Report - Work Package 5:

“Synthesis & Recommendations”

Armenia

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 Armenia” (RIMARA)

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Content

Executive summary

In the present study, German Sparkassenstiftung for International Cooperation e.V. (DSIK), the Hydrometeorology and Monitoring Center of the Ministry of Environment of the Republic of Armenia (HMC), 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 Armenia. IAMO carried out the data analysis and literature review. Important datasets for the analysis, such as weather station measurements and phenological observations, as well as translations and technical expertise were provided by HMC.

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 Armenia 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 two workshops that were organized jointly by HMC, DSIK and IAMO and 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 Armenia 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 Armenia, 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 Armenia, we highlight several predominant characteristics:

- Agriculture is one of the most important sectors in Armenia, contributing 12% of its GDP (NSS, 2020). In 2019, the real gross value of agricultural production was 852,800,000 million AMD. The regions Armavir, Ararat and Gegharkunik contributed the most to this value (NSS, 2019). Vegetables contribute the highest share to the gross harvest (NSS, 2020).
- Most farms in Armenia are either commercial or family farms (FAO, 2019). Many farms are without legal status and have less than five workers. Agricultural holdings without legal status typically have a size between 0.1 and 3 hectares, whereas those with legal status have farm sizes between 1 and 20 hectares. The annual economic turnover is between 1000 and 15,000 Euro for family farms, and between 1000 to 50,000 Euro for commercial farms. (NSS, 2014)
- Family farms outnumber commercial farms in sown area. Commercial farms tend to substitute forage crops for grain crops and legumes. Family farms show decreases in sown area for both grain crops, legumes and forage crops over time (NSS, 2020).

In the second part of WP1, we selected the economically most important crops of Armenia, based on production levels, harvested area, and yield: *Apricot, peach, apple, plum, winter wheat, spring barley, tomato, berries, potato and cucumber*. However, yield statistics and phenological observations were not available for *plum* and *berries*, which we therefore substituted for *silage maize, pear, quince* and *cornel*.

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”. Given the significance of adaptive capacity, the magnitude of relationship with the household resilience capacity index was very high. Efforts to improve the adaptive capacity of households will translate into an increased ability to mitigate climate change consequences. In this case, the households would become more adapted for example by improving access to extension services, strengthening the capacity of farms to fulfilling quality requirements as well as providing subsidies to enable the adaptation 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 0.05 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 Armenia. 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 Armenia. 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 Armenia. To do so, we combined the data from work package 2 with official province-level yield statistics from the years 2005 to 2020 published by the Statistical Committee of the Republic of Armenia, and with phenological observations and temperature measurements, which were recorded at a total of 48 agrometeorological stations and provided by HMC in the frame of a partnership agreement with DSIK.

For **grain crops and vegetables** (winter wheat, spring barley, silage maize, potato, cucumber, and tomato), we used the phenological observation record to define crop-specific development stages for which we summarized 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. Overall, we found that climatic means have been more important for yield levels than extreme weather events. Nevertheless, particularly the results of the grain crop models indicated negative effects of heavy precipitation during different development stages. For winter wheat, our model results disclosed the negative effect of high maximum temperature during anthesis, which is a typical characteristic of wheat (Farooq et al., 2011; Innes et al., 2015). Our vegetable models also revealed negative effects of heavy precipitation, but largely positive effects of high temperatures.

For **pomaceous and stone fruits** (apple, pear, quince, apricot, cornel, and peach), we determined the amount of chill temperatures that accumulate from autumn until the beginning of bud bursting in spring. Fruit 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 and temperature data from the agrometeorological stations and then applied 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 Armenia has been suitable for the production of the six fruit types considered. The mountainous regions of the northeastern part of the country provide more chilling than these fruits actually require, yet production levels are very low in these areas, probably due to other factors, such as adverse accessibility, which complicates the marketing of the produce, and low population density.

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. These models differ in their assumptions about radiative energy received by the earth and the atmospheric energy fluxes in the future. To calculate relative and absolute future climatic changes, we compared the future predictions with 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. For grain crops and vegetables, we assumed that the crop phenology and hence the onset dates of the development stages would not change in the future (Figure 1).

For winter wheat and spring barley, we predicted the highest decreases in the southern part of the country, and increases in some provinces in the north, whereas for tomato and cucumber, we mostly predicted yield losses. Our results also suggest that the suitability for pomaceous and stone fruits will decrease with increasing future warming, i.e. suitability will be lower under RCP 8.5 than under RCP 4.5 and lower in the far future than in the near future. We showed that pomaceous fruits (apple, pear, and quince) may be more susceptible to future warming than stone fruits (apricot, cornel, and peach). However, our models predict that the entire country will remain suitable for the production of all studied fruit crops, since the future amount of chilling is not projected to fall below the historically observed minima in any region. In the future, fruit 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 13.

