Report - Work Package 5:

“Synthesis & Recommendations”

Azerbaijan

submitted by the

Leibniz Institute of Agricultural Development in Transition Economies (IAMO)

within the assignment

“Development of an MSE Multi-Peril Risk Management Concept for Azerbaijan” (RIMARA)

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Content

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Executive summary

In the present study, German Sparkassenstiftung for International Cooperation e.V. (DSIK) and Leibniz Institute of Agricultural Development in Transition Economies (IAMO) have jointly worked on a nation-wide assessment about the effect of climate change on micro- and smallholder farmers in Azerbaijan.

We here provide empirical evidence for the impact of past and future climatic conditions and weather extremes on agricultural production in the country. For this, we first characterized the agricultural sector of Azerbaijan and selected the economically most important crops (work package 1). We sourced and processed environmental datasets to characterize historical climatic trends and the occurrence of wildfires in the country (work package 2). We analyzed the historical effects of different climate and weather parameters on the production and suitability of the selected crops (work package 3) and projected how yields and suitability will change in the future under different climate change scenarios (work package 4).

In this report, we summarize the main results of work packages 1-4. A more detailed technical report is available upon request. We also present the main conclusions from a workshop in which we discussed our study with local stakeholders from a variety of different sectors. We have summarized all spatial data that we have generated in the course of this study in an interactive data visualization tool, which we also present here. Finally, we provide recommendations on how the resilience of the agricultural sector in Azerbaijan against negative impacts of climate change can be enhanced in the long run, in terms of crop management adaptation, involvement of institutional stakeholders and considerations for future research activities.

1. Project results

Work package 1

In work package 1, we provide an overall description of the agricultural sector in Azerbaijan, define the target groups, select the most important crops and take stock of existing climate risk management strategies. Based on the key literature and official agricultural data, we characterized the agricultural sector and how it has changed over time on a sub-national level.

The first part of WP1 provides an overview of farm structures, agricultural production and crop area. Despite regional differences across the economic zones of Azerbaijan, we highlight several predominant characteristics:

- The farm structure in Azerbaijan is dualistic and agricultural enterprises coexist along with private family peasant as well as household farms. In 2019, an average agricultural enterprise had 20 employees, whereas five people worked on an average private farm. On average, an agricultural enterprise cultivates 110 hectares of land and generates an annual revenue of 270,000 Euros, whereas an average private farm cultivates 14 hectares and has an annual revenue of 13,000 Euros.
- Most private farms and agricultural enterprises are located in the Aran economic region. A large number of agricultural enterprises are also found in the economic regions of Ganja-Gazakh, Lankaran, and Guba-Khachmaz.
- More than half of the agricultural land is sown with wheat, maize, barley and pulses. Other key crops are vegetables, fruits and berries.
- The gross monetary output of agriculture differs substantially across farm types. The gross output of private farms increased from about 0.5 million AZN in 2000 to almost 4 billion AZN in 2019. At present, more than 90% of Azerbaijan's agricultural output is produced by private farms.

In the second part of WP1, we selected the economically most important crops of Azerbaijan, based on production levels, harvested area, and yield: *Wheat, barley, potato, tomato, onion, cucumber, pomegranate, persimmon, hazelnut and apple.*

Ultimately, we synthesized existing risk management concepts. Based on the Resilience Index Measurement and Analysis approach, we constructed four important capacity building pillars *(Access to Basic Services, Assets, Adaptive Capacity and Social Safety Nets)* by applying Structural Equation Modelling. The underlying data was obtained from selected specialists and from a previous survey called "On Commodity Supply Chains in Central Asia and Caucasus". The model showed that adaptive capacity has a positive and statistically significant relationship with household resilience. This means that the adaptive capacity of households can be increased for example by strengthening the capacity of farms to fulfil quality requirements (e.g. required to participate in formal supply chains), enabling access to market information and market extension services as well as providing subsidies towards the adoption of technologies.

Work package 2

In work package 2, we established the basis for the subsequent work packages by analyzing free and open-access geospatial environmental data. We processed daily rainfall records from the *Climate Hazards group Infrared Precipitation with Stations* dataset *(CHIRPS,* https://data.chc.ucsb.edu/products/CHIRPS-2.0/global_daily/netcdf/p05) and hourly temperature records from the *ERA5-Land* dataset (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land) of the *Copernicus* program. Both *CHIRPS* and *ERA5-Land* are gridded reanalysis products with a spatial resolution of 0.5 degrees (~5.5 km) and 0.1 degrees (~11 km), respectively, and are continuously updated in near-real time, which permits for updates of our results once new data becomes available. We used the *Caucasus Land Cover Map* from the *SILVIS lab of the University of Wisconsin* (http://silvis.forest.wisc.edu/data/caucasus) to create a cropland mask for the entire country of Azerbaijan. We applied this mask to the data from *CHIRPS* and *ERA5-Land* to calculate historical trends of changes in precipitation and temperature in agriculturally used areas of each administrative district of Azerbaijan. In addition, we also applied the cropland mask in assessing the trend in number and intensity of cropland fires by combining it with NASA's *Fire Information for Resource Management System* (*FIRMS*, https://firms.modaps.eosdis.nasa.gov/active_fire).

Work package 3

In work package 3, we developed predictive models to estimate the historical effects of climate and weather on the production of the most important crops in Azerbaijan. To do so, we combined the data from work package 2 with official district-level yield statistics from the years 2000 to 2019 published by the State Statistical Committee of the Republic of Azerbaijan, and with phenological observations recorded at a total of six agrometeorological stations.

For wheat, barley, potato, tomato, onion, cucumber, persimmon and pomegranate, we used the phenological observation record to define crop-specific development stages for which we summarize the climatic conditions of each growing cycle with a total of five climatic mean (minimum, average and maximum temperature, cumulative precipitation, and growing degree days) and six extreme weather variables (day heat, night heat, day heat waves, night heat waves, heavy precipitation, and frost). To understand which climate mean and extreme weather variables have been most important in determining yield in the past, we used these variables as yield predictors in a random forest model, a machine learning technique that has been widely used in crop modeling and is particularly capable of handling colinear predictor variables (Feng et al., 2018; Jeong et al., 2016; L Hoffman et al., 2020; Roell et al., 2020; Schierhorn et al., 2021; van Klompenburg et al., 2020; Vogel et al., 2019). In each crop-specific model, we obtained an importance value and a depiction of the functional relation with yield for each climatic variable, which we discussed in the light of the prevailing production patterns in the country and with respect to the existing literature on climate and weather effects on yield. For wheat and barley, most model results were surprising and little plausible - for example, we did not disclose the negative effect of high maximum temperature during anthesis, which is a typical characteristic of wheat (Farooq et al., 2011; Innes et al., 2015), and frost in the early vegetative phase had a positive effect on yields. The models for onion and potato showed rather unclear results. In the contrary, the results for cucumber and tomato largely resembled the expected effects of temperature and heat during the different plant development stages, and also the models for persimmon and pomegranate yielded results that are plausible and reflect the ability of these two crops to adapt to warmer and drier climates.

