"Development of an MSE Multi-Peril Risk Management Concept"

Technical Report - Azerbaijan

submitted by the

Leibniz Institute of Agricultural Development in Transition Economies (IAMO)

for the

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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).

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.

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.

Work Package 1:

“Sector characteristics, crop selection, and climate risk management”

Content

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1. Subnational assessment of the agricultural sector

1.1 Agricultural Sector

Agriculture, including forestry and fishing, comprised 5.7% of the national gross domestic product in 2019 in Azerbaijan (SSC 2020a) but 36% of population are directly involved in this sector. Arable land covered 2.06 million hectares (Mha) or 43% of the total utilized agricultural area (4.78 Mha) in 2019. Hayfields and pastures occupy 51% or more than 2.4 Mha and permanent crop land comprises 5.5% of the total utilized agricultural (Figure 1).

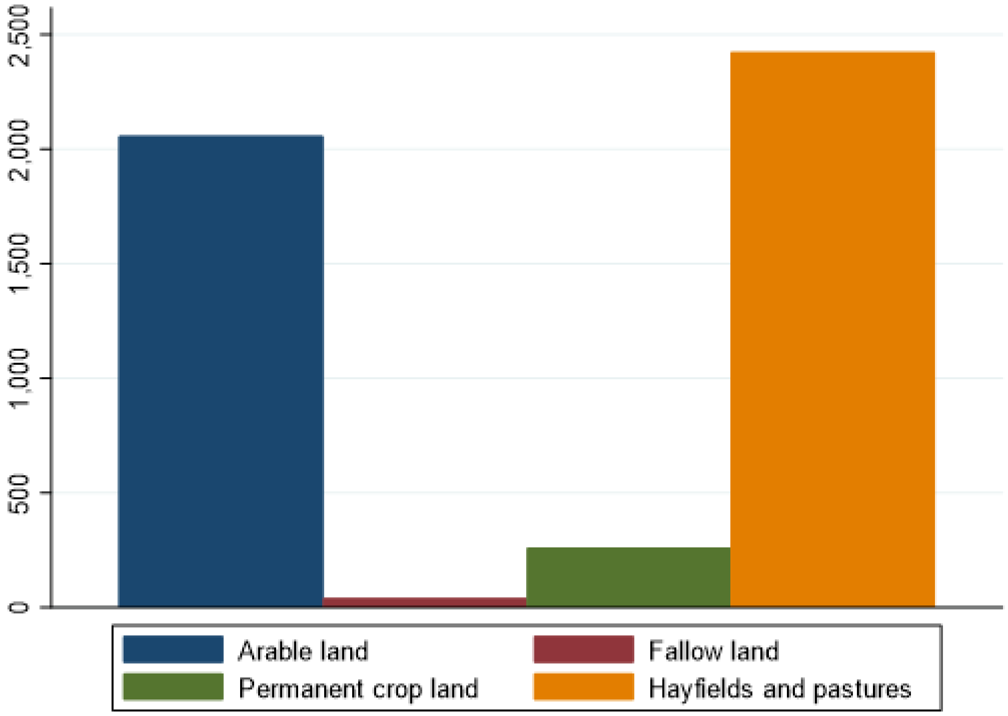


Figure 1: Utilised agricultural area in 2019 (1,000 ha)

Source: (SSC 2020a)

Azerbaijan is a net importer of agricultural products. The state adopted the Strategic Roadmap for Agricultural Production and Processing that aims to enhance the competitiveness of the agricultural sector (FAO 2021). The Roadmap includes short-term, medium-term (until 2025), and long-term objectives (after 2025), which seek to strengthen domestic agricultural production and to substitute imports.

1.2 Farm Structure

The farm structure in Azerbaijan is dualistic and agricultural enterprises coexist along with private family peasant as well as household farms. This is the result of the establishment and implementation of agricultural reforms between 1995 and 2003. Specifically, more than 50 decree and standard acts were issued (ADB 2014) to support land reform and farms restructuring (Sedik 2006). Most importantly, the State Commission on Agrarian Reform has been established by incorporating regional and local bodies to implement the land reform policies. As a result, the state was able to privatize the former collective farms of the Soviet period through a land allocation policy, which was the base to establish more than 870,000 family farms in the early 2000 (Oblitas 2011). At present, agricultural enterprises comprise government property, private property, municipal property, foreign property, and joint property (Table 1).

Table 1: Farm structure in numbers

	2015	**2016**	**2017**	**2018**	**2019**
Agricultural enterprises	1,695	1,716	1,727	1,751	**1,648**
Including:					
Government property	180	187	189	168	176
Private property	1,507	1,519	1,523	1,564	1,450
Municipal property	1	2	2	3	1
Foreign property	2	3	9	9	12
Joint property	5	5	4	7	9
Private farms	1,534	1,468	955	907	**910**

Source: (SSC 2020c)

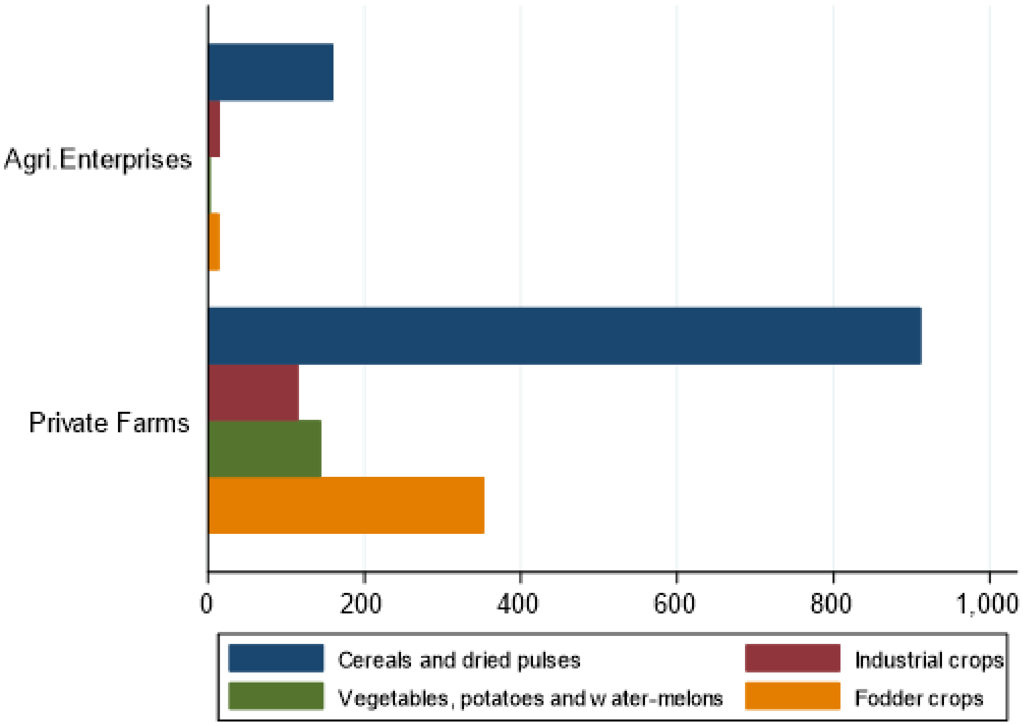


Figure 2: Sown area of agricultural plants in 2019 by farm categories (1,000 ha)

Source: (SSC 2020a)

88% of the agricultural enterprises are private properties. Almost all private farms (99%) are family owned, including individual farmers and households (Van Berkum 2018); here after we refer to these as "private farms". Therefore, **the target group** includes both agricultural enterprises and private farms. On average 20 employees were engaged in agricultural enterprises and five people on private farms in 2019 (SSC 2020c). In this respect, private farms occupy the largest share of the areas sown with crops (Figure 2). Generally, agricultural enterprises cultivate an average of 110 ha and generate an average annual revenue of EUR 270,000. Private farms cultivate 14 ha and yield a revenue of EUR 13,000 per year.

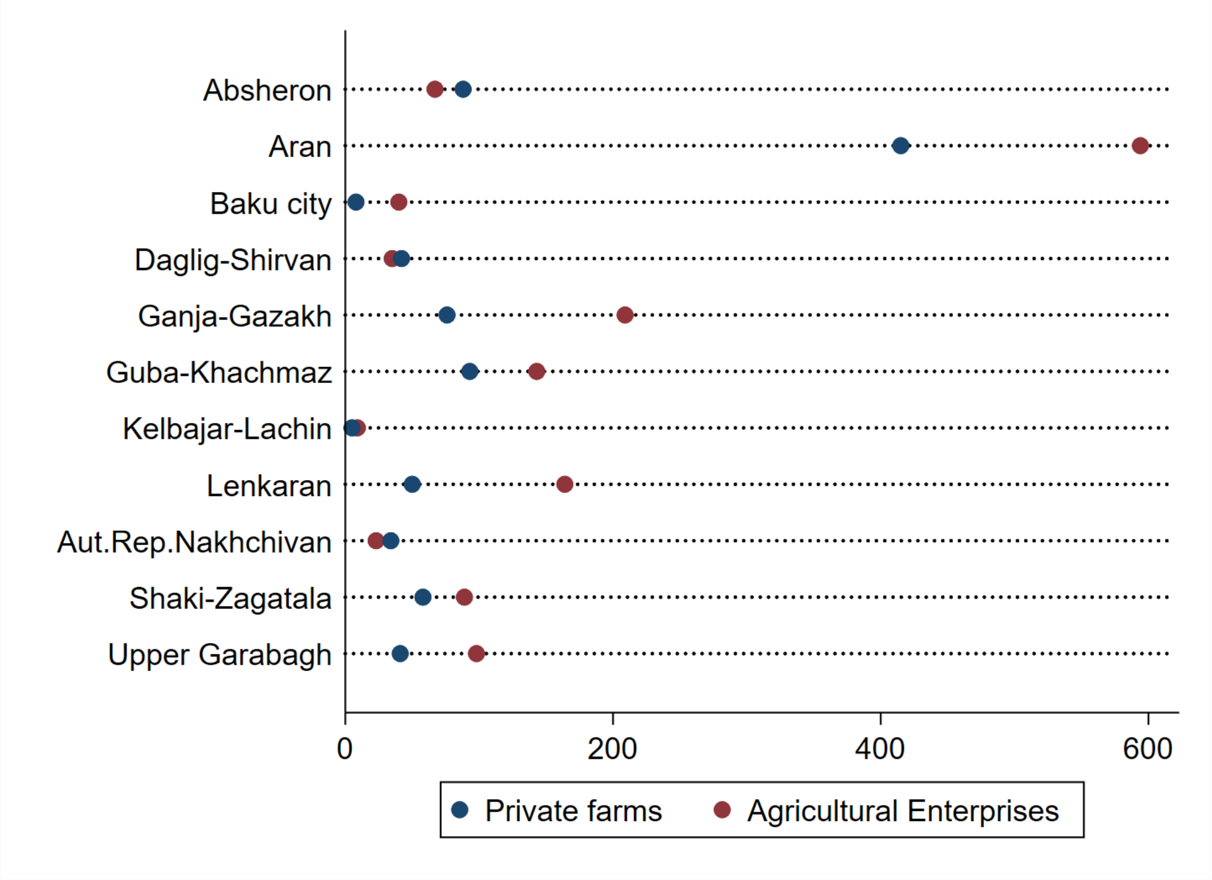


Figure 3: Number of farms across economic regions in 2019

Source: (SSC 2020c)

Azerbaijan is divided into different economic regions depending on the direction of specialization of the economy. By far most private farms and agricultural enterprises are located in the Aran economic region. A large number of agricultural enterprises are also found in the Ganja-Gazakh, Lankaran, and Guba-Khachmaz economic regions (Figure 3).

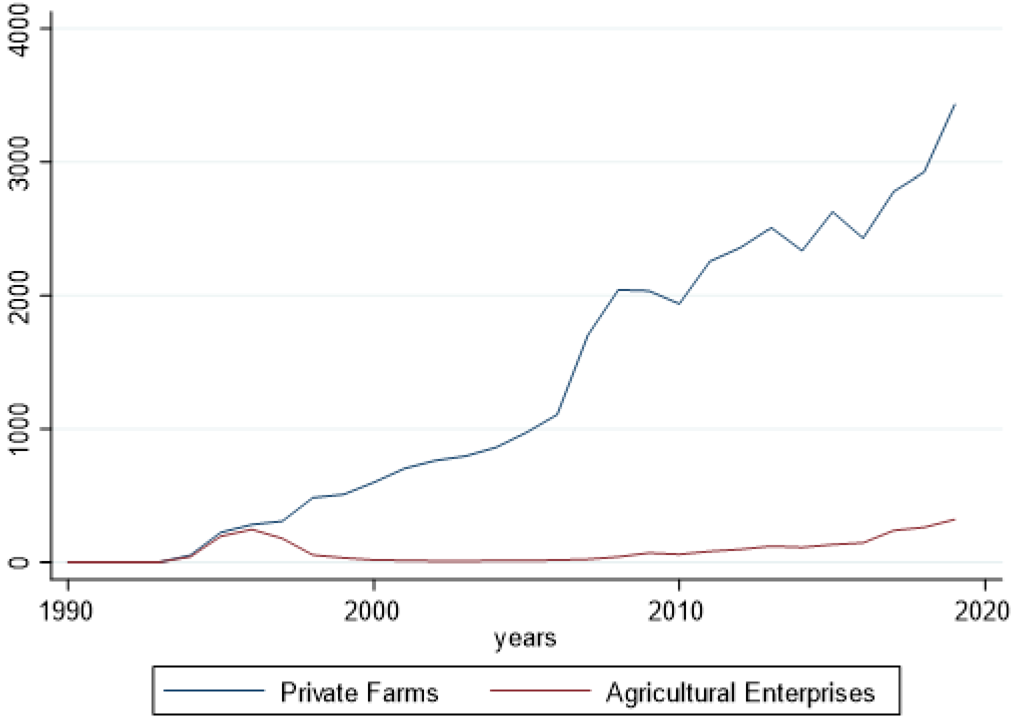


Figure 4: Agricultural production in actual prices (million AZN)

Source: (SSC 2020b)

Gross monetary output of agriculture differs substantially across the farm types. In 2019, 91% of agricultural products were produced by private farms (SSC 2020a). Also, the data from statistical committee confirm that 45% of the arable land, however, were used by agricultural enterprises. The importance of private farms started in the late 1990s, spurred also by international projects that gave impetus to support the transformation of agricultural sector into a market-based economy. It disbursed more than 1 billion AZN, which arguably contributed to the doubling of the gross output in agriculture in only a few years (Figure 4). The gross output of private farms mushroomed from about 0.5 million AZE in 2000 to almost 4 billion AZN in 2019. At present, more than 90% of agricultural output were produced by private farms in 2019.

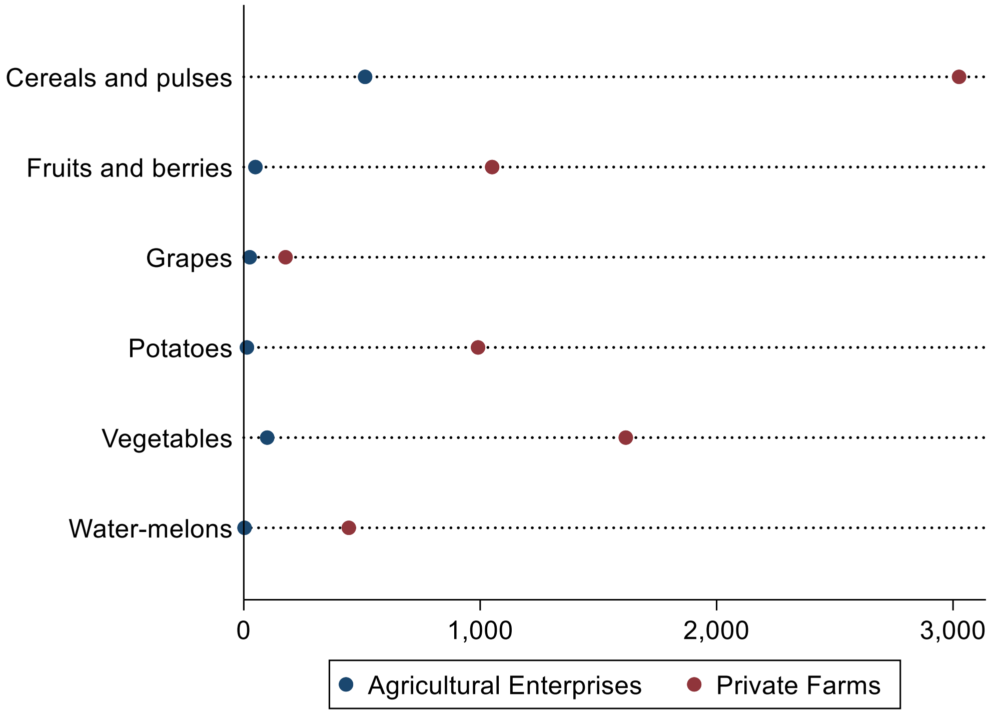


Figure 5: Agricultural production in 2019 by farm categories (1,000 tonnes)

Source: (SSC 2020a)

Cereals and pulses are the dominant crops for both farm types. Statistical findings show that a large part of the cereals and dried pulses are produced by family farms more than 3 million tons (Mt) in 2019 compared to 0.5 Mt produced by agricultural enterprises. Moreover, 1.6 Mt of vegetables were produced by private farms in 2019 while agricultural enterprises produced only 0.01 Mt. Fruit and berries are the second most important group of produce: Private farms harvested 1.051 Mt compared to 0.049 Mt that were harvested by agricultural enterprises. The largest share of potato production also occurs on private farm, where 1 Mt were produced, but only 0.013 Mt in the agricultural enterprises. The difference in the production of watermelon is also high and almost all (0.17 Mt) were produced on private farms.

1.3 Crop Areas

Generally, more than half of the area is allocated to cereals and pulses (Figure 6). Precisely, cereal and pulses were dominating crops taking 1 Mha or more than 60% of total sown area in 2019. They mostly comprise wheat, maize, and barley (Table A 4). Fodder crops occupy 19% and fruits and berries 11% of the cropland. Hazelnut, apple, pomegranate, and persimmon represent close to 65% of total harvested area of all orchards area (Table A 5).

Less than 10% of the total sown area (0.148 Mha in 2019) has been used for potatoes, vegetables, water-melons, and industrial crops (Table A 1). Vegetable production mainly concentrates on tomato, onion, and cucumber (Table A 2) but the cultivation extent of the vegetables decreased.

Azerbaijan is a net-exporter of tomatoes and cucumbers (Van Berkum 2018). The largest industrial crops are cotton and sunflower seeds (Table A 1). Around 1% of the cropland was used for grapes in 2019 but grape cultivation has recently increased.

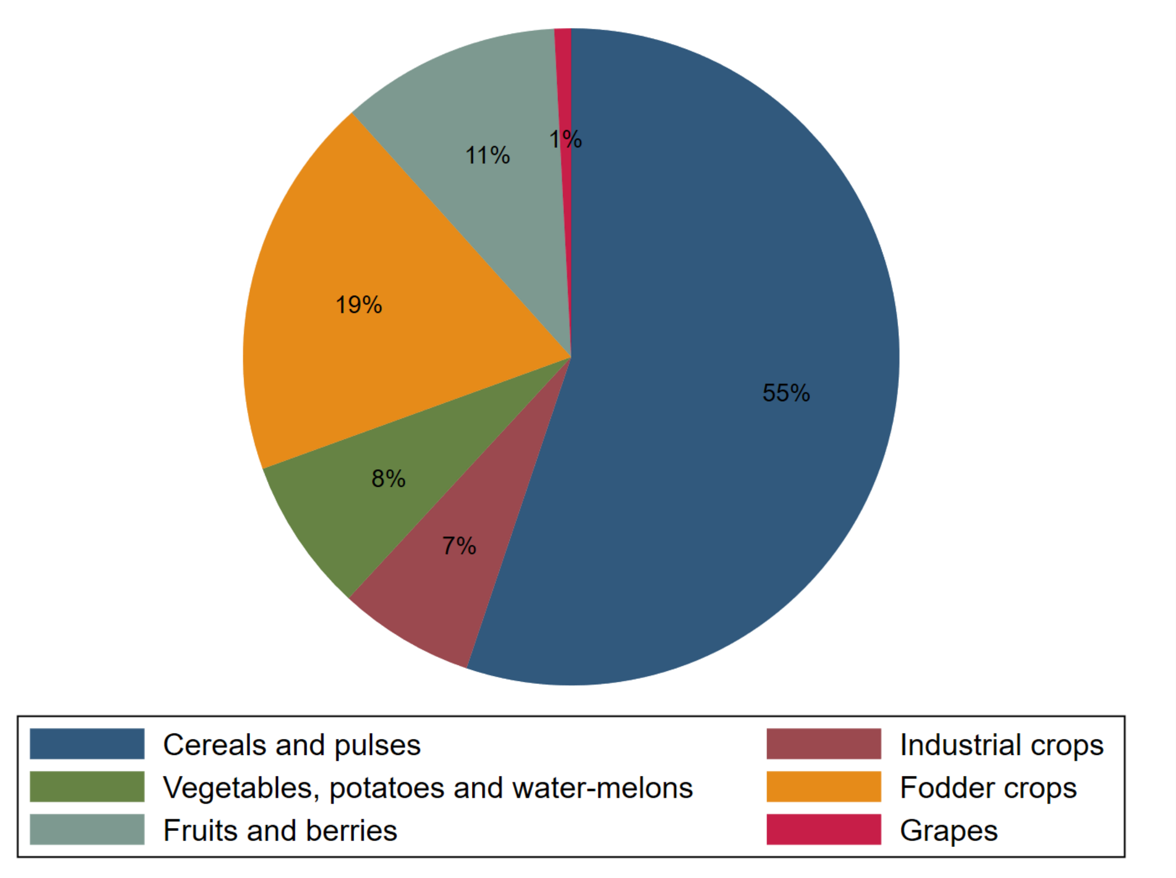


Figure 6: Shares of crop categories in the total cultivated area in 2019 (percent)

Source: (SSC 2020a)

The cultivated area for vegetables has decreased over the last 10 years while the area allocated to fruits and berries increased by 68%. The land area used for industrial crops increase three times between 2009 and 2019. Since 2009, there have been very changes in the area used for cereals and pulses.

Regionally, the Aran economic region harbours the largest amount of area that is used for crop cultivation with a total sown area of 0.75 Mha in 2019, which is equivalent to 43% of the total sown area of Azerbaijan. Sheki-Zagatala occupies second place with 0.184 Mha and Daghlig Shirvan third with 0.150 Mha. Yukhari Garabagh, Lenkaran, and Guba-Khachmaz economic regions all had around 0.1 Mha of sown areas in 2019 and all other regions used less than 0.1 Mha for crop production.

1.4 Agricultural Production

Cereals and pulses, vegetables, as well as fruits and berries dominate the amount agricultural production (Figure 7). Cereals and pulses produced about 43% of the total agricultural production in 2019 with 3.539 Mt. The share of agricultural enterprises in the production of cereals and pulses was relatively high with 14% in 2019 (SSC 2020a).

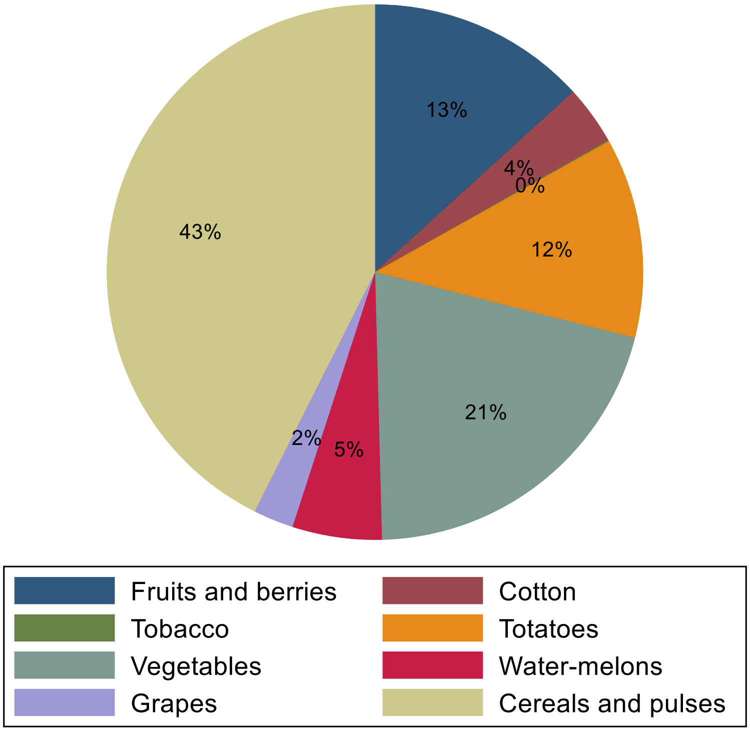


Figure 7: Agricultural production in 2019 (percent)

Source: (SSC 2020a)

The second predominant crop group are vegetables with a production volume of 21% of the total agricultural production or 1.715 Mt in 2019. There has been a noticeable rise in the production of vegetables, which increased by more than 30% over the decade (SSC 2020b). More than 94% of the vegetables were produced by private farms (SSC 2020a). The production volume of fruits and berries increased by 35% from 2009 to 2019, yielding a total production of 1.010 Mt (13% of the total) in 2019, almost all from private farms.

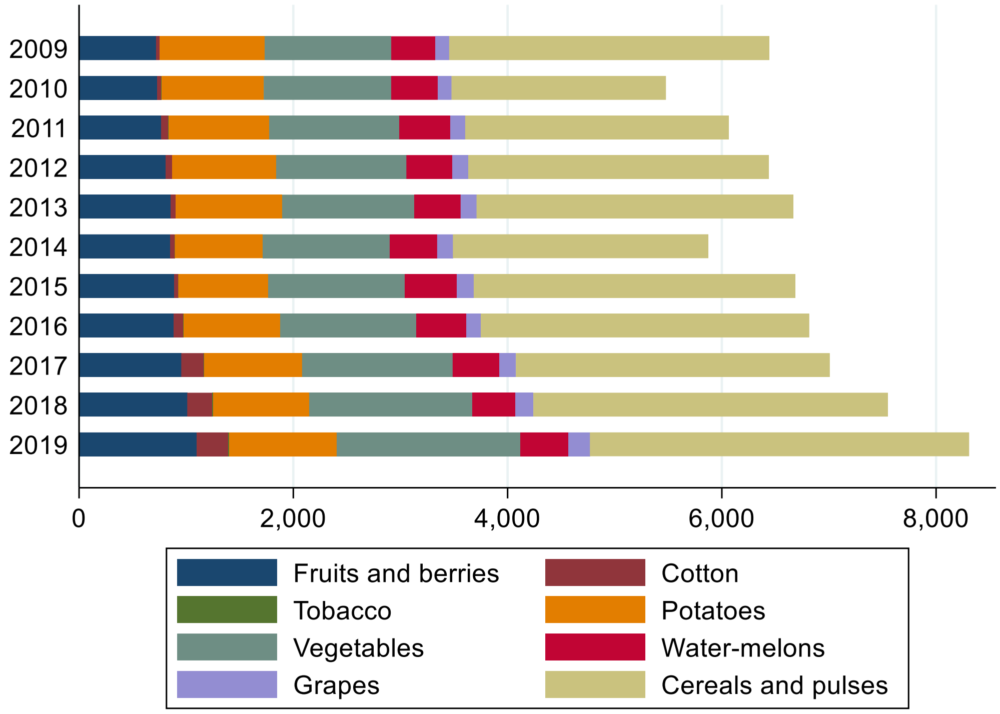


Figure 8: Agricultural production (1,000 tonnes)

Source: (SSC 2020a)

The production of potato made up 12% or 1.004 Mt in 2019. Correspondingly, the production of potato in the last 10 years witnessed a moderate 10% growth. The shares of watermelons and melons with 0.448 Mt and cotton with 0.295 Mt account for 5% and 4% of total crop production. In particular, cotton production has dramatically increased by 90%. Agricultural enterprises produced more than 8% of total production in 2019 while remaining share was done by private farms (SSC 2020a). Watermelons production also increased and are mainly produced on the private farms (SSC 2020a).

2. Selection of ten most important crops

Crop analysis is carried out based on production levels, harvest area and yield capacity (Sud et al. 2017). Three criteria are fundamental to farmers and policymakers for the decision making. Selected crops in Table 2 shows that it generally covers cereal and leguminous, industrial, vegetable, and fruit crops.

Table 2: Selected crops

Crops	Production (Mt)	Crop area (Mha)	Yield capacity (tonnes/ha)
Wheat	2.172	0.670	3.2
Barley	1.016	0.342	2.9
Potatoes	1.200	0.057	16.9
Tomatoes	0.698	0.017	19.5
Onions	0.267	0.012	21.4
Cucumbers	0.249	0.011	16
Pomegranates	0.181	0.031	8.5
Persimmons	0.177	0.012	16.1
Hazelnuts	0.054	0.080	1.2
Apples	0.293	0.023	10

Comparing crops based on the production shows that two cereals such as wheat and barley are dominant. Accordingly, wheat had the largest share among with 2.172 Mt in 2019. Less than a third of wheat was produced in Aran economic region, followed by Sheki-Zagatala (0.310 Mt) and Lenkaran economic region (0.236 Mt). Barley production reached 1.016 Mt and more than half originates from the Aran economic region.

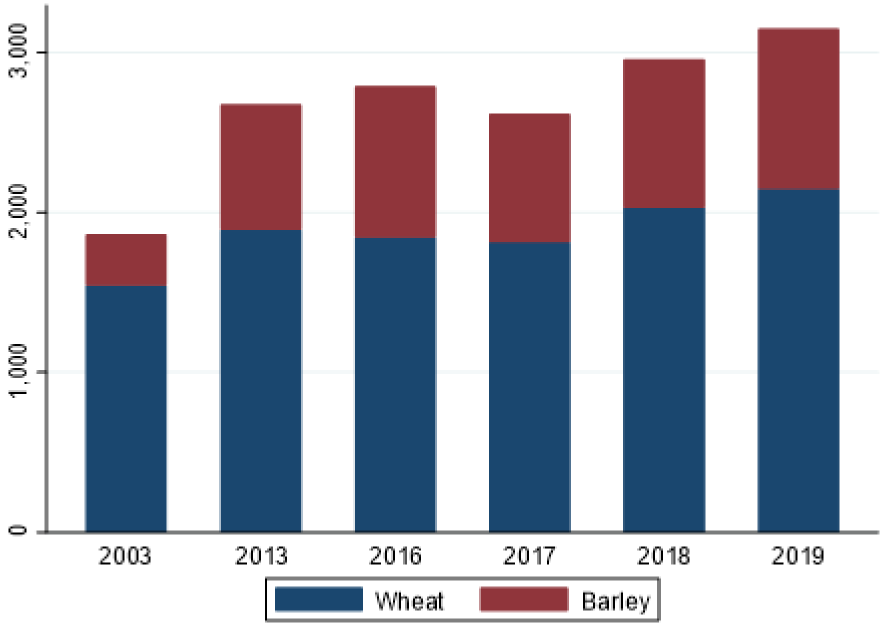


Figure 9: Production of cereals (1,000 tonnes)

Source: (SSC 2020a)

Looking at the trends, the production of wheat increased by around 30% from 2003 to 2019. During this time, barley production witnessed more than 60% rise, making Azerbaijan net exporter of barley and wheat (Van Berkum 2018). As for productivity, the yield capacity of wheat is 3.2 tonnes/ha while barley shows 2.9 tonnes/ha (SSC 2020a). Looking at sown areas of these crops, wheat and barley crops had the largest area indicating more than 0.670 Mha ha and 0.342 Mha in turn in 2019 (Table A 4).

The levels of potato production indicates that there has been an increasing pattern over the last years (Figure-11). Looking at regional differences, Ganja-Gazakh economic region produced 0.508 Mt of potato in 2019, which was more than 50% of total production in Azerbaijan (SSC 2020a).

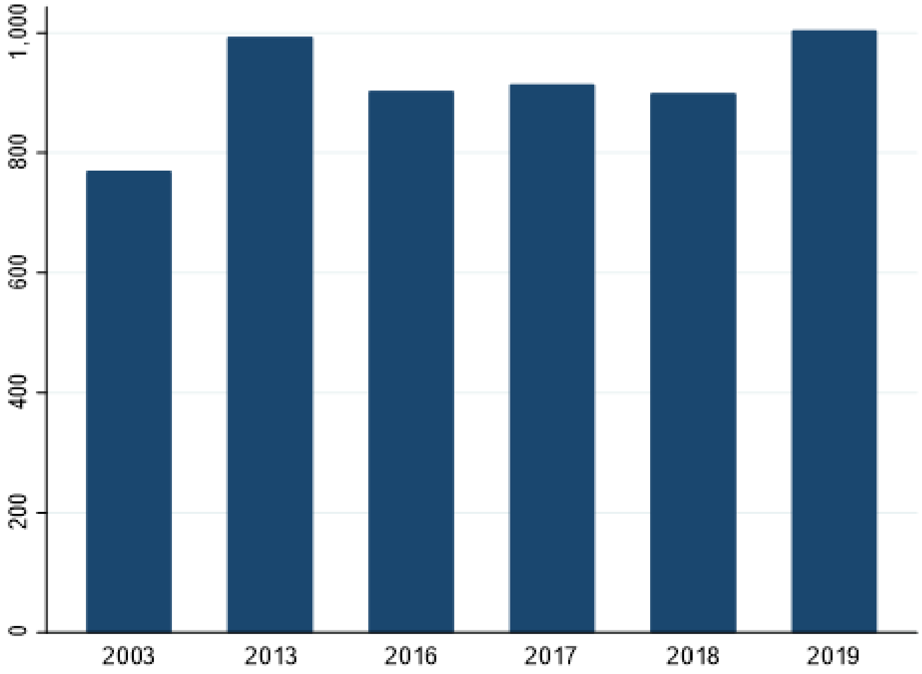


Figure 10: Production of potatoes (1,000 tonnes)

Source: (SSC 2020a)

The sown area for the production of potatoes was more than 0.057 Mha in 2019 (Table A 1), showing one of the largest harvested parts of arable cropping in Azerbaijan. It was 16.9 tonnes/ha for the yield of potatoes in 2019 (SSC 2020a).

Looking at the production, tomato, onion and cucumber feature prominently in the production (Table A 3). They together represented more than 70% in the total vegetable production in 2019. In Figure 12, a tomato production makes up 0.698 Mt, which is more than 40% of total vegetable production. For regional differences, more than 50% of tomato are based on Aran and Ganja-Gazakh economic regions (SSC 2020a). The next largest production is onion with 0.267 Mt. Yukhari Garabagh and Aran regions provide more than two-thirds of tomato (SSC 2020a). Cucumber production reaches 0.249 Mt representing the third largest vegetable crop production.

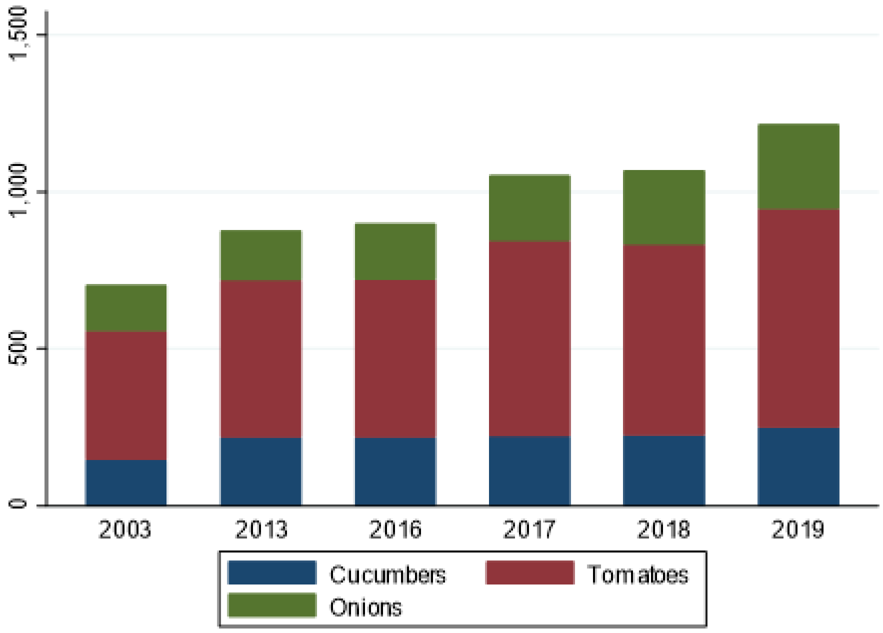


Figure 11: Production of vegetables (1,000 tonnes)

Source: (SSC 2020a)

Looking at the yield capacity, tomato and cucumber have 19.5 tonnes/ha and 16 tonnes/ha respectively (SSC 2020a). The yield of onion is relatively high at 21.4 tonnes/ha. The sown area of vegetable by types shows that the largest area for the production is used for tomatoes, cucumber and onion representing more than 0.01 Mha each (Table A 2).

Figure 12 shows the changes of gross production by fruit types from 2003 to 2019. Correspondingly, overall production of fruit products has increased noticeably over the last 16 years (Table A 6). Selected 4 types of crops made up more than 64% of total fruit outputs in 2019. Precisely, the production of apples increases noticeably reaching 0.293 Mt being the largest contribution of fruits and berries. Looking at the regional contribution, around 70% of production belongs to Guba-Khachmaz economic region (SSC 2020a). Both pomegranate and persimmon are the next predominant crops making up more than 0.181 and 0.177 Mt respectively. More than three quarters of pomegranate harvest are done in Aran economic region while close to four-fifth of persimmon are harvested in Ganja-Gazakh and Aran economic regions (SSC 2020a). Hazelnuts are the next predominant orchards. Accordingly, the production has reached more than a twice increase over the last 16 years. In this case, the production level in 2019 was 0.054 Mt with 70% of production in Sheki-Zagatala economic region (SSC 2020a).

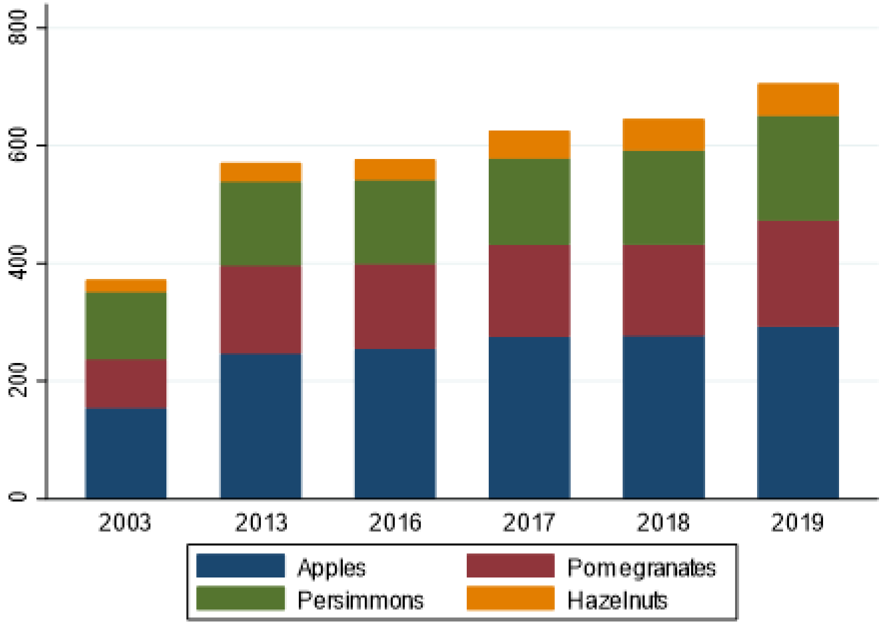


Figure 12: Production of fruits (1,000 tonnes)

Source: (SSC 2020a)

As for the productivity, the yield of apple production accounts for more than 10 tonnes/ha (SSC 2020a). Accordingly, other orchards such as pomegranates and persimmons have the yield capacity at 8.5 tonnes/ha and 16.1 tonnes/ha in turn. Between selected four crops, hazelnuts have the lowest yield capacity by having 1.2 tonnes/ha. Looking at gross harvesting area, hazel-nuts are harvested in the largest area in orchards at 0.080 Mha (Table A 5). The next largest harvest areas belong to apples and pomegranates with 0.031 and 0.023 Mha respectively. A gross harvesting area of persimmons is the fourth largest with 0.012 Mha.

3. Synthesis of existing risk management concepts

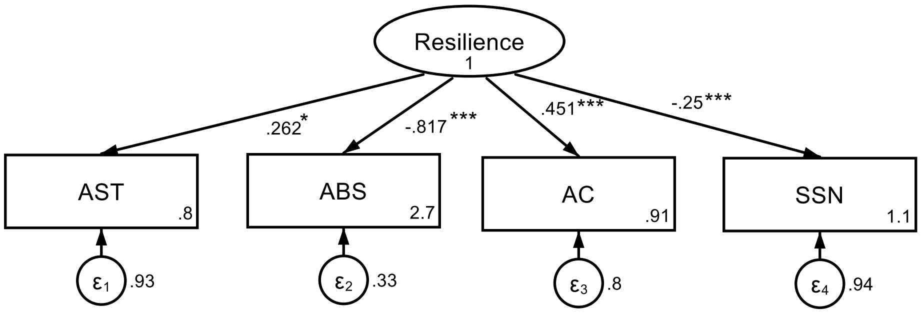
A resilience as a proxy is measured through observable factors (pillars). It shows how the households are able to cope with climate change shocks by activating available risk management strategies. By definition and statistical properties, resilience is defined as the capacity ensuring climate shocks do not have long-lasting consequences in farm livelihoods. According to RIMA methodology, there are four main factors or pillars to represent the resilience (FAO 2016). One of the key objectives of RIMA methodology is that it represents the linkage between resilience with climate change impact by analysing the response mechanisms of households.

- Assets (AST) represent household capital (mainly agricultural) to withstand the shock;
- Access to Basic Services (ABS) represent facilities and infrastructure of the household that is important to respond to the shock;
- Adaptive Capacity (AC) is related to the adaptability or ability to cope with the shock;
- Social Safety Nets (SSN) is related to any social capital or ties that can be used to react and bounce back from the shock.

In this respect, each pillar is measure through factor analysis (FA) under observable variables. Through factor analysis, the resilience itself can be formalized as:

$$Resilience\ Capacity\ Index\ (RCI)_h = f\ (AST_h, ABS_h, AC_h, SSN_h) \qquad (1)$$

RCI is measured by observable factors in which the capacity is indexed through four pillars. Available primary data from the survey “On Commodity Supply Chains in Central Asia and Caucasus” with 200 sample size in 5 regions of Azerbaijan include observable factors describing household characteristics for building resilience (Table A 7).