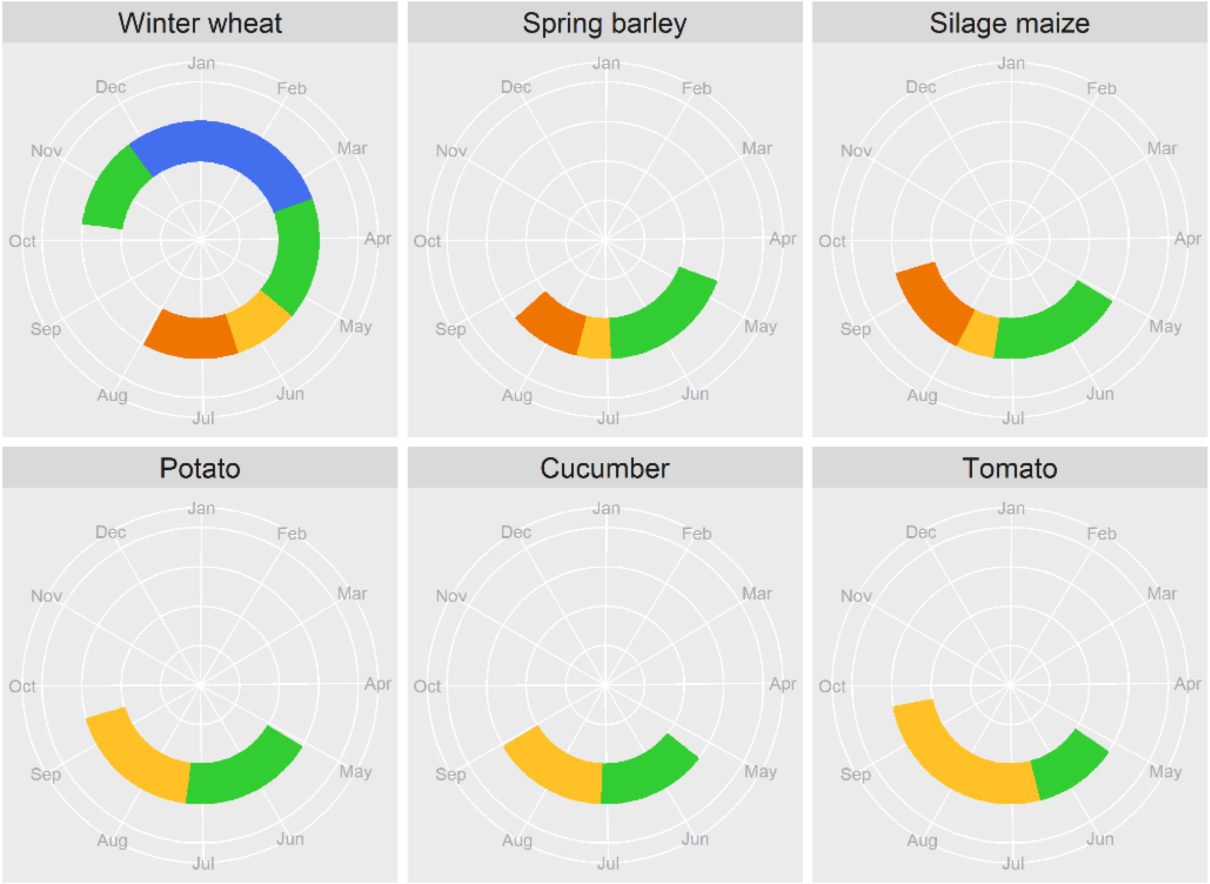

Figure 1: Future crop calendar for six grain crops and vegetables, based on the average dates of the historical observation record from agrometeorological stations.

🟦 Winter dormancy
🟩 Vegetative Stage
🟨 Reproductive Stage
🟧 Grain Filling

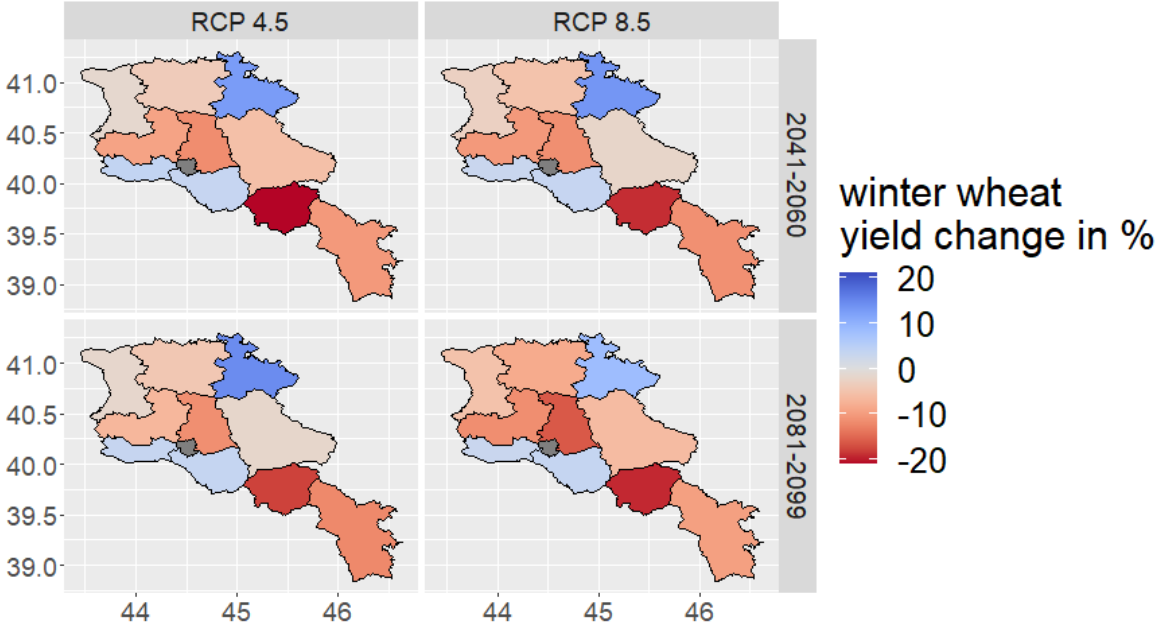

Figure 2: Predicted change in winter wheat yield in %, compared to historical long-year average yield levels (2005-2020), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in the future; red provinces are expected to experience a decrease.