For apple and hazelnut, we determined the amount of chill temperatures that accumulate from autumn until the beginning of bud bursting in spring. Fruit and nut trees require such intermediate chill temperatures during winter for proper development (Fraga and Santos, 2021; Luedeling et al., 2011; Luedeling and Brown, 2011). We calibrated this model with phenological data from the agrometeorological stations and then apply it to the whole country. Through this process, we obtained maps of the long-year average amount of accumulated chill temperatures, which we classified to obtain maps of the past suitability for the production of each fruit type. Our results suggest that entire Azerbaijan has been suitable for the production of apple and hazelnut.

Work package 4

In work package 4, we integrated future climate data into the models developed in the previous work package to predict future crop yields for grain crops and vegetables, and future suitability for pomaceous and stone fruits. We analyzed daily climate projections of four climatic variables (minimum, average and maximum temperature, and precipitation), for two future scenarios (RCP 4.5 and RCP 8.5) and for two future periods (2041-2060 - "near future"; 2081-2099 - "far future"). We obtained these data from the *ISIMIP* repository (https://data.isimip.org) and restricted our analysis to the four climate forcing models for which data is available for all mentioned parameters and scenarios: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC-5. To calculate relative and absolute future climatic changes, we compared the future predictions to the historical baseline model of 1971-2005. We did not restrict our analysis to a cropland mask, since the future allocation of cropland is highly uncertain. We assumed that the crop phenology and hence the onset dates of the development stages would not change in the future (Figure 1).

For wheat and barley, we predicted the highest decreases for the mountainous regions in the north, and for the economic region of Naxcivan in the west. We mostly predicted yield increases for onion and cucumber, but both considerable increases and decreases for potato and tomato. Surprisingly, the predicted future yields of cucumber and tomato, which are both largely grown in greenhouses, showed only little agreement. While we predicted decreases in persimmon yield for the two regions where this crop is grown most, comparably little changes in yields were predicted for the hotspots of pomegranate production.

Our models showed that the entire country will remain suitable for the production of apple and hazelnut, since the future amount of chilling is not projected to fall below the historically observed minima in any region. The lowland areas of Azerbaijan will likely experience the highest total amount of chilling in the future, albeit chilling will decrease there compared to the historical baseline. On the other hand, in mountainous regions, the total amount of chilling will remain comparably low, but these areas will experience an increase in chilling. In the future, fruit and nut production might have to gradually shift to higher altitudes to ensure sufficient winter chilling under ongoing climate change. In all these calculations, we did not account for any possible future adaptation measure in crop management, land use, or technology. The results should therefore be interpreted as what could be the climatic impacts on crop yields and suitability with current crop production, but under future climate conditions. We summarize the yield change and suitability predictions for each crop in the figures 2 to 11.

Figure 1: Future crop calendar for eight crops, based on the average dates of the historical observation record from agrometeorological stations.

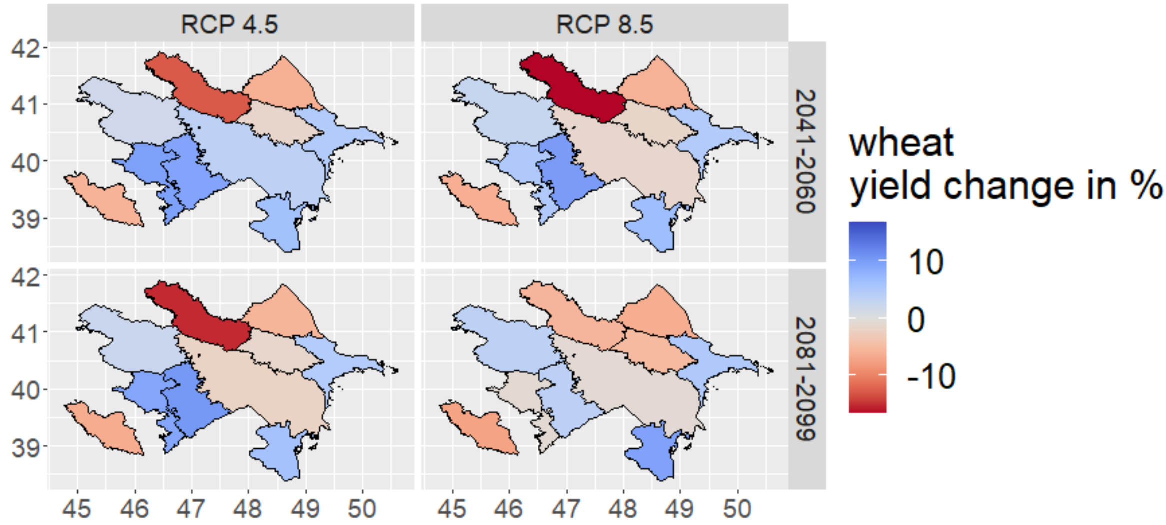

Figure 2: Predicted change in wheat yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue regions are expected to experience an increase in yield in the future; red regions are expected to experience a decrease.

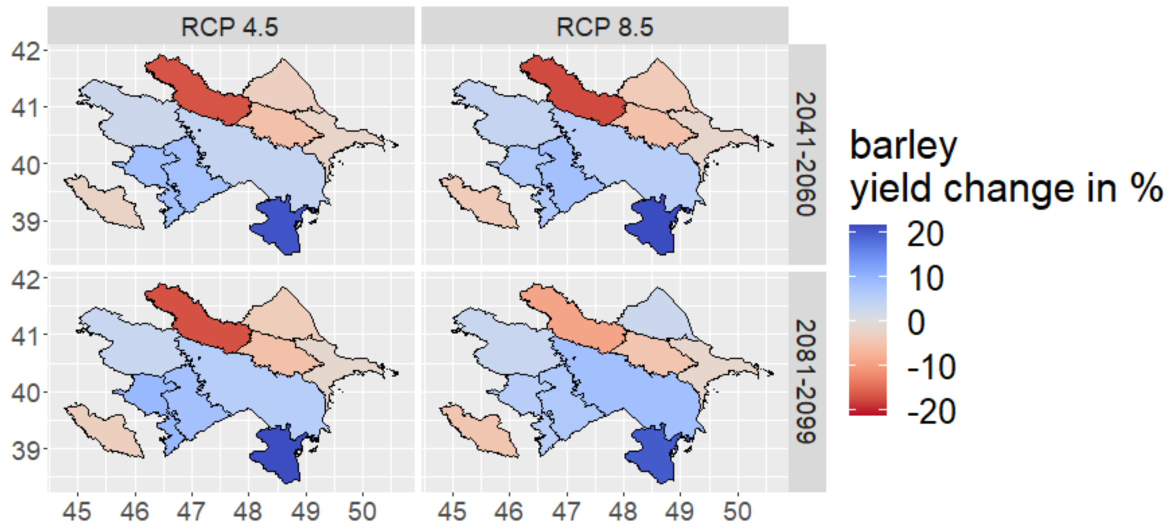

Figure 3: Predicted change in barley yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue regions are expected to experience an increase in yield in the future; red regions are expected to experience a decrease.

