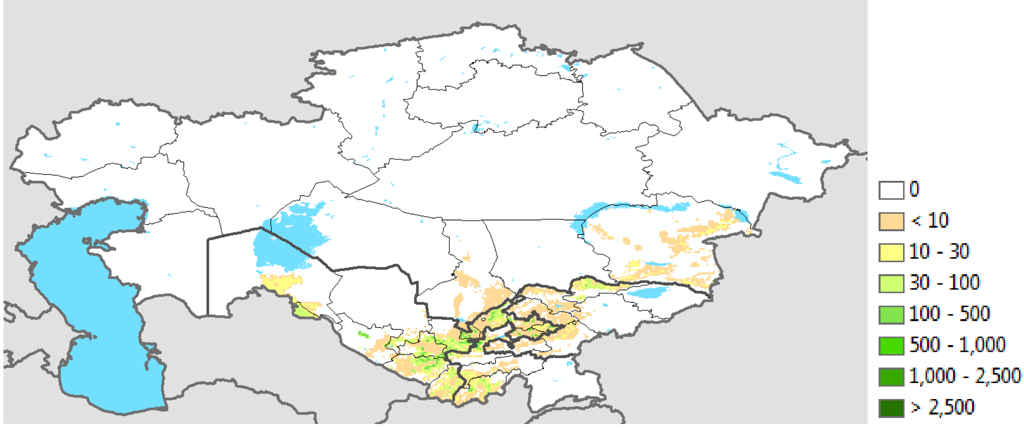
Source: *Authors' depiction using modeling results*

Figure 18. Percent yield change, spring barley, 2000-2050



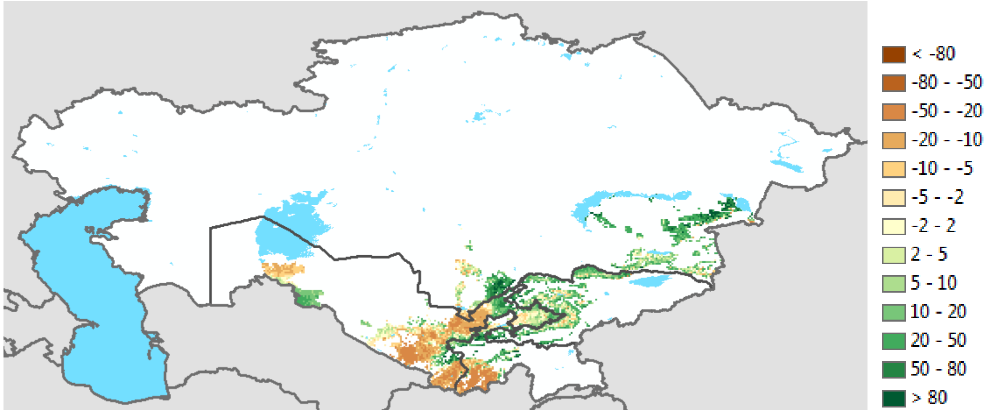
Source: *Authors' depiction using modeling results*

Figure 19. Hectares of winter barley harvested



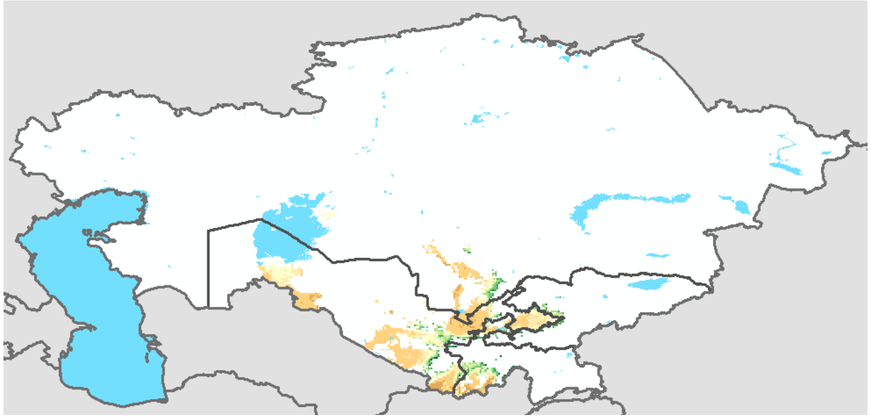
Source: *Authors' depiction using modeling results*

Figure 20. Percent yield change, winter barley, 2000-2050



Source: *Authors' depiction using modeling results.*

Figure 21. Percent yield change, cotton, 2000-2050



ALL IFPRI DISCUSSION PAPERS

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
www.ifpri.org

IFPRI HEADQUARTERS
1201 Eye Street, NW
Washington, DC 20005 USA
Tel.: +1-202-862-5600
Fax: +1-202-862-5606
Email: ifpri@cgiar.org