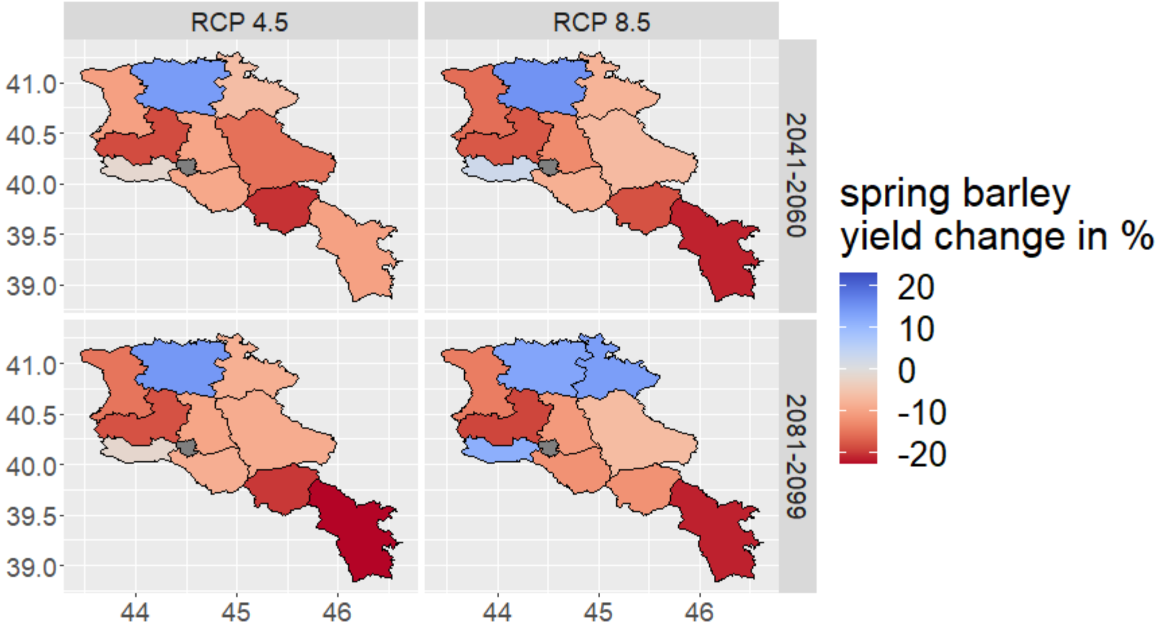

Figure 3: Predicted change in spring barley yield in %, compared to historical long-year average yield levels (2005-2020), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in the future; red provinces are expected to experience a decrease.

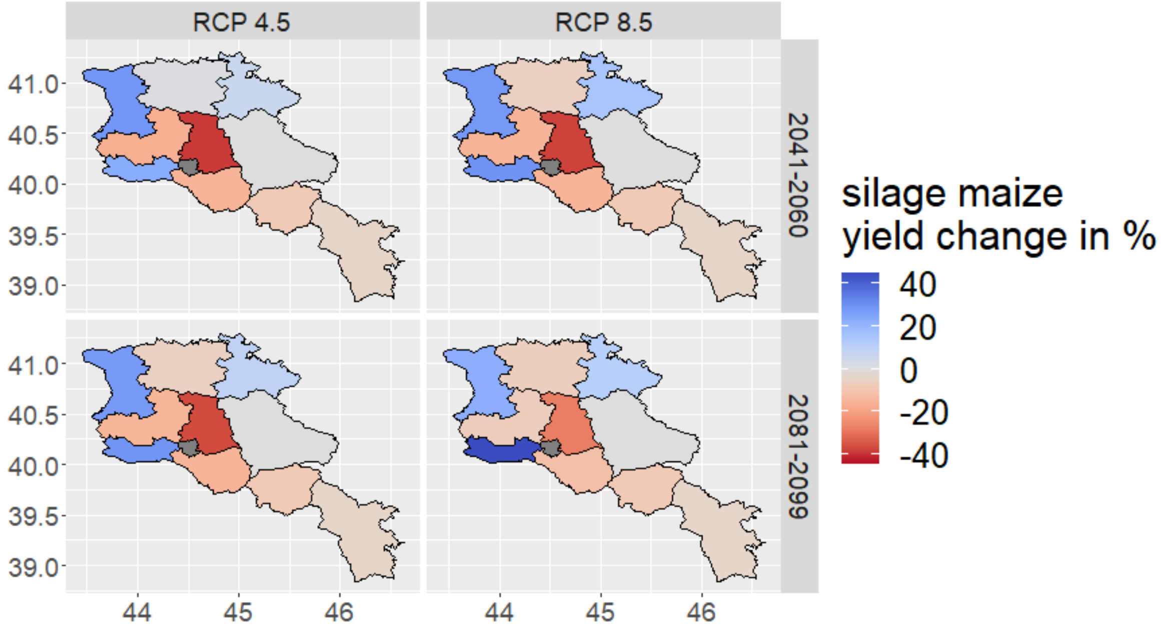

Figure 4: Predicted change in silage maize yield in %, compared to historical long-year average yield levels (2005-2020), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in the future; red provinces are expected to experience a decrease.