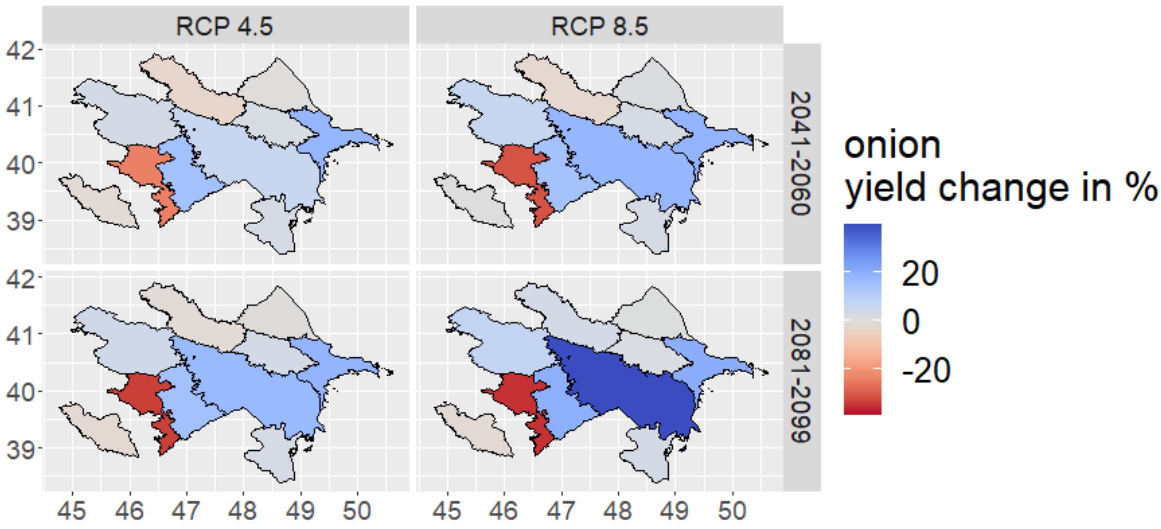

Figure 4: Predicted change in onion yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue regions are expected to experience an increase in yield in the future; red regions are expected to experience a decrease.

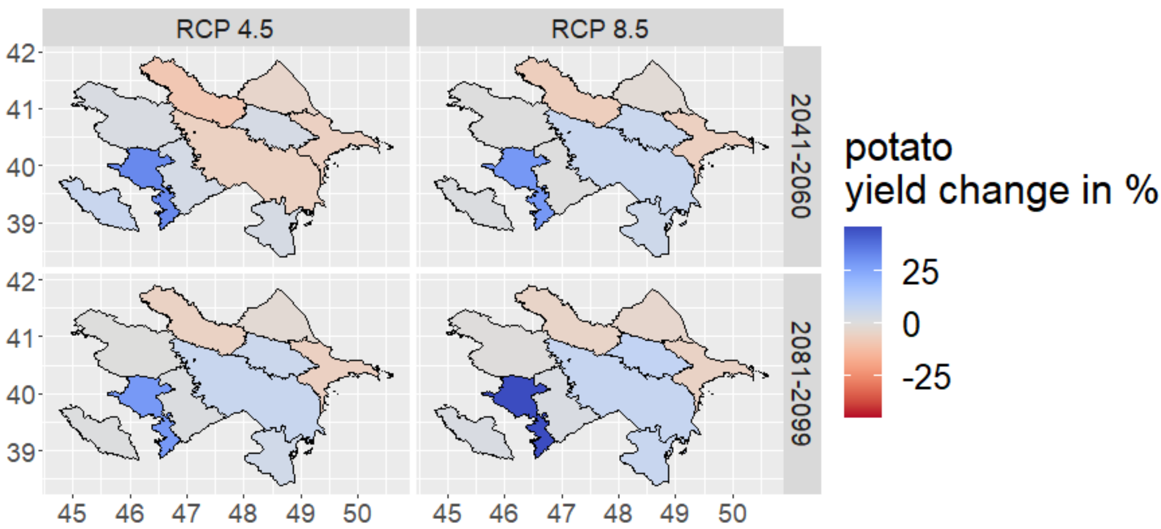

Figure 5: Predicted change in potato yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue regions are expected to experience an increase in yield in the future; red regions are expected to experience a decrease.

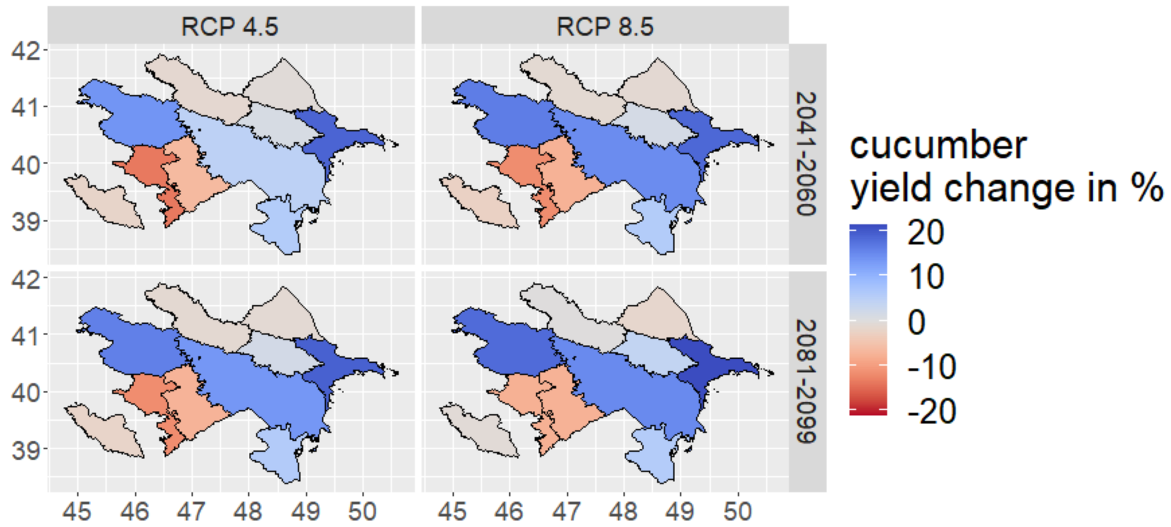

Figure 6: Predicted change in cucumber yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue regions are expected to experience an increase in yield in the future; red regions are expected to experience a decrease.