R squared: 0.706
N = 192
***p<0.01, **p<0.05, *p<0.1

Figure 13: Resilience measurement through Structural Equation Modelling (SEM), (AST-Assets; ABS-Access to Basic Services; AC-Adaptive Capacity; and SSN-Social Safety Network)

Figure 13 shows the results of SEM modelling for the estimation of household resilience to climate shocks. Generally, Adaptive Capacity (AC) pillar has a positive and statistically significant relationship with household resilience. In this case, the capacity of households becomes more adapted by strengthening fulfilling quality requirements, using market information or market extension, using different subsidies and others (Table A 7).

- Precisely, using machinery, credit, fuel, fertilizer and seed subsidized inputs tends to increase household ability to adapt to the changing environment. In a practice, the agricultural sector is inherently resilient from one side due to the National Agriculture and Rural Development Strategy (NARDS) by establishing the Regulation on Subsidies for the period of 5 years (2017-2021) in Moldova (Gerciu et al. 2017) or the law *"On state support of agriculture in Ukraine"* (OECD 2020). Similarly, the resolutions of Kazakhstan by the Ministry of Agriculture have been adopted to support farm activities through subsidy on inputs (FAO 2012).
- Both availability market information and extension services for farmers imply that households become more adapted by improving their conditions in their own environment. Considering extension possibilities taken under this pillar, farms participation in extensions services is likely to strengthen a risk coping probability, coupled with the availability of market information or marketing opportunities. For example, the project implemented to improve national extension services shows that extension services are likely to increase the likelihood to adapt in the climate change mitigation (FAO 2020). In this case, the context of Turkmenistan shows that developing access to climate smart advisory service under resilient extension approaches increases the capacity of farmers to apply climate adaptation strategies (Adaptation Fund 2017).
- The adaptive capacity of households is also strictly connected to the existence of annual earnings from land rent and crop selling showing the extent of diversification strategy. As long as crop selling is reflected on the level of diversification, it is likely to increase the capacity of household to adapt to climate changes. Correspondingly, the law *"On measures for further reforming and development of agriculture for the period of 2016-2022"* enhances small farms to diversify cotton into fruit and vegetable production in which the diversification from low-to high-value crops was central for climate-resilient strategy (CGIAR 2017). Therefore, the modernization and commercialization of farm activities in Azerbaijan should be emphasized especially on high marketable crops. In this case, high resilience on drought tolerant crops increases the ability to mitigate climatic risks. A similar approach to increase farm resilience is realized through the development of quality standards for drought-tolerant varieties and the establishment of portfolios adapted to drought conditions in Uzbekistan. Different projects have been initiated in expanding the development of fruit and vegetable variety portfolios under drought conditions and extreme temperature fluctuations in Uzbekistan. Seed and seeding production for drought in different agro-ecological zones are also supported that makes available super-elite and elite seeds demanded by beneficiaries or farmers. Another program establishing Crop Protection Fund by the Ministry of Industry and Agriculture in Mongolia has been helping farmers

to diversify crops (World Bank 2015). Therefore, greater efforts are needed to increase the diversification of drought tolerant crops in Azerbaijan.

- Related household members involved in agriculture, higher education level, and particularly fulfilling quality requirements retain the same functions to reorganize capacity of a household in reacting to climate changes. To ensure a strengthening local seed and seedling production systems (Table A 8), there has been a support to increase the supply and update the guidelines for seed production, testing, registration and certification (World Bank 2020). Similarly, the Government of Moldova implemented the regulation on the agro-food inspection and certification systems aimed to develop competitiveness of agriculture (Gerciu et al. 2017). As long as adaptive capacity (AC) includes the indicator showing whether the household fulfils quality requirements in the production, it is considered as one of alternative ways for farms in Azerbaijan to improve the resilience in risk management practices.

4. Literature

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Work Package 2:

“Data preparation and characterization of historical climatic trends”

Content

Figures

1. Data preparation

We describe here the process of collating and processing the basic geospatial datasets needed to accomplish the following work packages. We collect, analyze and evaluate land-use maps, climatological information, and historical fire records.

1.1 Land-Cover and Cropland Maps

To represent the status of land cover, we used the *Caucasus Land Cover Map* from the *SILVIS lab of the University of Wisconsin* (http://silvis.forest.wisc.edu/data/caucasus/) from the year 2015. The land-cover map is based on the classification of Landsat imagery and has a spatial resolution of 30 meters. The methodology used to derive the land-cover map is described in Buchner et al. 2020[1].

Cropland was classified from the Landsat imagery based on the shapes of the cultivated fields, the detection of evidence for plowing, and the vegetation greening cycle over the year. Sparsely vegetated areas, shrubs, and grassland were labelled as rangeland. The 2015 land cover map shows that the lowland areas of Azerbaijan are characterized by a mix of rangelands and croplands, whereas the mountainous areas are dominated by deciduous forests (Figure 1). Cropland is mostly concentrated in the central part of the country, while the provinces of Absheron, Nakhchivan, and Kalbajar-Lachin have little cropland.

In terms of land cover changes, Buchner et al. (2020) find that of the total land area of Azerbaijan, only 10% was continuously cultivated since 1987. Among the three Transcaucasian countries, Azerbaijan experienced the largest contraction of cropland with a reduction of its cropland extent by 15% from 1987 to 2015. Most of the lost cropland transitioned to rangeland, i.e., to sparsely vegetated areas, shrubs, and grassland.

We extracted all pixels that belong to the cropland class from the 2015 land cover map and resampled these to a resolution of 300 meters to omit isolated pixels and to increase the computational speed of later processing steps. This resulted in a cropland mask that we use as the boundary layer to restrict subsequent analyses to areas that are used for crop production. Figure 2 shows the final cropland mask that we used for all subsequent analyses.

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[1] Buchner et al. (2020), Remote Sens. Environ.: https://doi.org/10.1016/j.rse.2020.111967

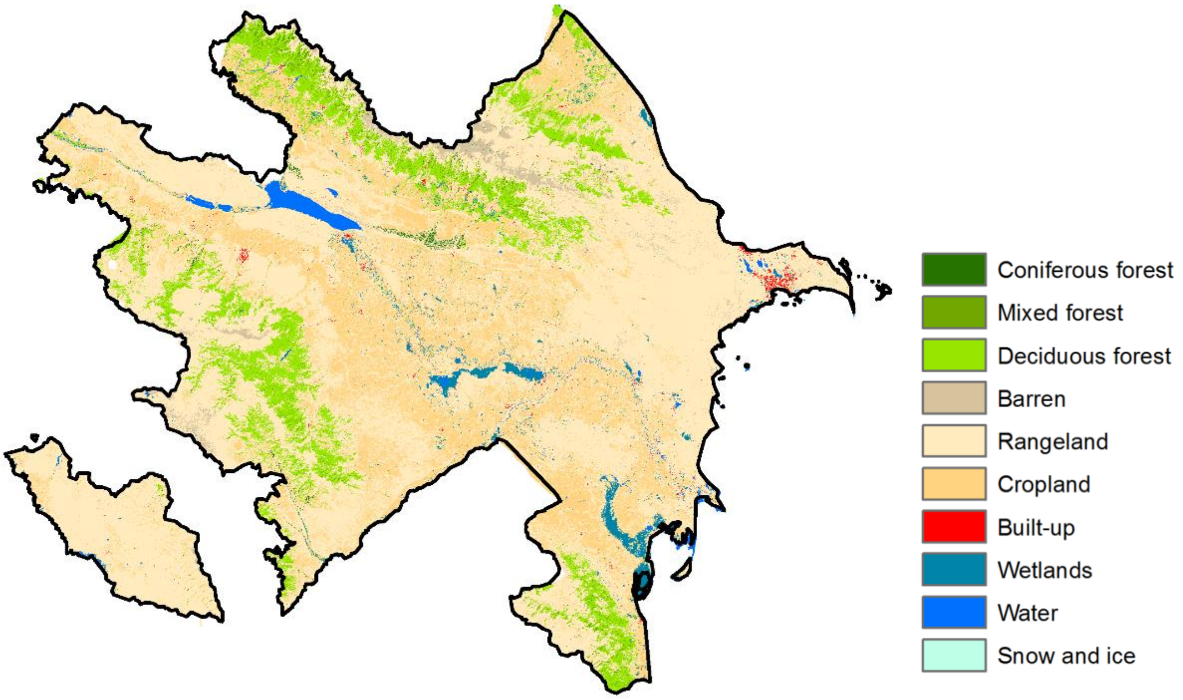

Figure 1: Land cover of Azerbaijan in 2015. Source: Caucasus Land Cover Map, SILVIS lab of the University of Wisconsin (http://silvis.forest.wisc.edu/data/caucasus/)

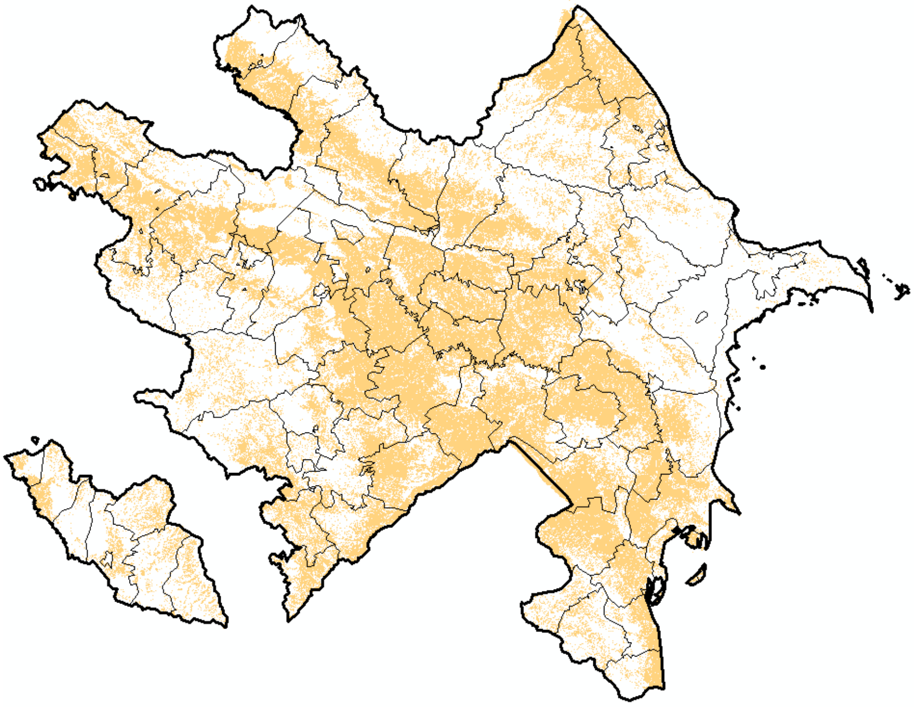

Figure 2: Cropland mask for Azerbaijan from the Caucasus Land Cover Map, resampled to a spatial resolution of 300 meters.

1.2 Modelled Climatological Data

We sourced rainfall data from the *Climate Hazards group Infrared Precipitation with Stations* dataset (CHIRPS, https://data.chc.ucsb.edu/products/CHIRPS-2.0/global_daily/netcdf/p05/), which comprises daily gridded estimates based on satellite and weather station data with a spatial resolution of 0.05° (~5 km). Temperature data stem from the reanalysis dataset *ERA5-Land* (**Fehler! Linkreferenz ungültig.**), provided by the climate data store of the *Copernicus* program and available at a spatial resolution of 0.1° (~11 km) and a temporal resolution of one hour. Both CHIRPS and ERA-Land are available for free and since January 1st, 1981. We used all data until December 31st, 2020 (14,610 days in total). Among the gridded climate datasets that are freely available, CHIRPS and ERA5-Land have the highest available spatial and temporal resolution. Moreover, both datasets are continuously updated in near-real time, which permits for updates of our results once new data becomes available.

We converted the downloaded CHIRPS NetCDF files into daily TIFF images. For the ERA5 product, we first summarized hourly values into daily minimum, average, and maximum values, transformed them from degrees Kelvin to degrees Celsius, and then converted them into daily TIFF images. The database with the preprocessed precipitation and temperature images contains a total of 4 x 14,610 = 58,440 files. Figure 3 exemplifies one layer for average temperature and one for precipitation.

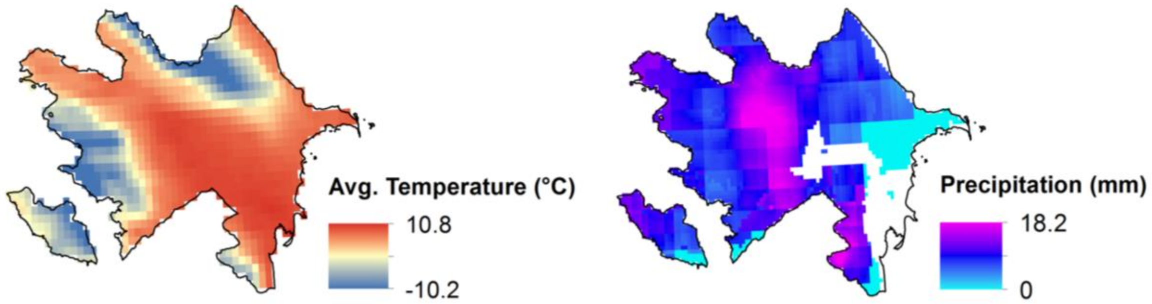

Figure 3: Average temperature on January 1st, 1981, from ERA5-Land (left) and precipitation on October 15th, 1981, from CHIRPS (right).

1.3 Historical Fire Records

Fires are a considerable threat to crop production in the region. We analyzed fire occurrence and intensity from the active fire data provided via *NASA's Fire Information for Resource*

Management System (FIRMS, https://firms.modaps.eosdis.nasa.gov/active_fire/). We use these data to assess the spatiotemporal occurrence of cropland fires in Azerbaijan. The FIRMS data are derived using a global algorithm that analyzes data from the *Moderate Resolution Imaging Spectroradiometer* (MODIS) imagery aboard the Terra and Aqua satellites (**Fehler! Linkreferenz ungültig.**) and from the *Visible Infrared Imaging Radiometer Suite* (VIIRS) aboard the Suomi NPP satellite, launched in 2011 (**Fehler! Linkreferenz ungültig.**). For the sake of consistency, we only relied on the fire data derived from the MODIS sensors to extract daily information about fire occurrences from 2001 to 2020 at a spatial resolution of 1 km. The VIIRS data has a higher spatial resolution at 375 meters, but is only available since 2012.

We downloaded all active fire records for Azerbaijan from 2001 to 2020 from the MODIS dataset. We then removed all records with a fire detection confidence below 20% to reduce the number of false alarms (see Giglio et al. 2016[2]). To focus on fires related to crop production, we only included those fires that occurred on cropland or less than 300 m away from the nearest cropland using the cropland mask (see chapter 1.1). The final data selection includes 26,242 active fire records.

All results area available online in an interactive format at:

https://rpubs.com/max_hof_mann/fires_azerbaijan

In the map “*Locations*”, each dot represents a single fire occurrence as recorded by the MODIS fire detection algorithm between 2001 and 2020. The brighter the dot, the hotter is a fire, measured in megawatts of fire radiative power (FRP). When zooming out, individual fire pixels are combined into clusters.

In a next step, we calculated the mean number and intensity of fires for each year from 2001 to 2020 within each district. The map “*Mean Yearly Number*” visualizes the average yearly counts. The map “*Change in Number*” shows the trend in number of fires from 2001 to 2020 based on the slope of a linear regression. For each district, we performed a Mann-Kendall test that assesses whether the calculated trend in number of fires over time is significant, considering both the normal variability in yearly fires and the occurrence of outlier years with exceptionally high or low numbers of fires. Districts with a significant trend line are highlighted with a black outline in the change map. We used the FRP measures to map the “*Mean Intensity*” of all fires per district and for all years. For the map “*Change in Intensity*”, we calculated for each district the average FRP of all fires in each year, and then fitted a linear regression model to calculate the change in yearly mean fire intensity from 2001 to 2020. Again, we performed Mann-Kendall tests to assess the significance of these changes. Districts with significantly positive or negative changes are highlighted with a black outline. The districts with the highest average number of fires per year are Fizuli (128 fires), Khojavend (95 fires) and Agdam (94 fires, Figure 4). We found the highest significant positive changes in number of fires in Agjabedi (increase by 2.5 fires per year), Kurdamir (1.7 fires per year) and Beylagan (1.2 fires per year, Figure 5). These districts also have the highest cropland cover in Azerbaijan (Figure 2). The districts with the highest average fire intensity are Absheron (71

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[2] Giglio et al. (2016), Remote Sens. Environ.: http://dx.doi.org/10.1016/j.rse.2016.02.054

MW), Samukh (68 MW) and Jebrayil (53 MW, Figure 6). Significant changes in fire intensity can only be observed for Agdam (yearly decrease of 1.3 MW), Barda (yearly decrease of 0.6 MW), and Naftalan city (yearly increase of 1.3 MW; Figure 7). Samukh experienced an average yearly increase of 4.1 MW, but this trend was not significant and is due to a series of fires with high FRP in 2020 (Figure 8).

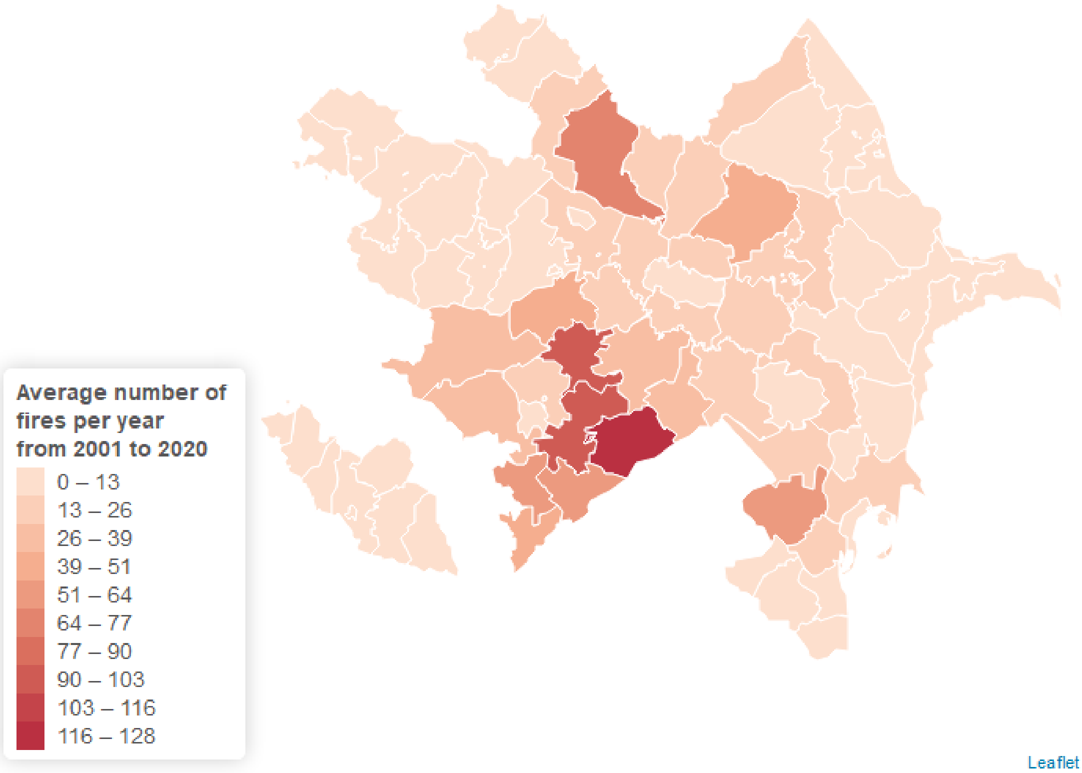

Figure 4: Average number of fires per year in Azerbaijan.

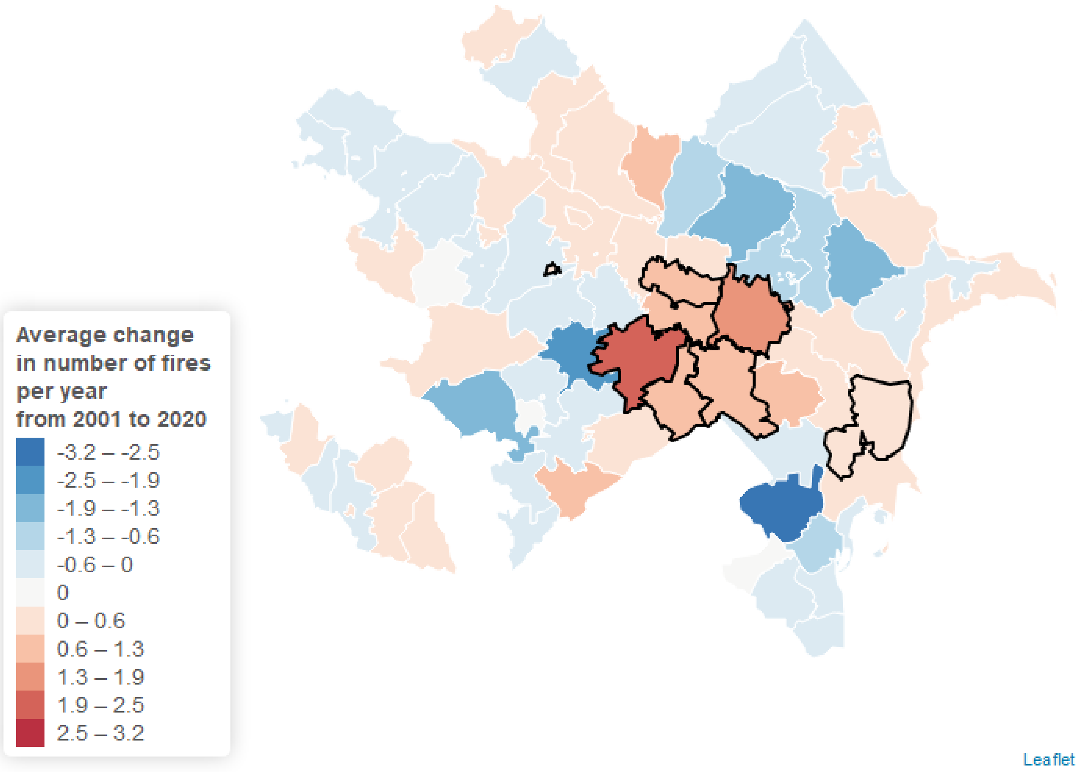

Figure 5: Average change in number of fires per year in Azerbaijan. Districts with a black outline had a significant positive or negative change between 2001 and 2020.

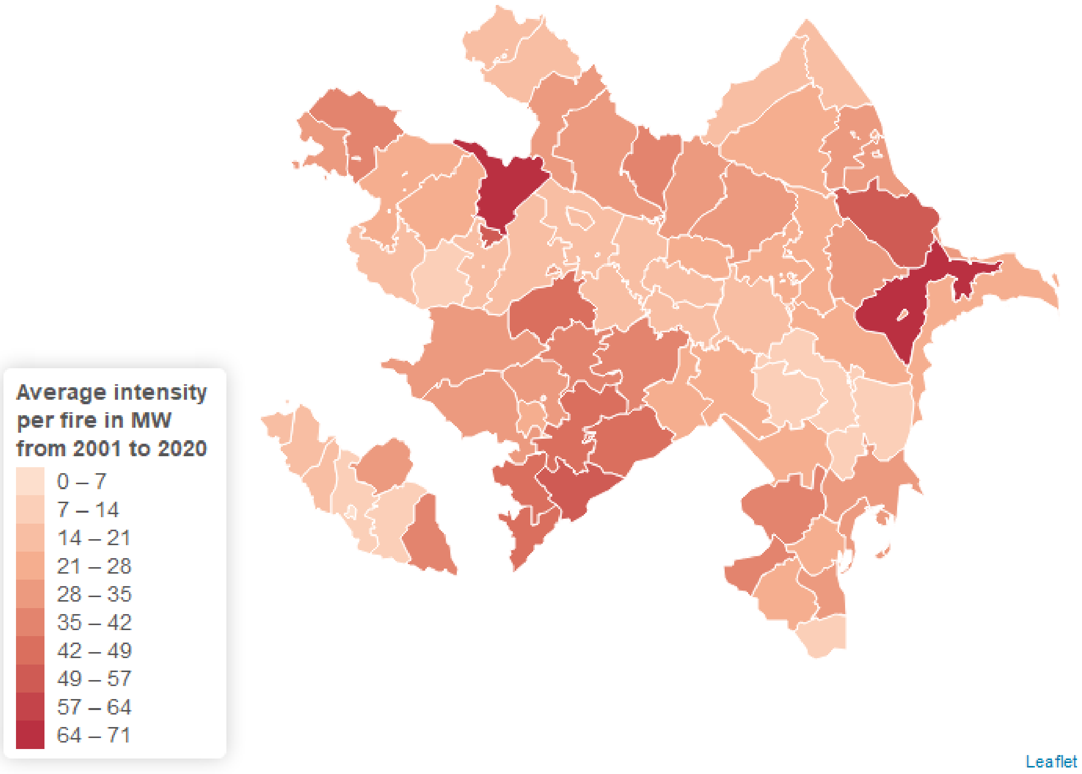

Figure 6: Average fire intensity in Azerbaijan.

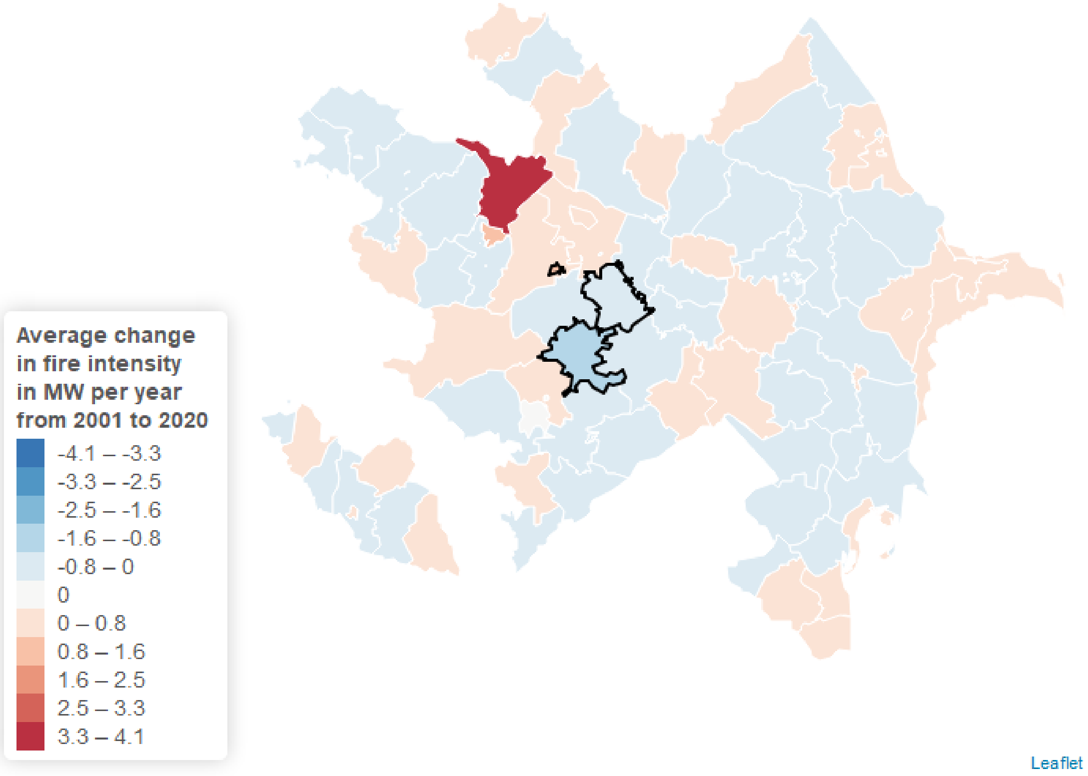

Figure 7: Average change in fire intensity per year in Azerbaijan. Only districts with a black outline show a significant change between 2001 and 2020.

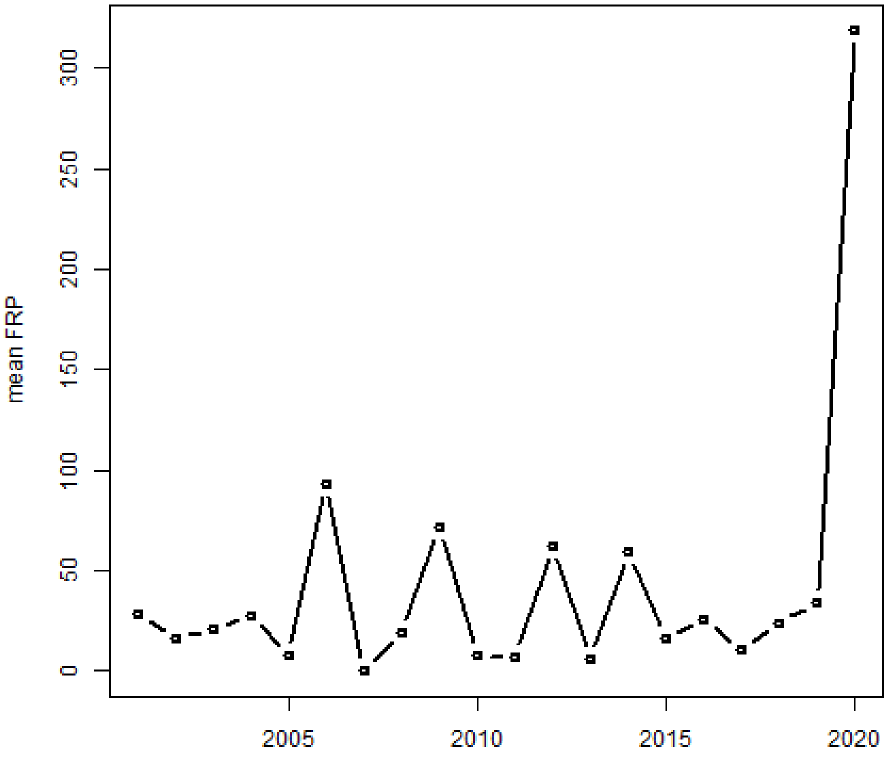

Figure 8: Yearly mean fire radiative power in megawatts, in Samukh district.

Satellite-sensed fire records have a series of limitations and one should be careful when drawing conclusions from this kind of data:

- There is no information on the duration of a fire. Fires that lasted a few hours, and fires that lasted for days, are not distinguishable from one another.
- There is no information on the area that was burnt by a fire. MODIS images are composed of pixels with a size of 1x1 km. A pixel is classified as an active fire as soon as the algorithm detects a fire therein, irrespective of the size that the fire actually covers.
- If two separate fires happen within one 1x1km pixel, they count as one fire.
- If a fire spans over several 1x1 km pixels, it will count as several separate fires.
- There is no information on the movement of fires. If a fire passes from one pixel to another, it will count as a new fire.
- There is no certainty about the type of fire. Natural wildfires, campfires, larger barbecues, or gas flares cannot be separated from each other.

We abstain from making any inferences about the future development of fire activity and intensity.

Vegetation fires are mediated by the biophysical conditions that prevail in a specific location, such as the availability of soil moisture, topographic features, such as slope and aspect, wind speed and direction, as well as precipitation and temperature patterns. Arguably, with rising average temperatures and more frequent drought periods, many landscapes in the Caucasus will become more susceptible for fires, including more frequent and more severe fires. However, it remains extremely challenging to anticipate future fire behavior because the occurrence of fire depends not only on biophysical conditions but on additional, often unpredictable management factors. These include, for example, land use management, such as the type and intensity of grazing. Higher extraction of biomass through grazing will reduce fuel loadings and thus tend to reduce the susceptibility of landscapes to fire. Moreover, some crop cultivation systems are more prone to fire than others. Stubbles left on the field, for example, can be easily ignited and can provide sufficient fuel loads to enable large cropland fires. Also changes in land use, such as the abandonment of cropland, will alter fuel loadings and can lead to higher fire risk, depending on the type of successional vegetation and the fuel load it provides. Hence, it has been shown that changes in land cover, land use, and land management are key factors for fire behavior, which is why it is not possible to predict fire occurrence into the future with any degree of confidence.

2. Characterization of historical climatic trends

2.1 Introduction

To get an overview on how climate has changed across crop production regions of Azerbaijan during the last four decades, we analyzed modelled climatic datasets with a daily resolution from 1981 until 2020. We use the CHIRPS dataset for precipitation and the ERA5-Land dataset for temperature. To focus only on cropped areas, we only consider those areas that fall into the cropland mask (defined in chapter 1.1). For one part of the analysis, we only considered the time period during a year that is relevant for crop growth. To do so, we define a main growing season from October to June, because crop yields in the study area are typically not affected by climate conditions during midsummer (July-September). However, we are aware that this is only a coarse approximation and specific crops might have a very different critical window during which climate can have a high impact on plant growth. Therefore, we also calculated climatic trends on a monthly basis. We analyze climatic trends with more detail in work package 3.

2.2 Approach

The whole workflow to estimate climate trends, including the processing steps of the cropland mask and ERA5-Land temperature data (see chapters 1.1 and 1.2), is shown in Figure 9. We first multiplied the binary cropland mask with all 14,610 daily layers of the four climate parameters from CHIRPS (precipitation) and ERA5-Land (minimum, average and maximum temperature), respectively (see chapter 1.2). We then overlaid all resulting 58,440 raster layers with the districts shapefile and calculated zonal mean statistics for each district. This procedure results in one value for mean precipitation, mean minimum temperature, mean average temperature, and mean maximum temperature for each district and day from January 1st, 1981, to December 31st, 2020 (see Figure 10). From these values, we calculated the sum of precipitation and mean temperature values for each month and for each growing season. That resulted in time series of 40 values for each month, and 39 growing season values. For each time series, we fitted a linear regression model to calculate the yearly trend in precipitation or temperature and the change from 1981 to 2019 (growing season values) or from 1981 to 2020 (monthly values) (Figure 11). The changes in precipitation and temperature shown in the subsequent maps always refer to the total change between 1981 and 2019/2020. We used the nonparametric Mann-Kendall test to assess if the observed changes in precipitation and temperature are statistically significant.

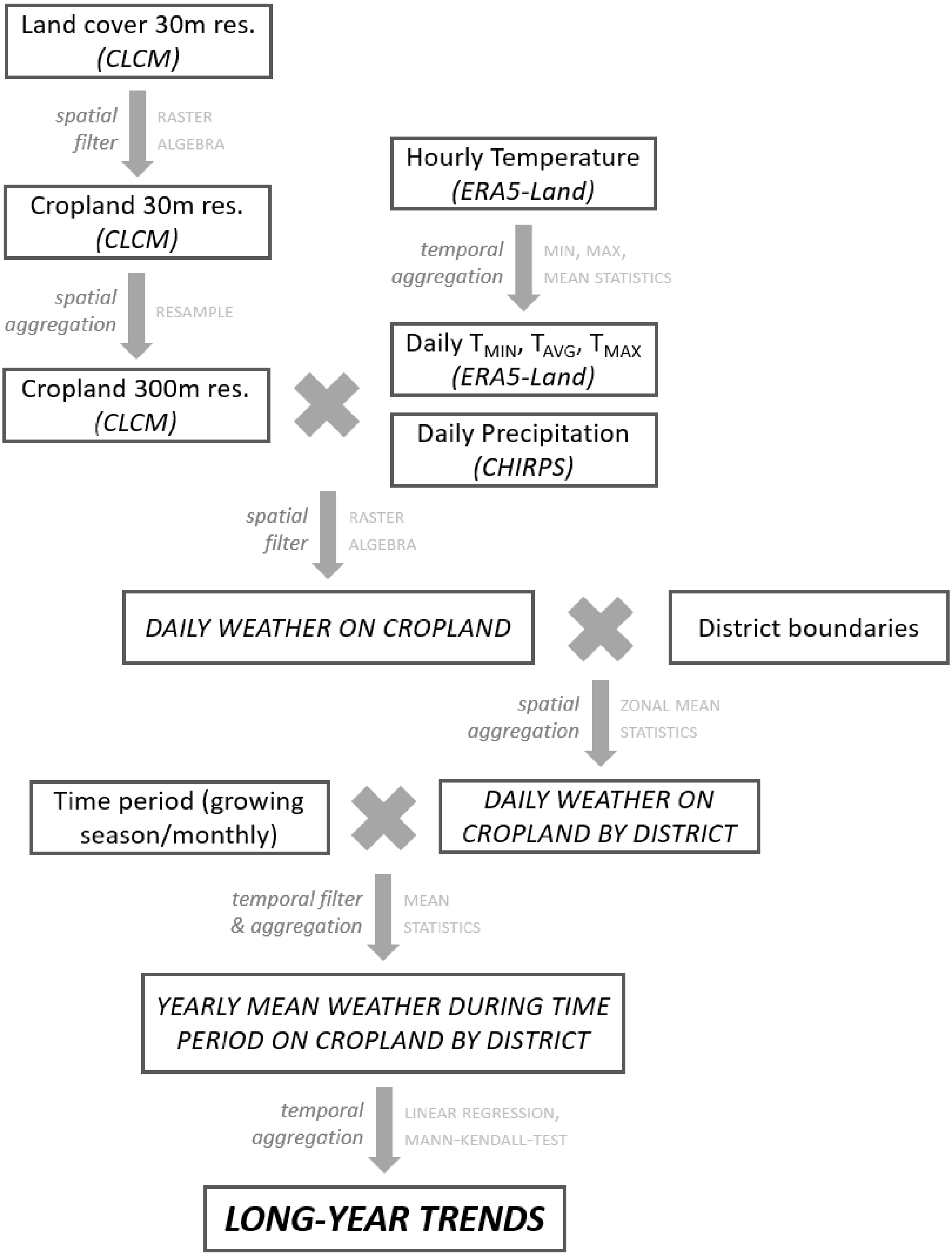

Figure 9: Workflow for estimating long-term climatic trends from cropland mask, daily temperature and precipitation data and district boundaries.

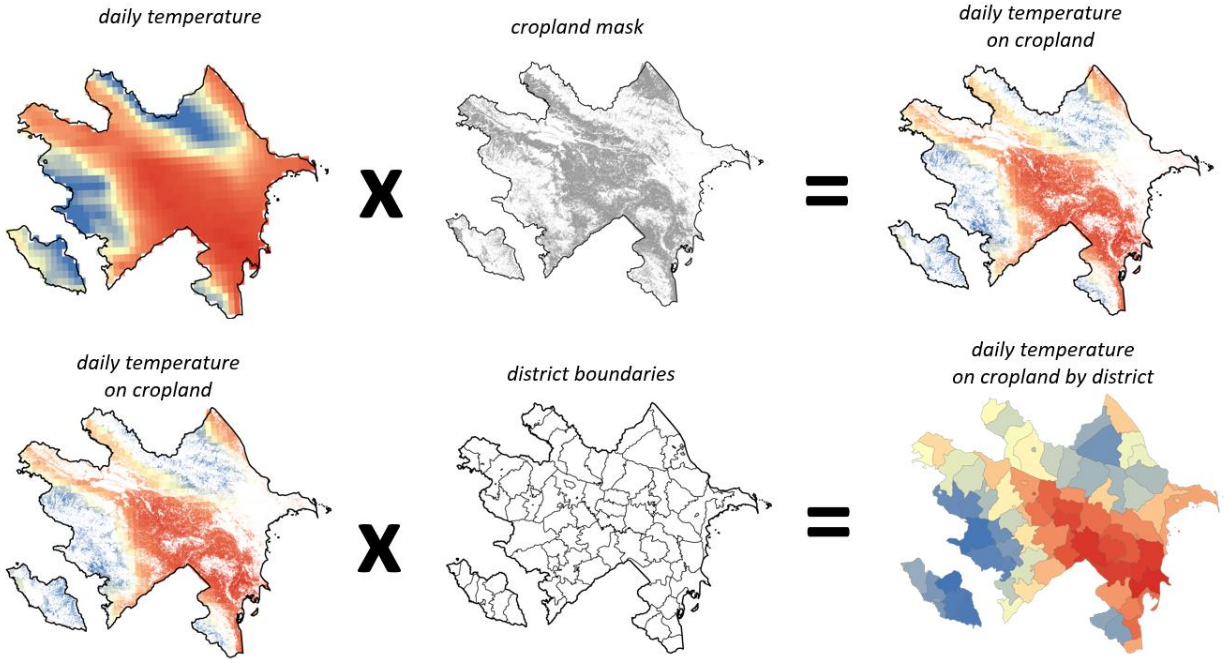

Figure 10: Illustration of a part of the workflow described in Figure 9. Daily temperature values are only kept for cropland locations. For each district, we summarized the underlying temperature values into one district average.

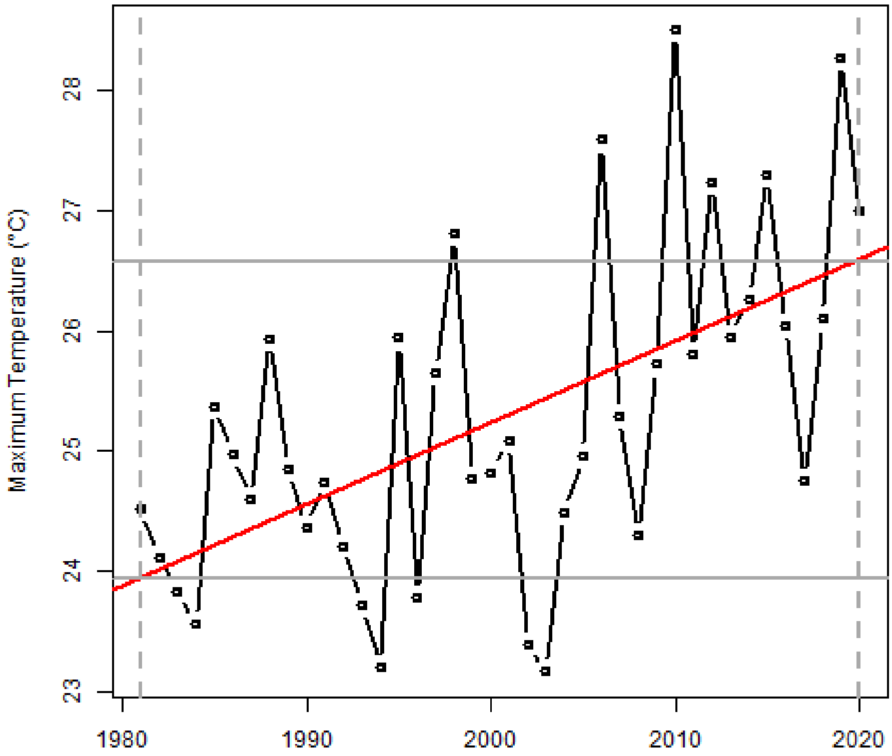

Figure 11: Yearly June temperature in the city of Baku. The mean daily maximum temperature in June has risen from 23.9 °C in 1981 to 26.5 °C in 2020, equivalent to a yearly increase of about 0.07 °C, or a total increase of 2.6 °C since 1981.

2.3 Results & Discussion

All results area available online in an interactive format at:

https://rpubs.com/max_hof_mann/climate_azerbaijan

The link contains the growing season and month-specific trends for precipitation, minimum, average, and maximum temperature on the croplands and summarized for each district. We here only present the maps for precipitation and average temperature.