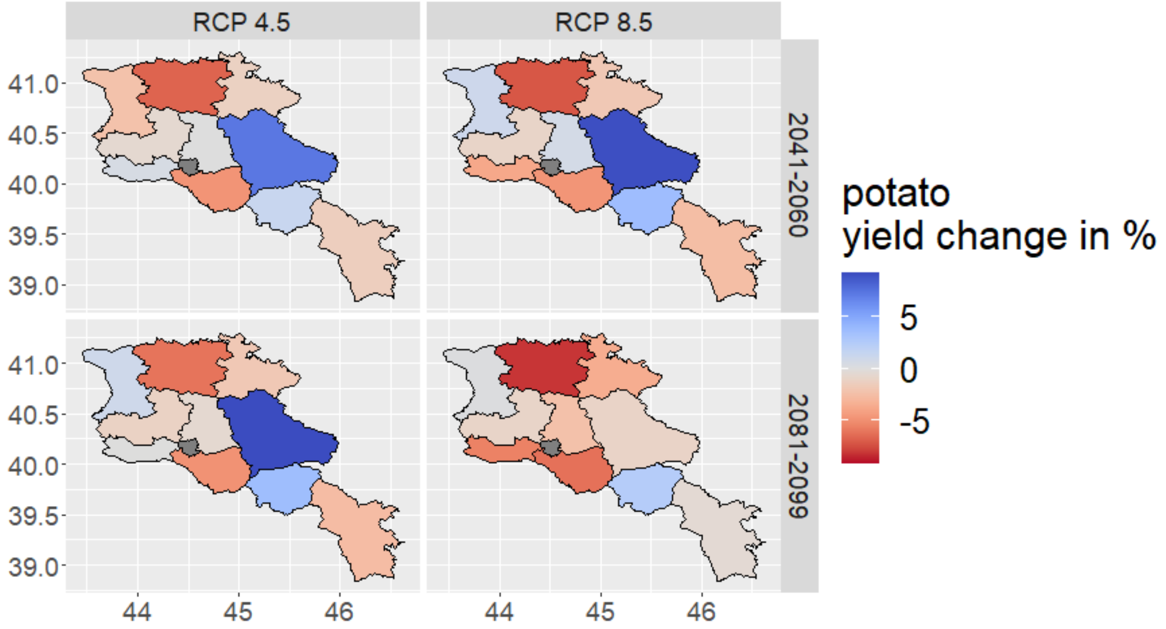

Figure 5: Predicted change in potato yield in %, compared to historical long-year average yield levels (2005-2020), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in the future; red provinces are expected to experience a decrease.

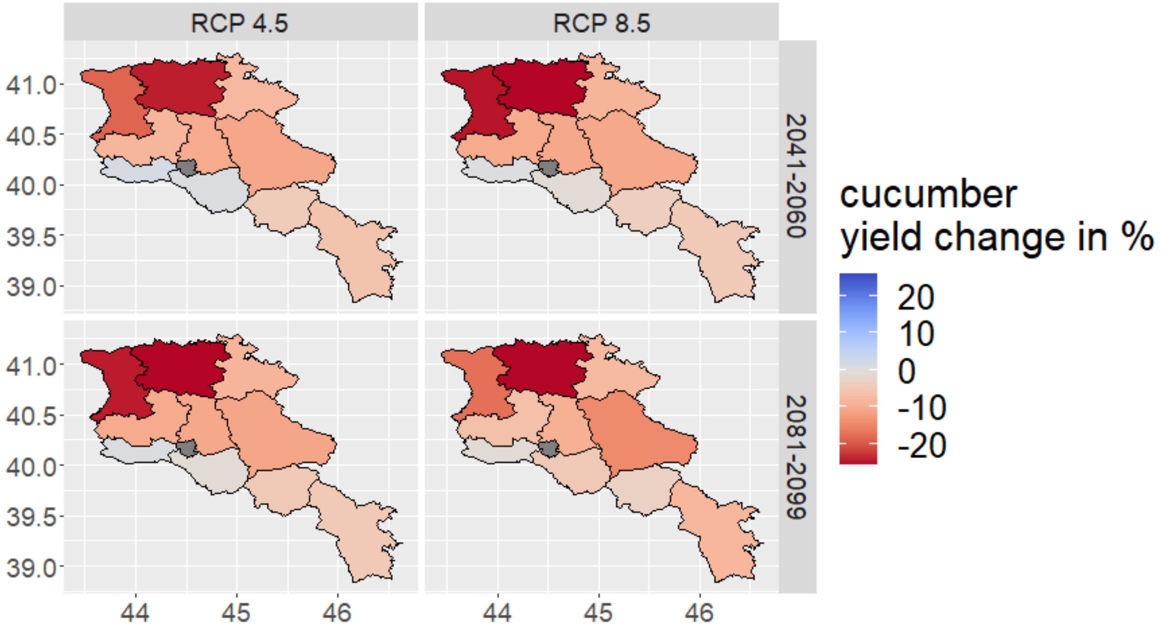

Figure 6: Predicted change in cucumber yield in %, compared to historical long-year average yield levels (2005-2020), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in the future; red provinces are expected to experience a decrease.

