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Environmental and socio-economic vulnerability of agricultural sector in Armenia

Ani Melkonyan *

University of Duisburg-Essen, Campus Essen, Faculty of Biology, Applied Climatology and Landscape Ecology, Schützenbahn 70, D-45127 Essen, Germany

HIGHLIGHTS

- Crop production has been analyzed in dependence on climatic parameters.
- Drought events have been investigated using drought indices.
- Agroclimatic resources have been assessed using an AMBAV model.
- Vulnerability analysis was carried out with the help of macroeconomic model.
- Crop production vulnerability was assessed in the current and future climate.

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ABSTRACT

Being a mountainous country, Armenia has undergone different kinds of natural disasters, such as droughts, floods, and storms, which have a direct influence on economy and are expected to occur more frequently in terms of climate change, raising the need to estimate economic vulnerability especially in agricultural sector. Agriculture plays a great role in national economy of Armenia, with 21% share in Gross Domestic Production (GDP). For this reason, the estimation of agricultural resources of the country, their vulnerability towards current and future climate, and assessment of economical loss of the agricultural crop production due to climate change are the main goals of the given study. Crop productivity in dependence on climatic elements — temperature, radiation, precipitation, wind field, etc. has been estimated, further on interpolating these relations for future climate conditions using climate projections in the region for the time period of 2011–2040.

Data on air temperature, precipitation, relative humidity, wind speed and direction for the period of 1966–2011 have been taken from 30 stations from the measuring network of Armenian State Hydrometeorological Service. Other climatic parameters like potential and actual evapotranspiration, soil temperature and humidity, field capacity, and wilting point have been calculated with the help of an AMBAV/AMBETTI (agroclimatic) model (German Weather Service).

The results showed that temperature increase accompanied with evapotranspiration increase and water availability decrease especially in low and mid-low altitudes (where the main national crop production is centralized) caused a significant shift in the phenological phases of crops, which is very important information for effective farming dates, giving an opportunity to raise efficiency of agricultural production through minimizing the yield loss due to unfavorable climatic conditions. With the help of macroeconomical analysis of the crop market, it was estimated that the economical loss of the wheat production due to even drier conditions in the future climate (2011–2040) will be more than doubled, causing essential problems in irrigation systems with sparse water resources.

1. Introduction

The crop production process is very complex and cannot be described with only classical meteorological data (air temperature, precipitation, etc. measured in the network of the National Hydrometeorological Service). Even though most of crop production variance can be explained by the classical meteorological parameters, important agricultural issues like sowing and harvesting periods, forecast of the crop production for the next year or adaptation mechanisms, like coverage and burial of crop during winter period (against freezing) can't be answered. Here the limiting factor is the absence of continuous measurements of crucially important parameters like soil temperature and

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* Tel.: +49 201 183 2723; fax: +49 201 183 3239.
E-mail address: ani.melkonyan@uni-due.de.
URL: http://www.uni-due.de/klimatologie.

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humidity at different depths, water content at field capacity, permanent wilting point, snow coverage, potential and actual evapotranspiration, stomata and stand resistance, leaf area index (Bannayan et al., 2011a, b) especially in developing countries. Holzkämper et al. (2011) defined crop development being dependent on average solar radiation, average minimum and maximum temperature, water balance (precipitation–evapotranspiration), phase length, and number of heat or frost days. The potential of all these hydrometeorological elements influencing the efficiency of crop production is called agroclimatic resources (Agroclimatic Resources of Armenia, 2011b). Different models calculate these parameters. Hattermann et al. (2011) used SWIM (Soil and Water Integrated model), getting as output not only the above mentioned parameters, but also river runoff (Elba basin, GLOWA project).

Within the frames of the given study the AMBAV/AMBETI model (‘*A*grarmeteorologisches *M*odell zur *B*erechnung der *a*ktuellen *V*erdunstung’) developed by German Weather Service in Braunschweig (Löpmeier, 1994) is applied to model the agroclimatic resources of Armenia. Input data on classical meteorology were taken from the measuring network of Armenian Hydrometeorological Service (ASHMS, 2011) and data on radiation budget were received from Satellite data (German Aerospace Centre; CM SAF, 2013). Permanent wilting point, field capacity, soil temperature in 5 and 10 cm depths, actual and potential evapotranspiration, and LAI (leaf area index) are received as output. These parameters are vitally important to examine the crop production. When water is accumulated and it becomes equal to field capacity (FC), this point is the onset of the plant or crop growing season or vegetative period length (Bannayan et al., 2011a). Generally this is the period, when the mean temperature is above 10 °C (Alexandrov and Hoogenboom, 2000). To complete the annual cycle (vegetative period) each crop needs specific amount of heat, that is the sum of daily average temperature accumulated from the beginning of vegetation until the end of maturity.