Growing season average temperature has significantly increased in all districts of the country (Figure 12). However, the central part of Azerbaijan, where croplands are mainly concentrated, has been less affected by rising temperatures than for example the southwestern part. The Autonomous Republic of Nakhchivan is the province where temperatures have risen the most; all districts with the highest increases are located there (Sadarek: 2.7 °C, Babek: 2.5 °C, Sherur: 2.5 °C). Note that there is only little cropland area in Nakhchivan (Figure 2).

Overall, since 1981 large parts of central and northern Azerbaijan have become significantly wetter during the growing season from October to June, whereas this is not the case for the southern part of the country (Figure 13). The districts with the highest increase in precipitation are Kurdamir (199 mm), Agsu (191 mm) and Shamakhy (185 mm). Average temperatures have substantially increased across Azerbaijan during the last four decades, including during most months and in most districts (Figure 14). In February and March, croplands have warmed up the most, however the highest increases occurred in the southern parts of the country, where there is little cropland (Figure 2). Temperature changes in April are largely negative, but insignificant (at the moment, we cannot explain why the temperature patterns in April deviate from the overall patterns). All districts experienced significant increases in average temperature during May and June, which is a critical phase for most crops. The significant increase in August temperature may not have had considerable effects on many crops, as most of them are harvested before August. For the months July, September and November to January, temperature increases are modest and only significant for a few districts.

Many months and districts have become wetter in Azerbaijan since 1981 (Figure 15). This change is most pronounced for January, June, and September, for which the increase is significant for many districts. Particularly the increase in June precipitation might have affected crop production, as this is a critical phase for the growth of many crops. Moreover, the districts with the highest increases in June precipitation are located in the central part of the country and are characterized by high cropland shares (Figure 2). August tends to become drier, and this decrease in precipitation is significant for three districts (Absheron, Jebrayil and Masally). However, since many crops are already harvested earlier than August, the precipitation decrease in August might not have had a substantial negative impact on crop growth.

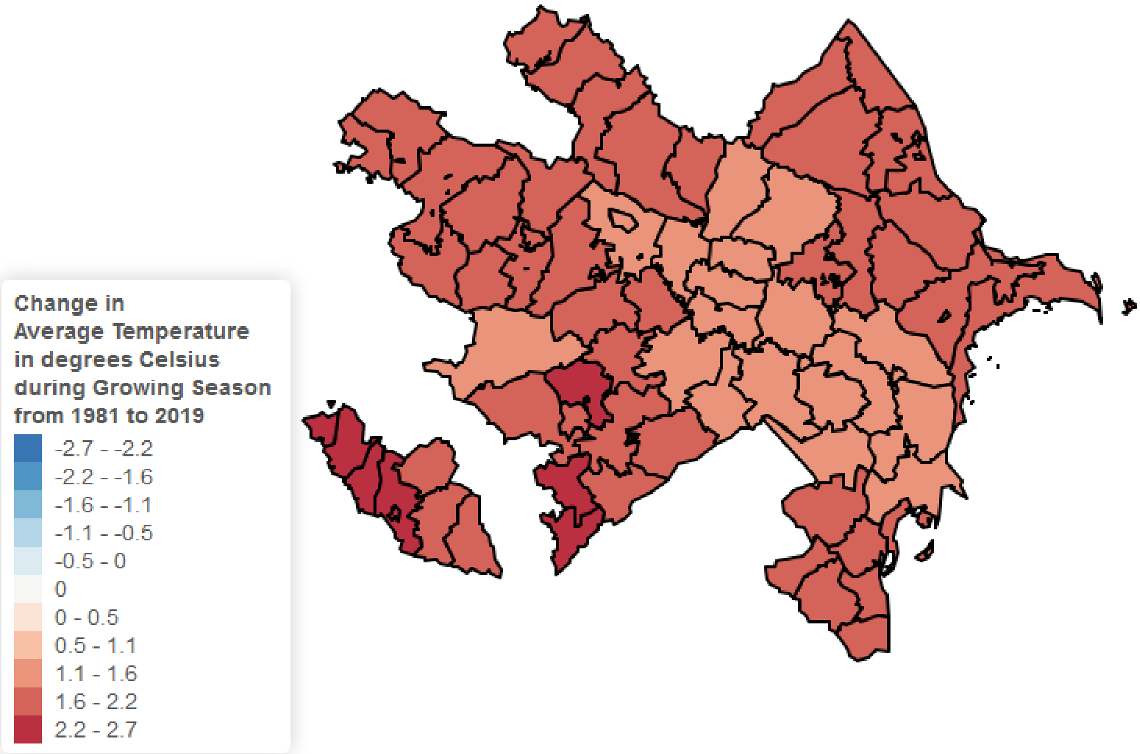

Figure 12: Total change in average temperature on croplands during the growing season. Only districts with a black outline show a significant change between 1981 and 2019.

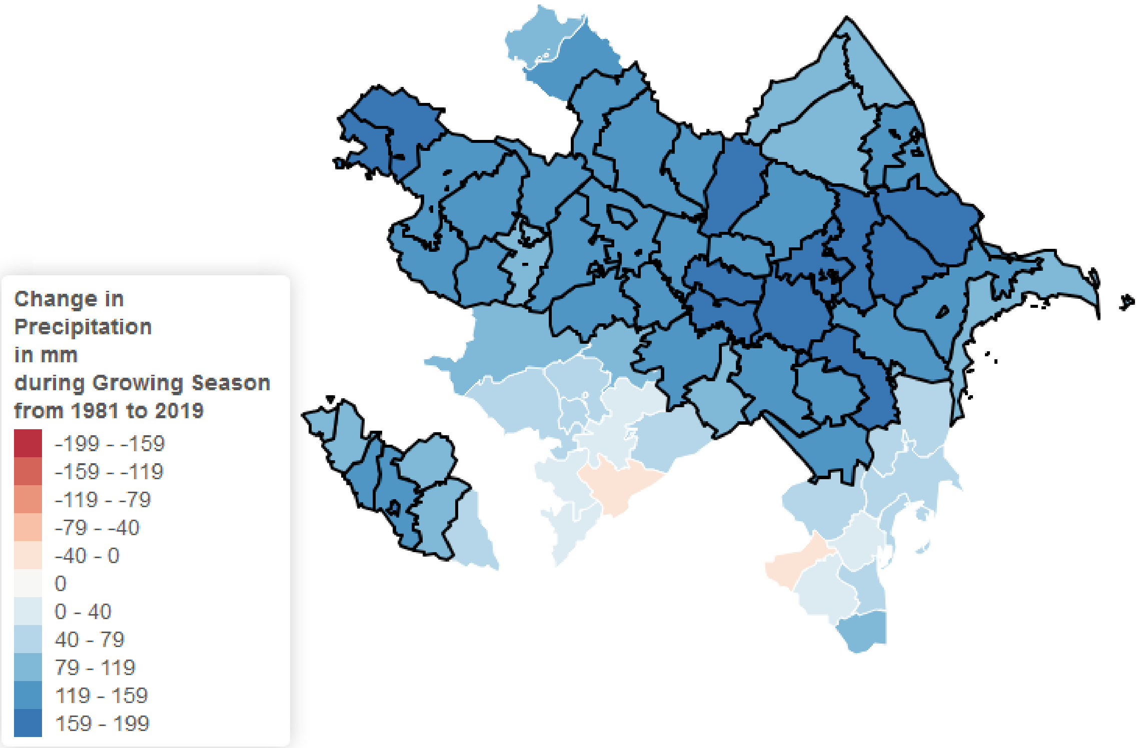

Figure 13: Total change in precipitation on croplands during the growing season. Only districts with a black outline show a significant change between 1981 and 2019.

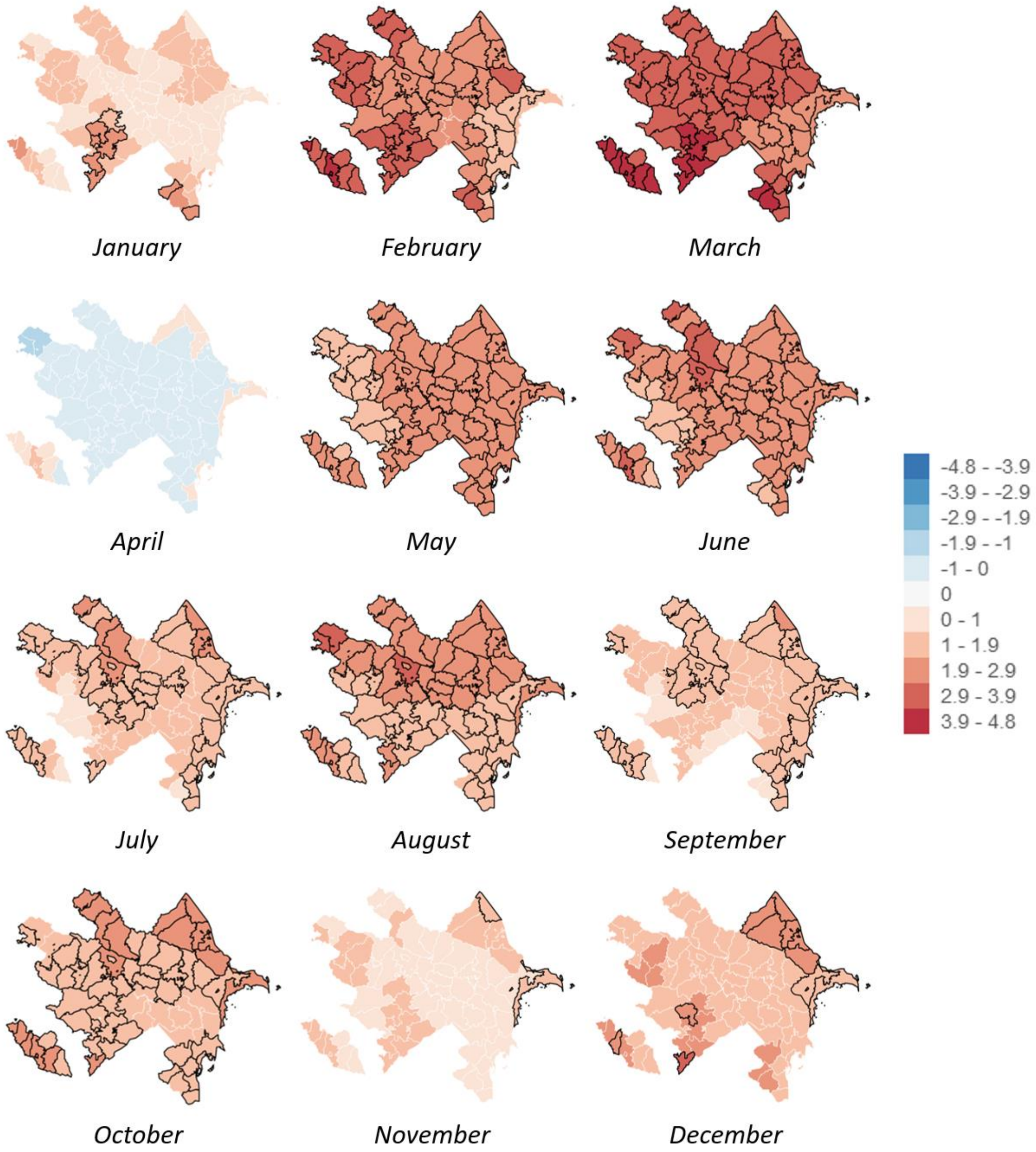

Figure 14: Total monthly change in average temperature on croplands from 1981 to 2020 in degrees Celsius. Only districts with a black outline show a significant change between 1981 and 2020.

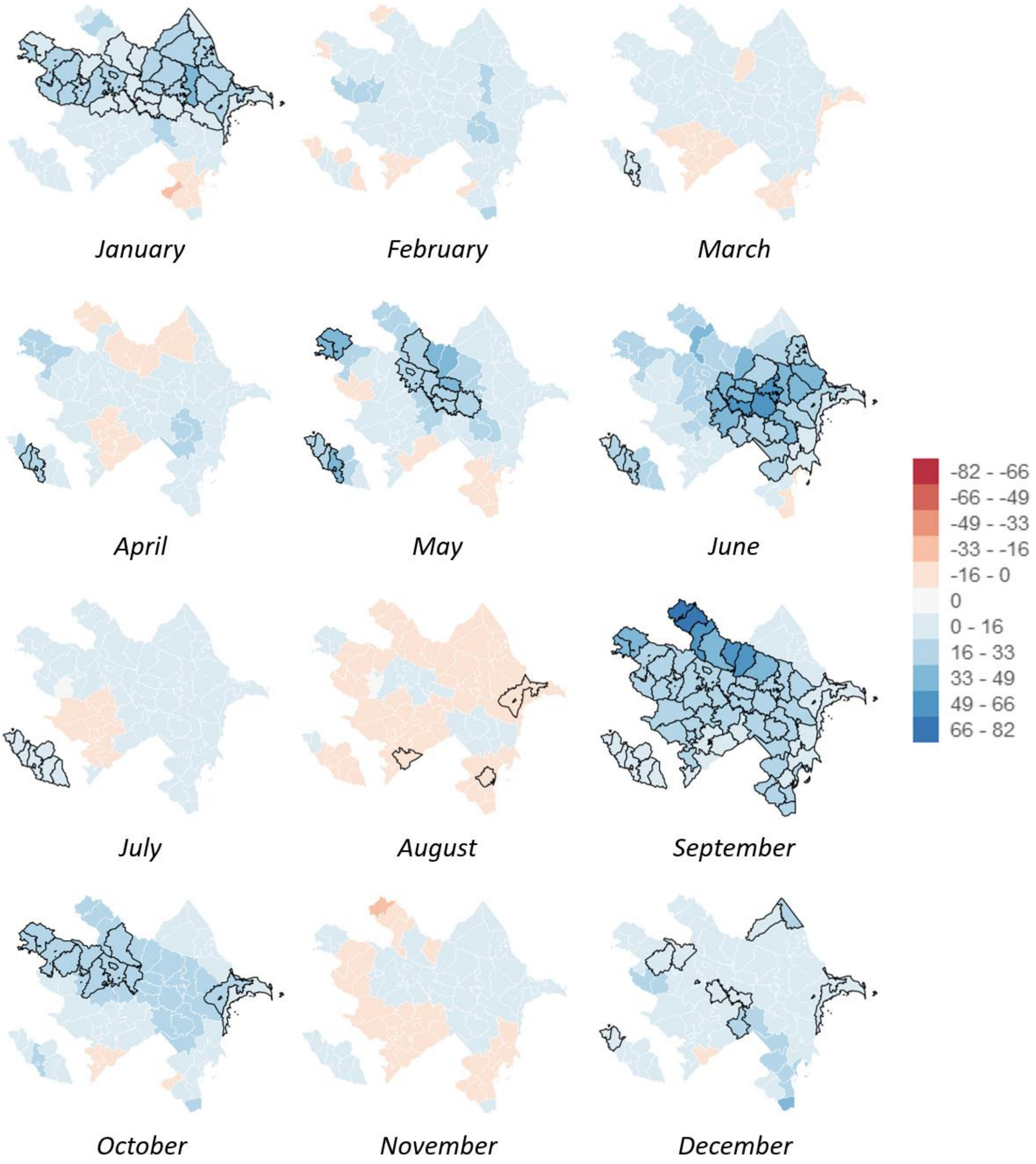

Figure 15: Total monthly change in precipitation on croplands from 1981 to 2020 in millimeters. Only districts with a black outline experienced a significant change between 1981 and 2020.

Work Package 3:

“Effects of Historical Climate and Extreme Weather Events on Yields and Crop Suitability”

Content

Annex

Annex A: Yearly weather and climate conditions
Annex B: Average levels and trends in weather and climate

Figures

Tables

1. Introduction

The aim of WP3 is to develop predictive models to estimate the historical effects of climate and weather on the production of the most important crops of Azerbaijan.

The occurrence of more frequent and intensive extreme weather events is one of the key challenges of ongoing climate change. Weather extremes constitute rare but impactful interruptions to crop production and already exert large damages globally (Asseng et al., 2011; Lesk et al., 2016; Zampieri et al., 2017)). Smallholder farmers can be more resilient to weather extremes when they rely on a diversified production portfolio. However, the impacts of weather extremes can nevertheless jeopardize the livelihoods of small and medium-sized farmers who rely on marketing surplus production for cash income from a few crops or are capital-strapped, and therefore more vulnerable to weather extremes (Jensen and Barrett, 2017) . Quantifying the changes in weather extremes together with the effect of long-term climate trends provides crucial impetus for informing and building adaptation strategies that improve the resilience of small and medium-sized farms.

Previous studies have shown the importance of climate and weather conditions in explaining crop yields (Lobell et al., 2012; Ray et al., 2015; Schierhorn et al., 2021). Long-term climatic means, such as average temperature and precipitation totals, are important determinants of yields because crops have specific temperature and precipitation requirements. For example, cereal crops need sufficient water during specific plant developmental stages (Ortiz-Bobea et al., 2019), and fruit trees require specific chilling conditions (Atkinson et al., 2013). In addition to climatic means, short-term extreme weather events can crucially impact crop yields. Severe weather conditions outside the norm of long-term weather observations include heavy droughts, excessive precipitation, extreme frost, or extreme heat. It is important to note that the impacts of weather extremes on crop yields depend on when they occur during plant growth (Farooq et al., 2011; Schierhorn et al., 2021).

High variability of crop yields may indicate that climate and weather conditions have decisively affected crop yields. In Azerbaijan, subnational statistical data suggests that crops yields are highly variable. However, the compound effects of climatic means and weather extremes on crop yields in Azerbaijan, particularly for specific plant development stages, are not well understood to date. We here assess the impacts of long-term climatic means and extreme weather events on yields for the developmental stages of eight crops with the help of Random Forests. We use detailed phenological observations to determine crop-specific developmental stages and characterize historical climate conditions and the occurrence of different types of extreme weather events during these stages. We couple this information with official district-level agricultural yield statistics to quantify which stage-specific weather and climate variables had the largest impact on the yields of these crops in Azerbaijan between 2000 and 2019. For two additional crops, apple and hazelnut, we apply a Chill Unit model to characterize the suitability for the production of these crops considering the amount of chill temperatures that accumulate between autumn and spring, particularly during winter dormancy, which is a critical phase for proper plant development in fruit and nut trees.

2. Data Preparation

2.1 Agricultural Statistics

2.1.1 Yield, Sown Area, Harvested Area and Production Amount

In WP1, we identified the 10 target crops that are most important for Azerbaijan in terms of production amounts, sown area and yield (Table 1). We obtained annual district-level agricultural statistics on yield, sown area and production from 2000 to 2019 from the *State Statistical Committee of the Republic of Azerbaijan* (*AZstat,* https://www.stat.gov.az/). Data is not available separately for winter and spring wheat, and winter and spring barley. We used yearly crop yield estimates of eight crops as the response variable in the Random Forest models. For two additional crops, apple and hazelnut, we applied a Chill Unit model to predict the suitability for their production, which did not require yield statistics (see chapter 4.2).

Table 1: Target crops in Azerbaijan.

Crop	***Model approach***
Wheat	Random Forest models
Barley	
Onion	
Potato	
Cucumber	
Tomato	
Persimmon	
Pomegranate	
Apple	Chill Unit models
Hazelnut	

To assess the validity of the agricultural statistics reported by AZStat, we compared the district-level total sown area of *AZStat* for 2015 with the district-level cropland area extent from the *Caucasus Land Cover Map* for 2015 (CLCM, *SILVIS lab of the University of Wisconsin*, http://silvis.forest.wisc.edu/data/caucasus/). This map was derived by classifying satellite imagery and has been validated with on-site observations. We found good overall agreement between the two estimates (Figure 1). However, for most districts, cropland extent from CLCM is higher than the cropland extent reported by AZStat. This analysis serves as a standard check of data quality, but did not affect our analysis and the subsequent use of the yield estimates in our models.

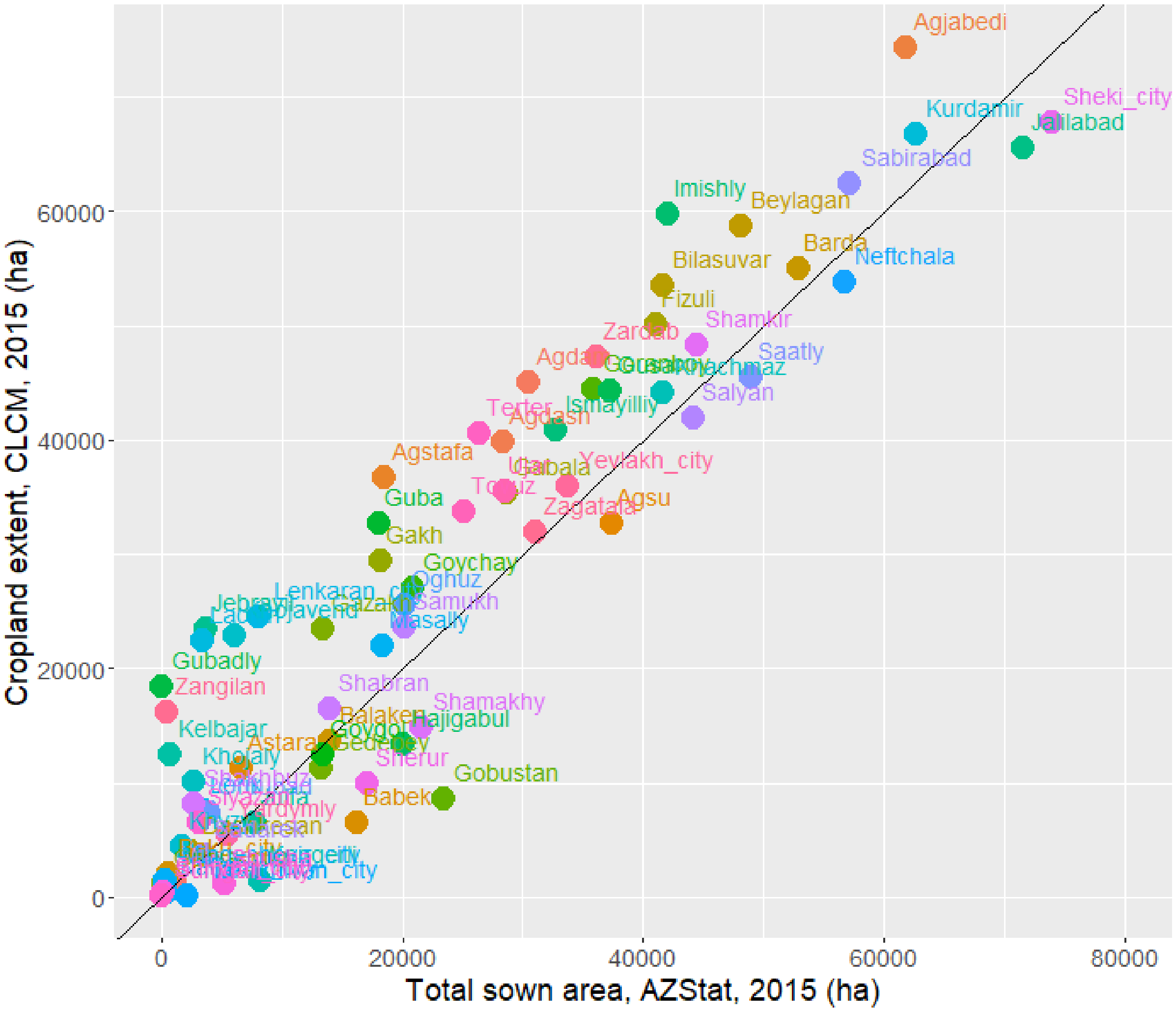

Figure 1: Cropland estimate from the Caucasus Land Cover Map (CLCM) in 2015 against total sown area reported by AZStat for 2015. Dots near the black line have more similar values on both axes.

For each district and each crop, we calculated the mean yield, mean sown area, mean harvested area and mean production over all years from 2000 to 2019. This allows to summarize the overall production patterns (Figure 2, harvested area not shown): For wheat and barley, yields are generally highest in the central lowland region and in the Autonomous Republic of Nakhchivan. Yields of onion, cucumber and tomato do not show such distinct patterns, and production of these two crops is highest in a few districts scattered across the country. Potato is mainly grown in three districts in the northwest, and in the district of Jalilabad in the south. For persimmon, production, sown area and yield are highest in a few districts in the northern part of the country, whilst pomegranate clearly concentrates in the central lowland region. Apple production is disproportionately high in the district of Guba in the north, but yields are highest in Nakhchivan. Hazelnut is also predominantly grown in the north, particularly in Zagatala, whilst yields are higher further south.

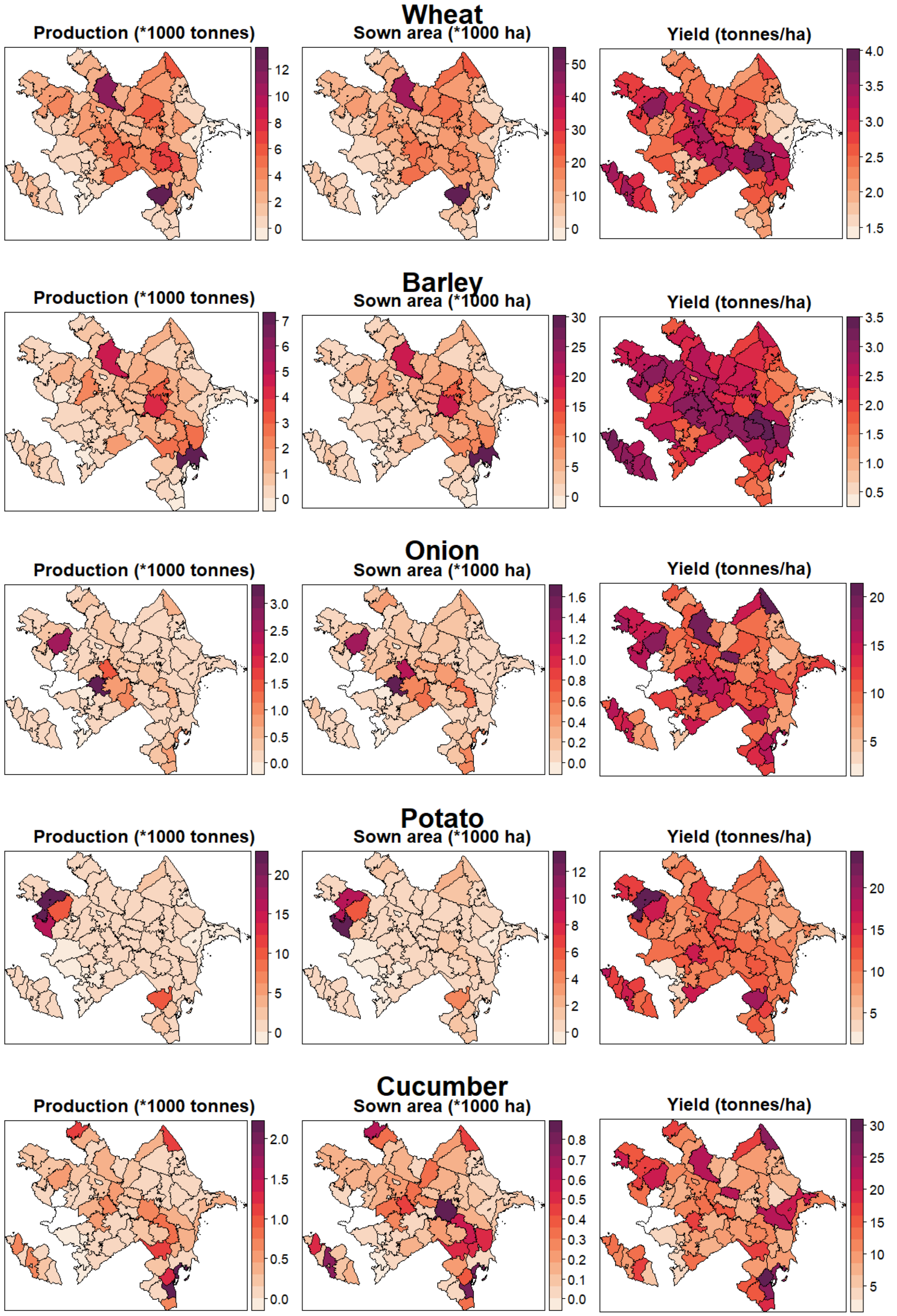

Figure 2: Mean sown area, yield and production from 2000 to 2019 for the target crops. Harvested area is almost identical to sown area and is not shown here.

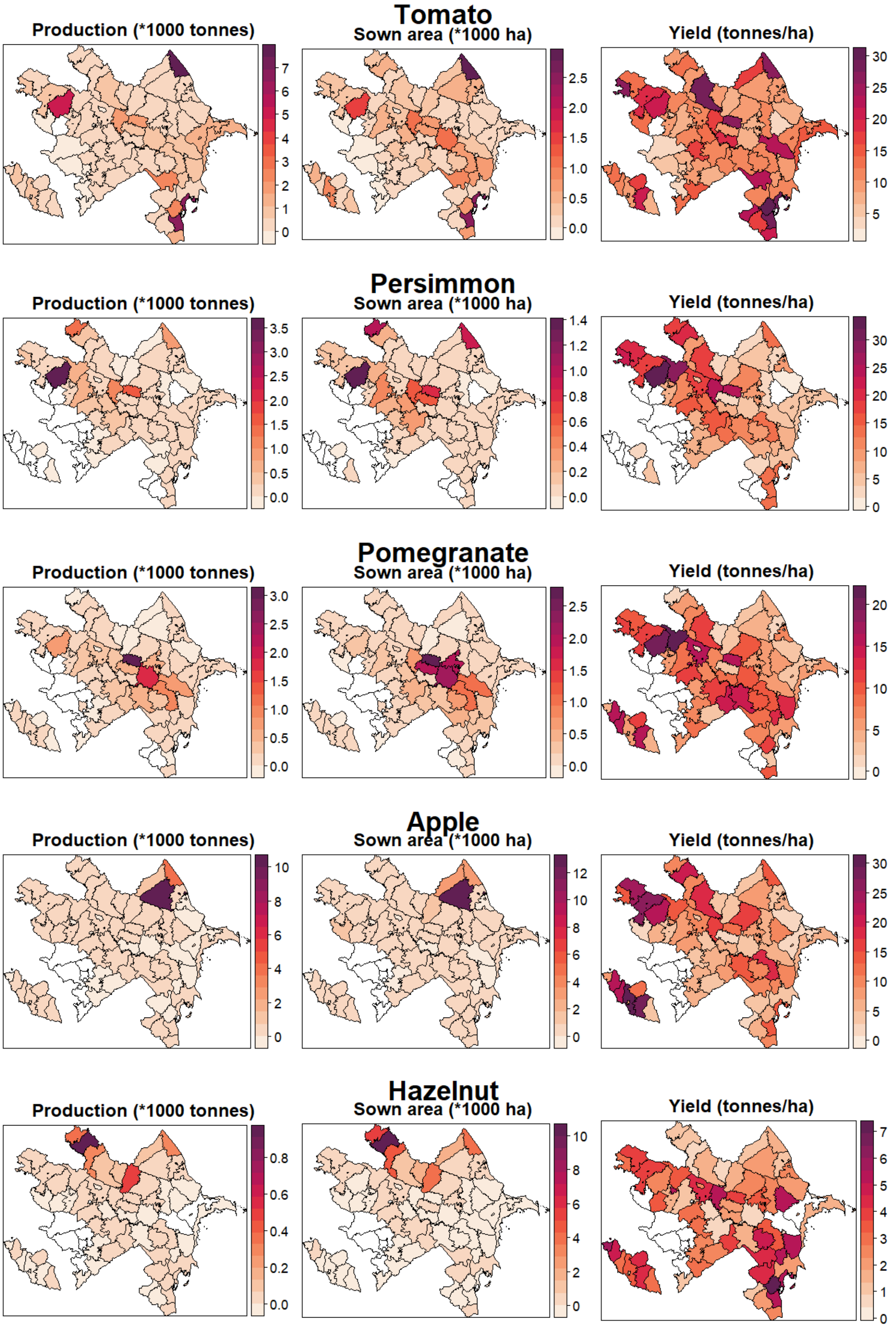

Figure 2 (continued): Mean sown area, yield and production from 2000 to 2019 for the target crops. Harvested area is almost identical to sown area and is not shown here.

2.1.2 Irrigation

Crop production heavily relies on adequate amounts of precipitation during specific crop developmental stages. For example, most grain crops require a certain amount of moisture during the vegetative stage. Irrigation systems can compensate moisture deficits and ensure that yield levels are maintained even under drought conditions. It is therefore important to consider the extent to which irrigation systems are in place when attributing climatic conditions to yields.

Irrigation is widespread in Azerbaijan: In 2020, about 80% or 1,480 thousand hectares of the country's agricultural land were classified as irrigated. However, these areas are often not fully irrigated due to local water shortages (State Statistics Committee, pers. comm.). Detailed information about the actual share of irrigation is missing, and the available statistics should therefore be interpreted with caution. We obtained district-level data on the extent of irrigated area under wheat and barley in 2020 from the *Ministry of Agriculture of the Republic of Azerbaijan*. The amount of irrigated sown area is highest in Jalilabad, where wheat production is also highest in general (Figures 2 and 3), and the share of irrigated sown area is between 90 and 100% in most districts of the central lowland region (Figure 3). Yearly information on the irrigation of other crops is available from a farmer's survey, however only for the years 2016 to 2019 and only for a part of all districts of the country. We did not consider this information to be sufficiently representative to be regarded in our analysis.

Since representative crop-specific irrigation data is only available for wheat and barley and only for one year, and because irrigation statistics do not reflect the actual amount of irrigation, we were not able to use irrigation as a variable in our models. However, we do consider the available information when we discuss the results of our models (see chapter 4.1).

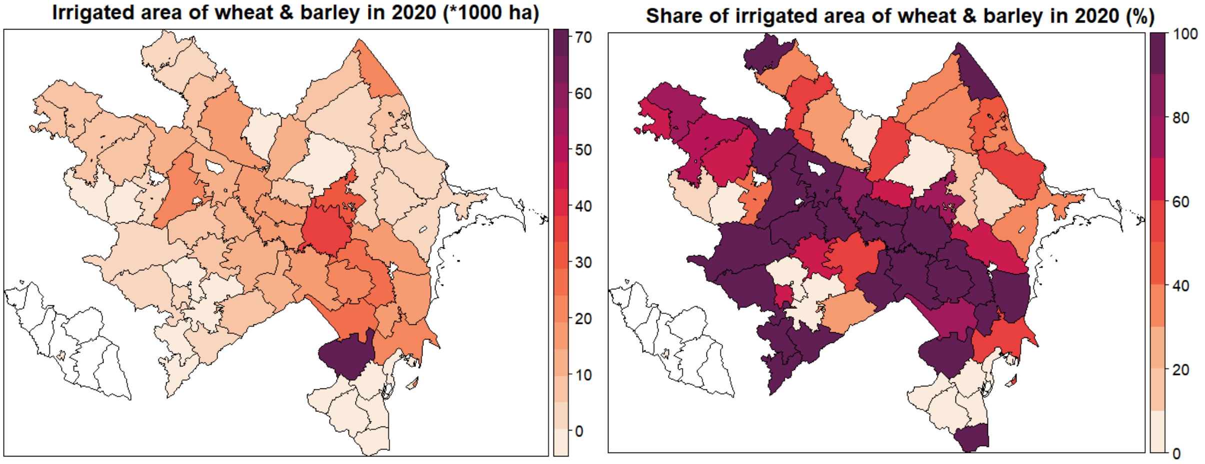

Figure 3: Total amount and share of irrigated sown area of wheat and barley in 2020.

2.1.3 Production in Greenhouses

Greenhouses can both (i) shield crops from excessive water supply by heavy precipitation and (ii) cushion negative effects from low temperatures that would otherwise compromise yields. On the other hand, greenhouses can also exacerbate heat waves and hence negatively affect crop growth in the absence of adequate ventilation or cooling. It is therefore important to consider the extent to which a crop is produced in greenhouses when attributing climatic conditions to yields.

We obtained data on the amount of greenhouse production from the *Ministry of Agriculture of the Republic of Azerbaijan.* The main vegetables cultivated under greenhouses in Azerbaijan are tomato and cucumber (Figure 4). Because there was a large increase in greenhouse production since 2017, we restricted our models for tomato and cucumber to the years 2000 to 2016. Vegetables are mainly produced in greenhouses in the districts of Shamkir, Absheron and Baku (Figure 5).

We lack information about the regional differences in greenhouse production for tomato and cucumber, and about yearly differences in district-level greenhouse production. We therefore were not able to use greenhouse production as a variable in our models. However, we do consider the available information about greenhouses when we discuss the results of our models (see chapter 4.1).

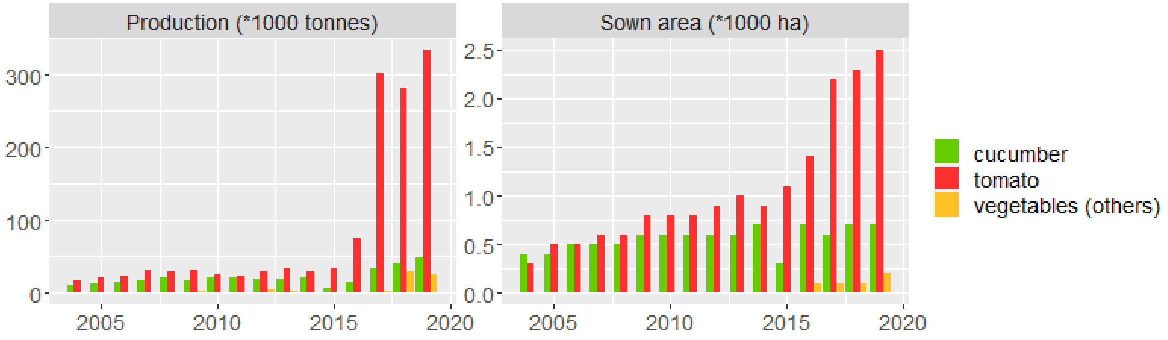

Figure 4: Yearly production and sown area of vegetables in greenhouses.

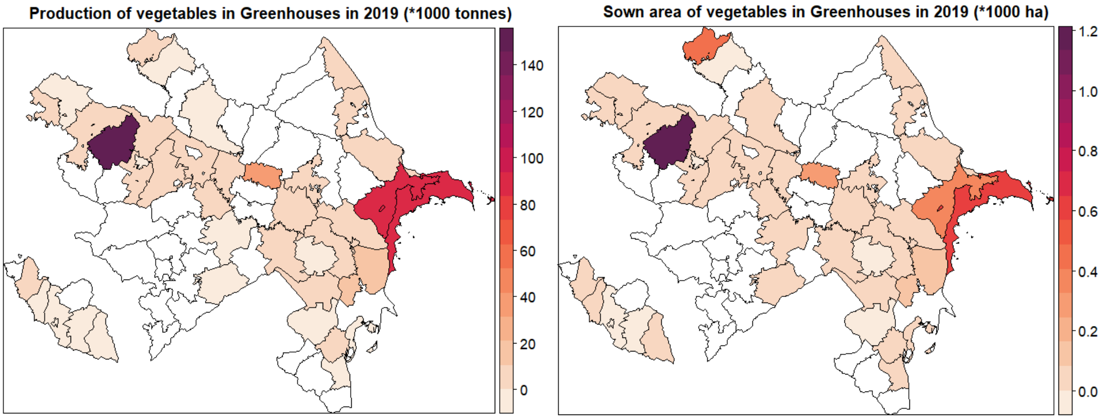

Figure 5: Production and sown area of vegetables in greenhouses conditions in 2019.

2.2 Phenological Observations and Crop Development Stages

Crops go through different development stages in their biological life cycle, such as the emergence of flowers or the ripening of fruits. The dates of such events are documented in phenological observation records and can change in response to weather anomalies or to long-term changes in climate. The timing and duration of these stages differ between crops, locations, and over time. Climatic conditions and weather extremes have distinct effects on yields during each development stage, and phenological observations are therefore important to associate the relationships between climatic means and weather extremes with crop yields (Schierhorn et al., 2021).

We obtained crop-specific phenological observations from the *National Hydrometeorological Service of Azerbaijan* for the years 2008, 2013 and 2019 for eight crops from a total of 6 agrometeorological stations (Figure 6, Table 2). For cucumber and onion, we obtained phenological information for five different economic regions from the *Vegetable Research Institute*. For wheat and barley, we excluded the year 2019 in *Jafarkhan* from all further analysis because of unusual phenological observations in winter. We then averaged the observations of *Jafarkhan*, *Goychay* and *Ganja* and assumed them to be representative for the central lowland region (Figure 6, blue area), while we assumed *Shaki* to be representative for the mountainous regions of the country (Figure 6, orange area). For all other crop, we averaged the dates of all phenological observations across all stations and years, or across all economic regions in the case of cucumber and onion.

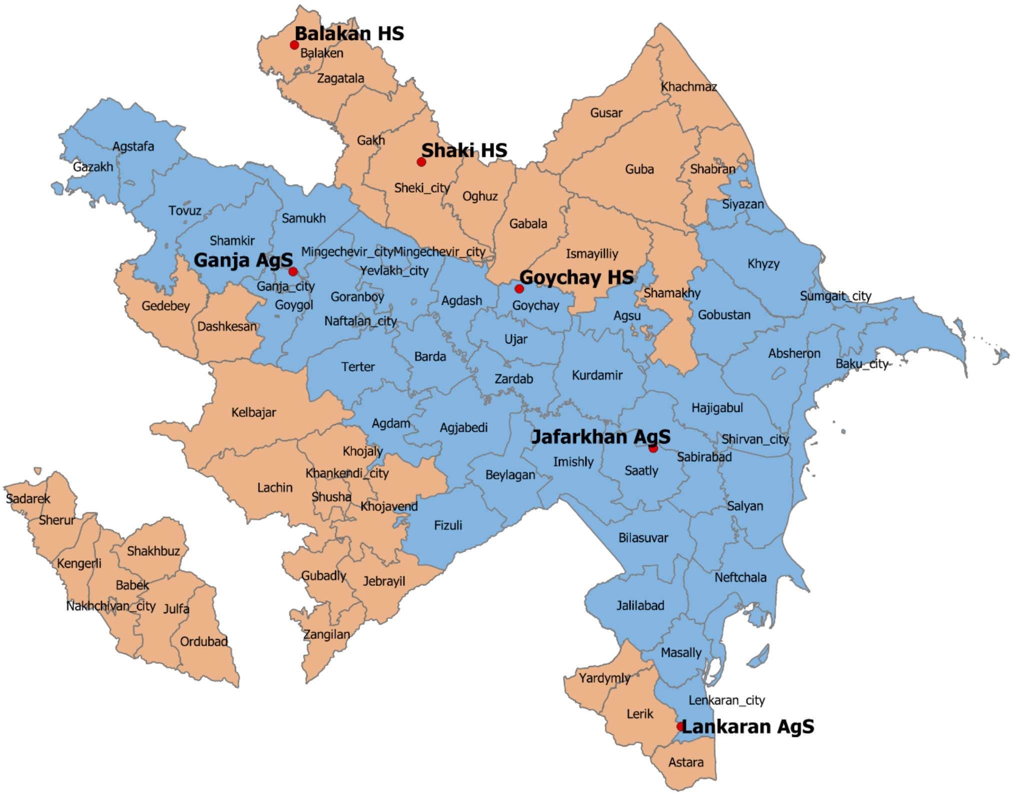

Figure 6: Location of the six phenological stations in Azerbaijan. The color of the districts refers to the sub-regions defined for the wheat and barley models: blue – central region, orange – mountains region.