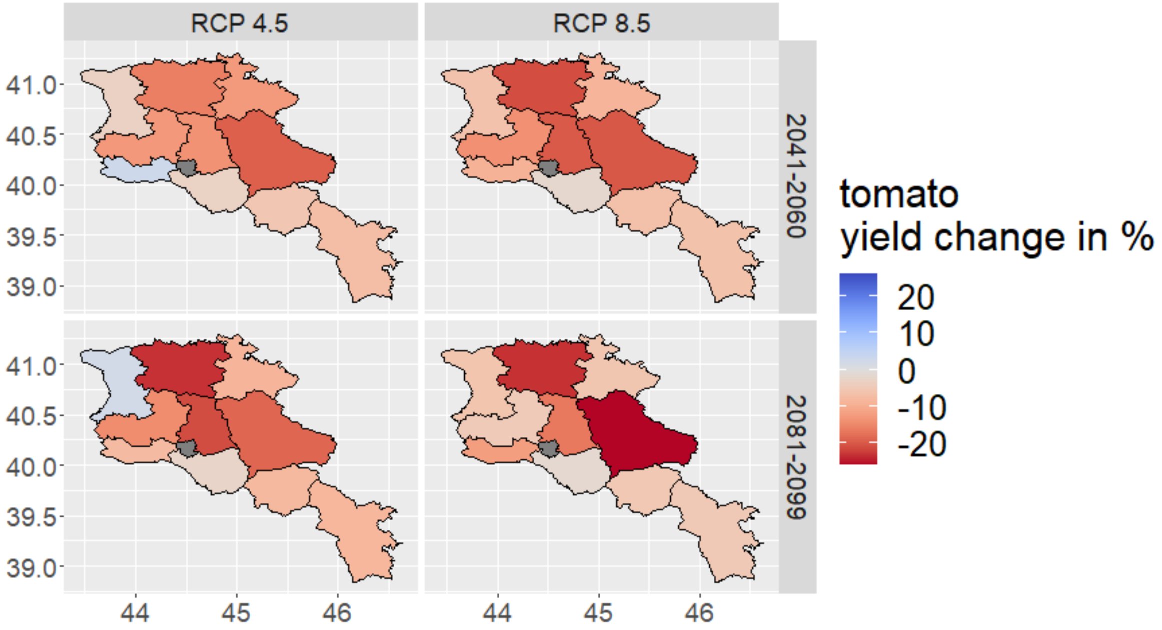

Figure 7: Predicted change in tomato yield in %, compared to historical long-year average yield levels (2005-2020), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in the future; red provinces are expected to experience a decrease.

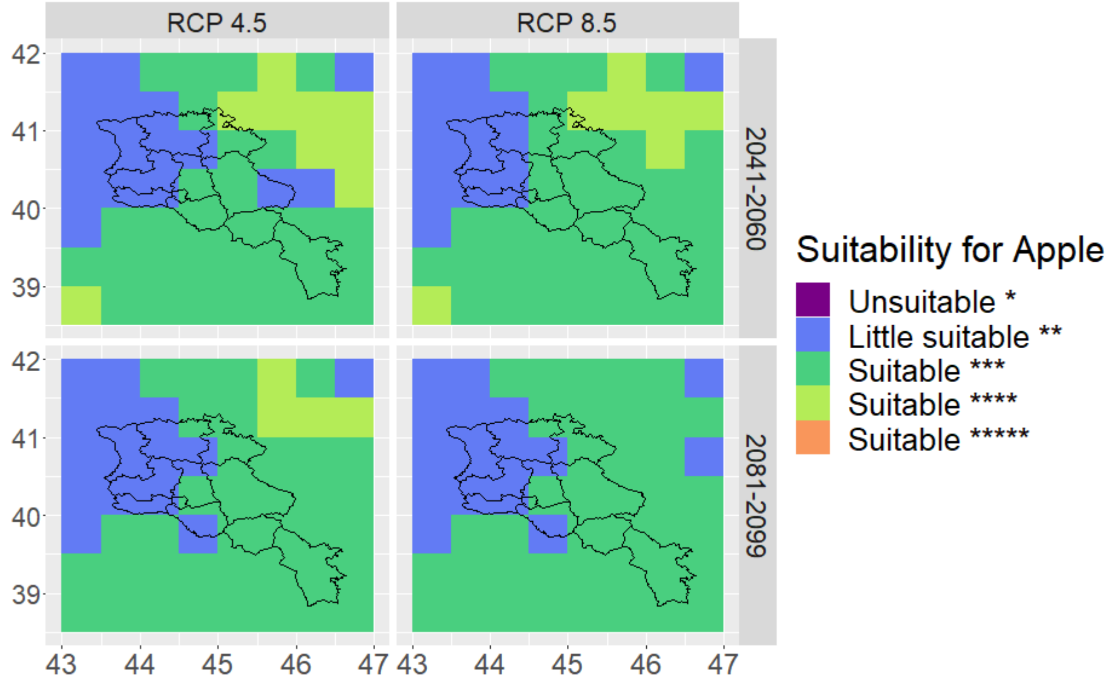

*Figure 8: Future suitability for the production of apple based on the average amount of chill units that accumulate until the end of each crop cycle, for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). *Chill Units are below hist. minimum; **below hist. average but above hist. minimum; *** around hist. average; ****above hist. average but below hist. maximum; ***** above hist. maximum at the time of bud bursting.*

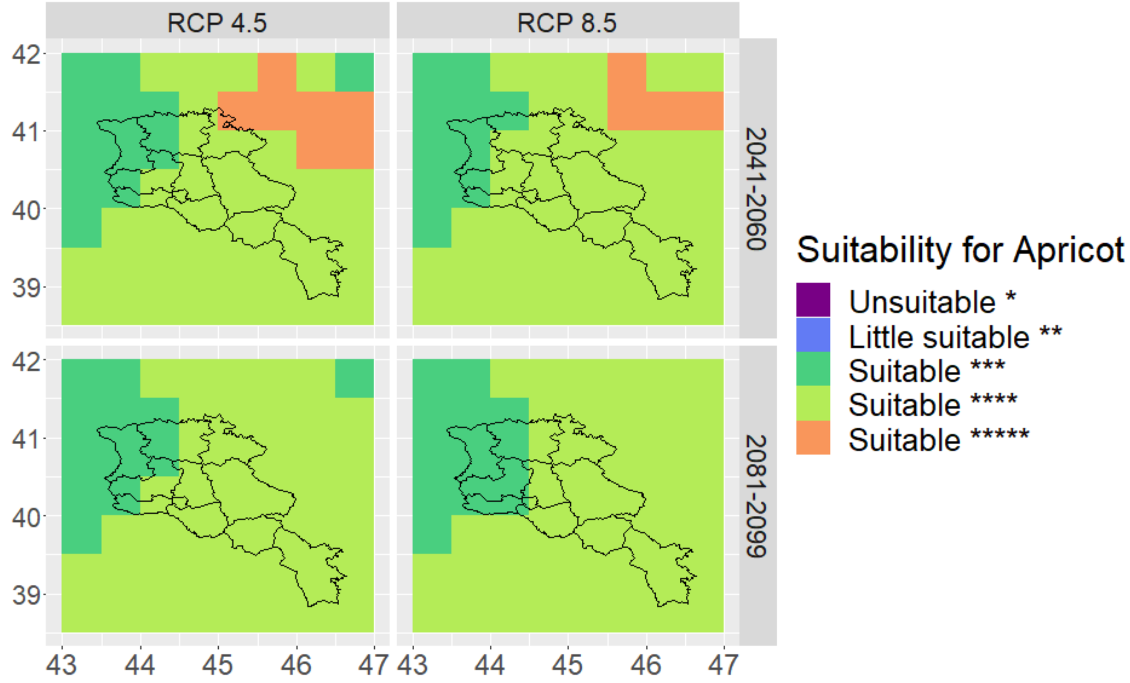

*Figure 9: Future suitability for the production of apricot based on the average amount of chill units that accumulate until the end of each crop cycle, for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). *Chill Units are below hist. minimum; **below hist. average but above hist. minimum; *** around hist. average; ****above hist. average but below hist. maximum; ***** above hist. maximum at the time of bud bursting.*