To generalize the dependence of crop sensitivity on meteorology, and analyze crop production in an arid region of Armenia, drought indices are used in this study (Standardized Precipitation Index (SPI), Selyaninov hydrothermal ratio and heat stress index), using the data of only temperature and precipitation, considering the fact that climate projections give reliable information only on these parameters for the future climate.

As a summary, the main aim of the given research is to evaluate agroclimatic resources of Armenia and their influence on agronomic production (winter wheat is considered here) and finding out the potential of raising crop production efficiency for a developing country (Armenia) with specific economic structure and climatic characteristics. These interrelations between climate and harvest enable to develop effective crop management programs in dependence on climate change projections protecting the economy from large GDP losses. The GDP losses due to drought events and water shortages have been evaluated and modeled for the future having used the macroeconomic model evaluating demand and supply of winter wheat in dependence on climatic parameters (Melkonyan and Asadoorian, 2013).

2. Theoretical background

Grain production is the most important in the world economy — nearly 1/6th of total arable land in the world is under wheat cultivation (Rezai and Bannayan, 2012), though cereal production in developing countries decreases by 5%. It is estimated that cereal imports will increase in developing countries by 10 to 40% by 2080 (Rosengrant et al., 2008). Using SRES A2 scenario Schmidhuber and Tubiello (2007) estimated that cereal prices will increase even by 170% by 2080 rescuing global food security. FAO defines food security as a ‘situation that exists when all people at all times have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life’. Full trade liberalization in agriculture would provide more efficient resource use and would lead to higher value added in agriculture globally supporting poverty reduction (Parry, 2007).

Keeping in mind the fact that climate plays a great role in agricultural production especially in the countries with transient economies and areas with complex topography, the issue to investigate efficiency of crop production in dependence on meteorological parameters arises, which generally is carried out with the help of multiple regression analysis. For instance, Alexandrov and Hoogenboom (2000) applied regression analysis, where crop production was taken as a dependent variable, temperature and precipitation (in March, July, August) as independent variables, further on developing a genetic grain cereal model (CERES), which calculates crop phase and morphological development as a function of temperature, daylight length and genetic characteristics. Application of this methodology (multiple regression analysis) is very important to project the crop production in the future under climate change. According to the climate projections carried out with four global circulation models — ACCESS (The Australian Community Climate and Earth System Simulator), MPIM (Max Plank Institute Model), CNRM (Centre National de Recherches Meteorologiques), and GFDL (Geophysical Fluid Dynamic Laboratory) for two scenarios (RCP 4.5 and 8.5 — radiation increase by 4.5 and 8.5 W/m^2) during three periods 2011–2040; 2041–2070; and 2071–2100, the country will have by 1.3 K (RCP 4.5) and 1.6 K (RCP 8.5), by 2.1 K (RCP 4.5) and 3.6 K (RCP 8.5), and by 3.0 K (RCP 4.5) and 6.0 K (RCP 8.5) higher temperatures, respectively for each period. But to monitor the temperature increase and its impact on crop production in the future, it is useful to investigate the temperature changes in the past on the basis of the long-term data, which has been carried out in this study.

Because of rapid increase in temperatures during the last four decades, the growing season has also been altered. The analysis of crop growth length is an important adaptation measure in water management through changing the planting date towards a less risky period or getting a possibility for the second harvest (Alexandrov and Hoogenboom, 2000; Bannayan et al., 2011b).

Reduction of precipitation by 6% has been reported during the last 80 years. The highest decrease was observed at the highest (2.41 mm/year) and the lowest (1.13 mm/year) altitude. The number of dry days (daily sum of precipitation is smaller than 1 mm) increased by 0.4 day per year in the region of Ararat (western state of Armenia), where the agricultural production is centralized (ASHMS, 2011).

The analysis of hydro-meteorological hazards including droughts, floods, heavy rains, and storms, showed that on average every day some hazardous events occurred in the territory during the period of 1975–2006. The highest number of days with hydro-meteorological hazards is recorded in 2003 and 2004 (ANRS, 2011a). Nevertheless, the most important natural disaster for Armenia is drought, towards which the whole territory of Armenia is highly vulnerable. Nearly 50% of the cultivated area is under irrigation. While irrigated areas are impacted by the severity of drought in varying degrees, the rainfed areas are directly affected by drought (Lazar et al., 1995; Rezai and Bannayan, 2012). The severe drought in 2000 resulted in a loss of 2.7% of the whole GDP and 10.1% loss in agricultural GDP. The total loss was estimated to be USD 57 million. Drought increases vulnerability towards other natural hazards, e.g. loss of soil moisture exacerbates the intensity of mudslides and spread of pests (Source; World Bank, “Drought: Management and Mitigation Assessment for Central Asia and the Caucasus”, 2005).