Table 2: Available phenological information about each crop.

	Year	Wheat	Barley	Onion	Potato	Cucumber	Tomato	Persimmon	Pomegranate	Apple	Hazelnut
Agrometeorol. Station											
Shaki	2008	x	x				x			x	
	2013	x	x							x	
	2019	x	x							x	
Lankaran	2008							x	x		x
	2013				x			x	x		x
	2019				x			x	x		x
Jafarkhan	2008	x	x				x		x		
	2013	x	x						x		
	2019	x	x						x		
Balakan	2008							x			x
	2013							x			x
	2019							x			x
Goychay	2008	x						x	x		
	2013	x						x	x		
	2019	x						x	x		
Ganja	2008		x								
	2013		x								
	2019		x								
Economic region											
Absheron	NA			x		x					
Guba-Khachmaz	NA			x		x					
Ganja-Gazak	NA			x		x					
Lankaran-Astara	NA			x		x					
Aran	NA			x		x					

2.2.1 Crops assessed with Random Forest models

We modelled eight of the ten target crops with Random Forest models (Table 1). To account for the different impacts of climatic means and weather extremes during the distinct development stages of these crops, we define the onset of each stage by averaging the available phenological information across all years and stations (Tables 3 to 10). In the following, we briefly review the literature on the sensitivity of these eight crops to climatic means and weather extremes during specific development stages, and summarize the available phenological information.

Wheat

Wheat is the most widely grown crop in the world, mainly because of its high climate tolerance. However, wheat is sensitive to very high and very low temperatures, particularly to extreme heat and drought conditions during the reproductive and grain filling stages as well as to late frost during ear emergence and anthesis (Harkness et al., 2020; Innes et al., 2015; Lobell et al., 2012). Exposure of wheat to short episodes of temperatures higher than 22°C during the reproductive stage causes male and female sterility and triggers damage to pollen tube growth and fertilization, resulting in lower grain number and grain yield; whilst later in the growing season, temperatures above 32°C during anthesis and above 34.3°C during grain filling are detrimental to grain weight, particularly if they occur as a heat wave (Farooq et al., 2011; Innes et al., 2015). Wheat growth and hence yield are also affected by frost: Wheat transitions through a process of cold acclimation toward hardened wheat plants, which protects the plants to low temperatures in winter (Barlow et al., 2015). However, severe frost in the absence of an isolating snow cover can lead to leaf chlorosis and yield loss (Harkness et al., 2020; Kolár et al., 2014). Scientific evidence from peer-reviewed international journals on the impact of climate change on wheat yields in Azerbaijan is not available to our knowledge.

In Azerbaijan, wheat is sown in early November (Figure 7, Table 3). Depending on the station and year, the emergence of the third leaf and shrub formation can happen either before or after winter dormancy. Flowering happens in mid-May, and harvest between late June and early July. We defined three development stages for two sub-regions: For the central sub-region, we averaged the dates of *Goychay* and *Jafarkhan*; for the mountains region, we assumed *Shaki* to be representative (Table 3).

Table 3: Development stages of wheat.

Sub-region	***Development Stage***	***Start***	***End***	***Start date***	***End date***
central	*Stage A (Vegetative stage)*	Sowing	Joint ligation	Nov 02	Mar 13
	Stage B (Reproductive Stage)	Joint ligation	Flowering	Mar 14	May 14
	Stage C (Grain filling stage)	Flowering	Harvest	May 15	Jun 26
mountains	*Stage A (Vegetative stage)*	Sowing	Joint ligation	Nov 04	Mar 31
	Stage B (Reproductive Stage)	Joint ligation	Flowering	Apr 01	May 14
	Stage C (Grain filling stage)	Flowering	Harvest	May 15	Jul 02

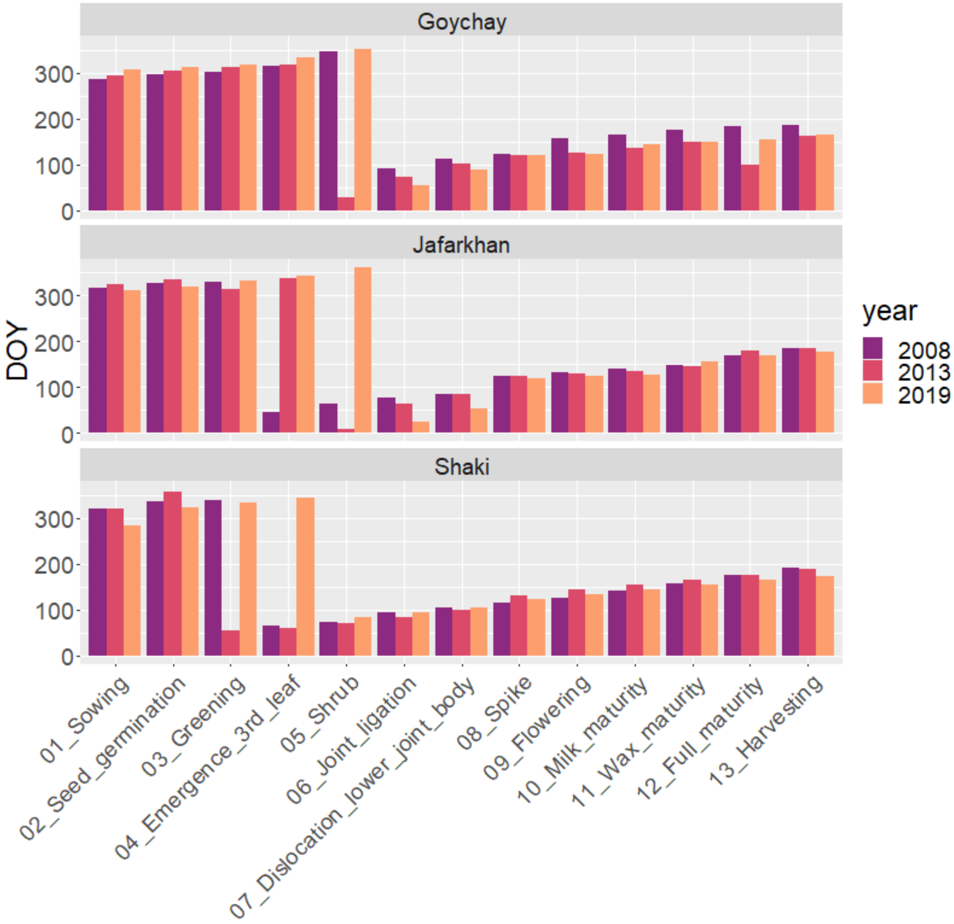

Figure 7: Phenological stages of wheat. DOY = day of the year.

Barley

Globally, barley ranks fourth in both produced quantity and sown area of cereal crops. It grows from the equator to the arctic circle at various altitudes. Like other cereals, barley is susceptible to extreme weather conditions, particularly heat and drought: Extremely high temperatures (generally above 35°C) around anthesis can severely reduce yield through reduced fertility, reduction in grain weight, and fewer grains per spike (Hossain et al., 2012; Murray and Brennan, 2010). High temperatures during the day followed by high night temperatures have further adverse effects on yield (Ugarte et al., 2007). Drought stress, particularly together with heat stress during the critical period for yield determination, results in severe yield reductions (Hossain et al., 2012; Murray and Brennan, 2010). This effect is particularly strong during anthesis (Arisnabarreta and Miralles, 2008; Frederiks et al., 2012). During the grain filling stage, severe drought stress lowers the net photosynthetic rate, shortens the grain-filling period, and decreases the number and weight of the grains per plant (Sánchez-Díaz et al., 2002). Climate change leads to more frequent exposure to heat stress, especially during the reproductive and grain filling stages (Hasanuzzaman et al., 2013). A few degrees increase in average daily temperature already results in significant yield losses in cereals (Lobell et al., 2011). For example, a temperature increase of 3 to 4°C would reduce barley yields by 15 to 35% in Africa and Asia, and by 25 to 35% in the Middle East (Ortiz et al., 2008). Research published in international peer-reviewed journals on the impact of climate change on barley yields in Azerbaijan is not available to our knowledge.

In Azerbaijan, barley is sown in early November (Figure 8, Table 4). Depending on the station and year, the emergence of the third leaf and shrub formation can happen either before or after winter dormancy. Flowering happens in mid-May, and harvest between late June and early July. We defined three development stages for two sub-regions: For the central sub-region, we averaged the dates of *Ganja* and *Jafarkhan*; for the mountain region, we assumed *Shaki* to be representative (Table 4).

Table 4: Development stages of barley.

Sub-region	***Development Stage***	***Start***	***End***	***Start date***	***End date***
central	*Stage A (Vegetative stage)*	Sowing	Joint ligation	Nov 08	Mar 24
	Stage B (Reproductive Stage)	Joint ligation	Flowering	Mar 25	May 14
	Stage C (Grain filling stage)	Flowering	Harvest	May 15	Jun 26
mountains	*Stage A (Vegetative stage)*	Sowing	Joint ligation	Nov 03	Mar 31
	Stage B (Reproductive Stage)	Joint ligation	Flowering	Apr 01	May 16
	Stage C (Grain filling stage)	Flowering	Harvest	May 17	Jul 04

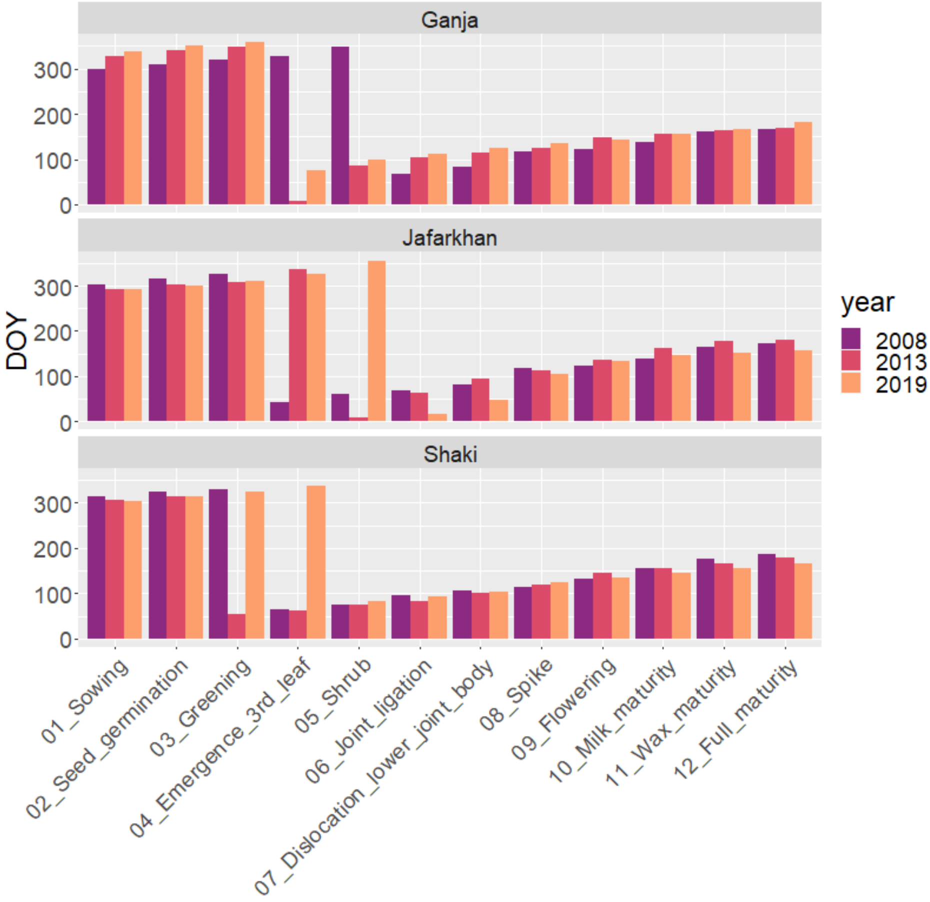

Figure 8: Phenological stages of barley. DOY = day of the year.

Onion

Bulb onion is an important vegetable crop, highly appreciated by consumers because of their distinctive sensory and beneficial compounds, and cultivated worldwide in a diverse range of climatic conditions varying from temperate to semi-arid. Asia (67.5% of total world production), Africa (12.9%), America (10.1%), and Europe (9.3%) are the largest producers of onion globally (FAOSTAT 2022, https://www.fao.org/faostat/). Onion is a shallow-rooted plant and hence prone to drought; approximately 30% of yield losses in onion are caused by drought stress (Ghodke et al., 2020). In addition to drought, onions are also vulnerable to extreme temperature injuries and waterlogging (Ghodke et al., 2018). In general, most onion cultivars require cool temperatures during early development and warmer temperatures during maturity. During bulping, it has been shown that high temperatures (25.5°C-31°C) or temperatures below 0°C depress yield (Khokhar, 2017).

In Azerbaijan, onion is sown in early February, the bulbs start to form mid-June, and harvest happens in late July, on average (Figure 9). We defined two development stages, accordingly (Table 5).

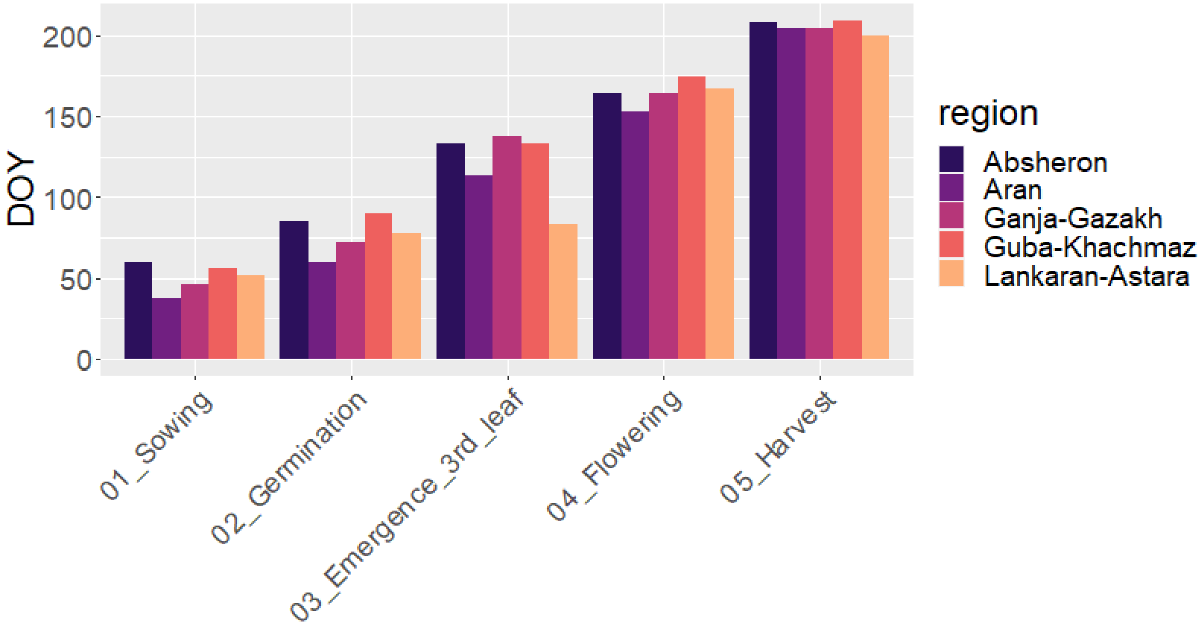

Figure 9: Phenological stages of onion. DOY = day of the year.

Table 5: Development stages of onion.

Development Stage	***Start***	***End***	***Start date***	***End date***
Stage A (Vegetative stage)	Seeding	Bulb formation	Feb 02	Jun 12
Stage B (Reproductive Stage)	Bulb formation	Harvest	Jun 13	Jul 24

Potato

Potato is grown mainly in temperate climates and grows best in cool but frost-free seasons (Haverkort and Verhagen, 2008). It is not well adapted to extreme heat and develops best around 20°C. Optimum temperatures for the aboveground part of the plant and for tubers vary. Experiments in growth chambers have shown that haulm growth is most rapid in a temperature range of 20°C to 25°C (Rykaczewska, 2015). The optimal range for tuber formation and growth is at 15°C to 20°C soil temperature. Soil temperature differs from air temperature, which complicates to quantify the impacts of climate and weather on yield. Extreme heat substantially inhibits tuber formation and the distribution of photo-assimilation to tubers, which leads to a drastic reduction in yield (Birch et al., 2012).

In Azerbaijan, potato is sown in mid-February, flowers in late April, and is harvested in mid-May, on average (Figure 10). We defined two development stages, accordingly (Table 6).

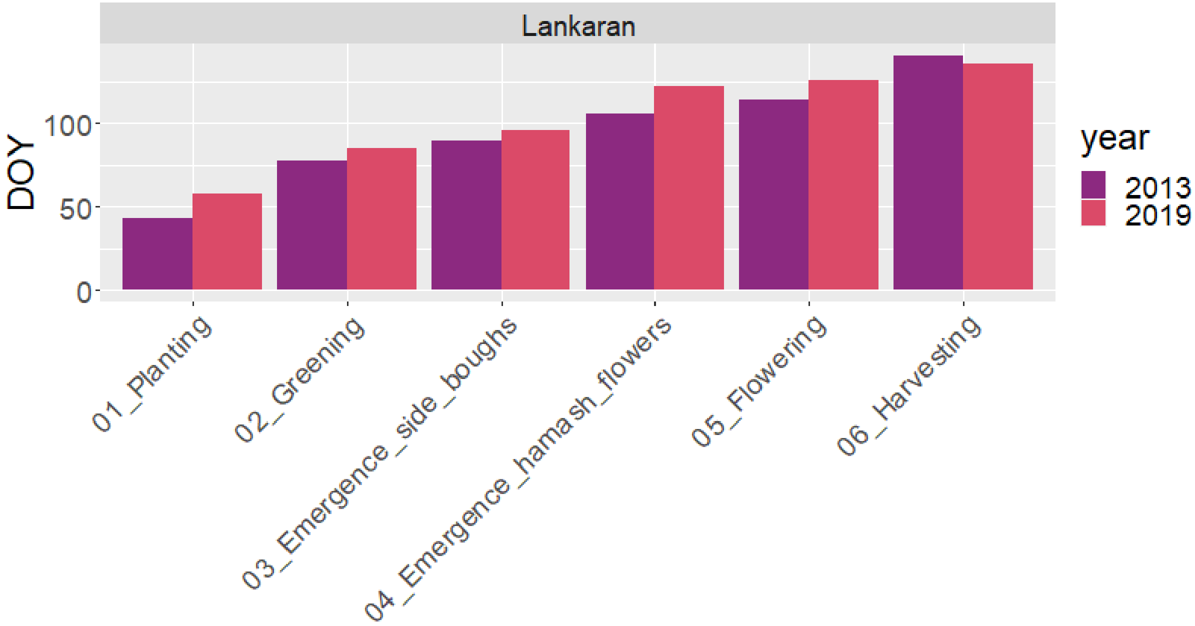

Figure 10: Phenological stages of potato. DOY = day of the year.

Table 6: Development stages of potato.

Development Stage	***Start***	***End***	***Start date***	***End date***
Stage A (Vegetative stage)	Seeding	Flowering	Feb 19	Apr 29
Stage B (Reproductive Stage)	Flowering	Harvest	Apr 30	May 18

Cucumber

Cucumber is one of the most important horticultural crops globally. It is a warm season crop and mostly planted in subtropical and temperate regions. Most suitable temperatures for growth and development are between 15°C and 32°C. High temperatures above 32°C, especially at the vegetative stage, may limit cucumber yield and quality, and can cause physiological injury to membrane lipids, carbon, and nitrogen metabolism (Zhao et al., 2011). Heat can also constrain photosynthesis and root growth (Xu et al., 2018). All these factors may translate into reduced yield and quality. Because of shallow root distribution and high water requirements, cucumber is also susceptible to drought (Li et al., 2014). Drought stress leads to various biochemical and physiological responses, which compromises cucumber growth and reduces yield (Li et al., 2018).

In Azerbaijan, cucumber is sown in early May, flowers in late June, and is harvested between late July and early August, on average (Figure 11). We defined two development stages, accordingly (Table 7).

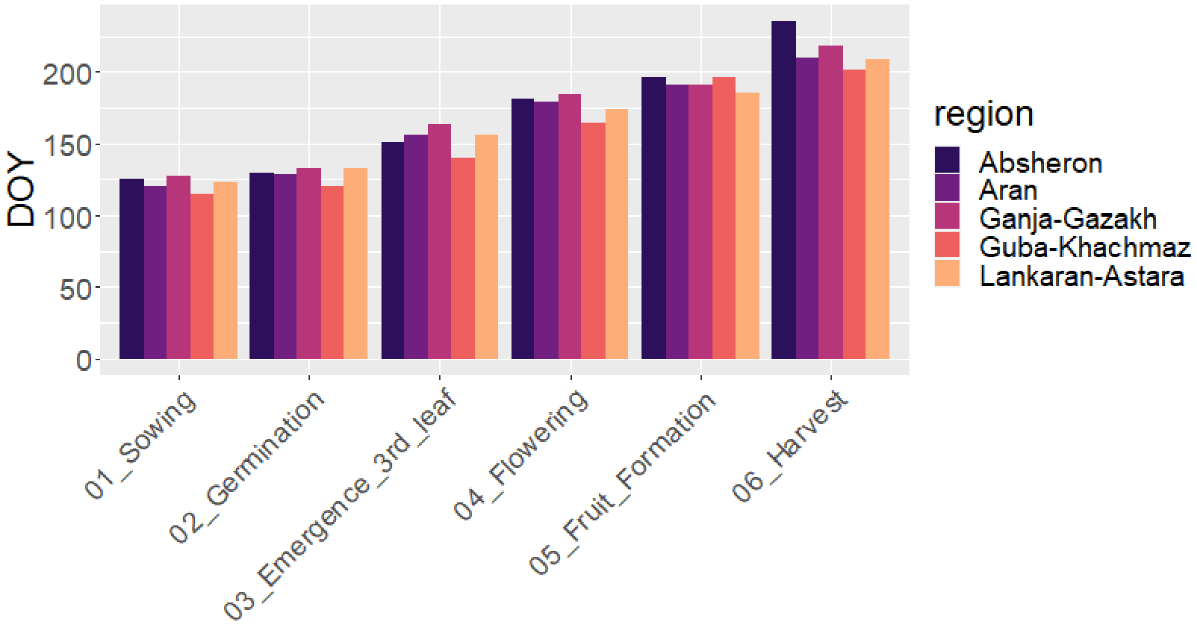

Figure 11: Phenological stages of cucumber. DOY = day of the year.

Table 7: Development stages of cucumber.

Development Stage	***Start***	***End***	***Start date***	***End date***
Stage A (Vegetative stage)	Seeding	Flowering	May 02	Jun 24
Stage B (Reproductive Stage)	Flowering	Harvest	Jun 25	Aug 03

Tomato

Tomato is an important vegetable that is consumed all over the world. Tomato grows under a wide range of climate conditions, with an optimal mean daily temperature range between 20°C and 25°C (Firon et al., 2006). Heat stress reduces tomato yield and quality, mainly by affecting male gametophyte development (Alsamir et al., 2021). Day temperatures above 26°C and night temperatures above 20° interrupt the fruit-set of most tomato cultivars (Lohar and Peat, 1998). However, modern, heat-tolerant genotypes can cope with higher temperatures (Pham et al., 2020). Cool temperatures also harm tomato yield because the plants are sensitive to chilling, which limits not only its productivity but also its geographical distribution (Allen and Ort, 2001; Ronga et al., 2018). Yield reductions occur if tomato plants experience temperatures below 10°C for more than 14 days or below 5°C for more than 6 to 8 days (Alsamir et al., 2021; www.omafra.gov.on.ca/english/crops/facts/info_tomtemp.htm). Temperatures below 10°C during flowering may affect pollination and cause fruit death (Alsamir et al., 2021).

In Azerbaijan, tomato is sown around early May, flowers in mid-June, and is harvested in early August, on average (Figure 12). We defined two development stages, accordingly (Table 8).

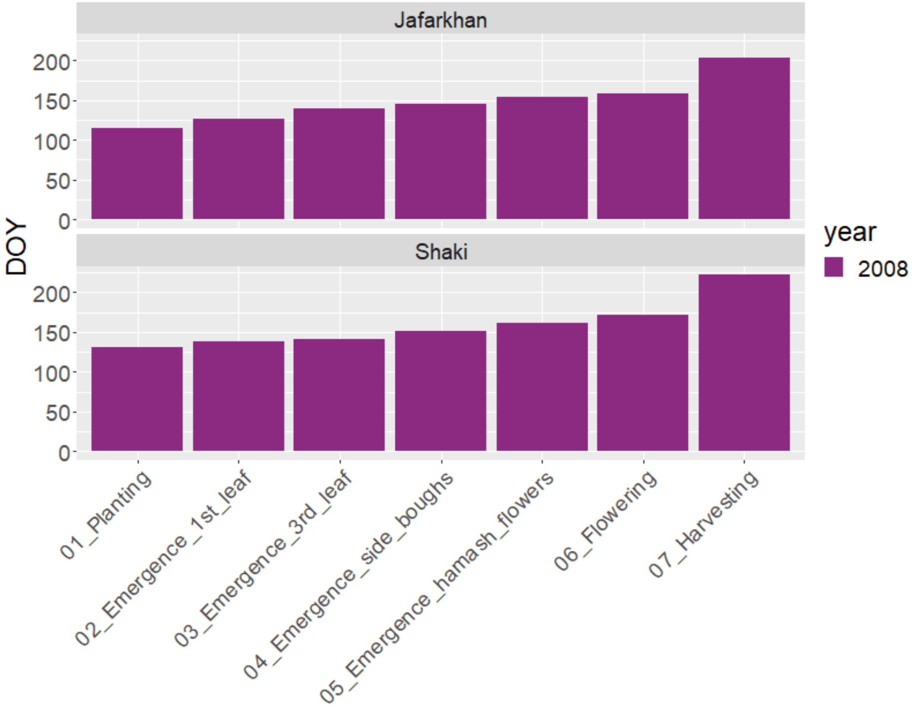

Figure 12: Phenological stages of tomato. DOY = day of the year.

Table 8: Development stages of tomato.

Development Stage	***Start***	***End***	***Start date***	***End date***
Stage A (Vegetative stage)	Seeding	Flowering	May 03	Jun 13
Stage B (Reproductive Stage)	Flowering	Harvest	Jun 14	Aug 01

Persimmon

Persimmon is one of the economically most important subtropical fruits. The deciduous tree is acclimated to a variety of climatic conditions, including subtropical regions (Zilkah et al., 2013). However, high temperatures and drought can reduce productivity: Most cultivars have an optimal temperature range between 20 and 25°C, and fruit size may be reduced if temperatures are below 15°C or higher than 30°C (George et al., 1997). The tree has lower fruit set if day temperatures are above 35°C (Zilkah et al., 2013). Although persimmon is resistant to cold temperature, floral and vegetative buds are damaged when exposed to low winter temperatures. After bud bursting, spring temperatures below -3.0 °C can damage or even kill floral buds (George et al., 1997).

In Azerbaijan, the shoots of persimmon start to swell in mid-March. The trees begin to flower around early May, and fruits ripen and are harvested by mid-October (Figure 13). We defined two development stages, accordingly (Table 9).

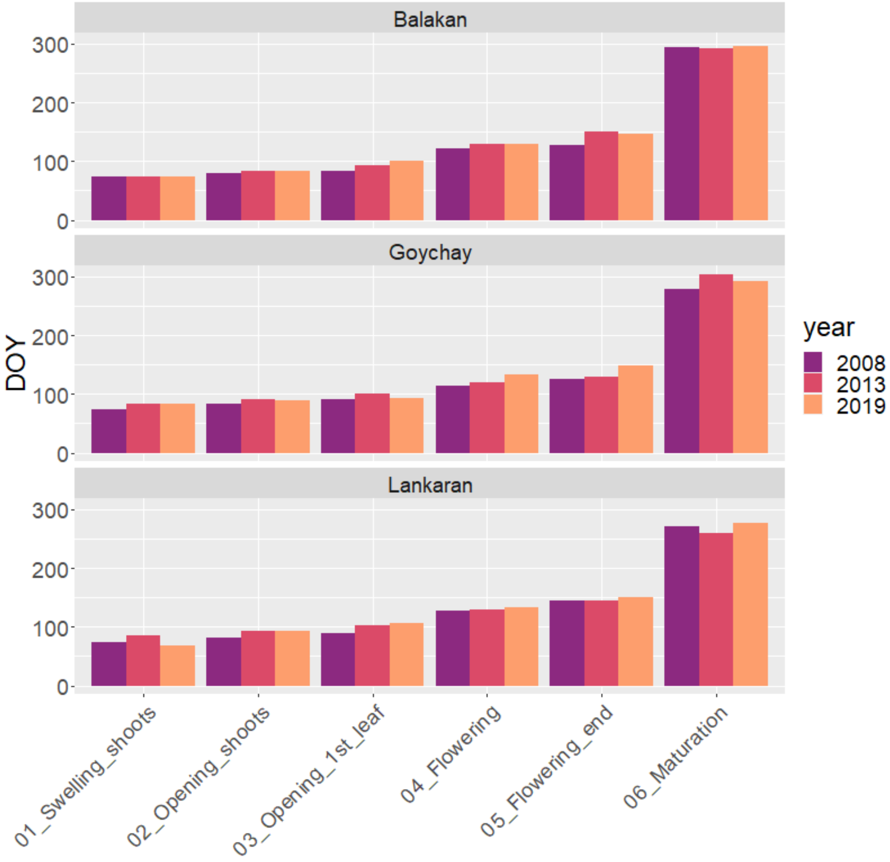

Figure 13: Phenological stages of persimmon. DOY = day of the year.

Table 9: Development stages of persimmon.

Development Stage	***Start***	***End***	***Start date***	***End date***
Stage A (Vegetative stage)	Shoot swelling	Flowering	Mar 17	May 06
Stage B (Reproductive Stage)	Flowering	Harvest	May 07	Oct 12

Pomegranate

Pomegranate is a fruit that is cultivated in many regions of the world, due to its high ability to adapt to a wide range of climate and soil conditions. Pomegranate has a high content of vitamins, minerals and antioxidants, and even shows positive effects in the treatment and prevention of cancer and other diseases (Lansky and Newman, 2007). Pomegranate is highly drought-resistant and thrives well in arid and semiarid areas, even under desert conditions (Rodríguez et al., 2012). However, in arid and semiarid conditions, to reach optimal growth, crop yield, and fruit quality, the crop requires regular irrigation throughout the dry season. It also requires low winter chill hours for breaking bud dormancy (Rodríguez et al., 2012). The fruit can withstand temperatures of -12 °C in winter and 42 °C in summer (Adiba et al., 2021).

In Azerbaijan, the shoots of pomegranate start to swell in late March. The trees begin to flower in mid-May, and fruits ripen and are harvested by early October (Figure 14). We defined two development stages, accordingly (Table 10).

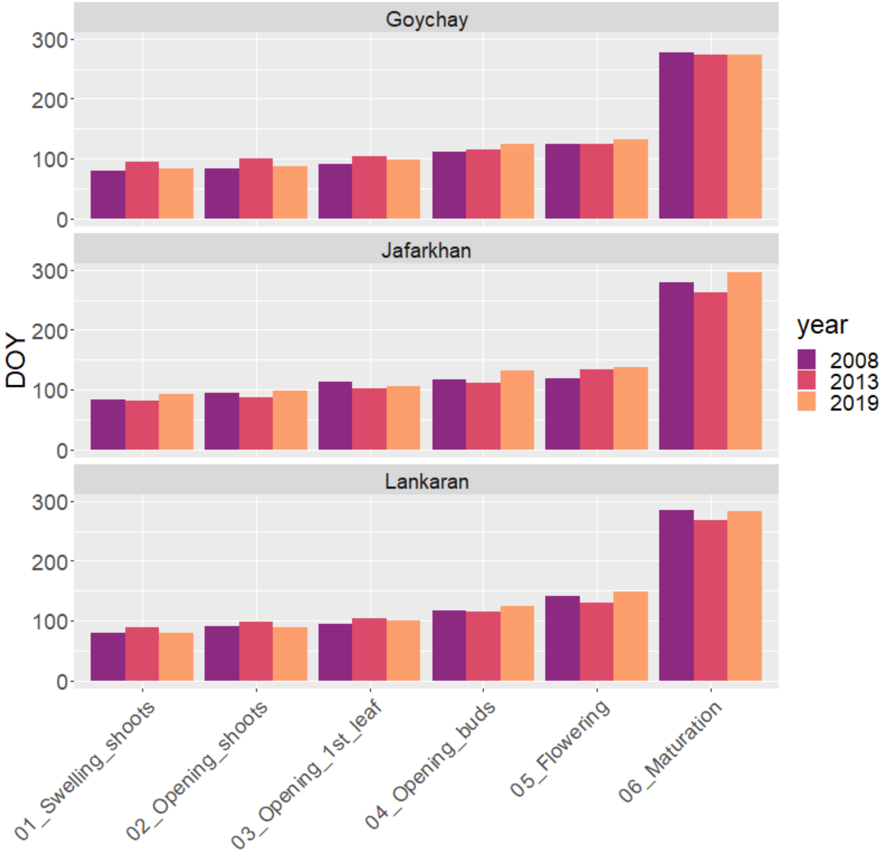

Figure 14: Phenological stages of pomegranate. DOY = day of the year.

Table 10: Development stages of pomegranate.

Development Stage	***Start***	***End***	***Start date***	***End date***
Stage A (Vegetative stage)	Shoot swelling	Flowering	Mar 26	May 11
Stage B (Reproductive Stage)	Flowering	Harvest	May 12	Oct 04

2.2.2 Crops assessed with Chill Unit models

We modelled two of the ten target crops, apple and hazelnut, with Chill Unit models (Table 1). These two crops predominantly depend on the amount of chill units that accumulate over the crop cycle, whereas extreme weather events mostly impact quality and aesthetical aspects (Fraga and Santos, 2021; Luedeling et al., 2011).

Chill units reflect the total amount of temperatures between 1.5 and 12.5 degrees Celsius that fruit and nut trees require to end winter dormancy and enter the flowering stage normally (Luedeling and Brown, 2011; Mehlenbacher, 1991; Salama et al., 2021). Chill units are essentially a conversion of daily temperatures, and are usually calculated for the period that starts when temperatures fall below 12.5 °C for the first time (typically in September or October) until the date when the buds of the fruit or nut trees burst in spring. For each phenological station, crop, and year, we determined the amount of chill units accumulated by the time of bud bursting by analyzing modelled grid-level temperature data at the stations (*ERA5-Land* dataset, see WP2). We then analyzed the ERA5-Land dataset for the whole country to examine where the amount of chill units accumulated at bud bursting has historically been reached at the end of the crop cycle. We assume that a location is suitable for production when, at the end of the crop cycle, the amount of accumulated chill units is at least as high as the amount accumulated at the time of bud bursting at the phenological stations (for more details, see chapter 4.2).

Apple

Apple is an important perennial fruit of the temperate regions that is grown throughout large parts of the northern hemisphere. Apple yields are more dependent on climatic mean conditions, particularly during spring, than on weather extremes (Li et al., 2020), but high temperatures above 30°C during flower bud initiation and above 26°C during flower bud development, drought conditions before harvest and low night temperatures can negatively affect production (Caprio and Quamme, 1999). Spring frost can also damage the quality of apples (Dalhaus et al., 2020), and the susceptibility of apple to frost damages may even increase under climate change (Unterberger et al., 2018). However, most important for proper plant development is the amount of winter chill temperatures (Cook and Jacobs, 2000; Maguylo et al., 2012; Tharaga et al., 2021), which correlates with fruit yield, size and quality (El Yaacoubi et al., 2020).

In Azerbaijan, the shoots of apple trees start to swell around mid-March. The trees begin to flower in mid-April, and fruits ripen and are harvested by early September (Figure 15). Apple buds bursted between April 01 and 08 at the station *Shaki* (Table 11).

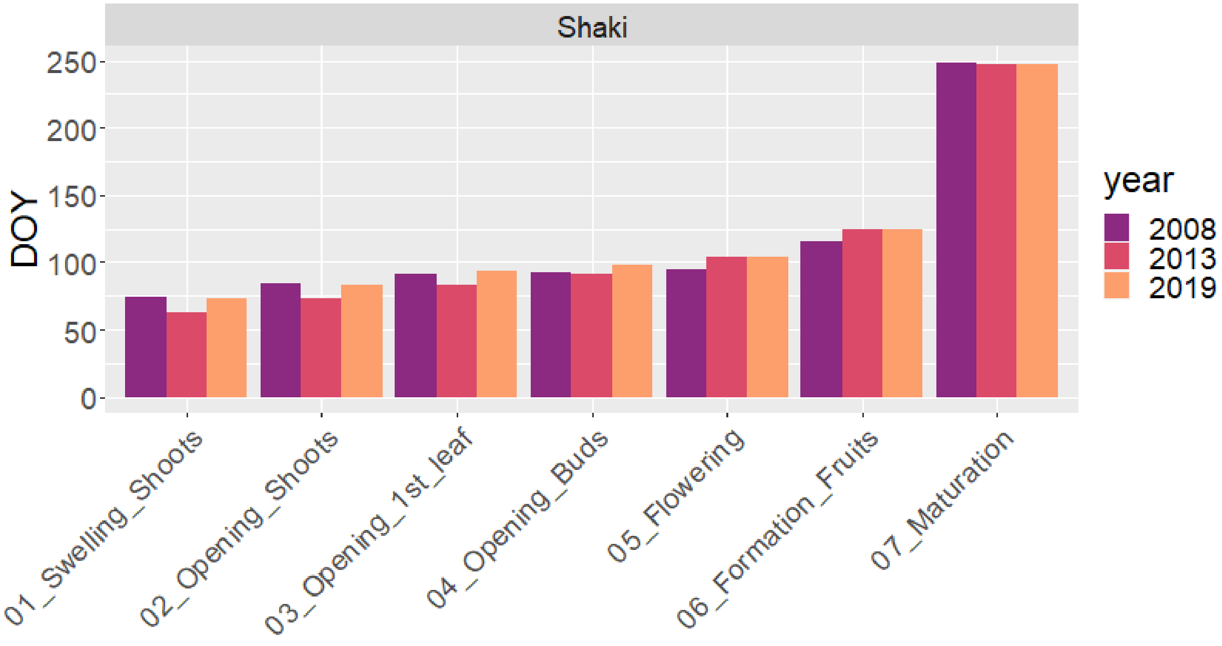

Figure 15: Phenological stages of apple. DOY = day of the year.

Table 11: Dates of bud bursting in apple.

Station	***Year***	***Bud bursting***
Shaki	2008	Apr 02
	2013	Apr 01
	2019	Apr 08

Hazelnut

Hazelnut is one of the most important tree nut crops in terms of worldwide production with a global hotspot in the Black Sea region (Cabo et al., 2020). In 2017, Azerbaijan was the third largest producer of Hazelnut globally (FAOSTAT 2022, https://www.fao.org/faostat/). Hazelnut is adapted to temperate climates and confined to areas with mild to warm summers, and cool winters (Črepinšek et al., 2012). Hazelnut trees have a low tolerance to heat, humidity and wind stress, and a high tolerance to extreme temperatures as low as -15 °C (Črepinšek et al., 2012). At the end of winter or during early spring, the dates of flowering and leafing are a function of the chilling requirements for buds and the heat requirements during the post-rest phase (Mehlenbacher, 1991). Chilling requirements differ between cultivars, but Hazelnut generally requires more chilling than most other species. The date of flowering varies greatly is very temperature-dependent and varies greatly from year to year (Piskornik et al., 2001).

In Azerbaijan, the shoots of hazelnut trees start to swell around mid-March. The trees begin to flower between early April and mid-May, and fruits ripen by August (Figure 16). Hazelnut buds bursted between March 30 and April 30 the stations *Lankaran* and *Balakan* (Table 12).

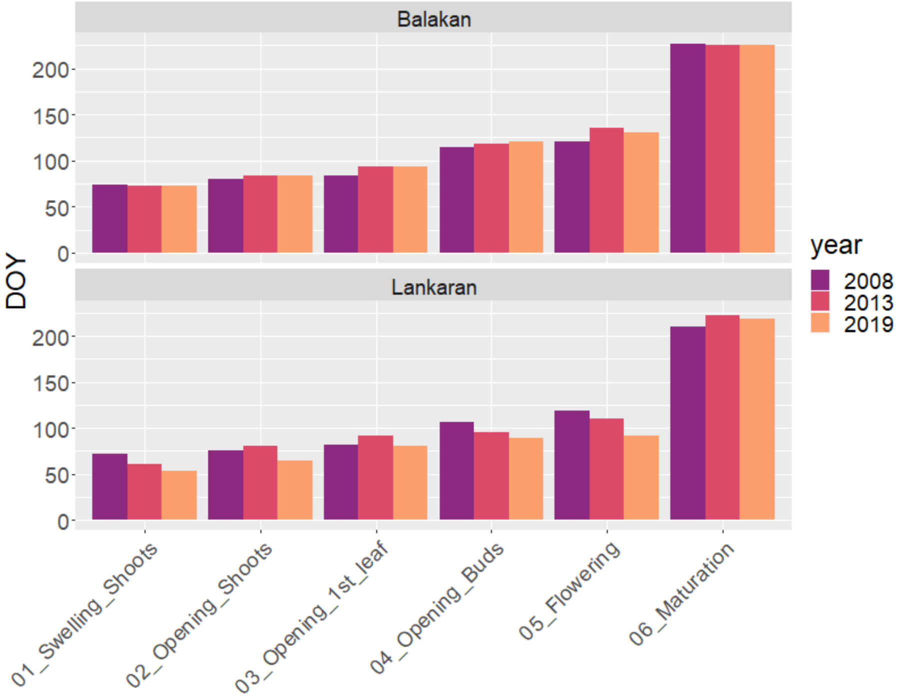

Figure 16: Phenological stages of hazelnut. DOY = day of the year.

Table 12: Dates of bud bursting in hazelnut.