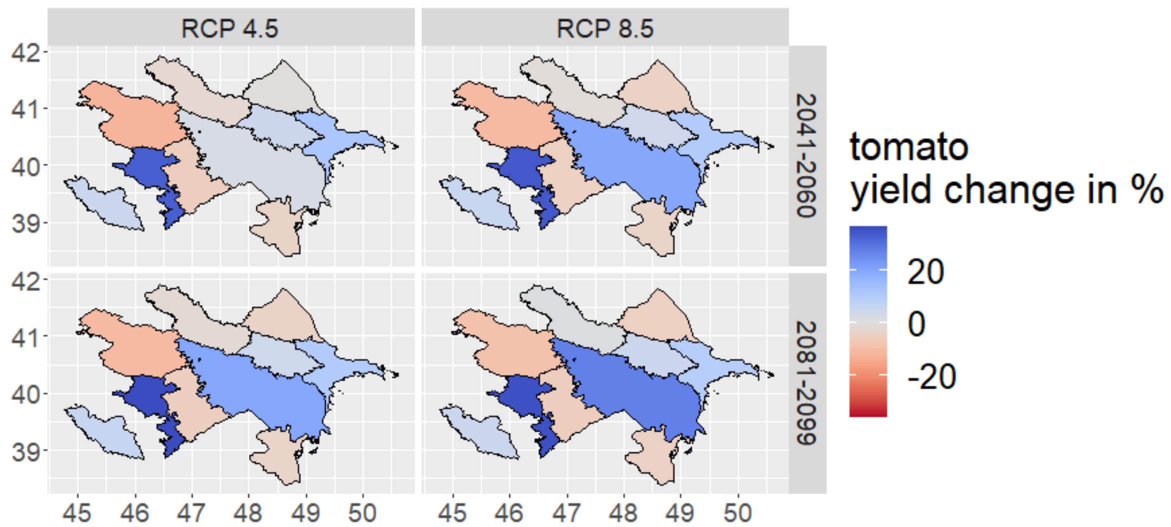

Figure 7: Predicted change in tomato yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue regions are expected to experience an increase in yield in the future; red regions are expected to experience a decrease.

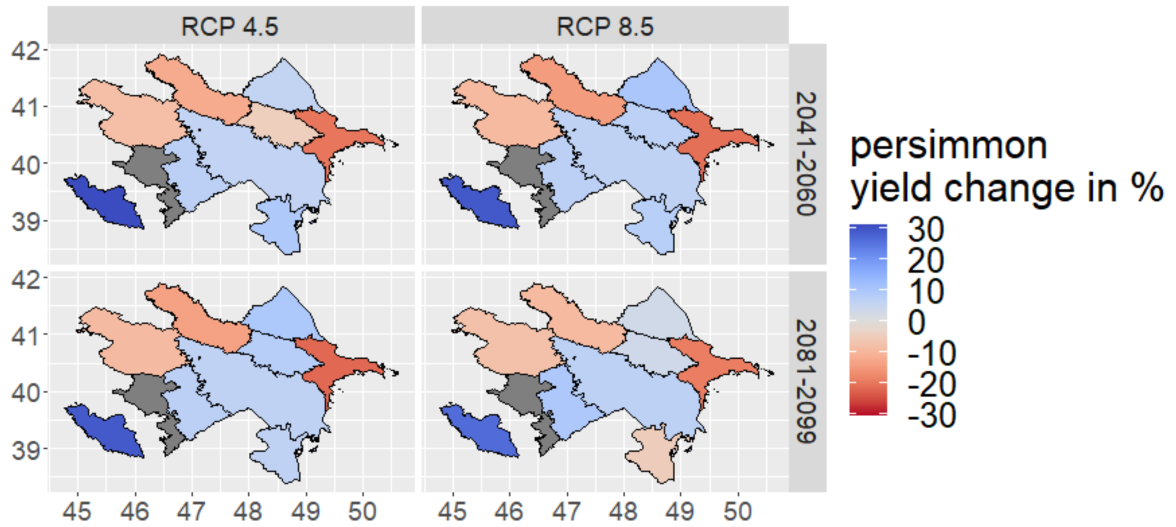

Figure 8: Predicted change in persimmon yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue regions are expected to experience an increase in yield in the future; red regions are expected to experience a decrease.

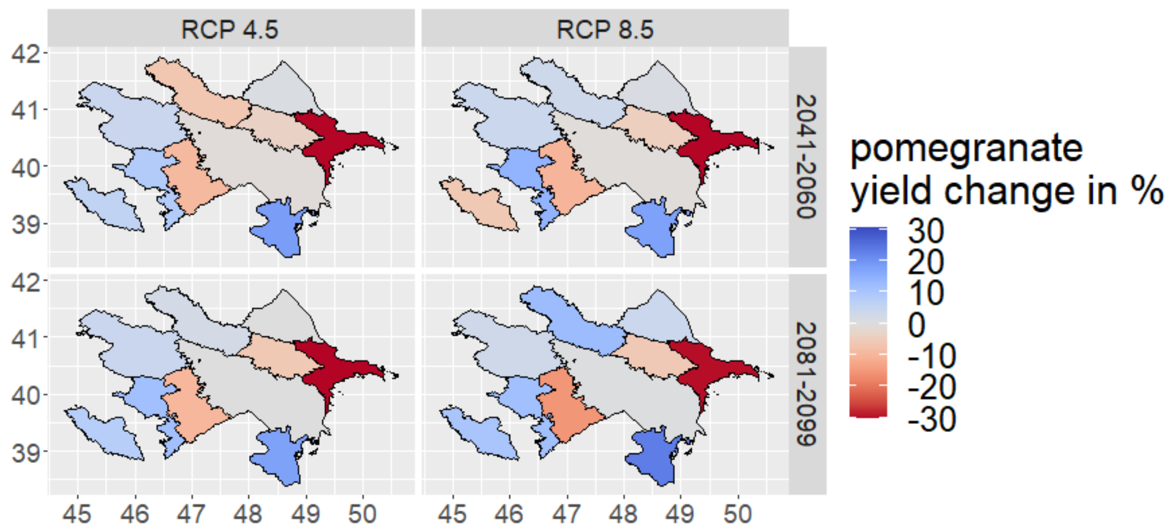

Figure 9: Predicted change in pomegranate yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue regions are expected to experience an increase in yield in the future; red regions are expected to experience a decrease.