During the drought episodes decreased water availability due to erratic rainfall and growing demand among all users of water is expected to reduce the availability of water for agriculture. To study drought events, there are a couple of drought indices used worldwide, such as Palmer index, Standardized Precipitation Index (SPI), Crop moisture index, Surface water supply index, and Selyaninov hydrothermal ratio (Guttman, 1998; Agnew, 2000; Heim, 2002; Breustedt et al., 2008; Leblois and Quirion, 2013). Some of these indices require a huge set of input data, which is very limited in Armenia. For this reason, SPI and

Selyaninov ratio have been applied in this study given the fact that they need data only on temperature and precipitation and that exactly these parameters are generally projected in climate change models. Further heat stress index after Challinor et al. (2005) has been calculated to analyze to which extent the crop production is sensitive to heat stress during the vegetative period.

At last, the macroeconomic model to assess the impact of meteorological parameters on crop production (Melkonyan and Asadoorian, 2013) and temperature projection with GCMs for the next three decades was used to evaluate potential economical loss of agricultural sector in the future.

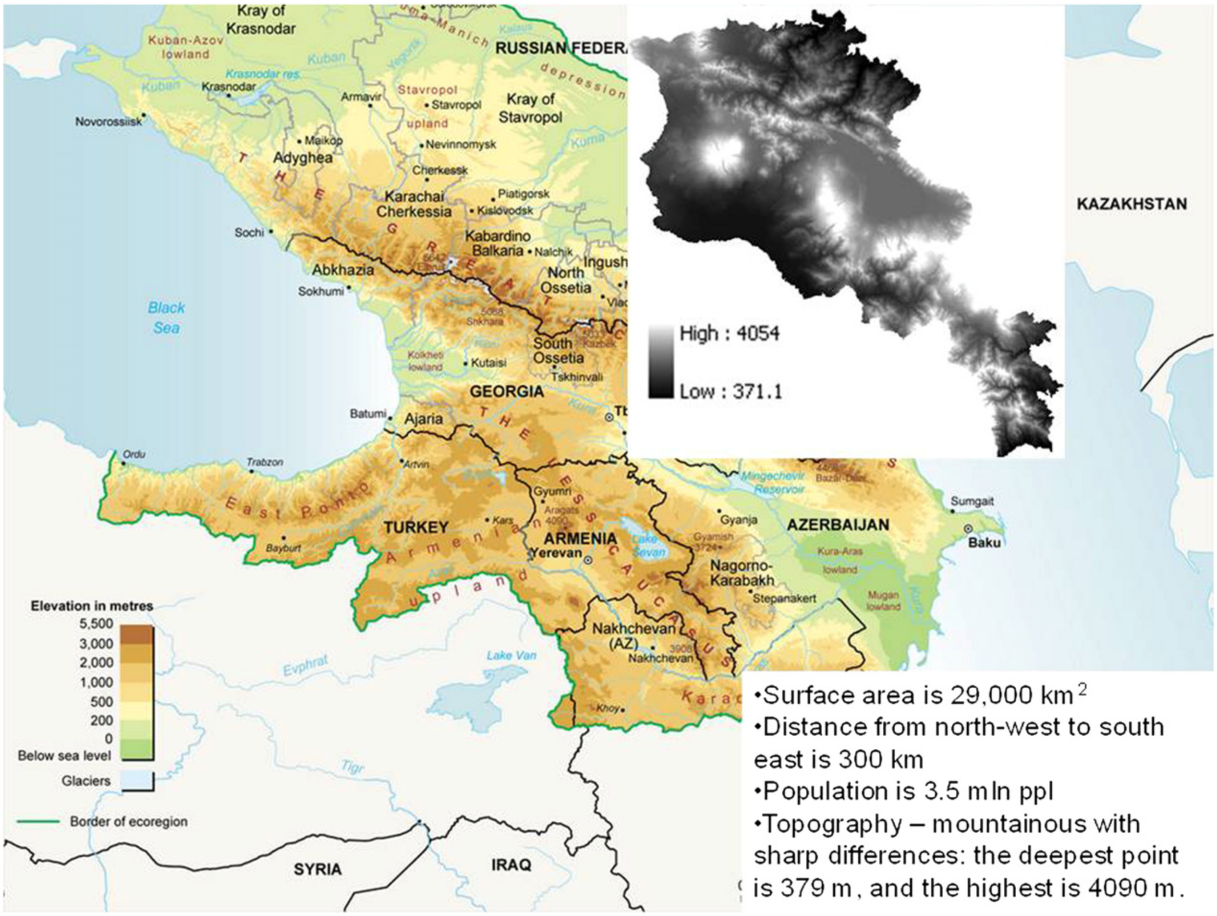
3. Research area

Armenia is a relatively compact, landlocked country in the Southern Caucasus (the latitude is between 38° and 42° N and the longitude is between 43° and 47° E), with an area of nearly 29,800 km^2, and population of about 3.2 million. Armenia is a typical mountainous country with a well-defined mountain relief and ramified river drainage. The average territorial elevation is 1800 m, the maximum height is 4090 m (Mount Aragats) and the minimum is 375 m above sea level (a.s.l.) (ASHMS, 2011) (Fig. 1).