Station	***Year***	***Bud bursting***		***Station***	***Year***	***Bud bursting***
Lankaran	2008	Apr 15		*Balakan*	2008	Apr 24
	2013	Apr 05			2013	Apr 28
	2019	Mar 30			2019	Apr 30

3. Characterization of Climate and Weather Conditions

3.1 Crops assessed with Random Forest models

We used modelled daily temperature and precipitation data that we corrected for cropland allocation (*ERA5-Land* and *CHIRPS*, see WP2 for further details) to characterize climatic mean and extreme weather conditions for each crop, development stage, year, and district. We calculated standard climatic mean conditions (average minimum, maximum, and mean temperature, precipitation and growing degree days (GDD), Table 13) and a total of six different extreme weather variables (Table 14). We defined heat wave events as periods of elevated temperatures for three or more consecutive days. For the characterization of day heat, day heat waves and GDD, we applied different heat thresholds for each crop and development stage, depending on the specific heat tolerance (Table 15). GDD reflect the accumulated sum of daily temperatures above 0°C and below the crop- and stage-specific heat threshold, GDD are therefore not recorded on days with frost, day heat or day heat wave events. The yearly values for each climatic mean and extreme weather variable, development stage and district are available in Annex A. The long-year average values and trends in these yearly values over the period from 2000 to 2019 are available in Annex B. Trends are in many cases not significant and should therefore be interpreted with caution.

Table 13: Climatic mean variables studied.

	name
PRCP	Precipitation
TAVG	*Average Temperature*
TMIN	Minimum Temperature
TMAX	Maximum Temperature
GDD	Growing Degree Days

Table 14: Definitions of studied extreme weather events.

	name	***condition***	***minimum spell***	***calculation of stage values:***
DH	Day heat	Max. temp. above a crop- and stage-specific heat threshold	-	Sum of daily temperature differences between max. temp. and respective heat threshold
DHW	Day heat wave		3 days	
NH	Night heat	Min. temp. >= 20°C	-	Sum of daily temperature differences between min. temp. and 20°C
NHW	Night heat wave		3 days	
HP	Heavy precipitation	Precip. >= 20 mm	-	Sum of daily differences between precip. and 20mm
FR	Frost	Min. temp. < 0°C	-	Sum of daily temperature differences between min. temp. and 0°C

Table 15: Crop- and stage-specific heat thresholds for the calculation of DH, DHW and GDD.

	Wheat	**Barley**	**Onion**	**Potato**	**Cucumber**	**Tomato**	**Persimmon**	**Pomegranate**
Stage A	30°C	30°C	30°C	30°C	30°C	30°C	42°C	42°C
Stage B	25°C	25°C	30°C	30°C	30°C	35°C	42°C	42°C
Stage C	34.3°C	34.3°C	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*

3.2 Crops assessed with Chill Unit models

Fruit and nut trees such as apple and hazelnut require adequate chilling for breaking their winter dormancy (Atkinson et al., 2013; Campoy et al., 2011; Mehlenbacher, 1991). We therefore analyzed the amount of chill units accumulated until bud bursting for each crop, station and year.

Chill Unit models simulate the amount of intermediate temperatures that a crop is exposed to, and require a record of hourly temperatures. We analyzed hourly temperatures available from the *ERA5-Land* dataset (see WP2 for further details) at the locations of the phenological stations. We converted hourly temperatures to hourly chill units, assuming that temperatures between 2.5°C and 9.2°C provide optimal chilling (Tharaga et al. 2021), whilst temperatures below 1.5°C and above 16°C have no chilling effect; higher temperatures even have an opposite effect (Table 16). We then summed up hourly chill units to daily chill units. If the daily sum of hourly chill units was negative, this sum was set to zero (Tharaga et al., 2021). We defined each crop cycle to start on August 1st and to end on July 31st of the next year, and accumulated daily chill units for this period. The relationship between daily average temperature, daily chill units, and accumulated chill units is illustrated in Figure 17 for the station *Shaki*: Chilling occurs in autumn and spring when temperatures are between 1.5 and 12.5°C, which is why accumulation starts mid-October, stagnates during winter when temperatures are low ("winter plateau"), resumes in early March, and reaches its maximum in mid-May when temperatures become too high. Chill unit accumulation curves for all years and stations are summarized in Figure 19; note that the winter plateau is largely absent.

We used the accumulation curves to determine for both apple and hazelnut how many chill units accumulated at each station and in each year until bud bursting. These values then serve as a reference to approximate the suitability for a fruit (see chapter 4.2). We assume that the amounts of chill units accumulated until bud bursting reflect the amounts that are actually required by each of the crops. On average, apple requires less chilling than hazelnut (Figure 18). The increase in accumulated chill units at bud bursting from 2008 to 2019 suggests there is a climate effect (Figure 18), but there is no such evidence when considering the full record for the last 20 years (Figure 19).

To map crop suitability, we repeated the above procedure of deriving accumulated chill units at the locations of the stations for all *ERA5-Land* grid cells in the country. For each crop cycle, we calculated and mapped the amount of chill units accumulated by July 31st (Figure 20). We then derived a long-year average that we used for crop suitability classification (Figure 21). We assume that a grid cell is suitable for production if, at the end of a crop cycle, it has accumulated at least as many chill units as are accumulated at the time of bud bursting. We also assume that the amount of chill units accumulated by the time of bud bursting are equivalent to the amount that is actually required for bud bursting.

Table 16: Conversion of hourly temperatures to hourly chill units, adapted from Tharaga et al. 2021.

Hourly temperature (T)	***Hourly chill unit***
< 1.5	0
1.5 <= T <= 2.5	0.5
2.5 <= T <= 9.2	1
9.2 <= T <= 12.5	0.5
12.5 <= T <=16.0	0
16.0 <= T <= 18.0	-0.5
> 18.0	-1

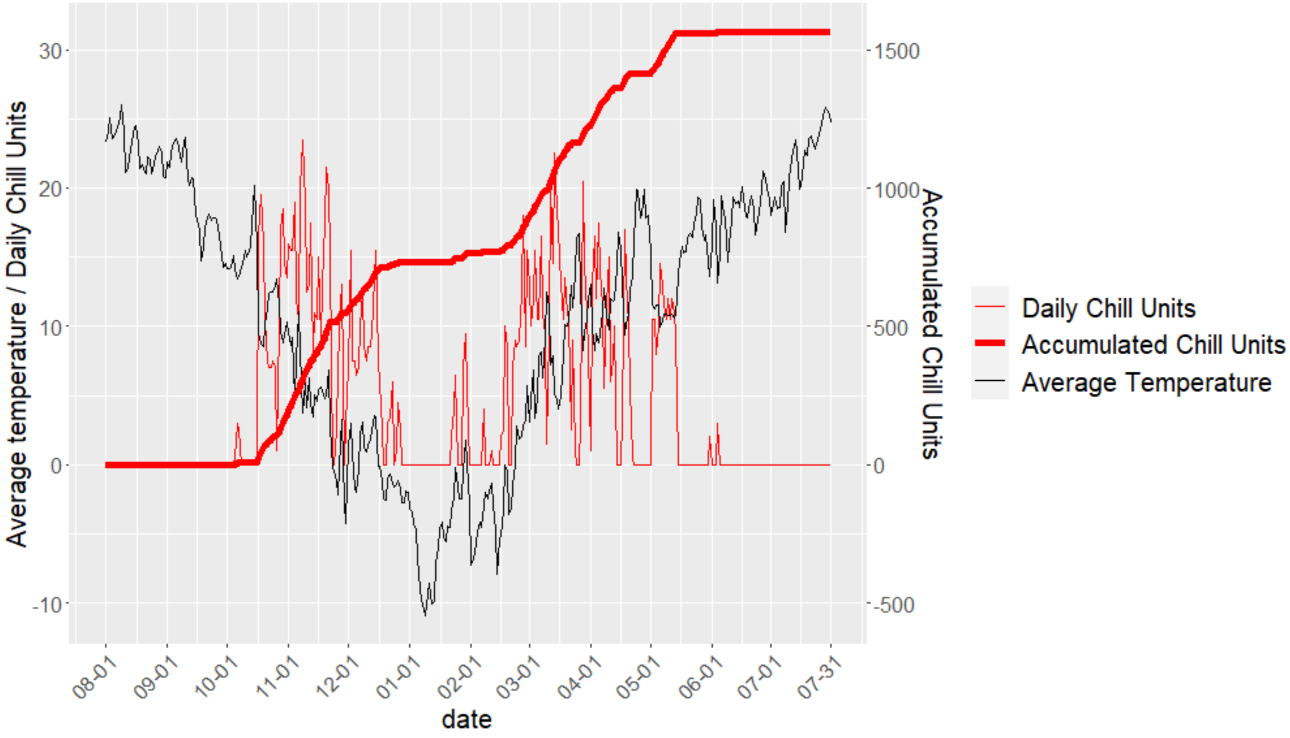

Figure 17: Daily average temperature, daily chill units, and accumulated chill units from August 1 2007, to July 31 2008 at Shaki station.

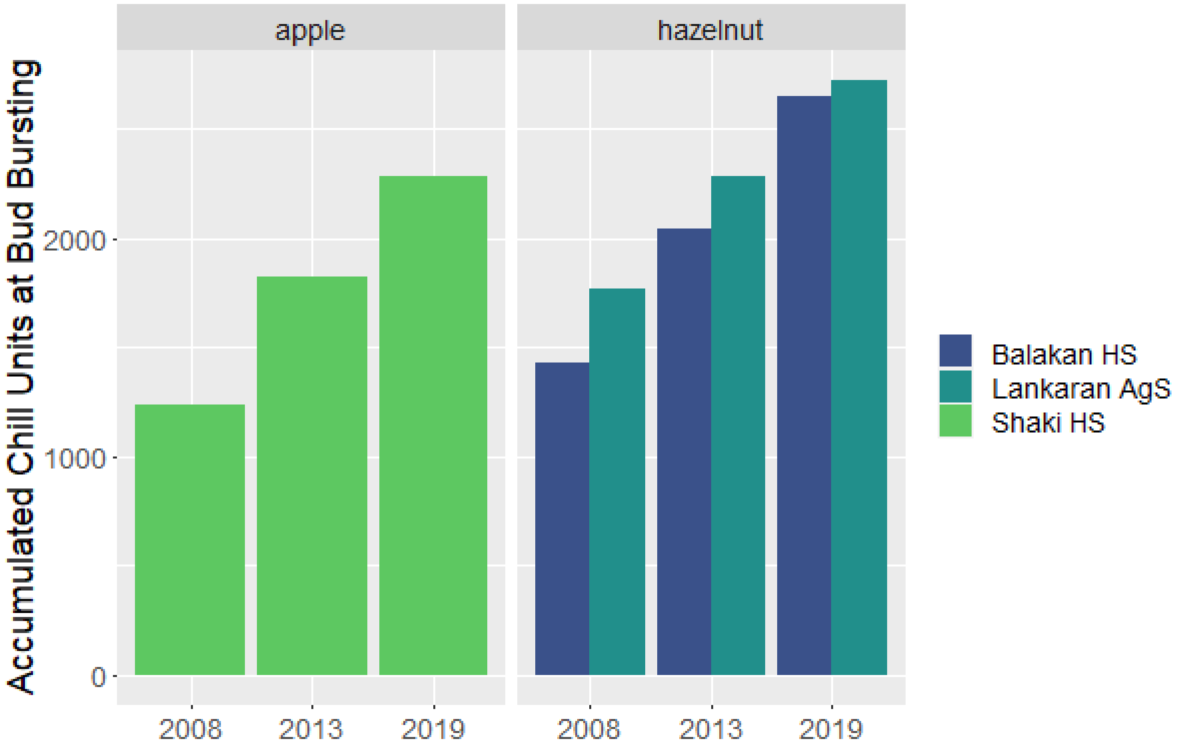

Figure 18: Accumulated Chill Units at the time of bud bursting in apple and hazelnut, at three agrometeorological stations.

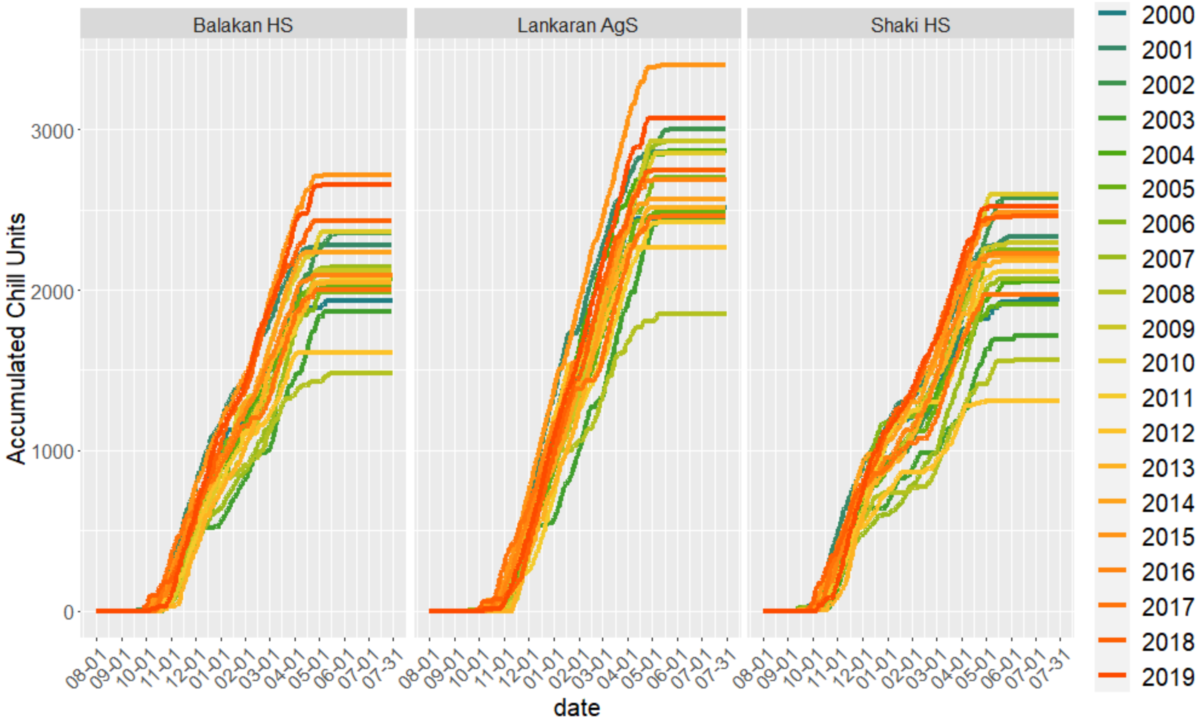

Figure 19: Accumulation of Chill Units during each crop cycle between 2000 and 2019, at three agrometeorological stations.

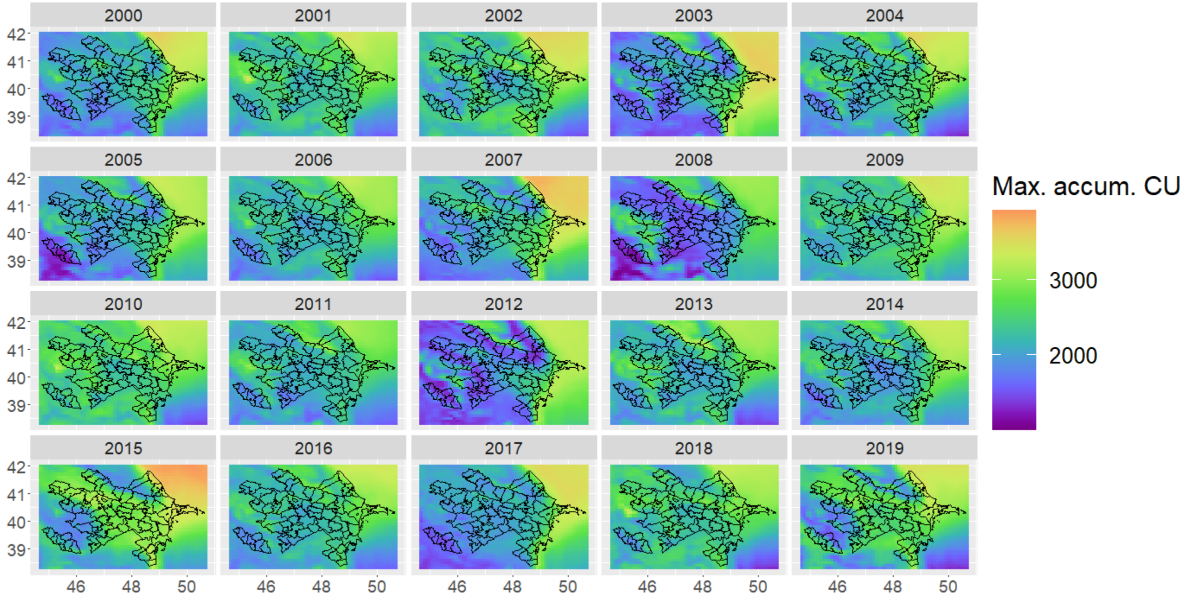

Figure 20: Yearly maximum amount of chill units accumulated throughout the crop cycle. Each year refers to the end of the crop cycle (based on modelled temperature data from ERA5-Land).

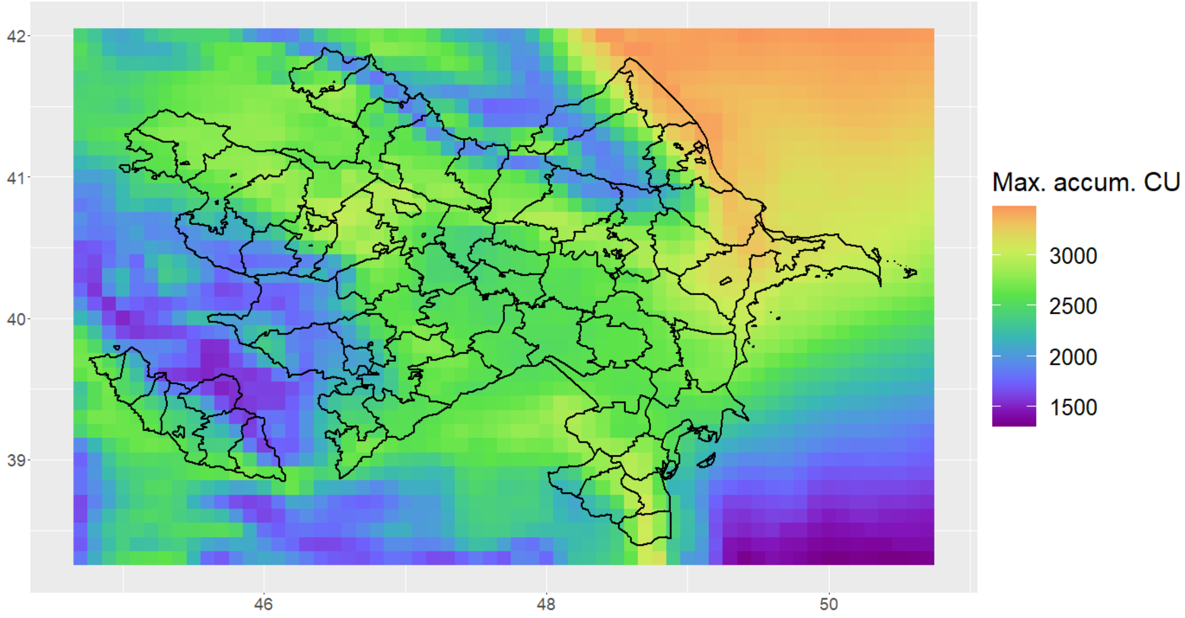

Figure 21: Long-year (2000-2019) average maximum amount of chill units accumulated at the end of a crop cycle (based on modelled temperature data from ERA5-Land).

4. Yield Models and Historical Crop Suitability

4.1 Crops assessed with Random Forest models

To predict historical yields with climatic mean and weather extreme variables, we used Random Forest models, a nonparametric machine learning algorithm (Breiman, 2001). Random Forest models have been widely applied in crop yield prediction (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) and are particularly suitable for our purposes because they can handle collinearity among the input data, a common issue for datasets that include many climate and weather variables (Breiman, 2001). However, whilst collinearity is not a problem for prediction, it can inflict on assessments of variable importance (Schierhorn et al., 2021). Therefore, prior to running the models, we assessed the collinearity of the predictor variables and reduced these in an iterative procedure until a sufficiently low level of collinearity was reached. Moreover, we excluded technological improvements that raise yields in the longer run (such as optimized fertilization and pesticide application, till practices, cultivar selection and mechanization) by detrending the yield data using a linear regression against time (Lu et al., 2017). Different districts may have different agricultural policies, technological standards, and cropping practices, which we accounted for by including a district identifier in our models, similar to a random effect in a regression model. We limited our analysis to the 50 districts with the highest long-year (2000-2019) average sown area for wheat and barley, and to the 25 districts with the highest long-year average sown area for the remaining crops. For each crop, we averaged the results of 50 model runs. In each run, we randomly assigned 70% of the observations as training dataset to predict the values of the remaining 30%, and assessed the model quality by calculating the R^2-value between observed and predicted yield levels. For each predictor variable, we assessed the mean variable importance across all model runs, expressed as the increase in mean squared error (%IncMSE) that the model would experience if the respective variable was excluded from the analysis. This permits to identify the variables that are most important in determining historical yield levels. The higher the %IncMSE value is for a given variable, the more would the predictive power of the model suffer if this variable would not be available. Note that the %IncMSE values are only comparable within one model, i.e. they cannot be compared to each other for different crops. We also calculated partial dependencies and plotted them to assess the functional relationships between climatic means or weather extremes and predicted yields. To obtain a measure of variable importance at the district level, we calculated the Pearson correlation coefficient between the yield data and all climate and weather variables for each district and crop development stage

Wheat

The Random Forest models for wheat had an average R² of 0.76. There is considerable interannual variability in wheat yields in Azerbaijan (https://maxhofmann.shinyapps.io/AZE_statistics/) and our models seem to explain that variation fairly well. However, wheat is irrigated in Azerbaijan (chapter 2.1.2, Figure 3), and irrigation can compensate negative effects of climate and weather on yield. Overall, climatic mean variables were more important that weather extremes. The most important variable was precipitation (PRCP) during phase A, followed by maximum temperature (TMAX) in phase C and frost (FR) in phase A (Figure 22). PRCP during phase A and had a negative relationship with yield (Figures 23), arguably due to excessive amounts of rain that cause flooding and water-logging (Malik et al., 2002). Maximum temperature (TMAX) is positively correlated with yield in phase C, and also in phase B, which is surprising because wheat should be particularly sensitive to heat during these stages (Farooq et al., 2011). The dry heat wave (DHW) variable shows a similar association with yield in phase C (Figure 24). High amounts of negative accumulated frost temperatures (FR) in phase A were associated with higher yields, which is also surprising, because frost can actually damage seedlings. On the district-level, there is low agreement among districts with regard to positive and negative associations between climate/weather variables and yield (Figure 25). For example, precipitation (PRCP) is negatively correlated with yield in some districts (e.g. Masally, Jebrayil), but positively in others (Agsu, Babek). Strikingly, maximum temperature (TMAX) in phase C is negatively correlated with yield in most districts, even though the partial dependence is positive on the country level (Figure 23). In Jalilabad, where wheat production and the amount or irrigated areas is highest (Figures 2 and 3), there are, with the exception of GDD in phase C, little negative associations between predictor variables and yield (Figure 23).

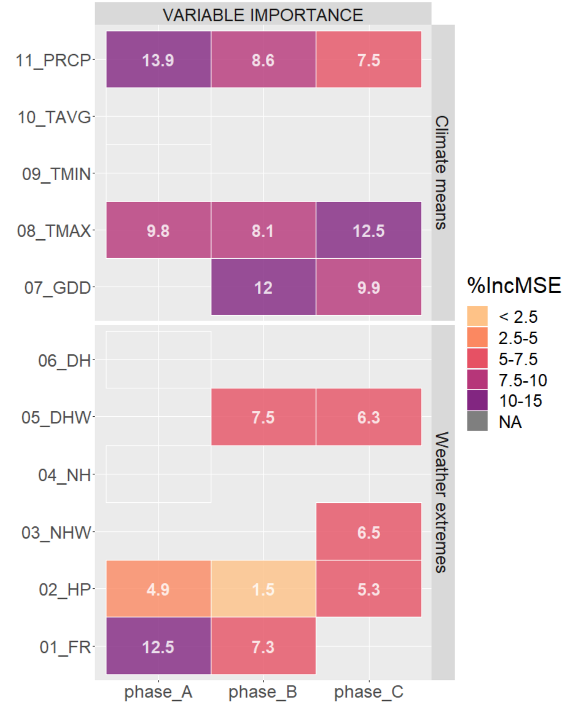

Figure 22: Variable importance for wheat. Darker colors indicate higher variable importance for yield prediction.

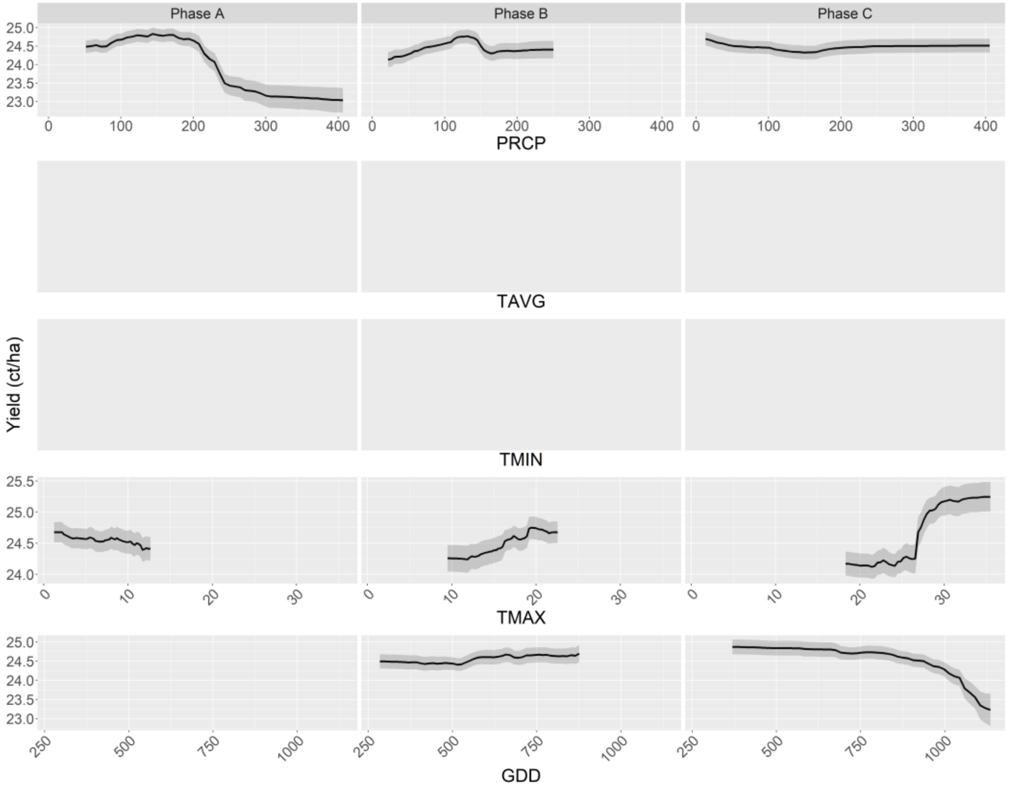

Figure 23: Partial dependencies of climatic mean variables and wheat yield. The shaded area around the lines represents one standard deviation.

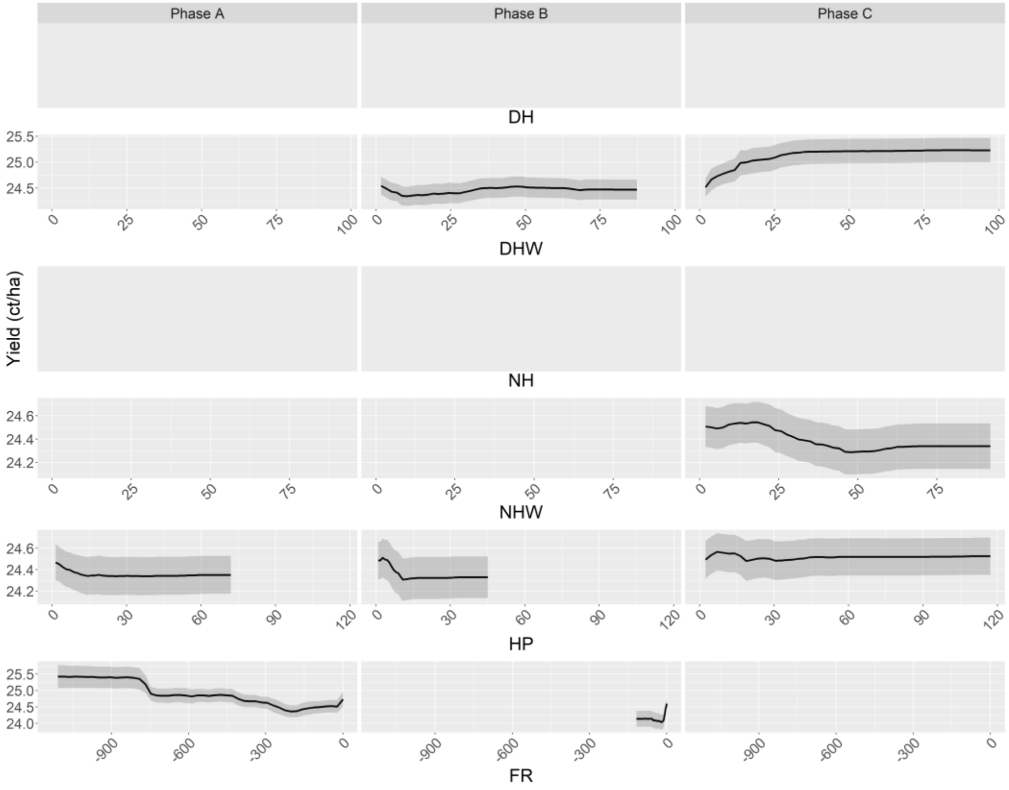

Figure 24: Partial dependencies of extreme weather variables and wheat yield. The shaded area around the lines represents one standard deviation.

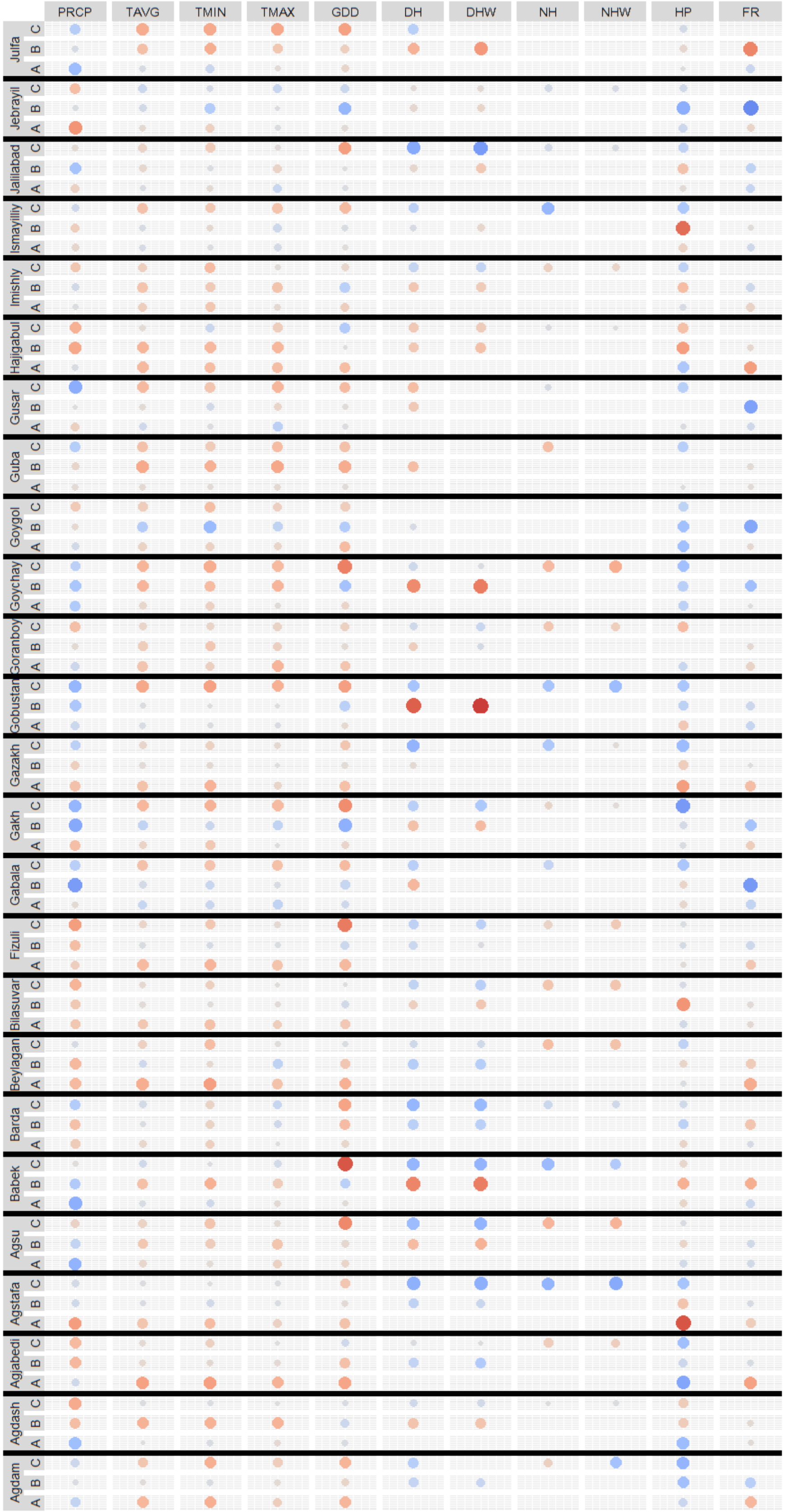

Figure 25: Variable importance for the 50 districts with most sown area for wheat, expressed as correlation coefficient with yield. The darker and larger the dot, the more correlated a variable is to yield levels. Red circles indicate negative correlations, blue circles indicate positive correlations. Frost is measured in accumulated negative temperatures, so blue circles imply that high amounts of frost are associated with low yield.

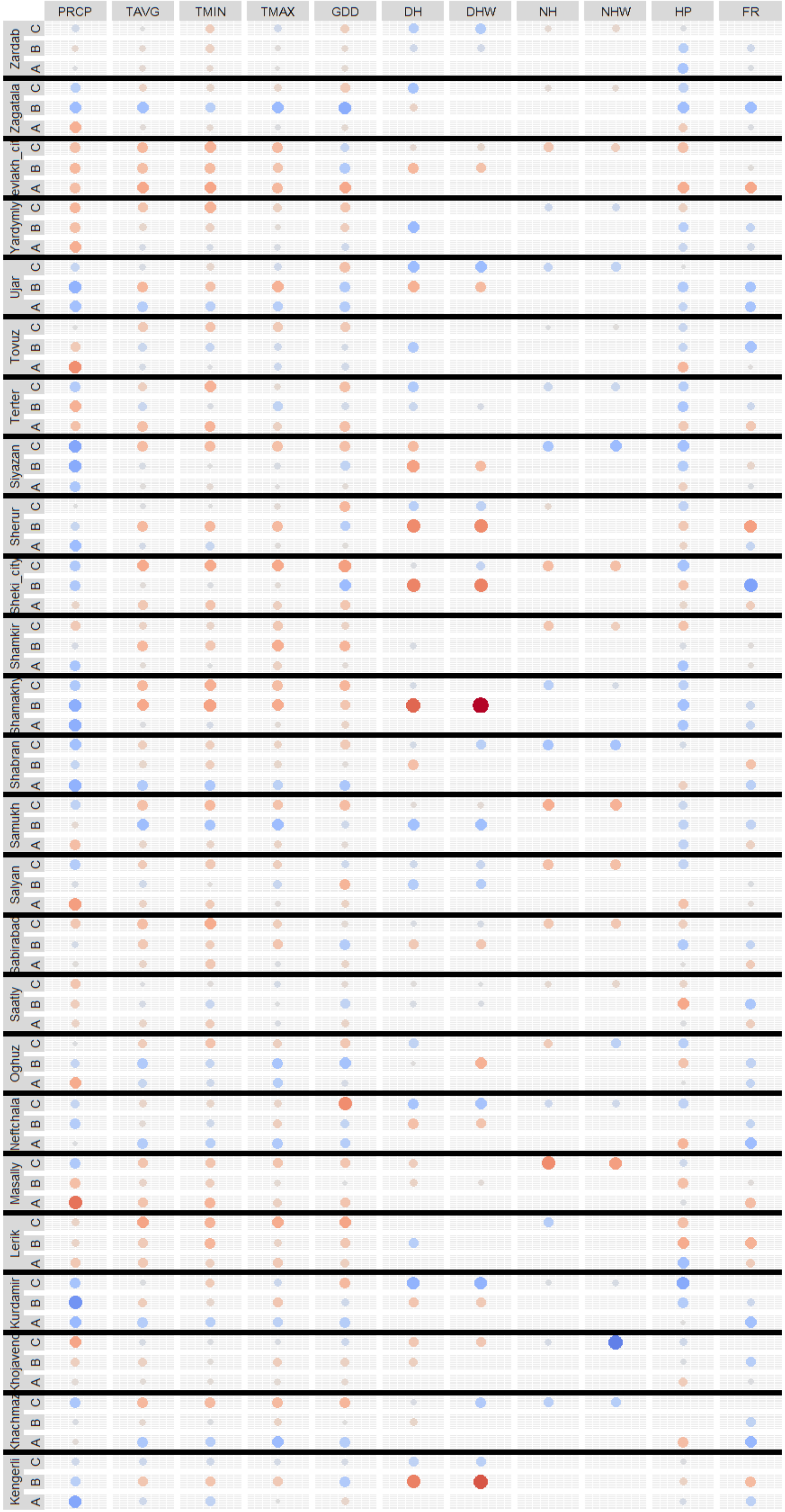

Figure 25 (continued): Variable importance for the 50 districts with most sown area for wheat, expressed as correlation coefficient with yield. The darker and larger the dot, the more correlated a variable is to yield levels. Red circles indicate negative correlations, blue circles indicate positive correlations. Frost is measured in accumulated negative temperatures, so blue circles imply that high amounts of frost are associated with low yield.

Barley

The Random Forest models for barley had an average R² of 0.68. There is considerable interannual variability in wheat yields in Azerbaijan (https://maxhofmann.shinyapps.io/AZE_statistics/) and our models seem to explain that variation fairly well. However, barley is irrigated in Azerbaijan (chapter 2.1.2, Figure 3), and irrigation can compensate negative effects of climate and weather on yield. The most important variables were maximum temperature (TMAX) during phase B and C, and frost (FR) and precipitation (PRCP) during phase A (Figure 26). As for wheat, we detect an increase in yield with increasing maximum temperature (TMAX) in phase B and C (Figure 27). This is surprising, because the literature suggests that barley is susceptible to high temperatures during anthesis (Hossain et al., 2012; Ugarte et al., 2007). High amounts of precipitation in phase A are associated with lower yields, which signals the importance of excessive rain and water logging during this phase (Malik et al., 2002). High amounts of negative accumulated frost temperatures (FR) in phase A were associated with higher yields (Figure 28), which is also surprising, because frost can actually damage seedlings. On the district level, the variables that are most negatively associated with barley yields are day heat (DH) and day heat waves (DHW) in phase B, for example in Kengerli, Goychay and Gobustan (Figure 29).

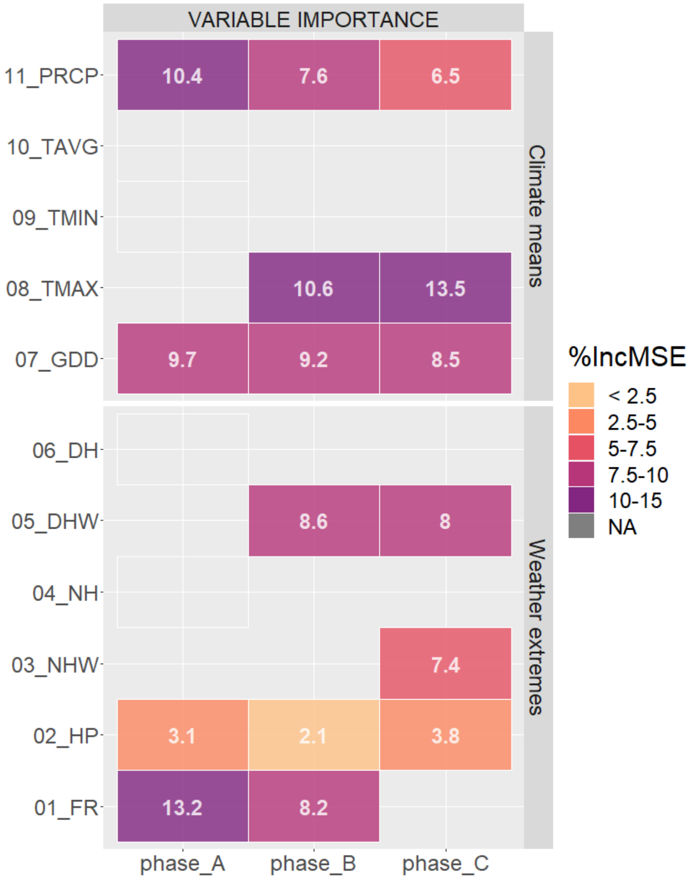

Figure 26: Variable importance for barley. Darker colors indicate higher variable importance for yield prediction.

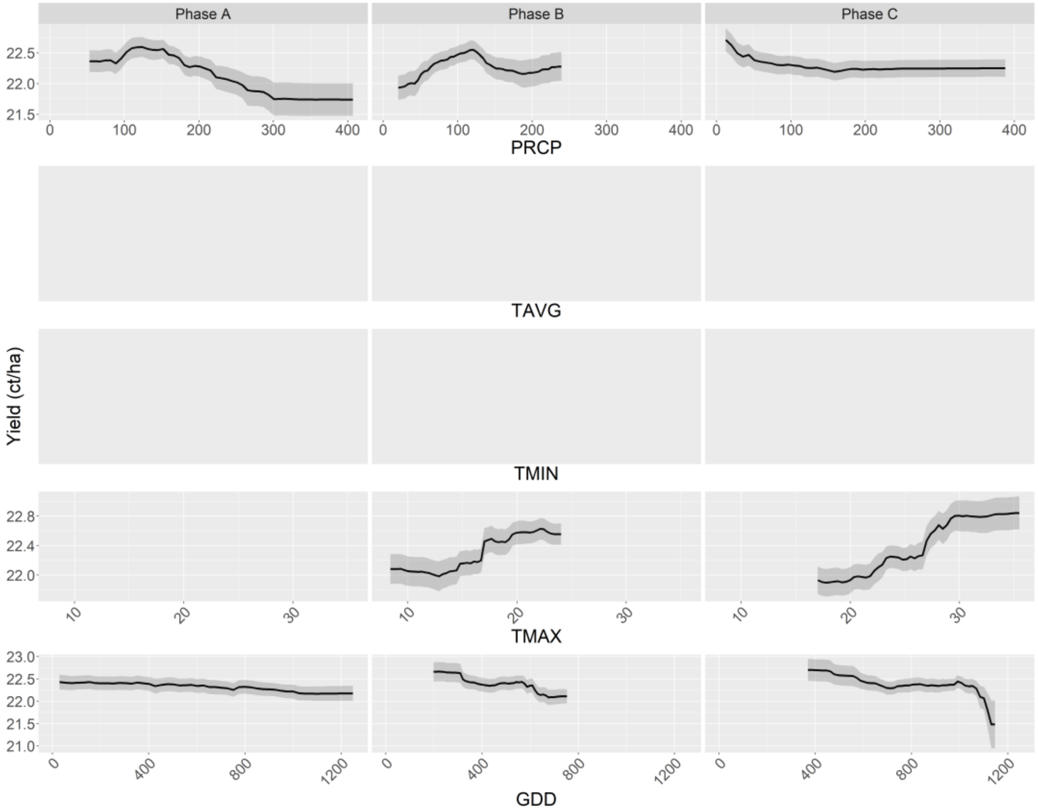

Figure 27: Partial dependencies of climatic mean variables and barley yield. The shaded area around the lines represents one standard deviation.