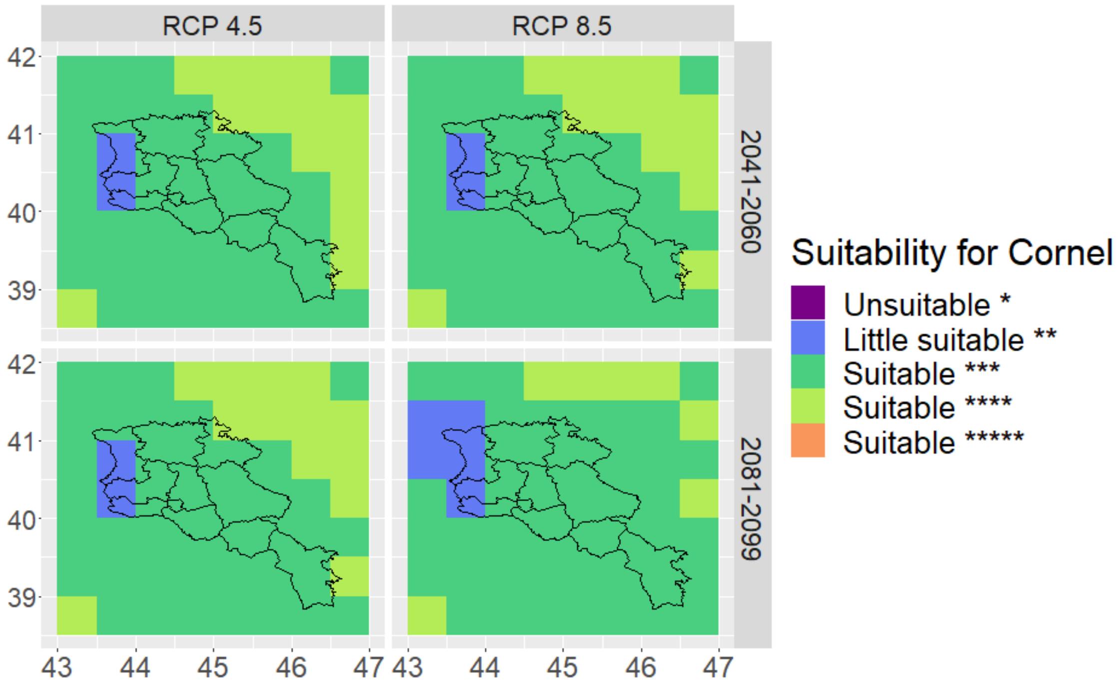

*Figure 10: Future suitability for the production of cornel based on the average amount of chill units that accumulate until the end of each crop cycle, for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). *Chill Units are below hist. minimum; **below hist. average but above hist. minimum; *** around hist. average; ****above hist. average but below hist. maximum; ***** above hist. maximum at the time of bud bursting.*

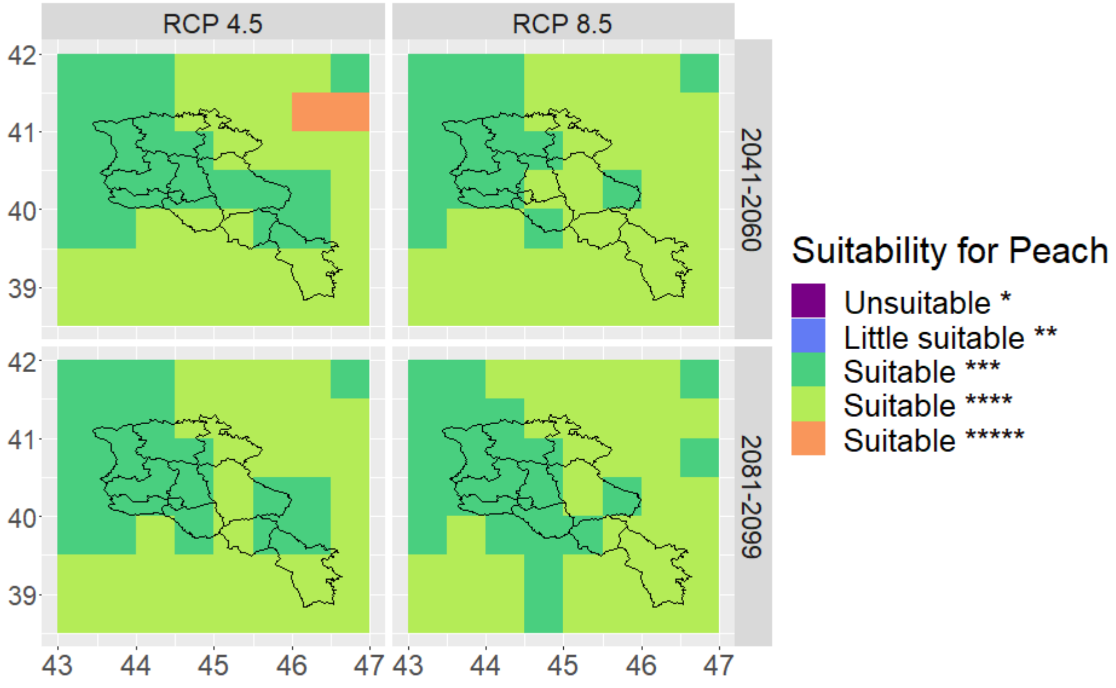

*Figure 11: Future suitability for the production of peach based on the average amount of chill units that accumulate until the end of each crop cycle, for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). *Chill Units are below hist. minimum;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