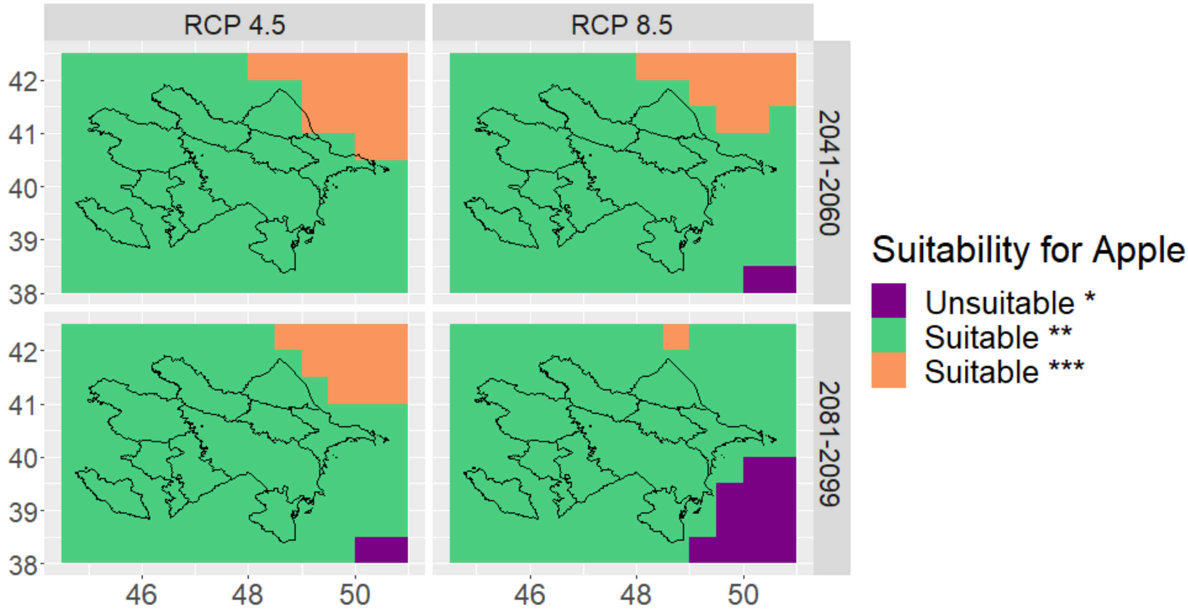

*Figure 100: Future suitability for the production of apple based on the average amount of chill units that accumulate until the end of each crop cycle, for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). *Chill Units are below hist. minimum; ** above hist. minimum and below hist. maximum; *** above hist. maximum at the time of bud bursting.*

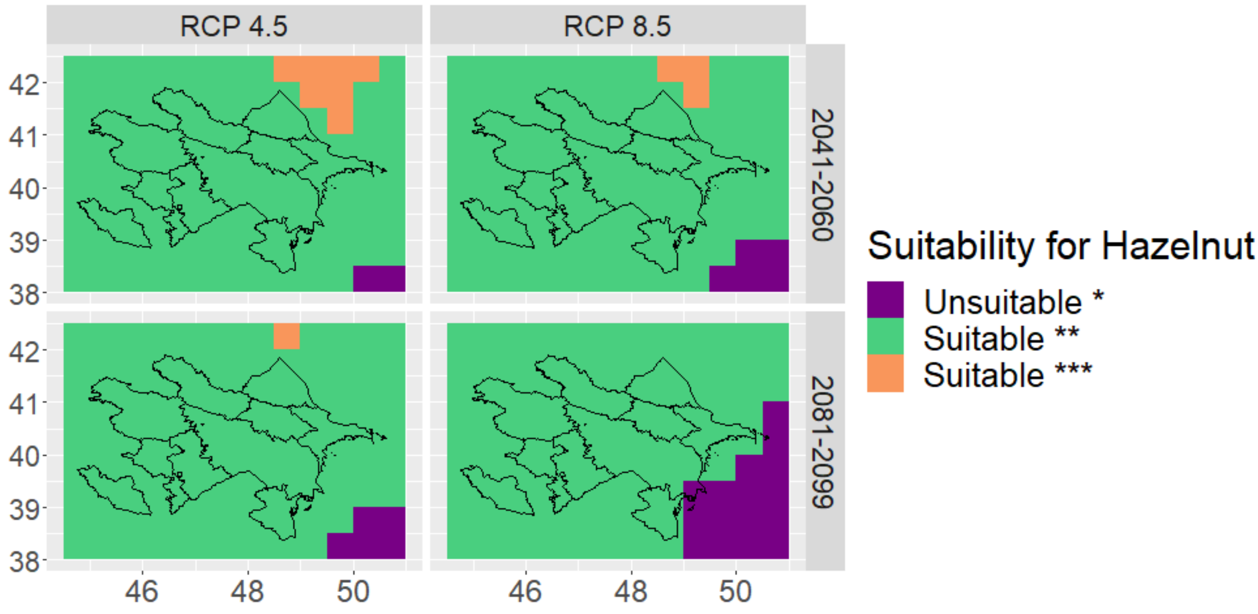

*Figure 11: Future suitability for the production of hazelnut based on the average amount of chill units that accumulate until the end of each crop cycle, for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). *Chill Units are below hist. minimum; ** above hist. minimum and below hist. maximum; *** above hist. maximum at the time of bud bursting.*

2. Stakeholder workshop

To validate and disseminate our results, we organized a workshop in which we presented our results and the accompanying data visualization tool to Azerbaijani researchers, crop specialists and institutional stakeholders to discuss possible synergies with other ongoing research projects and to find ways in which our results could be transferred to and applied in ongoing adaptation measures. We here briefly summarize the main learnings from this workshop; a separate, more detailed report of the workshop is available upon request.

Many participants showed interest in our analyses and helped us to better understand how we could develop this project further and where there is potential to improve the analyses. We learned about local projects and international collaborations that are already ongoing in the field of climate change adaptation. The workshop greatly helped us to put our results in the regional context and to reflect on methodological challenges and ways in which our analyses could be improved in the future. For example, the participants agreed in that the current results are very valuable, but would need to be further adapted and processed to a format that can actually be of use for local stakeholders and, ultimately, micro- and smallholder farmers.

The workshop also greatly helped to spot additional data sources that we had not considered before and that might made be available for future studies. For example, additional phenological observation records, meteorological information from an agrometeorological atlas, and high-resolution production and yield data could be mobilized relatively easily. There is also a database with farm-level information about cropland allocation, irrigation, input use and cultivar types that may be shared in the future.

3. Data visualization tool

We have visualized all maps produced in work packages 3 and 4 in an interactive online tool that is available in both English and Azeri language under the following links:

English: https://maxhofmann.shinyapps.io/AZE_crop2
Azeri: https://maxhofmann.shinyapps.io/AZE_crops_translated

This tool was designed to serve as a blueprint of how multi-layered geospatial information on environmental conditions and agricultural indicators can be made available to inform decision-making in a risk management process. We have included explanations for each map in the tool, but kept them short for the sake of simplicity and conciseness. The tool should be understood as complementing our detailed technical report that includes all information about the methodology and data from which the maps were derived.