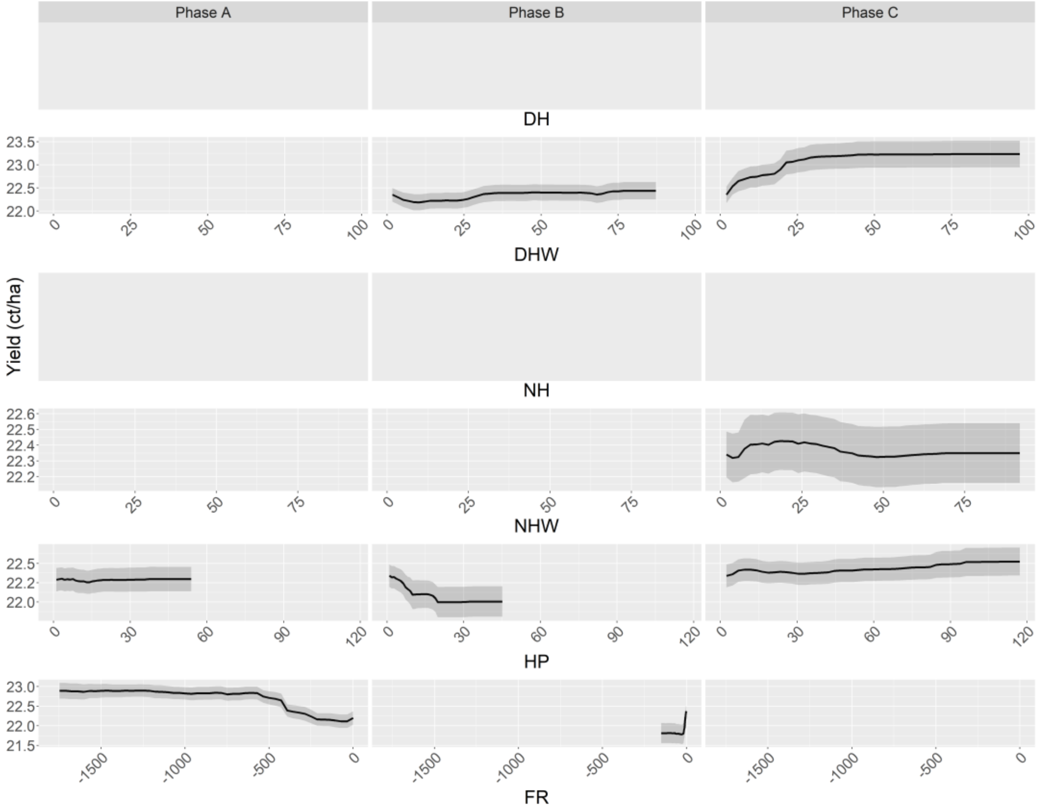

Figure 28: Partial dependencies of extreme weather variables and barley yield. The shaded area around the lines represents one standard deviation.

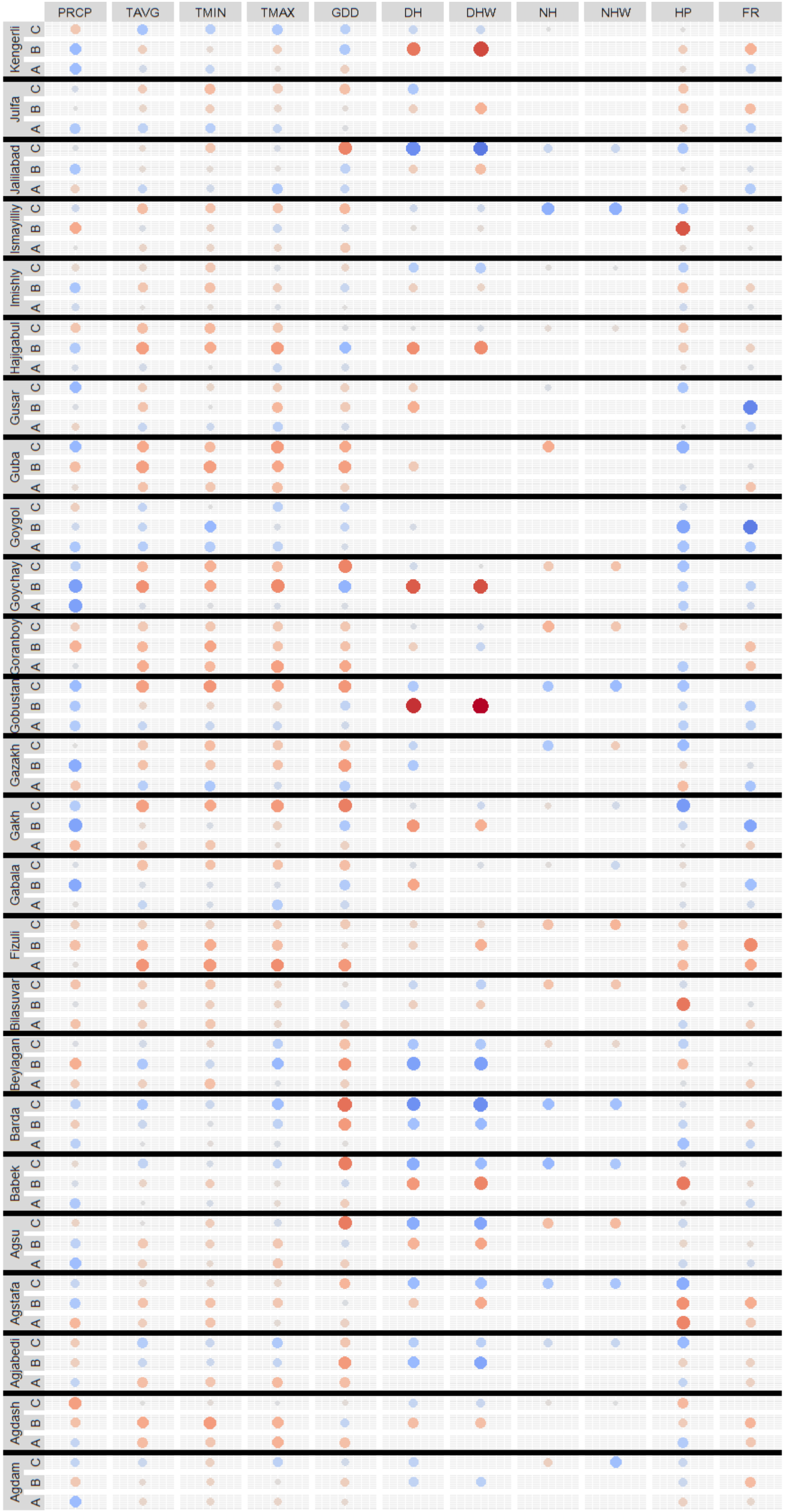

Figure 29: Variable importance for the 50 districts with most sown area for barley, expressed as correlation coefficient with yield. The darker and larger the dot, the more correlated a variable is to yield levels. Red circles indicate negative correlations, blue circles indicate positive correlations. Frost is measured in accumulated negative temperatures, so blue circles imply that high amounts of frost are associated with low yield.

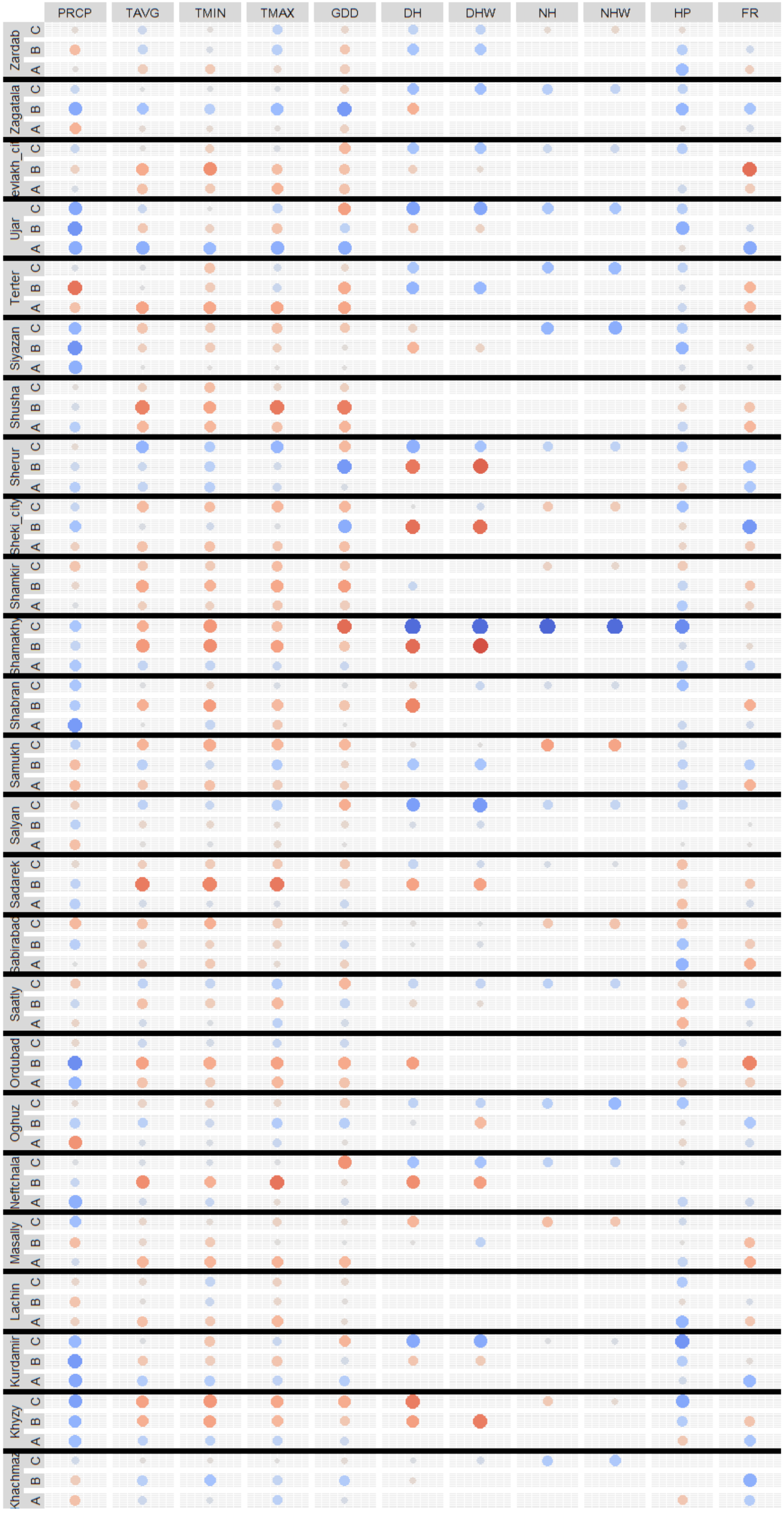

Figure 29 (continued): Variable importance for the 50 districts with most sown area for barley, expressed as correlation coefficient with yield. The darker and larger the dot, the more correlated a variable is to yield levels. Red circles indicate negative correlations, blue circles indicate positive correlations. Frost is measured in accumulated negative temperatures, so blue circles imply that high amounts of frost are associated with low yield.

Onion

The Random Forest models for onion had an average R^2 of 0.67. The most important variables were growing degree days (GDD) during phase B, day heat waves (DHW) and frost (FR) during phase A, and night heat waves (NHW) during phase B (Figure 30). The relationship of these variables with yield is clearest for GDD in phase B, which is highly positively associated with yield (Figure 31), but we had expected that GDD would be more important during phase A, when the plants are most dependent on adequate growth temperatures. High amounts of day heat waves (DHW) are associated with higher yields (Figure 32), but there is high uncertainty in the partial dependence estimates for high DHW values, probably because agreement among districts is rather low for this variable (Figure 33). Notably, the districts of Yevlakh, Ujar and Agdash show largely negative correlations for heat variables that are either weakly or strongly positively correlated with yield in other districts. For the three districts where onion production is highest (Shamkir, Barda and Agdam; Figure 2), the correlations between climate/weather variables and yield are generally low (Figure 33).

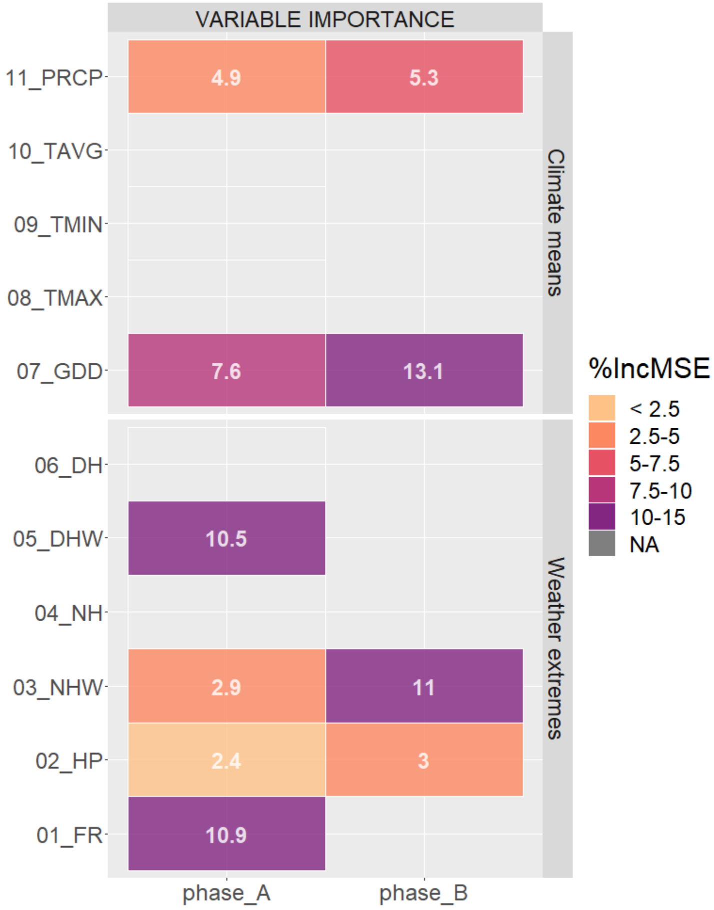

Figure 30: Variable importance for onion. Darker colors indicate higher variable importance for yield prediction.

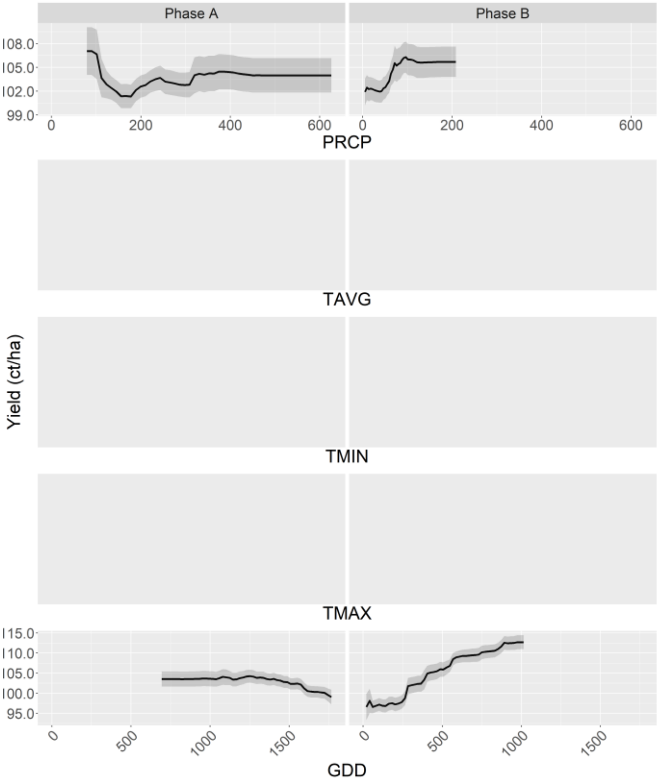

Figure 31: Partial dependencies of climatic mean variables and onion yield. The shaded area around the lines represents one standard deviation.

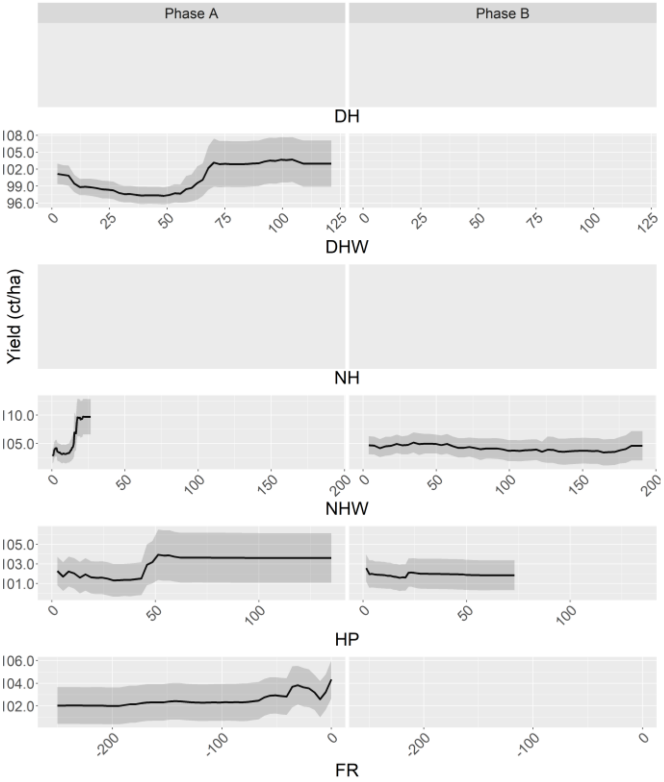

Figure 32: Partial dependencies of extreme weather variables and onion yield. The shaded area around the lines represents one standard deviation.

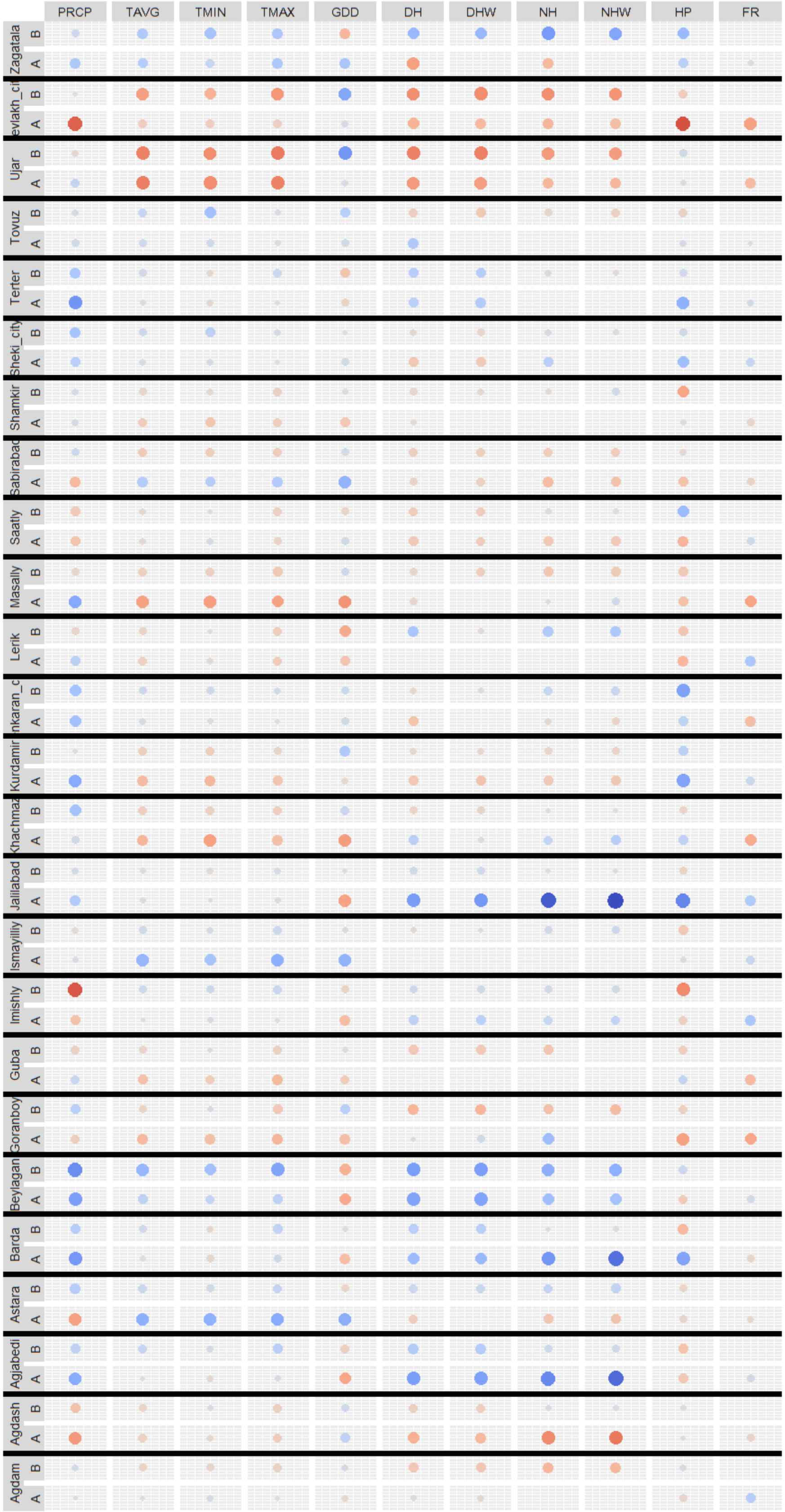

Figure 33: Variable importance for the 25 districts with most sown area for onion, expressed as correlation coefficient with yield. The darker and larger the dot, the more correlated a variable is to yield levels. Red circles indicate negative correlations, blue circles indicate positive correlations. Frost is measured in accumulated negative temperatures, so blue circles imply that high amounts of frost are associated with low yield.

Potato

With an average R² of 0.71, the potato models seem to have performed very well. Maximum (TMAX) and minimum temperature (TMIN) variables and frost (FR) in phase A were most important (Figure 34). However, the functional relationships between climate/weather variables and yield are rather unclear (Figures 35 and 36), probably due to relatively low interannual yield variation. There is a drop in yield when TMAX in phase B is above 23°C (Figure 35), however the effect on yield is rather small and there is high uncertainty in the estimations. Also, district-level variable importances show low agreement (Figure 37), making it difficult to draw conclusions from these results. Potato production and yield are highest in the districts of Tovuz, Gedebey, Shamkir and Jalilabad (Figure 2), but these do not show any particular patterns with regard to variable importances (Figure 37).

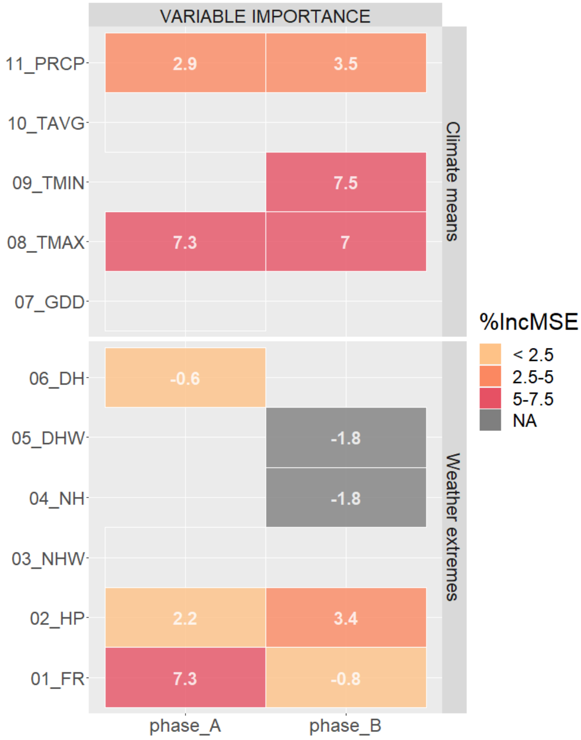

Figure 34: Variable importance for potato. Darker colors indicate higher variable importance for yield prediction.

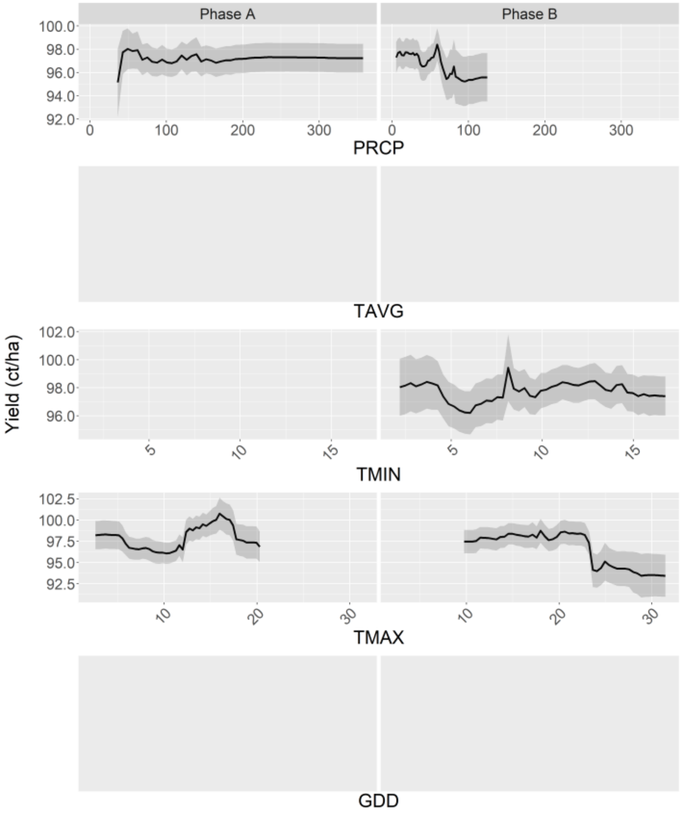

Figure 35: Partial dependencies of climatic mean variables and potato yield. The shaded area around the lines represents one standard deviation.

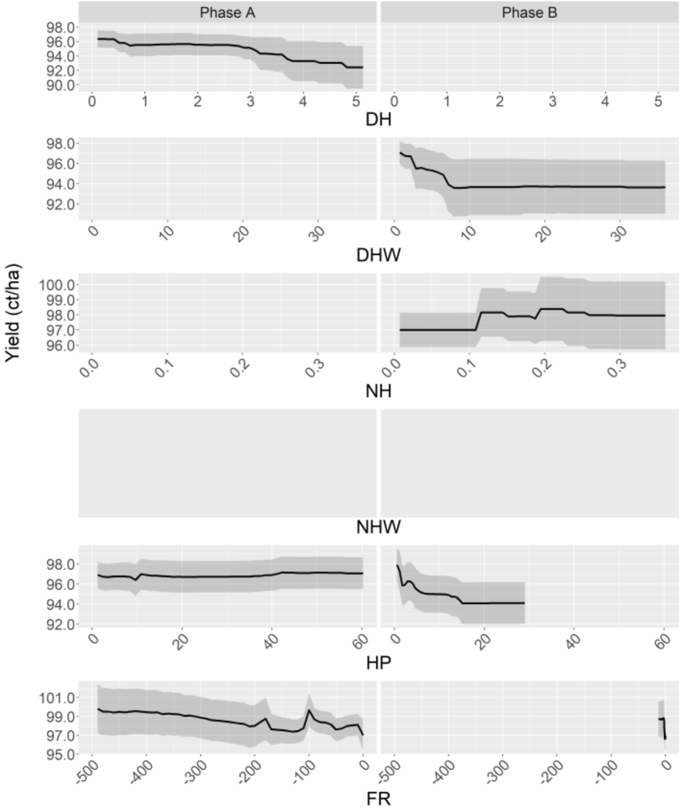

Figure 36: Partial dependencies of extreme weather variables and potato yield. The shaded area around the lines represents one standard deviation.

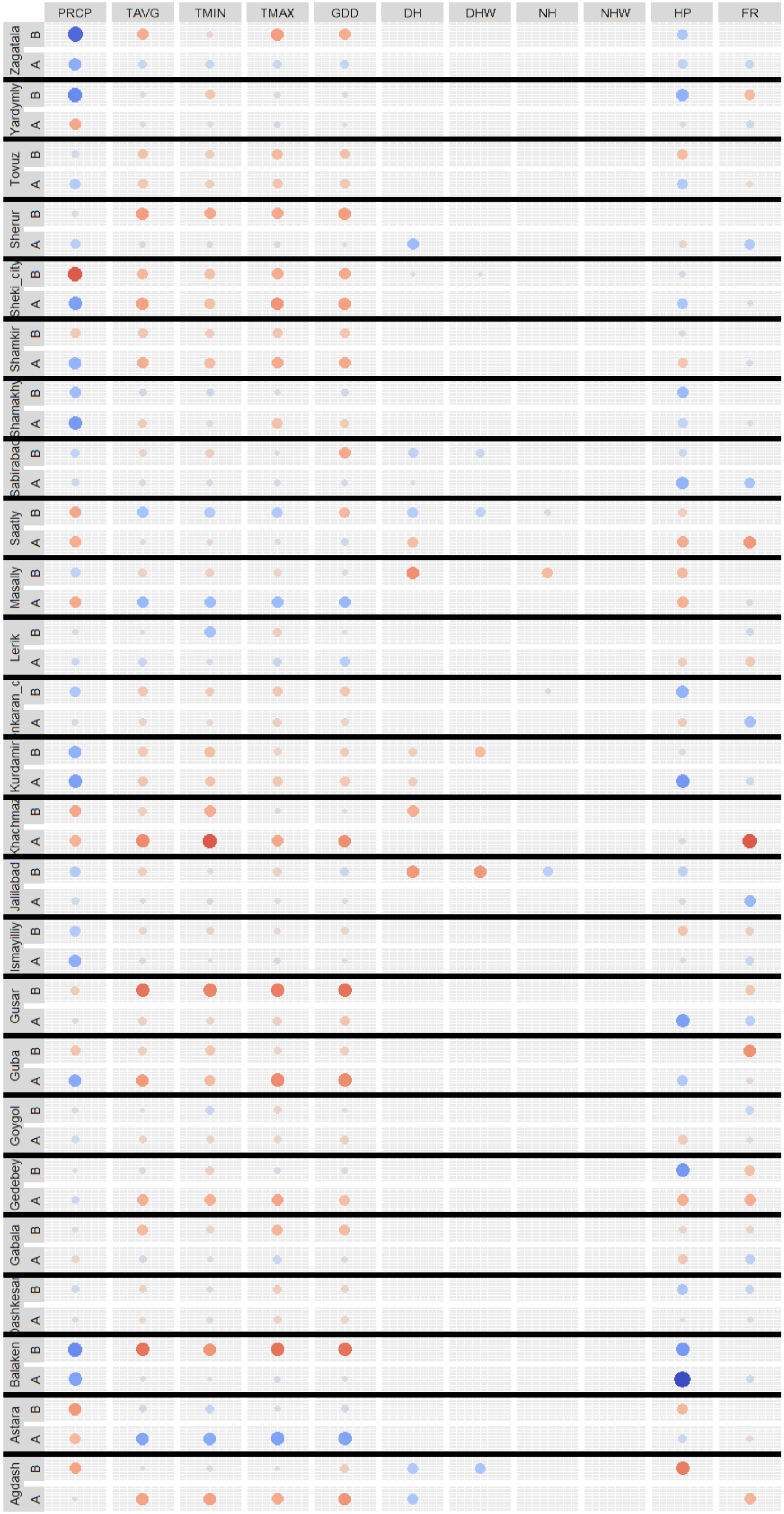

Figure 37: Variable importance for the 25 districts with most sown area for potato, expressed as correlation coefficient with yield. The darker and larger the dot, the more correlated a variable is to yield levels. Red circles indicate negative correlations, blue circles indicate positive correlations. Frost is measured in accumulated negative temperatures, so blue circles imply that high amounts of frost are associated with low yield.

Cucumber

The Random Forest models for cucumber have a very high mean R² of 0.89. Climatic means were generally more important than weather extremes (Figure 38). Many of the relationships between climate/weather variables and yield are very clear: Cucumber yield increases with increasing minimum temperature (TMIN) in phase B and increasing growing degree days (GDD) in phase A, and decreases with increasing maximum temperature (TMAX) in phase A and day heat waves (DHW) in phase B (Figures 39 and 40). The effect of TMIN in phase B is in line with previous findings about minimal temperature requirements of cucumber (Zhao et al., 2011). Cucumber is also known to be susceptible to high temperatures during the vegetative stage (phase A), but only if temperatures are above 32°C (Zhao et al., 2011); here, we see this effect starting at a maximum temperature (TMAX) of about 25°C already (Figure 39). Drought stress can also affect cucumber growth (Li et al., 2018), which is well reflected by the negative association between yield and dry heat waves (DHW) in phase B (Figure 40).

In Azerbaijan, cucumber is grown in greenhouses (Figure 4), and greenhouses are most widespread in Shamkir, Absheron and Baku. However, cucumber production is relatively low in these three districts, so that they are not among the 25 districts that were included in the cucumber model. District-level variable importances show low agreement and can be entirely opposite, such as in the case of Agdam and Babek (Figure 41). Yield and sown area of cucumber are highest in Kurdamir, Lenkaran and Masally (Figure 2), these three districts do not show any particular patterns with regard to variable importances (Figure 41).

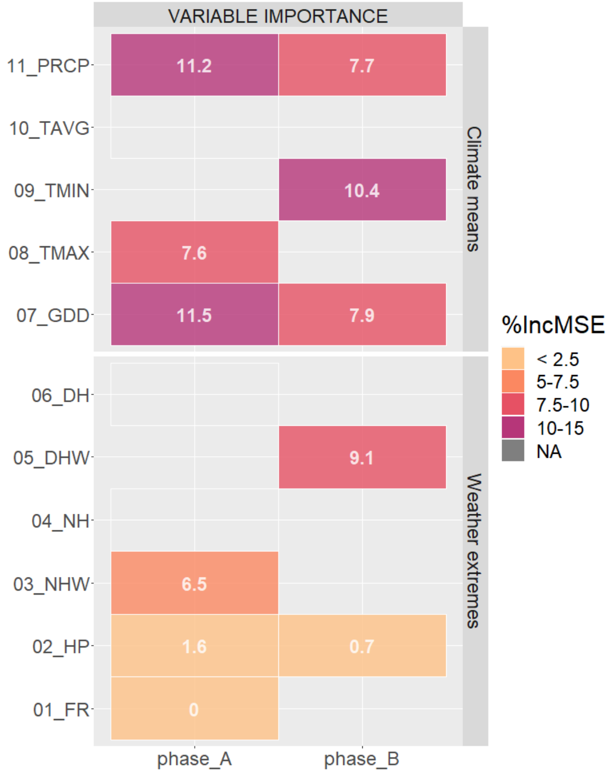

Figure 38: Variable importance for cucumber. Darker colors indicate higher variable importance for yield prediction.

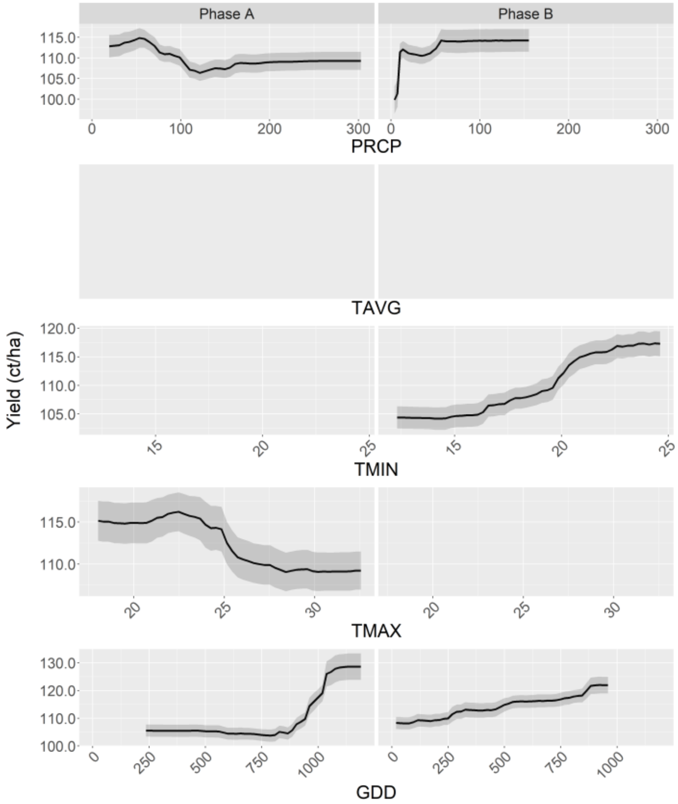

Figure 39: Partial dependencies of climatic mean variables and cucumber yield. The shaded area around the lines represents one standard deviation.

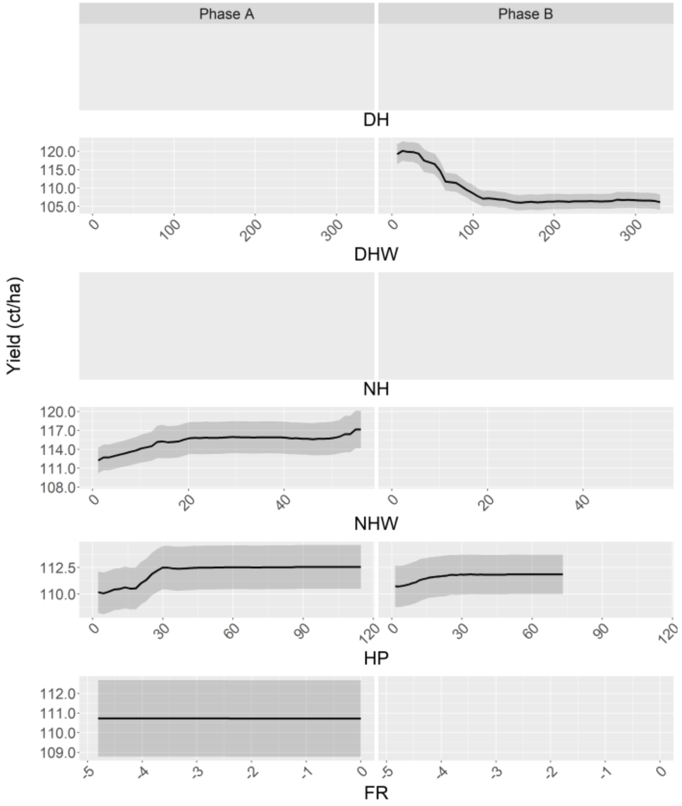

Figure 40: Partial dependencies of extreme weather variables and cucumber yield. The shaded area around the lines represents one standard deviation.

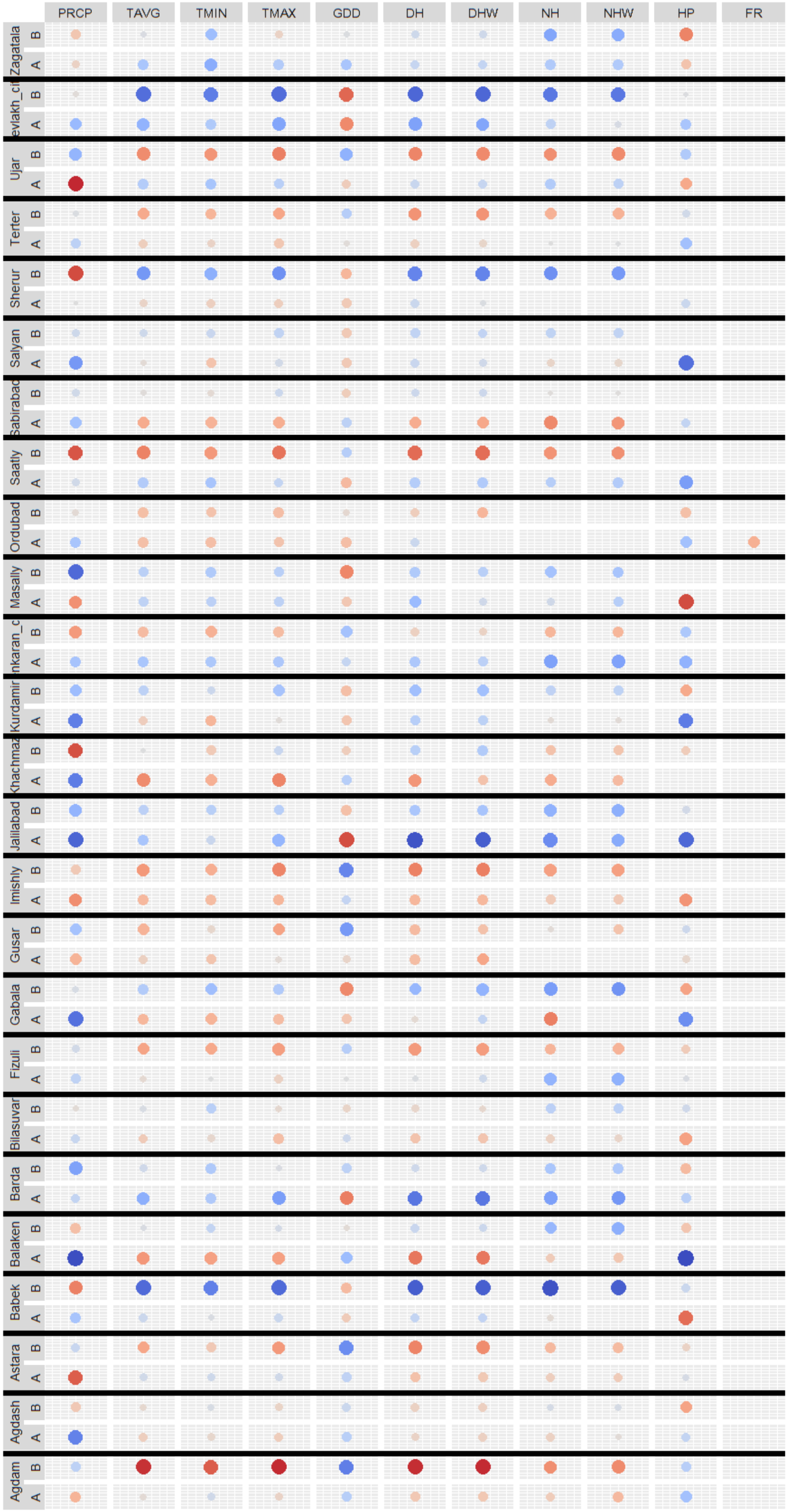

Figure 41: Variable importance for the 25 districts with most sown area for cucumber, expressed as correlation coefficient with yield. The darker and larger the dot, the more correlated a variable is to yield levels. Red circles indicate negative correlations, blue circles indicate positive correlations. Frost is measured in accumulated negative temperatures, so blue circles imply that high amounts of frost are associated with low yield.