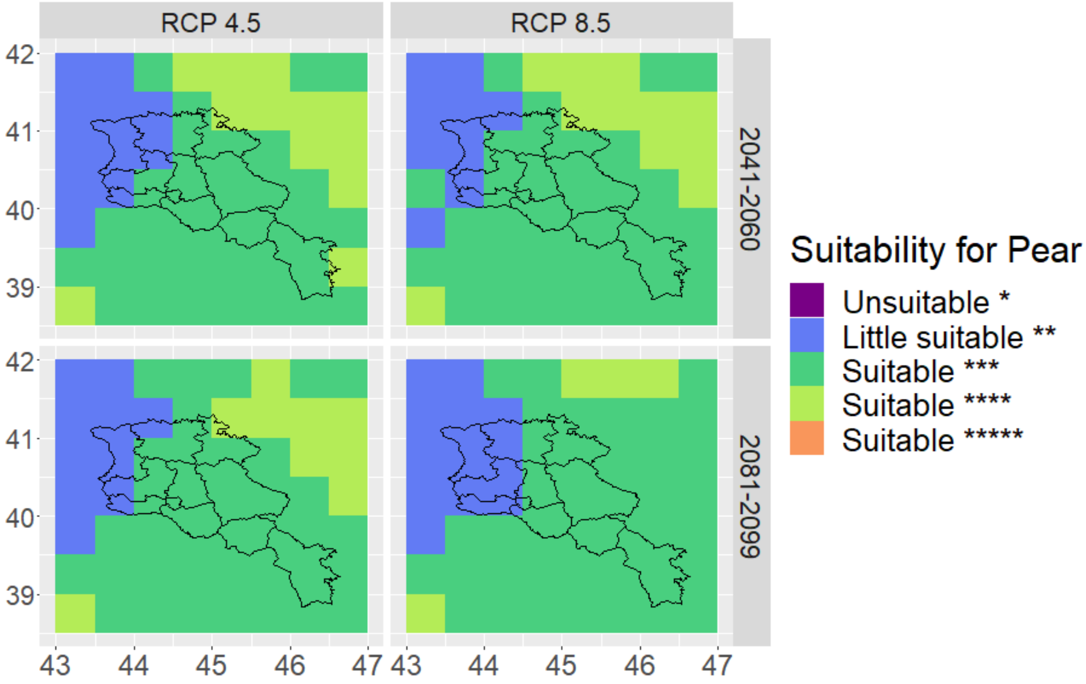

*Figure 12: Future suitability for the production of pear based on the average amount of chill units that accumulate until the end of each crop cycle, for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). *Chill Units are below hist. minimum; **below hist. average but above hist. minimum; *** around hist. average; ****above hist. average but below hist. maximum; ***** above hist. maximum at the time of bud bursting.*

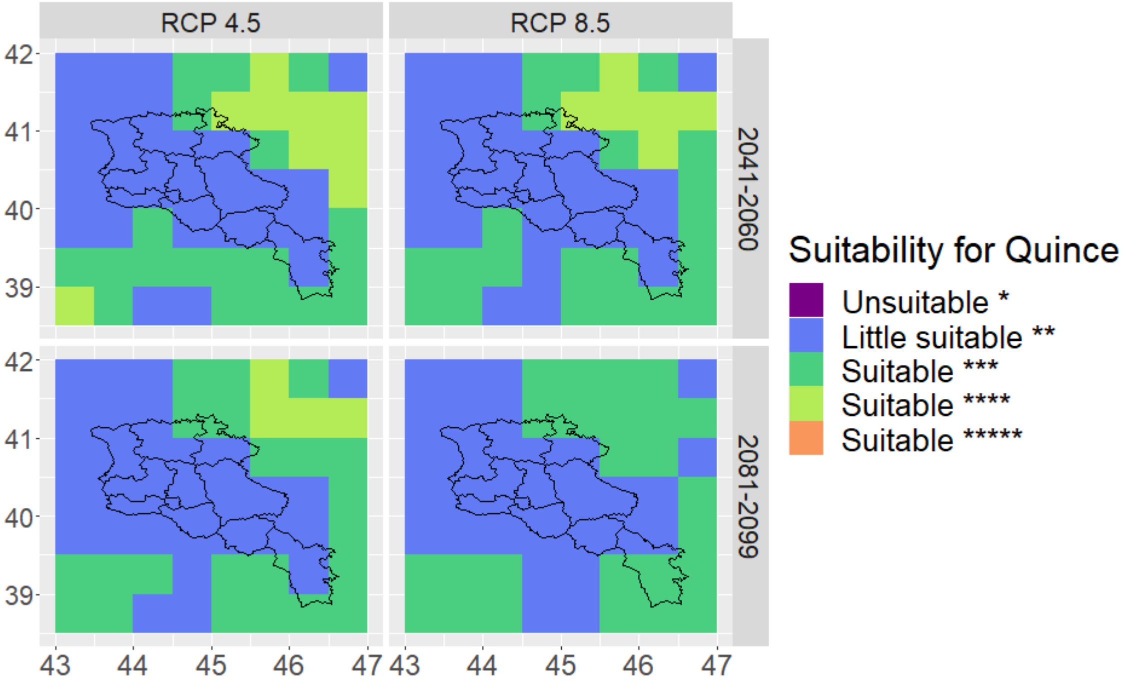

*Figure 13: Future suitability for the production of quince based on the average amount of chill units that accumulate until the end of each crop cycle, for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). *Chill Units are below hist. minimum; **below hist. average but above hist. minimum; *** around hist. average; ****above hist. average but below hist. maximum; ***** above hist. maximum at the time of bud bursting.*

2. Stakeholder workshops

We conducted two separate workshops to validate our results and discuss their relevance for the development of a risk management strategy. We here briefly summarize the main learnings from these workshops; a separate, more detailed report of the workshops is available upon request.