In total, the tool contains about 2000 different maps. Each map is defined by a certain combination of parameters to be selected by the user in the left side-menu, and belongs to one of the following five types of analysis:

<table>
<tr><th>Analysis</th><th>Crops</th><th>Spatial resolution</th><th>Work package</th></tr>
<tr><td>Historical Suitability</td><td rowspan="2">Apple, hazelnut</td><td>Grid cells (0.1°)</td><td>WP3</td></tr>
<tr><td>Future Suitability</td><td>Grid cells (0.5°)</td><td>WP4</td></tr>
<tr><td>Historical Climatic Conditions</td><td rowspan="3">Wheat, barley, potato, tomato, cucumber, onion, persimmon, pomegranate</td><td>Districts</td><td>WP3</td></tr>
<tr><td>Future Climatic Conditions</td><td>Grid cells (0.5°)</td><td>WP4</td></tr>
<tr><td>Future Yield Changes</td><td>Economic regions</td><td>WP4</td></tr>
</table>

This tool was created with the software R and the package extension “shiny”. For future risk management trainings, the tool could be expanded for example by including the following functionalities:

- Retrieving data from a set of maps for a common geographical marker
- Comparison of different maps and/or markers in interactive diagrams
- Interpretation of the data in the form of a risk scoring
- Options to download data tables, images and PDF reports
- Visualization of secondary environmental data, e.g. soil maps, weather station networks, land cover classes, etc.

4. Recommendations

In the following, we provide a series of recommendation which should be considered to enhance the resilience of the agricultural sector in Azerbaijan against the negative impacts of climate change. We propose changes in crop management that farmers can carry out in the field (*Management adaptation*). We then discuss the role of different institutions in supporting farmers adapt to climate change in the long run (*Stakeholder engagement*). Ultimately, we discuss how our scientific results should be treated in such process, and propose priorities for future scientific projects and data collection (*Future research activities*)

Management adaptation

In previous work in this project, we have found that heat and water stress reduce yields of some crops such as wheat in Azerbaijan. Therefore, there is a need to adapt crop production to the increasing heat and drought in the country in order to avoid yield losses or to allow higher yield variability. Crop production is already widely dependent on irrigation and, given scarce water resources in the South Caucasus, the challenge to increase water use efficiency is increasing. At the same time, there is evidence that excessive water supply, particularly through heavy rainfall, compromises the yields of most crops in Azerbaijan. Given a forecasted positive trend in heavy rainfall events, measures to avoid the yield-limiting effects of water logging and floods are urgently needed. In this chapter, we discuss what climate change adaptation measures are available and how effectively these measures could be applied.

Climate-adapted crop varieties

A first important adaptation option is to grow heat- and drought-tolerant crop varieties that root to deep soil layers, have better growth characteristics under drought stress, and transpire more efficiently. Our research suggests that climate-adapted varieties are already grown in some cases, but climatic conditions are changing rapidly so that we anticipate further need to adapt cropping systems. Breeding advances, particularly through new methods such as CRISPR/Cas, are promising strategies to adapt plant material to changing environmental conditions. In particular, breeding for varieties resistant to drought and extreme temperatures should continue to be a focus of national breeding programs (Zhang et al., 2015). Heat- and drought-resistant cereal varieties can compensate for yield fluctuations, although yield losses must also be planned for in climatically more favorable years. Therefore, it must be investigated here in detail and in a spatially differentiated manner which strategy will result in the highest and most stable yields in the long term. Our research also suggests that some crops can better cope with the prevailing climate conditions than others. For example, spring barley, maize and vegetables in Azerbaijan had a lower sensitivity to heat conditions than wheat. More focused research is needed to investigate which specific crop rotations (and crop cultivars) are best suited to local climate conditions in the future.

Climate adaptation through conservation agriculture (CA)

A second important adaptation measure is conservation agriculture (CA), which has already been proven to be an effective method to counter the negative effects of climate change, especially in arid and semi-arid regions. The three central elements of CA are no-till or minimum tillage, mulching, and diversification of crop rotations. The main goal of CA is to increase the humus content in agricultural soils. This can have positive climate effects, but also counteracts crop yield reduction through warming, increasing drought, and even excessive water supply. For example, soils with high humus content are less susceptible to erosion and increase the water retention capacity of the soil which could counteract the widespread yield-limiting effects of heavy rainfall in Azerbaijan. It has often been shown that CA is particularly effective when the different elements of CA are combined. To our knowledge, studies on the effectiveness of CA against drought and heat are not available for Azerbaijan. We therefore evaluate studies on CA conducted in regions that have geographically and climatically similar conditions to Azerbaijan.

CA measures can sustainably increase nutrient and water content and thus also increase crop yields. Improved soil water-holding capacity and low evapotranspiration rates as a result of CA application can protect crops from periods of extreme heat. Reduced tillage, such as through the use of no-till technologies, improves soil water storage and reduces water demand for irrigation, thus conserving groundwater resources. In northern India, for example, no-till and sub-mixing of crop residues led to increases in irrigation efficiency of 20% (Parihar et al., 2016). In southern Russia, no-till resulted in a significant increase in soil water content compared to conventional tillage (Kühling et al., 2017). This effect probably increases with decreasing precipitation, so no-till probably also helps to adapt cropping to increasing water scarcity under climate change in Azerbaijan. However, more focused research is needed for more robust insights. In addition to the positive effect on soil water, soil conservation or no-till tillage contributes to the formation of soil organic carbon in the upper soil layers. Therefore, CA can potentially combine climate adaptation and climate change mitigation. A disadvantage may be increased weed pressure, which often has to be solved by pesticide application and thus may also result in negative environmental impacts.

Another effective CA method is mulch application, which could act as an effective buffer against extreme temperatures at the soil surface (Mrabet et al., 2001). Gusev et al. (2018) modelled the effect of four different cultivation techniques (deep plowing/moldboard, irrigation, minimum tillage, and mulching) on soil water and yield of winter wheat in southern Ukraine. Mulching with biological biomass resulted in a significant increase in water availability (up to 15%). This also significantly increased yields in the model. Gusev et al. (2018) also showed that a mulch layer of about 5 cm is optimal for increasing water availability. The authors conclude that mulching in combination with reduced tillage leads to an increase in soil water content, increased yields and improved energy efficiency. We recommend to carry out follow-up studies to assess impacts of such CA methods on water availability and crop productivity under changing climate conditions.

Climate adaption through drip irrigation

Irrigation is an important technical method to enable crop production in hot and dry locations. Irrigation is already widely used in Azerbaijan, but there is an urgent need to increase the efficiency of water use to better utilize the scarce and diminishing water resources in the South Caucasus. Drip irrigation is a promising technology in this context.

In the scientific literature, drip irrigation is predominantly described as a water-efficient as well as yield- and income-increasing technique. Water is transported directly to the root zone of the plants, reducing losses due to evapotranspiration and runoff (Alonso et al., 2019). Therefore, drip irrigation can theoretically have higher irrigation efficiency than conventional techniques such as furrow or sprinkler irrigation. In a regional modeling study conducted in central Morocco, large-scale application of drip irrigation resulted in a 20% reduction in water demand (Rochdane et al., 2012).