Tomato

The tomato models have an average R² of 0.89. Climatic means were generally more important than weather extremes, with the exception of night heat waves (NHW) in phase B (Figure 42). Many of the relationships between climate/weather variables and yield are very clear: Tomato yield increases with increasing minimum temperature (TMIN) in phase A, increasing growing degree days (GDD) in phase B and increasing night heat waves (NHW) in phase B, and decreases with increasing maximum temperature (TMAX) in phase B (Figures 43 and 44). The negative effect of maximum temperature in phase B above 30°C is well in line with previous findings (Alsamir et al., 2021; Lohar and Peat, 1998).

In Azerbaijan, tomato is grown in greenhouses (Figure 4), and greenhouses are most widespread in Shamkir, Absheron and Baku. Shamkir is one of the districts where overall tomato production is also highest (Figure 2), but this district shows slightly negative correlations between yield and temperature variables in phase B (Figure 45). District-level variable importances show generally low agreement and can be entirely opposite, such as in the case of Ujar and Babek (Figure 45).

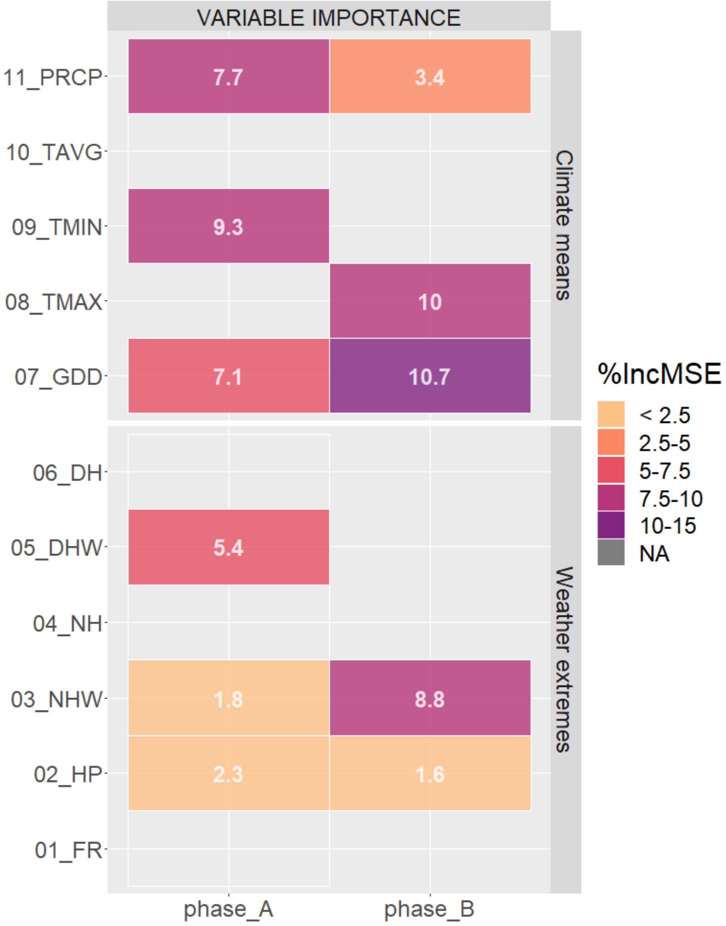

Figure 42: Variable importance for tomato. Darker colors indicate higher variable importance for yield prediction.

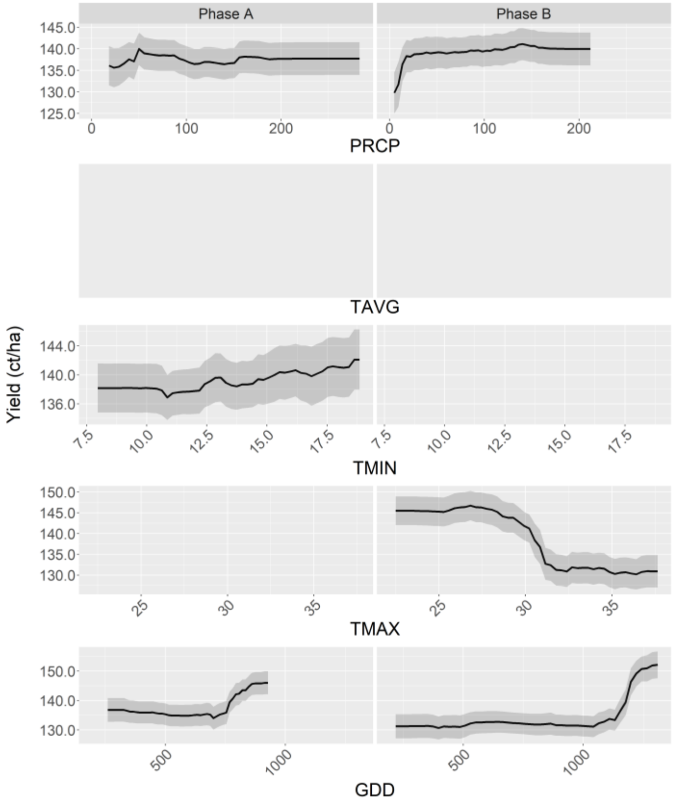

Figure 43: Partial dependencies of climatic mean variables and tomato yield. The shaded area around the lines represents one standard deviation.

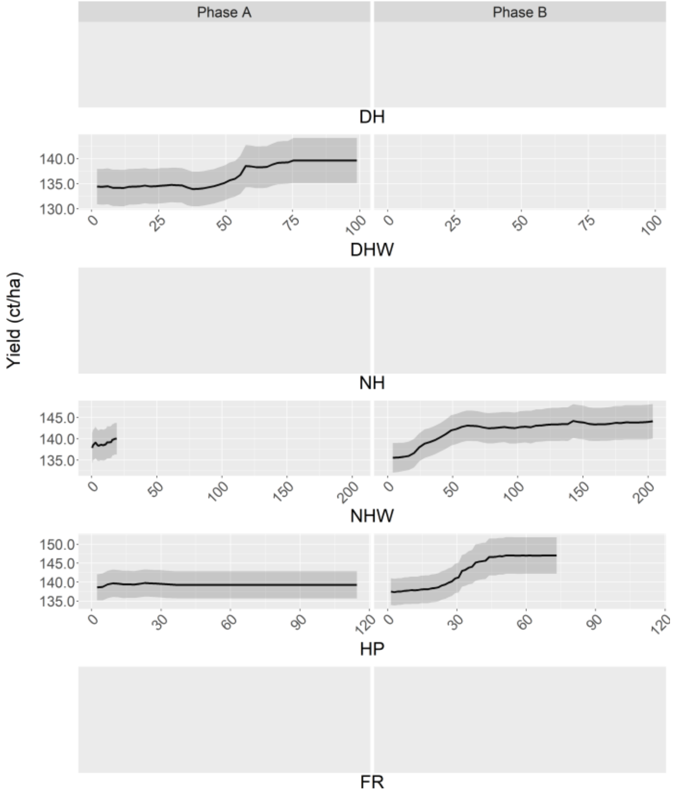

Figure 44: Partial dependencies of extreme weather variables and tomato yield. The shaded area around the lines represents one standard deviation.

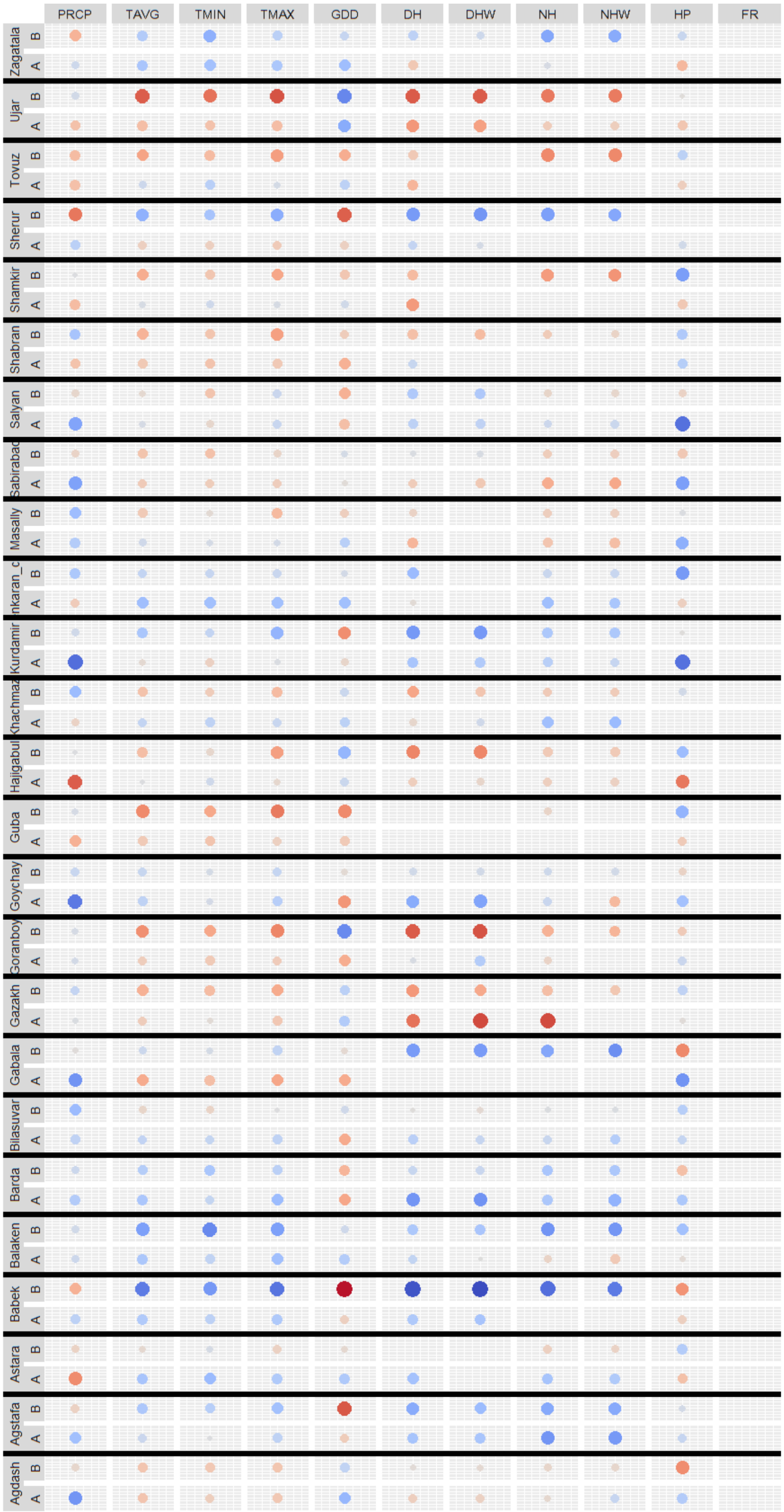

Figure 45: Variable importance for the 25 districts with most sown area for tomato, expressed as correlation coefficient with yield. The darker and larger the dot, the more correlated a variable is to yield levels. Red circles indicate negative correlations, blue circles indicate positive correlations. Frost is measured in accumulated negative temperatures, so blue circles imply that high amounts of frost are associated with low yield

Persimmon

The Random Forest models for persimmon have a mean R^2 of 0.72. Climatic means were generally more important than weather extremes (Figure 46), particularly precipitation in phase B. High levels of precipitation (PRCP) and high maximum temperature (TMAX) in phase B are associated with higher yield (Figure 47), whereas night heat waves (NHW) have a negative effect (Figure 48). The negative relationship between yield and minimum temperature (TMIN) in phase A (Figure 47) should be interpreted with caution, because there is high uncertainty at low levels of TMIN, and the variable importance is of TMIN in phase A is rather low (Figure 46). District-level variable importances show generally low agreement, and the districts where persimmon production is highest (Shamkir, Balaken, Goychay and Agdash; Figure 2) do not show any particular patterns with regard to variable importances (Figure 49).

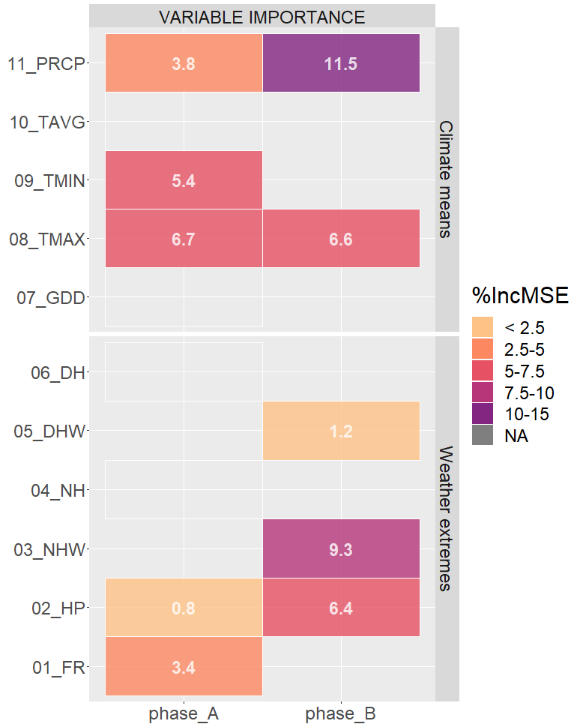

Figure 46: Variable importance for persimmon. Darker colors indicate higher variable importance for yield prediction.

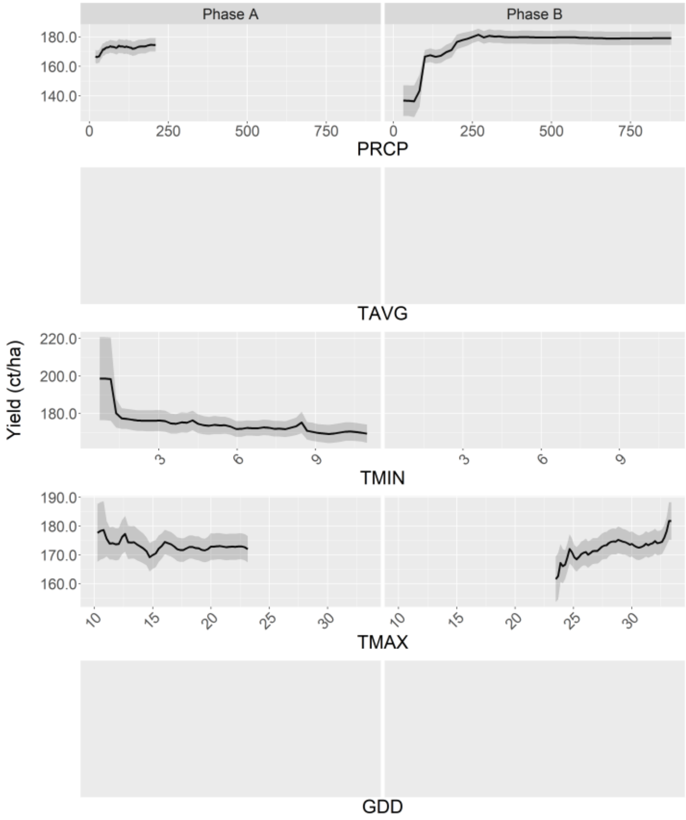

Figure 47: Partial dependencies of climatic mean variables and persimmon yield. The shaded area around the lines represents one standard deviation.

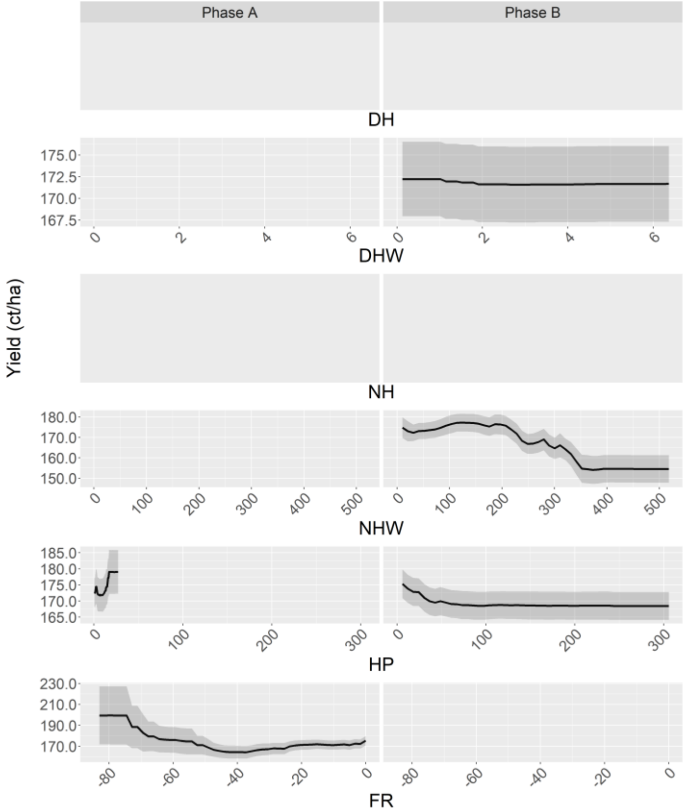

Figure 48: Partial dependencies of extreme weather variables and persimmon yield. The shaded area around the lines represents one standard deviation.

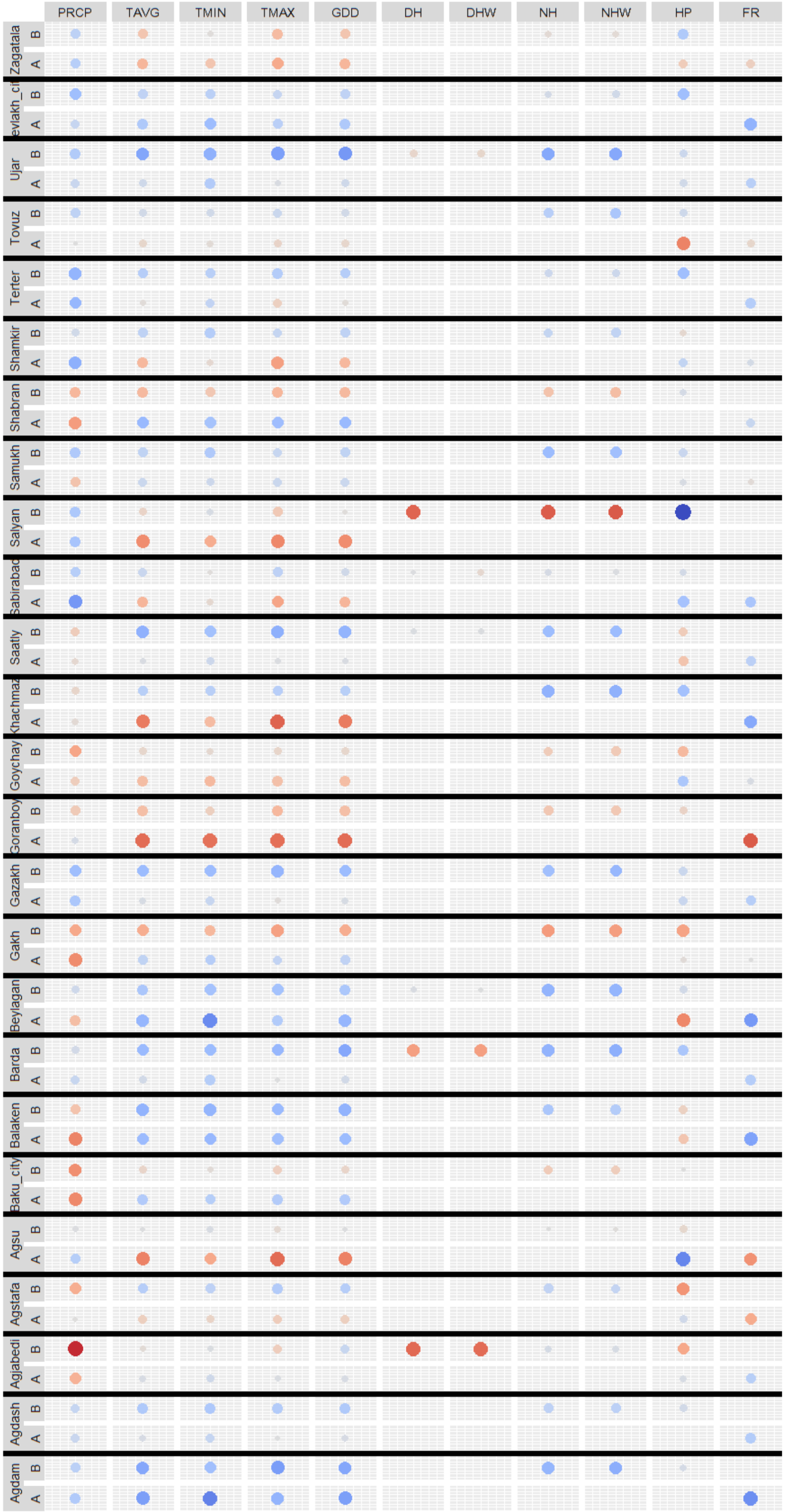

Figure 49: Variable importance for the 25 districts with most sown area for persimmon, expressed as correlation coefficient with yield. The darker and larger the dot, the more correlated a variable is to yield levels. Red circles indicate negative correlations, blue circles indicate positive correlations. Frost is measured in accumulated negative temperatures, so blue circles imply that high amounts of frost are associated with low yield

Pomegranate

The Random Forest models for pomegranate have a mean R² of 0.77. Climatic means were generally more important than weather extremes (Figure 50). Overall, the model results confirm that pomegranate is well adapted to heat, but requires adequate amounts of water: Precipitation (PRCP) in phase B was the most important variable, followed by maximum temperature (TMAX) in that phase, and both are positively correlated with yield (Figure 51). Night heat waves (NHW) in phase B were the third most important variable, but there is no clear relationship with yield (Figure 52). The negative effect of heavy precipitation (HP) in phase B should be interpreted with caution, because this variable had a low overall variable importance (Figures 50 and 52). District-level variable importances show generally low agreement (Figure 53). Goychay, the district where production and sown area of pomegranate are highest (Figure 2), shows a particularly strong negative correlation of precipitation (PRCP) and heavy precipitation (HP) with yield (Figure 53).

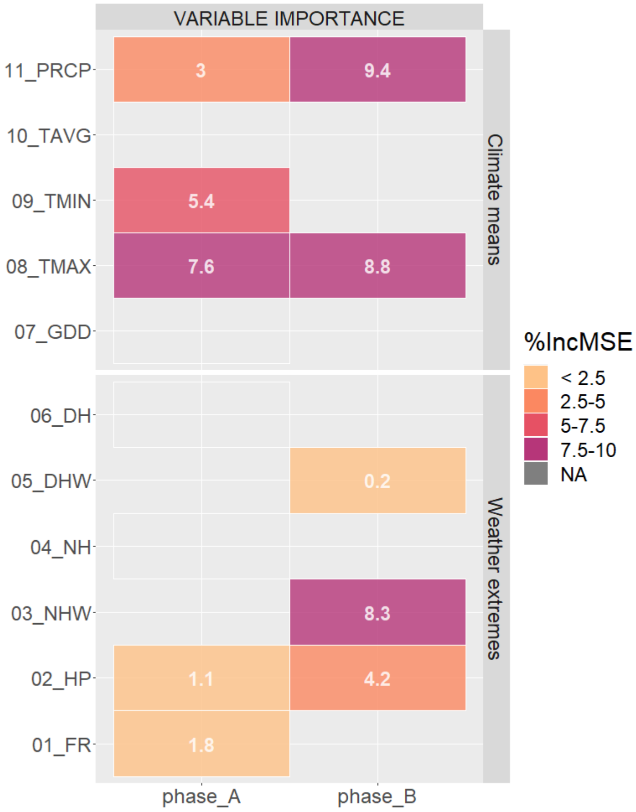

Figure 50: Variable importance for pomegranate. Darker colors indicate higher variable importance for yield prediction.

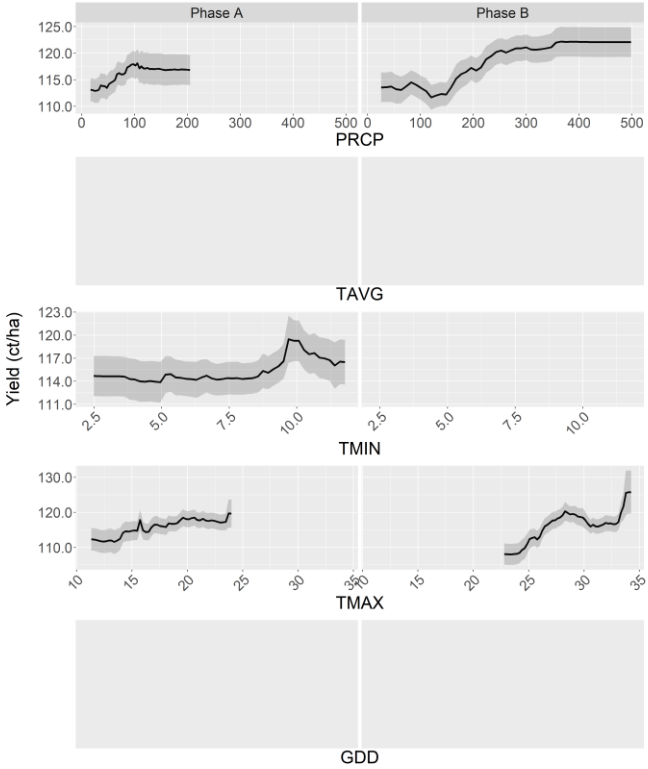

Figure 51: Partial dependencies of climatic mean variables and pomegranate yield. The shaded area around the lines represents one standard deviation.

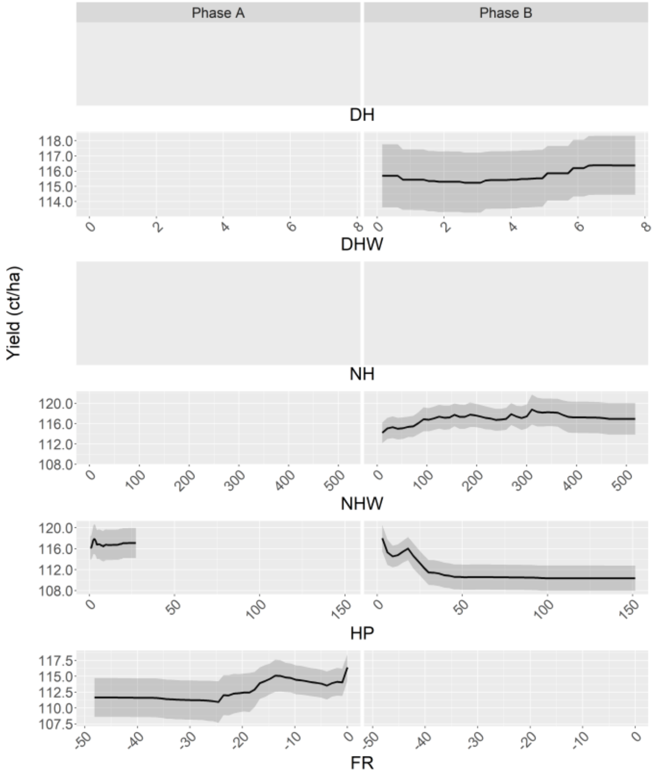

Figure 52: Partial dependencies of extreme weather variables and pomegranate yield. The shaded area around the lines represents one standard deviation.

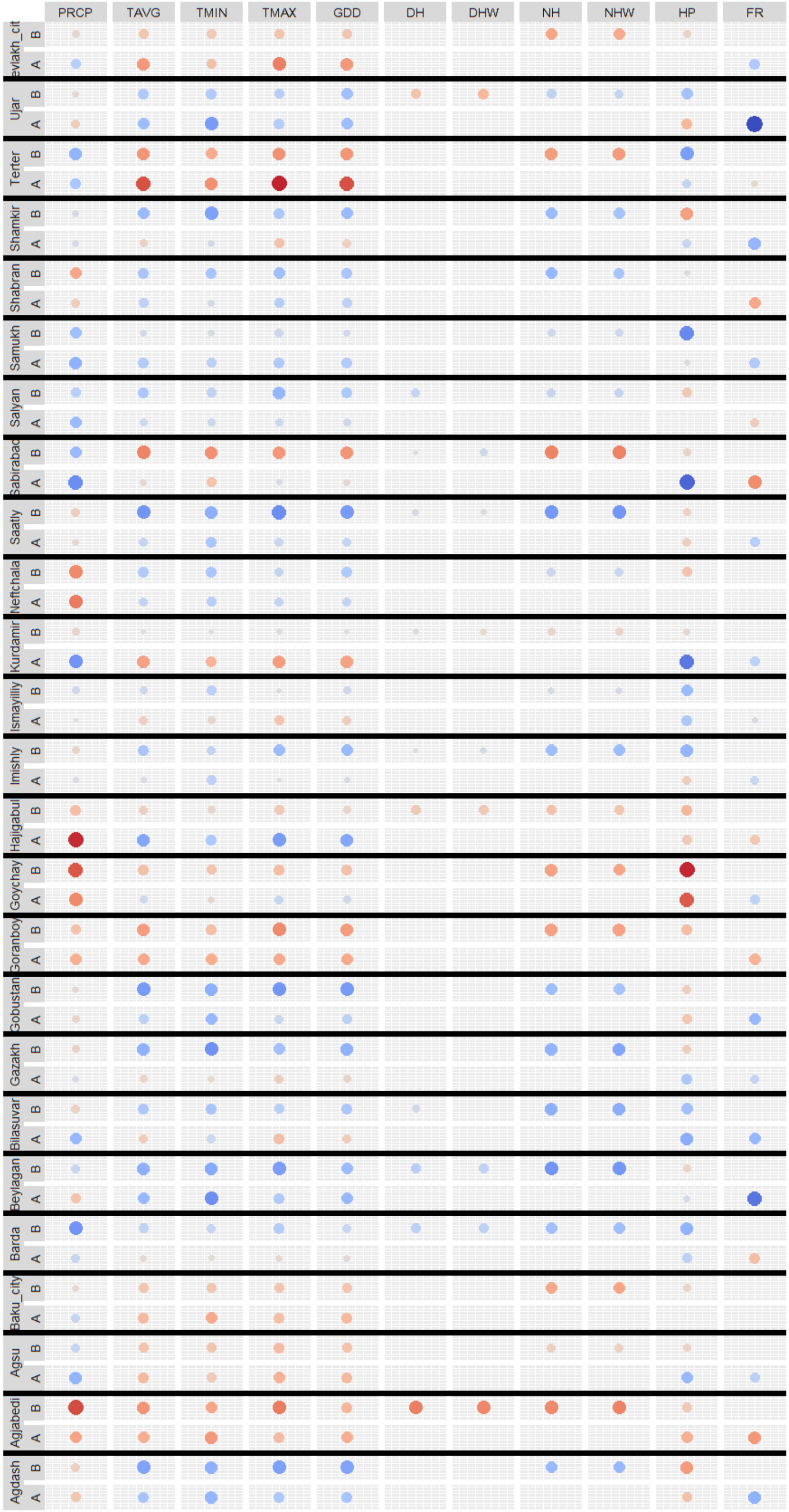

Figure 53: Variable importance for the 25 districts with most sown area for pomegranate, expressed as correlation coefficient with yield. The darker and larger the dot, the more correlated a variable is to yield levels. Red circles indicate negative correlations, blue circles indicate positive correlations. Frost is measured in accumulated negative temperatures, so blue circles imply that high amounts of frost are associated with low yield

4.2 Crops assessed with Chill Unit models

We used the determined amount of chill units reached at the time of bud bursting (Figure 18) to recategorize the map of the long-year average of maximum accumulated chill units (Figure 21) into three suitability classes:

A. **insufficient amount of chill units (CU) beyond current observations**: Long-year average amount of chill units at the end of the crop cycle is below the minimum observed amount of chill units accumulated at bud bursting.

B. **optimal amount of CU**: Long-year average amount of chill units at the end of the crop cycle is above the minimum and below the maximum observed amount of chill units accumulated at bud bursting.

C. **amount of CU is above average and beyond current observations**: Long-year average amount of chill units at the end of the crop cycle is above the maximum observed amount of chill units accumulated at bud bursting.

Historically, sufficient chill units have been available for the production of both apple and hazelnut throughout the entire country and regional shortcomings in chill unit supply seem therefore absent to date (Figure 54). Surprisingly, the mountainous regions of Azerbaijan accumulate less chilling than the central lowland region (Figure 21). This is probably due to very mild winters in the lowland regions, where accumulation of chill units does not stagnate in winter. However, when temperatures continue to rise in the future, the mountainous areas may eventually accumulate more chilling than the lowland regions and become the most suitable regions for production of apple and hazelnut, whilst the amount of chill temperatures will decrease in the lowlands because of warmer spring and autumn temperatures. We will investigate this in work package 4. Overall, apple had a lower amount of chill units accumulated at the time of bud bursting (Figure 18) and might therefore in the future be more resistant to warming winters than hazelnut.

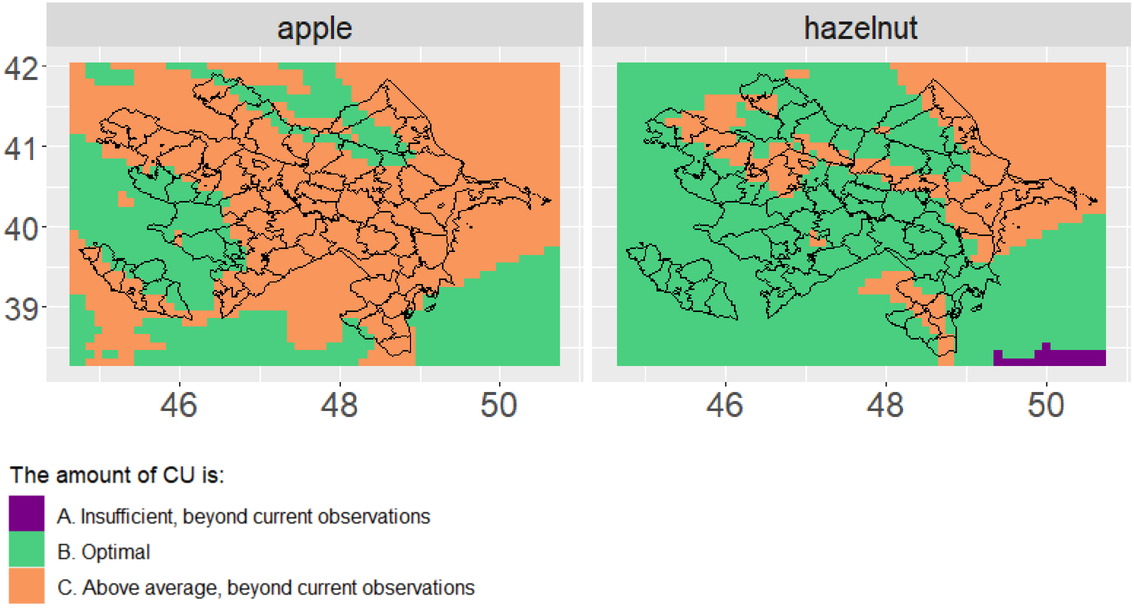

Figure 54: Historical suitability for apple and hazelnut production based on the average amount of CU that accumulate until the end of a crop cycle.

5. Summary and Recommendations

Our results provide detailed insights into the climatic and weather factors that determine the production patterns of the ten selected crops in the country. We used Random Forests to model historical, sub-national yields of eight crops with phenological, climate and weather data: wheat, barley, onion, potato, cucumber, tomato, persimmon and pomegranate. We also applied a Chill Unit Model to map the historical suitability of apple and hazelnut. The statistical analyses indicate possible explanations of historical yield variability. All results should be discussed and put into perspective with local experts, who can share their expertise on the specific regional conditions.

Crops assessed with Random Forest models

Overall, we found that climatic means, such as temperature and precipitation, have been more important for yield than extreme weather events, such as heat waves or frost. We found little overall agreement of variable importances at the district level. We also did not find any consistent patterns in variable importances for those districts where yield, production, sown area, greenhouse production or irrigation are particularly high for a given crop.

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 known from other countries (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.

Our results highlight the need to acquire appropriate data on irrigation and greenhouses to be considered in crop yield models. Irrigation regimes complicate the assessment of the contribution of climate and weather on yields because irrigation affects soil moisture, soil temperature, and hence yield. Unfortunately, detailed data on irrigation is missing, which prohibits to differentiate between rainfed production and irrigated production. Wheat and barley are to a large extent irrigated in Azerbaijan, which might be an explanation why our results show that yield was positively affected by high temperatures around anthesis. It is also possible that particularly heat-resistant varieties of wheat and barley are grown in Azerbaijan, or that yield-damaging temperature levels have not been reached yet. Production in greenhouses can further complicate the analysis, because temperature and irrigation can be controlled in greenhouses to a certain degree. We partly accounted for greenhouse production by limiting the models for cucumber and tomato to the years 2000 to 2016.

We modelled yield with climatic mean and extreme weather variables while accounting for long-term technological improvements and for regional differences in management, policies, and mechanization levels by using detrended yield levels and district identifiers. This is a simplification that we cannot avoid with the available data. More accurate yield models would require data on additional parameters, for example, for pesticide and fertilizer application rates and cropping practices. There is also a series of other environmental variables that can affect yields and that we cannot model, such as hail events, landslides, soil parameters, or pest infestations. We also did not consider quality aspects of the crops.

The data that we processed with the Random Forest models have a series of limitations, which complicates the assessment of climate impacts on yields. To improve on this, we have the following technical recommendations:

- The yield data possibly suffers from different or inaccurate data collection methodologies, and should be validated by local experts. Yield information is only available for the past 20 years. A longer time series would yield statistically more robust results and better allows for assessments of the effect of climate change on crop production, for which long time-series of crop yield data are necessary.

- There is no detailed information in the literature about the crop varieties cultivated in Azerbaijan and the climate and weather requirements of these varieties. Our definitions of weather extreme variables hence stem from the literature of other countries, which may not properly reflect the physiology of Azerbaijani cultivars. For example, our results suggest that weather extremes are less important yield determinants than climatic means, but it remains unclear if this is because the Azerbaijani crop cultivars are well adapted to extreme weather conditions. This should be further discussed with local experts.

- There was only little phenological data available for this report which might not be representative for the entire country. The representativeness of the stations should be validated by local experts. Phenological observations from additional stations and for additional years are available from the *National Hydrometeorological Service of Azerbaijan* and should be considered to be integrated in future assessments.

- We used modelled, coarse-resolution temperature and precipitation data from *ERA5-Land* and *CHIRPS* for our analysis because we could not get access to local weather station measurements. A thorough analysis using weather station data could greatly improve the accuracy of the climatic mean and weather extreme variables that were used for the yield predictions.

Crops assessed with Chill Unit models

The results of our Chill Unit models showed that entire Azerbaijan has been suitable for the production of apple and hazelnut. We suspect that under climate change, winter chilling will decrease across the lowland parts of the country, and higher elevations might become comparatively more suitable for the production of apple and hazelnut. We will assess that in work package 4.

Chilling requirements can differ between cultivars; however, we do not have any information about the apple and hazelnut cultivars grown in Azerbaijan. We acknowledge that production of these two crops might also be constrained by other factors than chilling, such as water supply and irrigation, yet such input data are lacking.

The data that we processed with the Chill Unit models have a series of limitations. Several technical improvements may relieve some of these limitations:

- Phenological observations are only available from three years, for one station in the case of apple, and two stations in the case of hazelnut. We assume that this selection may not be representative for the entire country. To make the Chill Unit models more robust, we suggest to consider mobilizing additional phenological data from other sources, which would greatly improve the accuracy of the models.

- We used modelled grid-cell temperature measurements from the *ERA5-Land* dataset. We suggest to consider mobilizing actual hourly weather station temperature measurements, which would greatly improve the accuracy of the Chill Unit models.

- We did not establish a link between suitability and yield. However, we suspect that local yield observations may be available from the agrometeorological stations for which we obtained phenological data. Such data would benefit the validation of the suitability maps.

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Work Package 4:

“Future Effects of Climate and Extreme Weather Events on Yields and Crop Suitability”

Content

Annex

Figures

1. Introduction

Future climate change will crucially affect crop yields worldwide (Jägermeyr et al., 2021; Zhao et al., 2017). In the last decades, Azerbaijan already experienced a decrease in rainfall and increases in temperature and the occurrence of extreme weather events (USAID, 2017). With on-going climate change, this trend is expected to continue in the future (World Bank Group and Asian Development Bank, 2021).

Future climate projections have been developed for so-called Representative Concentration Pathways (RCPs). These describe the components of the radiative forcing that shape the global climate system, i.e. greenhouse gas emissions, aerosol concentration, and land use (van Vuuren et al., 2011). The RCPs span various stabilization and mitigation scenarios until 2100 and are expressed as the radiative forcing in Watt per square meter on the ground (W/m^2). RCP 8.5, for example, is a pathway characterized by high GHG concentration in the atmosphere that contributes to an estimated radiative forcing of about 8.5 W/m^2 and closely represents the trajectory of GHG emissions at the time of writing. RCP 4.5 is an intermediate pathway that anticipates substantial emissions reduction where GHG concentrations stabilize at around 650 ppm, equivalent to about 4.5 W/m^2.

Under the very stringent RCP 2.6 scenario, the mean annual temperature in Azerbaijan will rise by approximately 1.2 °C until the 2090s, compared to the baseline of the years 1986 to 2005. Under RCP 8.5, temperatures in Azerbaijan are projected to rise by approximately 4.7°C by the 2090s, which is far above the global average increase. Climate models suggest that annual temperatures in the western part of Azerbaijan will increase faster than in the eastern part of the country. Precipitation is likely to slightly increase under most RCPs, but model results are not consistent. Heavy rainfall events are expected to intensify and occur more frequently in the central and northern parts of Azerbaijan. It is also very likely that the probability of the occurrence of severe droughts will significantly increase by the 2090s. As many models predict a rise in the probability of severe droughts, it is likely that most parts of Azerbaijan will transition to a chronically drought-affected environment. Besides, heat stress is likely to become much more regular under climate change. Under RCP 4.5, RCP 6.0 and RCP 8.5, Azerbaijan is projected to experience maximum temperatures above 40°C on an annual basis by the 2090s. Heat waves will intensify and become more frequent under most RCPs, and are expected to affect all regions of the country (World Bank Group and Asian Development Bank, 2021).