The first workshop took place online on March 16, 2022 and mainly involved local crop experts and focused on the plausibility of our results, their applicability for farmers, and additional data sources that may be mobilized for future analyses. There was a great consensus that the coarse spatial resolution renders the results of this study difficult to be directly taken up by farmers, for which local microclimatic conditions would have to be considered to the best possible extent. Several participants expressed their interest in collaborating on disseminating the results of our study and in developing it further. This also concerned the provision of data that might be made available for follow-up studies. For example, we have learned that expert assessments of crop type distributions and more robust yield estimates are in principle available for the entire country. Such information and data would substantially improve our estimates.

The second workshop took place in Yerevan on March 23, 2022 and targeted a variety of different stakeholders, such as the Ministries of Economy and Environment of the Republic of Armenia, international development institutions such as UNDP, FAP, UNICEF and GIZ, agricultural NGOs, cooperatives, consulting companies and financial institutions. A total of 67 invited participants attended. The workshop connected relevant stakeholders involved in agricultural climate change adaption in Armenia, successfully fostered exchange among the participants and increased their awareness of ongoing activities and efforts in Armenia. The main part of the workshop focused on the result of the work packages 1 to 4, which IAMO presented remotely in a hybrid setting. In three breakout groups, the participants discussed how the results of the present study could be further tailored to meet the demands of local farmers and how they could support ongoing risk management activities and awareness raising efforts. All groups 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 participants presented several different strategies for communicating the results and using them to raise awareness about the challenges of climate change, both among farmers and the public. The breakout sessions also helped to find solutions for existing shortcomings in the exchange of information and knowledge between institutions, and even resulted in some very concrete ideas and suggestions for future mutual support among each other.

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 Armenian language under the following links:

English: https://maxhofmann.shinyapps.io/ClimateAtlasARM_eng/
Armenian: https://maxhofmann.shinyapps.io/ClimateAtlasARM_arm/

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:

Analysis	**Crops**	**Spatial resolution**	**Work package**
Historical Suitability	Pomaceous and stone fruits	Grid cells (0.1°)	WP3
Future Suitability	Pomaceous and stone fruits	Grid cells (0.5°)	WP4
Historical Climatic Conditions	Grain crops and vegetables	Provinces (marzes)	WP3
Future Climatic Conditions	Grain crops and vegetables	Grid cells (0.5°)	WP4
Future Yield Changes	Grain crops and vegetables	Provinces (marzes)	WP4

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 different maps at once for a location defined by the user
- 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 recommendations which should be considered to enhance the resilience of the agricultural sector in Armenia 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 Armenia. 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 Armenia. 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 Armenia 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 Armenia. 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 Armenia. We therefore evaluate studies on CA conducted in regions that have geographically and climatically similar conditions to Armenia.

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 Armenia. 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 Armenia, 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. In southern Kazakhstan, i.e. in a similar latitude to Armenia, 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). Further research is needed to assess how drip irrigation can be used to save water in practice, when farmers would first have to make high investments. In the long term, it must be financially profitable for farmers to invest in modern irrigation systems. Moreover, to scale up the use of drip irrigation, farmers also have to be technically trained and be aware of the risks that overexploitation of water resources can have at the regional scale.

Stakeholder engagement

Awareness raising

According to the short survey carried out during the stakeholder workshop, most farmers in Armenia are still quite 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 further 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 could 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 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 the respective local context.

Increasing adaptive capacities

More 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 scope for improvement regarding the linkage between agricultural extension services and capacity building practices still remain challenges in the country. 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 tailored and purposeful 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. 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, investments into infrastructure, and the design of subsidy and incentivization schemes.

Agricultural insurance products

Extreme weather events are expected to become more frequent and severe with ongoing climate change. This is particularly concerning for smallholder farmers who often have limited access to financial products because of high interest rates or collateral requirements, which hampers investments into precautionary climate change adaptation measures. It is therefore crucial to facilitate access to insurance and credit products for capital-constrained smallholders to secure both livelihoods and food security.

There are different types of tools by which micro- and smallholder farmers can be insured against adverse extreme weather events:

- Remote sensing index insurances allow to assess production shortfalls with the help of satellite images. Such indices are forgery-proof and can be applied over a large area at very low cost. Most index insurance products rely on indices of modelled rainfall and vegetation greenness to approximate losses in agricultural yields (Benami et al., 2021).
- Risk-contingent credits (RCC) can facilitate access to financial products for smallholders. RCC include an index-based insurance component that triggers offset loan payments when production losses are expected because of unfavorable environmental conditions, and that thereby works as a collateral substitute (Shee and Turvey, 2012).
- In picture-based insurances, farmers use smartphones to take pictures of their insured plots which are then used by the insurer to verify claims, thereby reducing verification costs and basis risk (Ceballos et al., 2019).

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 further 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 closer 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 further 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, 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

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 Armenia, 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 Armenia. 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. 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 (**Fehler! Linkreferenz ungültig.**). 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 Armenia, 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, policy-makers 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.

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 Armenia. 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. Further promotion of experimental farms in different biophysical environments of Armenia 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. Ideally, that data would be made openly available in an online repository:

- 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 and phenological observations from a geographically representative collection of weather 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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