Drip irrigation can also distribute polluted water more safely, has advantages over older irrigation techniques in steep terrain, and is valued by farmers as a technology that generates significant labor savings (van der Kooij et al., 2017). Drip irrigation is also traded in the literature as a kind of innovation and modernization bandwagon that can lead the whole agriculture away from outdated and dirty land use to a cleaner and more sustainable era (van der Kooij et al., 2017).

Numerous publications have appeared on this topic; however, no studies have been carried out in Azerbaijan to our knowledge. In southern Kazakhstan, i.e. in a similar latitude to Azerbaijan, a field trial was conducted to investigate the effect of drip irrigation in combination with the plastic mulching method on yields as well as water productivity of sugar beet (Massatbayev et al., 2016). During the study period (2011-2012), up to 40% of water was saved compared to the conventional system. Here, firstly, the main advantage of drip irrigation came into play, i.e. that plants are only irrigated when they actually need water. Secondly, the plastic overlay reduced evaporation. The study also calculated a water volume at which optimal water productivity is achieved. Importantly, in terms of acceptance of this system, plastic mulching alone resulted in a 50% increase in yield (Massatbayev et al., 2016). However, a weighty disadvantage of plastic mulching certainly is the high demand of plastics.

Numerous studies conducted in India, a country with extremely large irrigated fields, have shown that drip irrigation results in an increase in yield as well as in water productivity compared to conventional techniques such as furrow irrigation (Qin et al., 2016; Sinha et al., 2017; Surendran et al., 2016). For example, in a study conducted at Punjab Agricultural University, a field trial with sunflower showed that drip irrigation required one third less water than furrow irrigation (Sinha et al., 2017). There is also a need for research on how technically efficient drip irrigation can be used in a water-saving manner in its real-world application. For this, farmers need to be technically trained.

Stakeholder engagement

Awareness raising

Many farmers in Azerbaijan might still be unaware of the consequences that climate change will eventually have on agricultural production, and are on a low level of adaption to climate change. In line with many suggestions raised by the workshop participants, we believe that both governmental and non-governmental institutions should invest in awareness raising campaigns to inform about the risks of climate change and possible ways in which to prepare for them. On one hand, this should be done via multi-channel media campaigns, but should on the other hand be complemented by on-the-ground workshops and advisory that specifically target farmers. Public authorities and NGOs may already have the needed local networks to carry out such efforts at large scale. Particular emphasis should be put on properly communicating scientific findings for such efforts, and special attention should be paid to considering the respective local context.

Increasing adaptive capacities

Regional programs are needed to build and strengthen viable climate change adaptation strategies for farmers. In this respect, a variety of different types of institutions should be engaged to create market linkages and to facilitate access to financial resources and subsidies. An over-emphasis on resilience building for risk management practices and the lack of institutional roles to create the linkage between agricultural extension services and capacity building practices still remain challenges in the country. Such difficulties to create the linkage for capacity building, agricultural advisory and extension services are one of main reasons exacerbating the severity of climate change impact. In order to induce the process of providing extension services and adopting innovative approaches, supporting capacity building programs by different institutional stakeholders would be an important contribution. Another approach to increase the adaptive capacity of farmers and to shape climate mitigation incentives in the long-run is to increase their participation and to recognize their specific needs. Dissemination of resilience capacity for risk mitigation also requires a proper approach for learning certain tools and technologies. In doing so, the role of development agencies and farmer organizations would be complementary solutions based on available resources.

Science for decision-making

The scientific insights into the effects of climate change on agriculture can only be of practical value if they are properly translated into policy and management recommendations that target different institutional stakeholders at the right level of decision making. We call for regular exchange among politicians and public authorities, farmers' associations, NGOs and research and financial institutions to identify which type of evidence is needed at which scale. For example, farmers need to understand the locally prevailing risks and how financial products can render their production more resilient, and should be given flexible options for financial resources to fit their specific needs for anchoring resilience-enhancing investments. Particularly promising tools to ensure micro- and smallholder farmers against adverse extreme weather events are picture-based insurances (Ceballos et al., 2019), remote sensing index insurances (Benami et al., 2021) and risk-contingent credits (Shee and Turvey, 2012). Moreover, scientific results should also be properly digested to inform and guide financial institutions and extension services and help them to properly integrate environmental data into the design of financial products and into their advisory works. On a large scale, country-wide assessments should inform long-term strategies and investments such as infrastructure development and the design of subsidy and incentivization schemes.

Future research activities

Results validation and updating

We call for a rigorous check of our model assumptions and results by local agronomists to evaluate how future yield models can be tailored to local environmental circumstances and the specific cultivars grown in the country. In the workshops, several participants pointed out that such validation would be indispensable and should also encompass local studies and the grey literature. We believe that both local research institutions and agricultural, meteorological and environmental authorities have the regional expertise and interest to not only evaluate the quality of our study, but also to develop it further in the future.

Strengthening research capacities

Few peer-reviewed studies exist on the relationships between climate change and agriculture for the lower Caucasus. This is unfortunate, given that climate change will likely exert transformative changes on agricultural production and rural livelihoods. It will therefore be pertinent to invest in strengthening the research capacities for monitoring and analyzing climate change, examining the impacts of climate change on agricultural production, and developing scientifically-based adaptation pathways. This will require interdisciplinary collaboration among experts from many different areas, such as meteorology, agronomy, remote-sensing and crop modeling. Local institutions should seek to intensify exchange among each other and with international scientific centers, for example in the form of study visits or joint projects, to ensure that the highest research standards and state-of-the-art approaches are applied, and that results are published in English language, peer-reviewed journals and thereby made openly accessible to the international research community. We think that research capacity building should therefore, on one hand, entail training on data management, data processing and statistical analysis; and on the other hand, promote the development and maintenance of data collection systems, protocols and IT infrastructure, and financially support academic exchange and careers.

Knowledge management and data sharing

In the long-run, all stakeholders involved in assessments and risk management strategies related to agricultural adaptation to climate change would benefit from a joint strategy for the collection and sharing of relevant data and protocols. We advocate environmental and agricultural data to be centrally and openly stored in the future, with common and interoperable data and metadata standards to ensure free and easy exchange of information between institutions. Workflows and methods should be well documented, preferably in the form of free-to-access reports or scientific publications. Regular exchange among data providers and users would help build trust, establish long-term collaborations and ensure that data requirements are properly met.

Public involvement

In the absence of sufficient institutional resources, citizen science, i.e. the involvement of laymen in scientific projects, can support data collection and validation. For example, one breakout group in the stakeholder workshop mentioned that, for a future early warning app on extreme weather conditions, the end-users of that app themselves should provide feedback on whether the predictions of that app hold true. When appropriately communicating that citizen scientists can benefit from the projects they are contributing to, there is great potential to involve farmers and the general public in also collecting, for example, phenological observations and meteorological data from privately run weather stations.