In Azerbaijan, future climate change is expected to result in a decline of productivity of most of the crops that we selected to study in this assignment (UNDP & GEF, 2015). Additionally, increasing frequency and intensity of droughts and heat will render production more volatile. The increase in the number of days with extremely high temperatures will likely lead to more frequent yield damages for most crops that are currently cultivated in the country (World Bank Group and Asian Development Bank, 2021).

In work package 3 (WP3), we show that historical changes in climate and weather conditions have already substantially affected crop yields in Azerbaijan. We used Random Forest models, a machine learning algorithm, to assess the impacts of climatic mean and weather extreme variables on yields of eight crops, and Chill Unit models to approximate the historical suitability for the production of apple and hazelnut. In WP4, we integrate future climate and weather data in our models to predict future yields and future suitability. To our knowledge, comparable models for Azerbaijan are not available to date.

However, we caution the reader to interpret the modeling results with care because we had to take several assumptions for these calculations, and because of the uncertainty of future developments. First, we used the relationships from the historical models to predict future yield effects. This implies that we keep the functional relationships between climate, weather, and yields constant. This in turn abstracts from any adaptation of farmers in terms of land management or land use. In reality, farmers will adapt input use, crop types planted, and where land use takes place to the changing climatic conditions. Besides, technological improvements in plant breeding and digitalization will allow to adapt crop management to changing climate and weather conditions. These adaptation measures cannot be accounted for with our approach. The results should therefore be interpreted as what could be the impacts on crop yields with current crop production, but under future climate conditions.

2. Future Yield Predictions and Crop Suitability

We analyzed future climate projections of four daily 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/search/) and restricted our analysis to the four climate forcing models for which data was available for all mentioned parameters and scenarios: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC-5. The datasets are in a gridded format and have a resolution of 0.5 degrees, which in Azerbaijan is equivalent to a cell size of approximately 55 km height x 39 km width. Bias-corrected climate projections with a higher spatial resolution are, unfortunately, not available from ISIMIP. 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.

2.1 Crops assessed with Random Forest models

We used the future climate projections to calculate five daily climatic mean and six daily weather extreme variables for each target crop and each development stage (see WP3, Tables 13 to 15). To approximate the start and end date of each development stage in the future, we averaged the respective start and end dates of all historical observations, i.e., across all years and all phenological stations, which resulted in a future crop calendar (Figure 1). We hence assume that phenology will not change in the future, and so the crop calendar does not distinguish between near and far future. We calculated stage-specific climatic mean and weather extreme variables on the grid-cell level for each year, RCP, and climate forcing model. We then averaged the estimates for the plant development stages for all years and all periods (historical baseline, near future, far future), and averaged the resulting estimates across the four climate forcing models to obtain long-year model ensemble rasters for each RCP and period. For each crop, development stage, climatic mean and weather extreme variable, RCP, and future period, we visualized these long-year model ensemble rasters and the absolute changes between them and the historical baseline in Annex A.

We applied a zonal mean function to the long-year model ensemble rasters to estimate climatic variables at the provincial level. We used the resulting data to run a separate Random Forest model for each province (see WP3, chapter 4.1) that we first trained on the historical climatic and yield data. We report the variable importances of these models for each crop and province in Annex B, and the corresponding functional relationships in Annex C. We then re-estimated the trained model with the future climatic data to predict future yield levels under each RCP and for each future time period. Finally, we compared the future yield estimates against the historical long-year average yields (2000 to 2019) and calculated percent yield changes (Figures 2 to 9).

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

Wheat

Wheat yields are highest in the central lowland region of Azerbaijan, such as in Gence-Qazax and Aran (WP3, Figure 2). For these provinces, we predict only slight yield changes (Figure 2), and the variable importances of these models are rather low (Annex B), so that it is difficult to infer about which climatic variables determine the changes. In the lowland region, wheat is largely irrigated (WP3, Figure 3), which could explain why we do not see any high negative impact of climate on yields in this region. However, for both RCPs and both future periods, we predict considerable yield decreases for Naxcivan and the three northern provinces Quba-Xacmaz, Dagli-Shirvan and Sheki-Zagatala, the latter of which shows by far the highest predicted yield decrease (Figure 2). In Quba-Xacmaz and Sheki-Zagatala, the most important variables are frost during the reproductive phase and precipitation during the grain filling phase (Annex B). Low precipitation is associated with low yields here (Annex C). The projected decrease in precipitation in the future (Annex A) could explain the predicted yield decrease; however less frost is associated with higher yields (Annex C), which is, given the future decrease in frost (Annex A), in contrast to the predicted yield decrease.

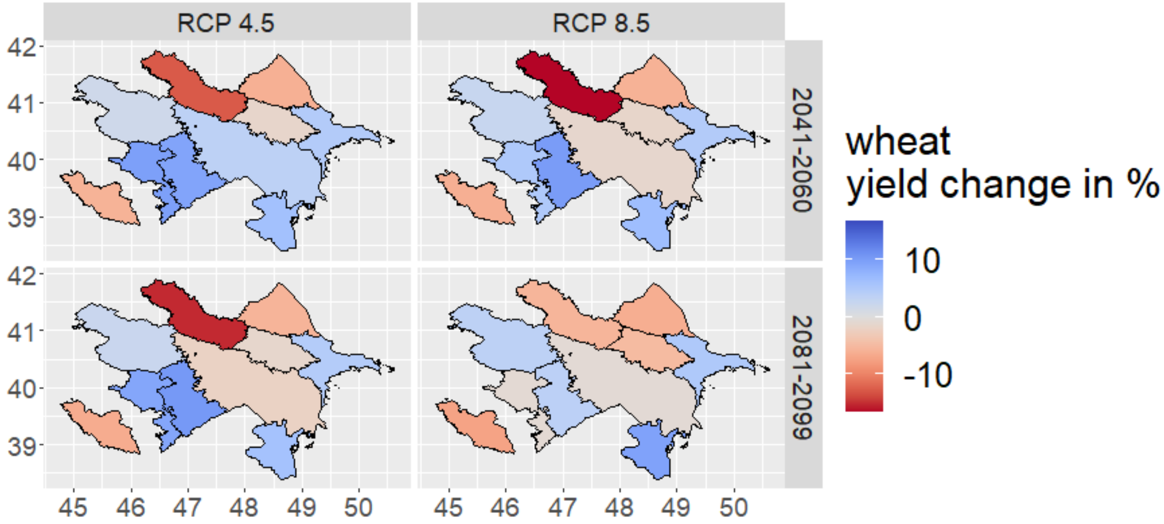

Figure 2: Predicted change in wheat yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in the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

Barley

The production patterns of barley largely resemble those of wheat: Yields are highest in the central lowland region of Azerbaijan, such as in Gence-Qazax and Aran (WP3, Figure 2). We predict slight yield increases for the entire lowland region (Figure 3), and a particularly high increase for Lenkeran in the south. As for wheat, Naxcivan and the provinces in the north, but also Absheron, are predicted to experience yield decreases, which are again highest in Sheki-Zagatala. Unfortunately, the variable importances of all province models are rather low (Annex B), so it is difficult to infer about which climatic variables determine the predicted yield changes. In the lowland region, barley is largely irrigated (WP3, Figure 3), which could explain why we do not see any high negative impact of climate on yield in this region. However, for both wheat and barley, future climate change may increase the water stress particularly in the lowland regions where extreme heat will become more frequent (Annex A), so attention should be paid to ensuring sufficient water supply for irrigation in the future.

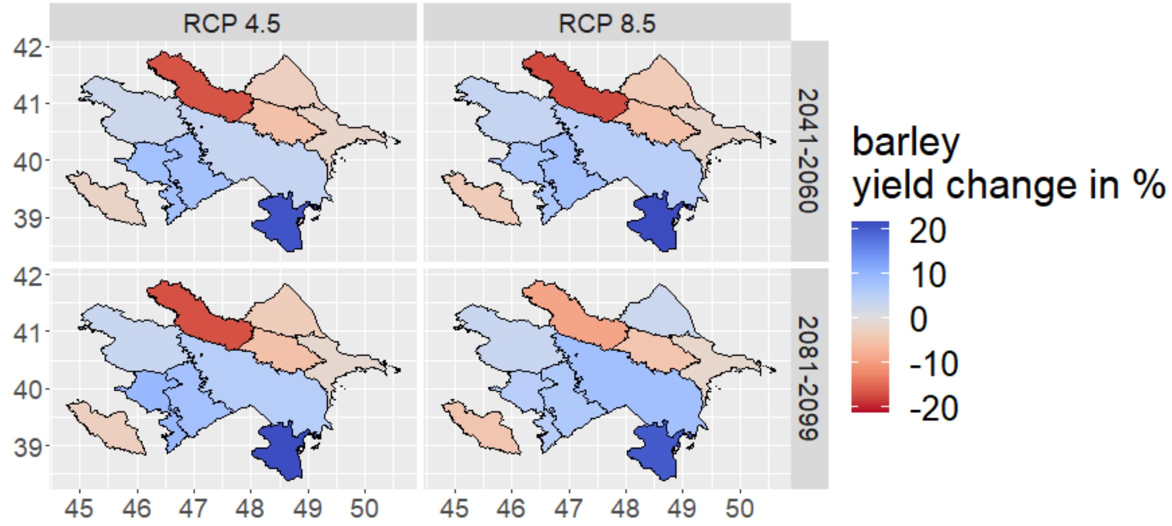

Figure 3: Predicted change in barley yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in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

Onion

Onion is cultivated throughout most parts of the country (WP3, Figure 2). We predict mostly slight yield increases for the future that are highest in Aran, Yuxari-Qarabag and Absheron, and a considerable yield decrease for Kelbecer-Lacin. Notably, both the increase in Aran and the decrease in Kelbecer-Lacin intensify with higher future warming, i.e. become more extreme between RCP 4.5 to 8.5, and between the near to the far future (Figure 4). The model results for Aran do not point to a particularly important variable (Annex B), so it remains unclear which exact climatic factor drives the predicted yield increase there. Minimum temperature during the reproductive phase was the most important variable in Lenkeran, Yuxari-Qarabag, Gence-Qazax and Absheron (Annex B) and is positively associated with yield in these provinces (Annex C). The projected increase in minimum temperature during this phase in the future (Annex A) can hence explain many of the predicted yield increases. As for Aran, the model results for Kelbecer-Lacin are also difficult to interpret (Annex B and C). However, there is very little onion grown in this province (WP3, Figure 2), so the predicted yield decrease should not be overinterpreted.

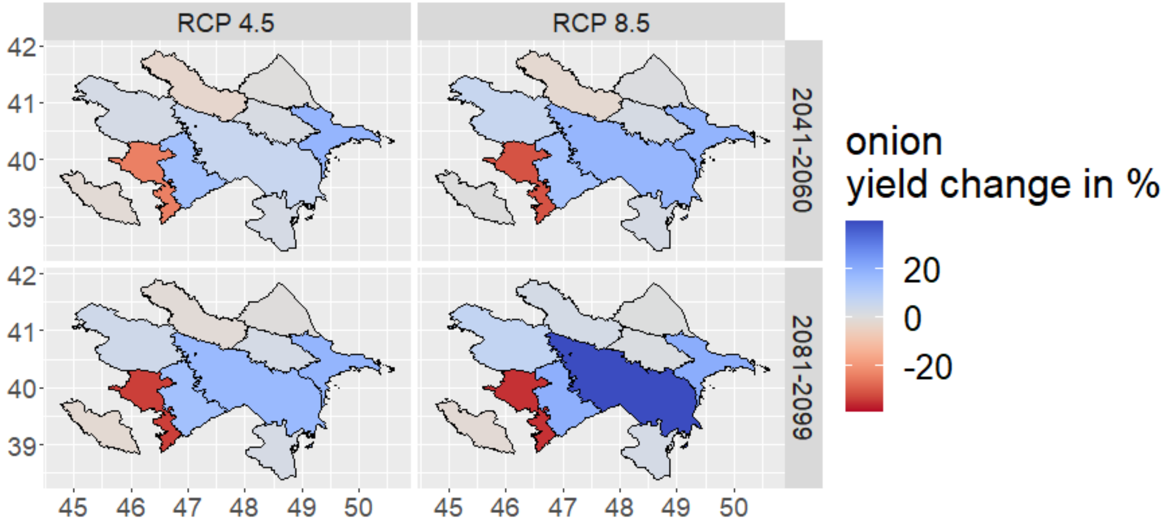

Figure 4: Predicted change in onion yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in the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

Potato

Production and yield of potato are highest in the northwest and southeast parts of Azerbaijan, namely in Gence-Qazax and Lenkeran (WP3, Figure 2), for where we predict only slight yield changes (Figure 5). The highest yield increase is predicted for Kelbecer-Lacin, but potato production is very low in this province (WP3, Figure 2), and the variable importances of the corresponding model are also all very low (Annex B), so it is difficult to infer about which climatic variable determines the predicted yield increase. In Aran, the most important variable is maximum temperature during the reproductive phase (Annex B), which is positively correlated with yield (Annex C). The projected increase in maximum temperature in the future (Annex A) could explain why our model predicts a yield increase for Aran for the far future under RCP 4.5, and for both future periods under RCP 8.5 (Figure 5). For Sheki-Zagatala, the most important variable is minimum temperature during the reproductive phase (Annex B), which will also increase in the future (Annex A). However, we predict a yield decrease for Sheki-Zagatala (Figure 5) even though high minimum temperatures are associated with high yields (Annex C), which seems little plausible and suggest that other factors might be more decisive for potato yield in this province.

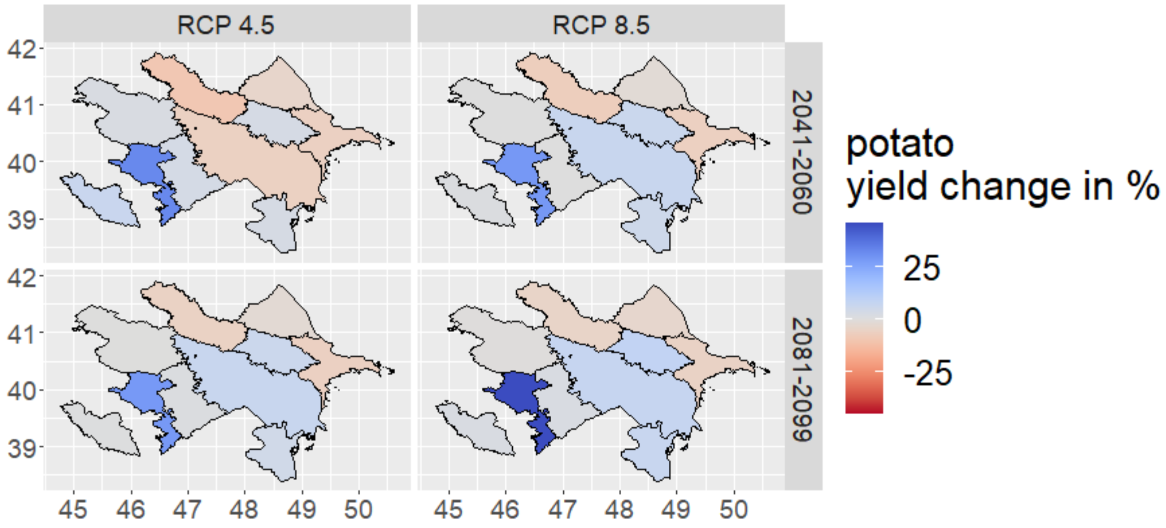

Figure 5: Predicted change in potato yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in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

Cucumber

Cucumber production is quite scattered across the country, the highest yield is reached in Lenkeran in the south (WP3, Figure 2). Cucumber is often grown in greenhouses in Azerbaijan, which are mainly located in Absheron and Gence-Qazax (WP3, Figure 5). For these provinces and for Aran, we predict yield increases for the future, whereas we predict decreases for the northern and southwestern part of the country (Figure 6). In the models for Lenkeran, Absheron, Gence-Qazax and Aran, minimum temperature and/or growing degree days are the most important variables (Annex B) and are positively correlated with yield (Annex C). As these variables will increase in the future (Annex A), the predicted yield increases for these provinces are plausible. Controversially, minimum temperature during the vegetative phase is also the most important variable for Yuxari-Qarabag (Annex B) and is also positively associated with yield there (Annex C), even though we predict a future decrease in yield for Yuxari-Qarabag (Figure 6). For Kelbecer-Lacin, where the predicted yield decrease is highest, the most important variable is heavy precipitation during the vegetative phase (Annex B), which is negatively correlated with yield in this province (Annex C). The climate models project a slight increase of heavy precipitation for the southwestern part of Azerbaijan (Annex A), which could explain the predicted yield decrease for Kelbecer-Lacin. Note that cucumber production is very low in both Yuxari-Qarabag and Kelbecer-Lacin (WP3, Figure 2).

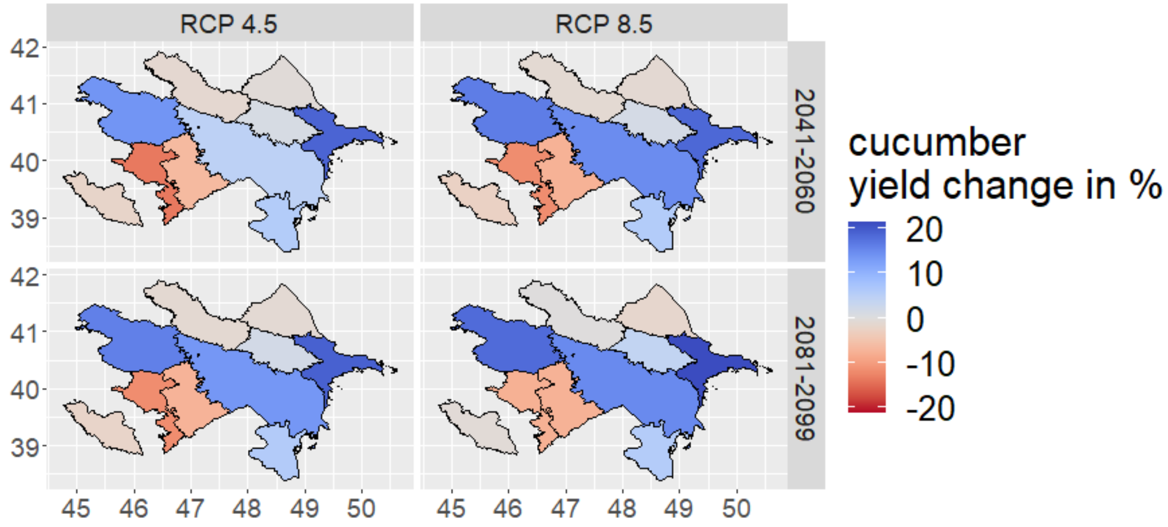

Figure 6: Predicted change in cucumber yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in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

Tomato

The patterns of tomato production largely resemble those of cucumber, with the highest yields found in Lenkeran in the south, and in some parts in the north (WP3, Figure 2). Tomato is also often grown in greenhouses in Azerbaijan, which are mainly located in Absheron and Gence-Qazax (WP3, Figure 5). Despite these similarities, the predicted future tomato yields show a pattern that is opposite to that of cucumber in the western half of the country (Figures 6 and 7). We predict only slight yield changes for the high-yielding regions, but a large increase for Kelbecer-Lacin and Aran, and a considerable decrease for Gence-Qazax (Figure 7). The most important variables in the model for Kelbecer-Lacin are precipitation during the vegetative, and heavy precipitation during the reproductive phase (Annex B), which are positively and negatively correlated with yield, respectively (Annex C). As precipitation will decrease in the future, and heavy precipitation events will increase (Annex A), the predicted yield increase is the opposite of what would be plausible. Note there is very little tomato grown Kelbecer-Lacin after all (WP3, Figure 2). For Aran, the most important variable is minimum temperature during the vegetative phase (Annex B), and higher minimum temperatures are associated with higher yields in this province (Annex C), so the predicted yield increase is more plausible. The most important variable in the model for Gence-Qazax is heavy precipitation during the reproductive phase (Annex B) and is, contrary to Kelbecer-Lacin, positively correlated with yield (Annex C), so the predicted yield decrease is also not plausible. However, for Gence-Qazax, yield developments may be actually decoupled from climatic patterns because of widespread greenhouse production.

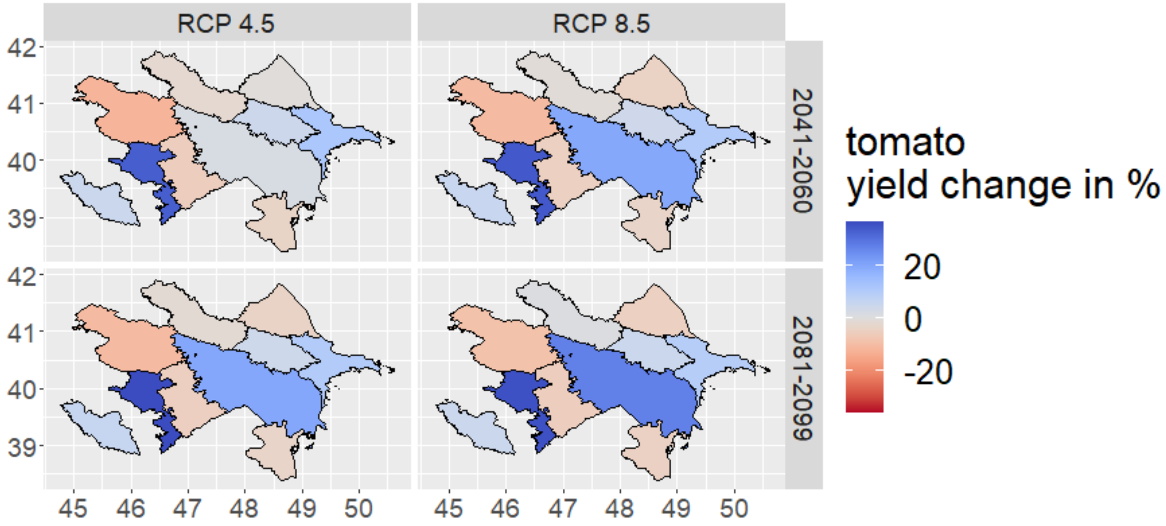

Figure 7: Predicted change in tomato yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield in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

Persimmon

The highest persimmon yields and production amounts can be found in Gence-Qazax, Sheki-Zagatala and parts of Aran (WP3, Figure 2). In Naxcivan, for where we predict a high yield increase, there is almost no persimmon grown, so we do not discuss the results for this province here. We predict future yield decreases for both Gence-Qazax and Sheki-Zagatala, and an even higher yield decrease for Absheron (Figure 8). Precipitation during the vegetative phase is the most important variable in Gence-Qazax (Annex B) and is positively correlated with yield (Annex C). According to the climate projections, there will be a slight increase in precipitation during this phase in the future (Annex A), which is in contrast to the predicted yield decrease. For Sheki-Zagatala, the most important variable is frost during the vegetative phase (Annex B). Less frost is associated to higher yields in this province (Annex C). As frost will decrease in the future (Annex A), this observation is also in contrast to the predicted yield decrease for Sheki-Zagatala. However, the second most important variable for Sheki-Zagatala, precipitation during the vegetative phase (Annex B), is, plausibly, negatively correlated to yield (Annex C). The most important variable for Absheron is frost during the vegetative phase (Annex B). Less frost is associated to lower yields in Absheron (Annex C), which could explain the yield decrease predicted for this province.

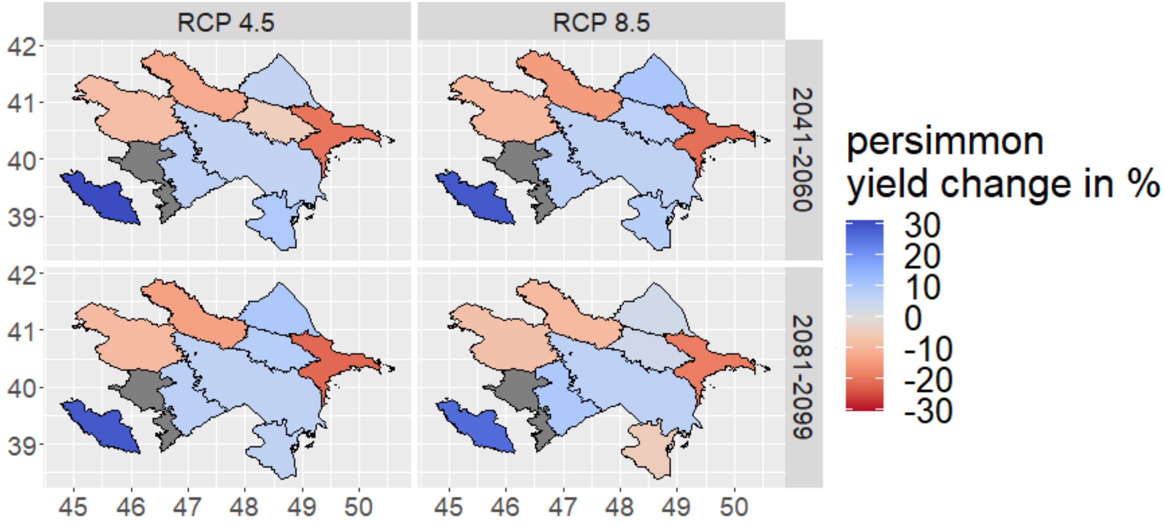

Figure 8: Predicted change in persimmon yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield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

Pomegranate

In Azerbaijan, most pomegranate is produced in Aran, while yield is highest in Gence-Qazax (WP3, Figure 2). We predict virtually no yield change for Aran; an increase in yield for most of the western provinces and Lenkeran in the south, and a large decrease for Absheron. The most important variable in the Absheron model is precipitation during the vegetative phase (Annex B), which is positively correlated with yield (Annex C). The decrease in precipitation expected in the future (Annex A) probably leads to the predicted yield decrease, which in Absheron would be particularly problematic because the province largely lacks natural water resources that would be needed to compensate rain deficits through irrigation. We also predict high decreases for Yuxari-Qarabag, however here, the driving factor is the future increase in maximum temperature during the vegetative phase (Annexes A to C). Note there is only little pomegranate production in Absheron and Yuxari-Qarabag (WP3, Figure 2).

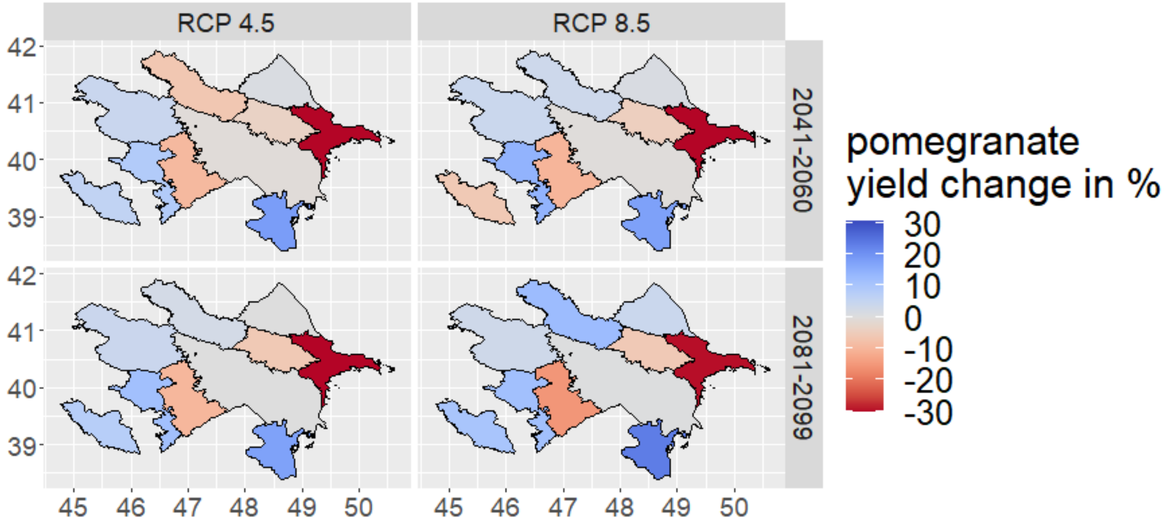

Figure 9: Predicted change in pomegranate yield in %, compared to historical long-year average yield levels (2000-2019), for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). Blue provinces are expected to experience an increase in yield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

2.2 Crops assessed with Chill Unit models

We calculated accumulated chill units at the grid-cell level with the procedure described in chapter 3.2 in the report of WP3 for each year, RCP, and climate forcing model separately. We then averaged the yearly maximum amount of accumulated chill units across all years of the respective period (historical baseline, near future, and far future), and averaged the resulting estimates across all four climate forcing models to obtain long-year model ensemble rasters for each RCP (Figure 10). We calculated the change between the long-year model ensemble rasters and the historical baseline period for each future period and RCP (Figures 11). Finally, we reclassified the maps according to the procedure described in chapter 4.2 in the report of WP3 to obtain maps of future suitability for apple and hazelnut (Figures 12 and 13).

Overall, the total amount of accumulated chill units will be lowest in the mountainous regions of Azerbaijan (Figure 10). However, the lowland regions will experience a decrease in accumulated chill units, probably because spring temperatures will exceed 12.5 °C more often, whereas the mountainous regions will experience a slight increase, probably because winter temperatures will exceed 1.5 °C more often (Figure 11). We predict that the entire country will remain suitable for the production of apple and hazelnut, because the total amount of chill units that accumulates at the end of a crop cycle in the future is still within the range of historically observed accumulated chill units at bud bursting for both crops (Figures 12 and 13). We do not predict that the amount of accumulated chill units would fall below the historical minimum for any part of the country (these areas would be purple in Figures 12 and 13). Note that the phenological record that was available for this study consists of very few observations (see WP3 for more details).

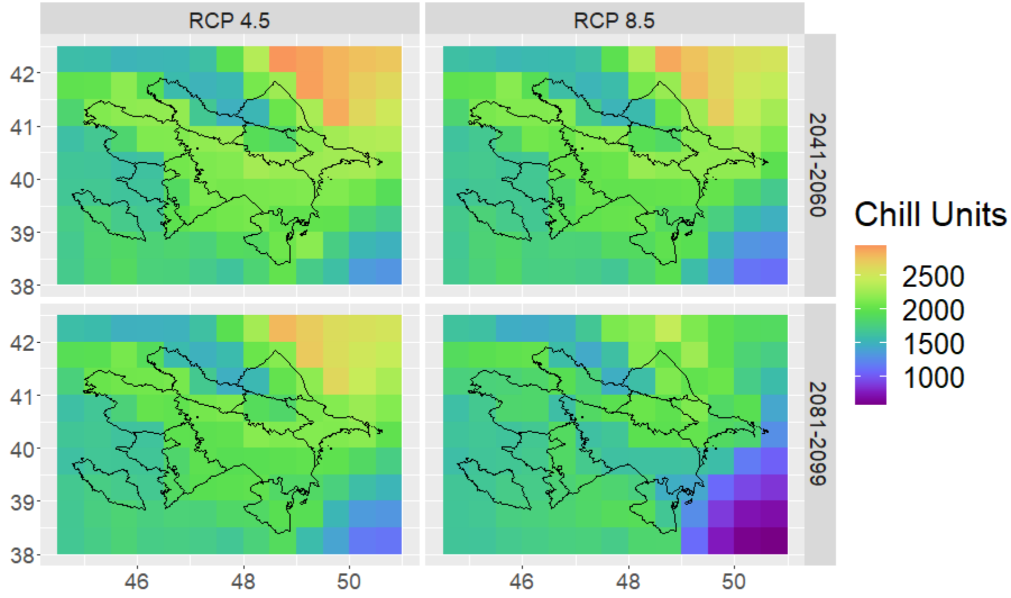

Figure 10: Maximum accumulated chill units for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099).

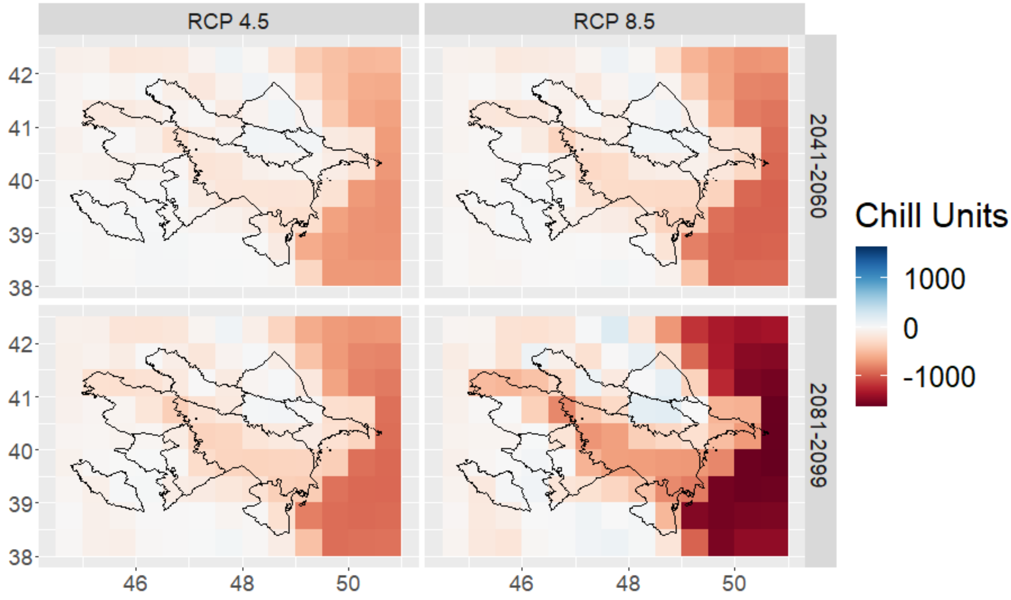

Figure 11: Change in maximum accumulated chill units for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099).

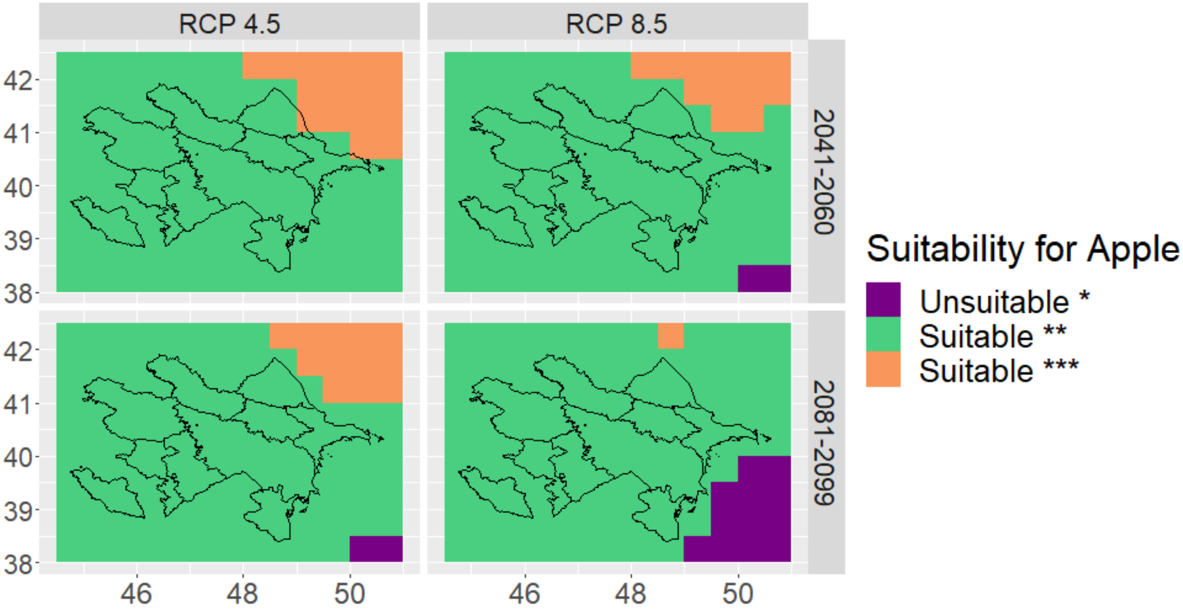

*Figure 12: Future suitability for the production of apple based on the average amount of chill units that accumulate until the end of each crop cycle, for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). *Chill Units are below hist. minimum;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

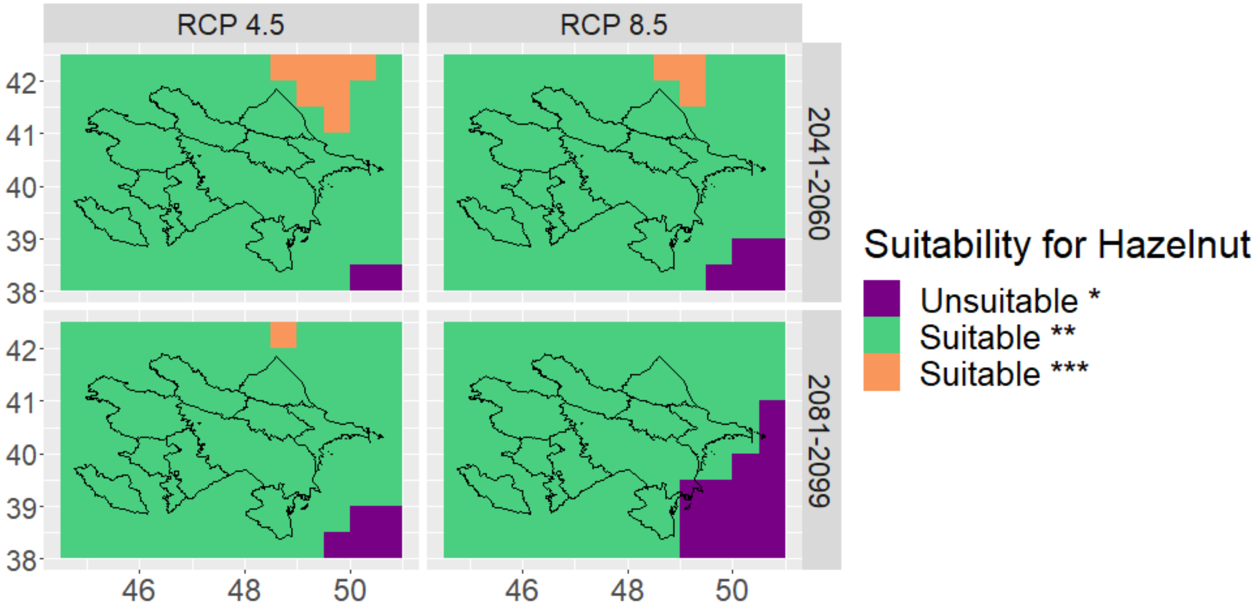

*Figure 13: Future suitability for the production of hazelnut based on the average amount of chill units that accumulate until the end of each crop cycle, for two representative concentration pathways (RCP 4.5 and 8.5) and two future time periods (2041-2060 and 2081-2099). *Chill Units are below hist.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

3. Discussion

We predicted future yield changes for eight crops on the province level with climate projections and Random Forest models. We also predicted future production suitability for apple and hazelnut on the grid cell level with a Chill Unit model. We assessed future conditions for two RCP scenarios and two time periods. Our results suggest that yields of will considerably change in the future, whilst the suitability for the production of apple and hazelnut will be maintained. In these calculations, we did not account for any adaptation measure in crop management, land use, or technology.

Many crops show considerable differences in predicted yield changes between provinces, and many show quite distinct overall spatial patterns, with the exception of the future yield predictions of wheat and barley, for which similar phenological calendars and similar spatial production patterns might be responsible. For wheat and barley, we predict the highest decreases for the mountainous provinces in the north, and for the province of Naxcivan in the west. The high yield changes predicted for Kelbecer-Lacin for onion, potato, cucumber and tomato should not be overinterpreted because production of these crops is extremely low in this province. For the remaining provinces, we mostly predict yield increases for onion and cucumber, but both considerable increases and decreases for potato and tomato. It is surprising that the predicted future yields of cucumber and tomato, which are both largely grown in greenhouses, show only little agreement. While we predict decreases in persimmon yield for the two provinces where this crop is grown most, comparably little changes in yields are predicted for the hotspots of pomegranate production. The contribution of climatic factors such as temperature, heat, heavy precipitation and frost to the predicted yield changes is very context-dependent and differs for crops and provinces. In general, there is a high agreement between the four yield prediction models that we carried out for each crop (RCP 4.5 and 8.5, near and far future). In many instances, the predicted yield increases or decreases intensify with higher future warming (RCP 8.5 represents more warming than RCP 4.5, and there is more warming in the far than in the near future).

Our models predict 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. While temperature increases in winter can lead to an increase in chilling when the minimum suitable temperature threshold of 1.5 °C is surpassed, temperature increases in spring can lead to less chilling when temperatures exceed 12.5 °C (see WP3, chapter 3.2 for methodological details). The predicted increase in mountainous areas is probably due to winter warming, whereas the decrease in lowland areas is probably due to spring warming. Even though all areas of Azerbaijan are predicted to experience amounts of chilling temperatures that are still within the range of historically observed amounts at bud bursting of both apple and hazelnut, we consider the overall tendency of decreasing chilling in lowland areas as a warning sign. In the future, fruit and nut production might have to gradually shift to higher altitudes to ensure sufficient winter chilling under ongoing climate change.

The predicted yield changes and suitability maps should be interpreted with caution and only in relative terms. We emphasize to consider the following fundamental assumptions and limitations of our approach, in addition to the issues discussed in WP3:

- Our future yield predictions are based on empirical relationships between historical crop yields and historical climatic mean and weather extreme variables. We assume that these relationships will remain constant in the future. However, farmers will respond to climate change by adapting the crop management and the selection of crops and varieties planted. The deployment of irrigation systems or greenhouses and the use of drought-resistant cultivars could result in different empirical relationships between yield and climate in the future than what we found for the past. We cannot foresee how farmers will adapt to climate change and how the interlinkages between yield and climate will change in the future. It is also beyond the scope of this report to anticipate to which areas of Azerbaijan cropland will likely expand in the future and where it may be abandoned.

- For some crops and regions, our models suggest considerable yield increases. Worldwide, agricultural yields have greatly improved over the last decades, but the annual percent yield gains have decreased in the last years and crops have physiological yield maxima that cannot be surpassed (Ray et al., 2012). We cannot account for such physiological limits in our models because we lack data about the cultivars grown in Azerbaijan.

- We defined the future onset dates of crop development stages based on the average dates of the historical phenological record. However, crops will probably respond to climate change by changing their phenology. We cannot reliably forecast how such shifts will develop into the future under climate change.

- In WP3, we discussed the limitations related to historical climate and weather data, phenological observations, and yield statistics. Future predictions contain much higher uncertainty: The uncertainty in the Random Forest models propagates and amplifies when we include future climate data. Moreover, the climate projections themselves contain uncertainty. While temperature can be predicted with high agreement among models, predictions of precipitation and extreme weather events are highly uncertain for the future.

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