Research agendas

To improve the understanding of the effects of climate change on agriculture in Azerbaijan, we propose to put emphasis on the following topics in the future:

Conduct local in-depth studies

Our study contributes to a better understanding of the complexity of past and future effects of climate change on agriculture in Azerbaijan. While nation-wide studies provide a good overview for the entire country and contribute insights for a high management level, they fail to accurately quantify effects on the local scale. To gain more detailed insights, future research should therefore entail localized studies that focus on few specific crops, making use of the best-resolution available data and integrating local knowledge about the characteristics of the locally grown cultivars. This will permit deep insights into local level processes and substantiate policy making towards sustainable adaptation pathways.

Land cover and crop type mapping

Spatial data about the exact spatial distribution of cultivated crops is indispensable to accurately model the prevailing climatic and hydrological risks for that crop. Satellite remote sensing is a crucial pillar for providing such data at high spatial and temporal resolution, but remote sensing seems to receive little attention in Azerbaijan. At present, the best available map of land-cover types for the entire lower Caucasus was produced by the University of Wisconsin-Madison for the year 2015. Detecting fine-scale vegetation signals using state-of-the-art land-cover mapping could help to reveal the temporal dynamics of the extent of each major grain crop type, orchards, greenhouses, and irrigated areas, uncover changes in land use due to climate change, and improve the statistical data basis of the distribution of crops. Efforts to strengthening the methodological and computational capacities to process satellite data should be complemented by a national system of ground-truthing observations to be used for training and validation of remote sensing algorithms, such as the LUCAS survey for the EU-27 countries (https://land.copernicus.eu/imagery-in-situ/lucas). To acquire state-of-the-art remote sensing knowledge and skills, it is likely indispensable to send promising young scholars abroad for high-quality education in big-data processing.

Process-based crop growth modeling

In our study, we statistically associated meteorological data with yield records to infer about climatic effects on crop yields. However, such associations can be blurred by imprecise yield data, different management regimes, coarse data resolution and other, unmeasured environmental variables. An alternative is to calibrate crop growth models like EPIC (https://epicapex.tamu.edu/epic) that simulate a series of biophysical processes such as water, nitrogen, and carbon cycling to approximate yield. Such models can deliver more precise results, but also require more precise information about crop management and environmental conditions, e.g. on fertilizer application, irrigation, and soil properties. Once well calibrated and validated, crop growth models can be used to test scenarios and assess how adaptation measures affect crop yields. Future research efforts should try to raise cultivar-specific input data to calibrate crop growth models for Azerbaijan, for example with data from experimental stations in key producing regions.

Hydrological modeling

Water scarcity will constitute a major bottleneck for maintaining or increasing crop yields under climate change. With climate change, agricultural water consumption will likely increase due to higher evapotranspiration rates. Arguably, there will be areas that will require regular irrigation to ensure adequate plant growth. Measuring, monitoring, and analyzing crop-water usage, assessing future water demands, and analyzing adequate crop and livestock production that can cope with rising water scarcity will constitute important future research avenues. Reinforcing research activities in hydrological modeling and assessments of crop water requirements over space and time is recommended to better understand the impacts of water resource availability for agriculture.

Scientific data collection

To provide the necessary basis for future research projects, we propose to intensify and develop further the collection of the following data types:

Agricultural statistics

Existing data on crop yields, extent of irrigation and greenhouses, input usage, and plant cultivars do not permit for high-quality analyses at fine spatial, temporal, and thematic scales. At present, science-based monitoring and assessments of the impacts of climate change on agricultural production suffer from a lack of high-quality subnational agricultural statistics that are accessible for use in research. Insufficient data quality and data availability hinder solid assessments of the relationship between climate change and agricultural production. More efforts should be undertaken to collect agricultural census and geospatial data to support the monitoring of environmental and agricultural changes. Provision of data that are well documented and free to access will enable implementing agencies, ministerial staff at different levels, and academia to advance their efforts in monitoring, assessments, and research. Embracing open data concepts would also provide for better participation of civil society organization and the interested public and may contribute to reducing corruption.

In particular, the lack of high-resolution yield data is a bottleneck that hampers the assessment of how climate change has affected crop yields because crop yields constitute a crucial productivity metric. Only credible yield data allows to assess the effects of weather on yields. The golden standard for yield estimation are crop-cuts. Crop cut measurements are systematically placed quadrants that are laid over a plot; everything that grows in each quadrant is then harvested, dried, and weighed.

Environmental data

Accurate and precise environmental data is pertinent to examine agricultural and rural development in the face of climate change. High-quality spatial data facilitate better assessment of efficient and effective climate adaptation options. This may include the establishment of additional meteorological stations, including small-scale on-farm stations that could be managed autonomously by farmers. Such data could be automatically fed into a centralized online cloud database that is freely accessible to everybody. Ideally, meteorological measurements at such stations would be complemented by phenological observation records and soil property measurements. The station system should be geographically representative and cover all bioclimatic and elevational zones of Azerbaijan. Such measurements could be automatically processed in the cloud, for example to produce seamless maps of environmental conditions through interpolation methods, that could then serve as a basis for agricultural advisory at the local level.

Farm-level data

Detailed farm-level data on plant cultivars, input application, plot-scale yields, and crop management coupled with fine-scale and temporally refined meteorological data would allow to examine with more accuracy how climate and weather stress impact crop yields. Establishing, for example, experimental farms in different biophysical environments of Azerbaijan could yield a valuable cross-section. Farm-level data should also include the day of sewing and harvest and information on irrigation and soil properties. Such data could be collected in the frame of household surveys, which could also help to better understand the financial situation of the farmers to assess which crop management options of climate change adaptation are economically feasible.

For a follow-up of our present study, we suggest to specifically evaluate whether the following data exists or could be collected, for the longest time series possible:

- Yearly crop-type maps with a spatial resolution of 30 meters
- Yearly district-level and crop-specific yield estimates separated for irrigated vs. non-irrigated lands, and for greenhouses vs. open lands
- Yearly crop-specific yields at the agrometeorological stations
- Yearly water amounts withdrawn for irrigation; irrigated area, production amounts and yield under irrigated conditions, for each district and crop
- Yearly district-level and crop-specific production amount, sown area and yield under greenhouses, incl. applied irrigation amounts
- Yearly farm-level use of different fertilizers
- Daily meteorological measurements from a geographically representative collection of weather stations
- Daily crop-specific phenological observations from a geographically representative collection of stations
- For each cultivar planted: name/accession, production amount, sown area and yield, for each year and district; required and optimal climatic conditions (e.g. optimal temperature range, water requirements, heat tolerance, frost tolerance)

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