Armenia has a dry climate, which is reflected in low vegetation coverage. The greatest share of vegetation is in the western and north-eastern parts of the territory, because of the favorable weather conditions in this region. Therefore, different regions of the country are used for cultivation of various crop types according to the thermal and water needs of the crops, soil types, texture and thickness, which are relevant for irrigation requirements. The regions with low temperatures and relatively high precipitation sums are used mainly for grain cultivation, due to the fact that cereal crops need relatively high water supply to fight water stress in comparison to fruits and vegetables (Table 1). Required water supply for crop production is given with the term CWR (crop water requirement), which represents total amount of water to be supplied for avoiding water stress. In other words, it is the amount of water needed to compensate the evaporation rate. The amount of water (in addition to precipitation), that must be applied to meet crop's evapotranspiration needs is given with IR (Irrigation requirements). CWR and IWR values are presented as an example for the western region of Armenia (with dominantly clay type of soil made up of particles less than 0.002 μm in diameter and containing higher soil organic carbon) in Table 1, showing high values for winter wheat in comparison to vegetables. Nearly 135,000 tons (or 32,000 ha) of grain production must be permanently irrigated, which makes about 58% of the whole yield of the country requiring irrigation (FAO, 2009), making grain production very sensitive towards irrigation and water balance.

Having a look at the land use map of Armenia (Fig. 2), it can be noticed that nearly half of the territory is used for agriculture. Arable lands and pastures have the highest share in the whole agricultural territory with 35% and 49%, respectively. 40% of the land being used for agricultural production requires systematic irrigation causing a high water demand.

The production of main agricultural crops within eleven states of Armenia is presented in Table 2 (Melkonyan and Asadoorian, 2013), where it can be seen that grains (55% of agricultural production of the total sown area), fruits and grapes (30%), potatoes (11%) and vegetables (6%) are the most important agricultural products in Armenia being



- Surface area is 29,000 km^2
- Distance from north-west to south east is 300 km
- Population is 3.5 mln ppl
- Topography – mountainous with sharp differences: the deepest point is 379 m, and the highest is 4090 m.

Fig. 1. Map of South Caucasus countries and Armenian topographic map.
ASHMS, 2011, modified.

Table 1
Crop water requirement (CWR) and irrigation requirement (IR) for winter wheat and vegetables in Ararat Valley (ANRS, 2011b).

Years	Winter wheat		Vegetables	
	Total CWR (mm)	IR (mm)	Total CWR (mm)	IR (mm)
1967–1982	539	398	336	269
1994–2009	582	463	365	307

sown especially in the states of Ararat and Armavir (located in western part) because of low height a.s.l. (up to 1000 m).

4. Data and methods

4.1. Data collection

All the meteorological data were obtained from Armenian State Hydrometeorological Service for 47 stations (distributed within 11 political states); 30 stations out of them have been chosen because of the reliability of data quality and the length of the dataset. All the data are measured eight times a day and are running from 1966 to 2010. Data have been validated for quality through the use of box-plots to avoid poor quality. Outliers account for no more than 1% of the data.

Information on economical damage (in millions of Armenian Drams) caused by natural disasters (droughts, floods, storms, other extreme events) is provided by Armenian National Rescue Service.

Economic data (i.e., GDP in agricultural production; GDP in the planting sector; prices, quantity demanded and quantity supplied of wheat flour and bread; public income) for the period of 1995–2012 are received from National Statistical Service of Republic of Armenia (NSSRA, 2012).

4.2. Methods

Drought events have been examined with the help of SPI and Selyaninov hydrothermal ratio. SPI deals with the frequency distribution of the precipitation monthly sums during the vegetative period which always follows a gamma distribution (Thom, 1966). After doing Z transformation — converting gamma distribution into the normal distribution, the median corresponds to the value of 0 in the normal distribution. The values smaller than 0 represent drought conditions and the values larger than 0 represent wet conditions. Because of the fact, that only precipitation is used in SPI, and for projecting drought conditions in the future, temperature plays also a great role, another index — Selyaninov hydrothermal ratio, is estimated using Formula (1) (afterwards these indices are correlated to obtain reliable results using the both methods):

$$Sel\ coef = {}^{\sum P}/_{\sum T * 0.1} \tag{1}$$

where $\sum P$ is the sum of the precipitation and $\sum T$ is the sum of temperature during vegetative period (April to October) (ANRS, 2011b). The sum of temperature higher than 10 °C is then correlated with the corresponding mean temperature (through April–September) (Fig. 3) to be able to evaluate the sum of temperature and hence Selyaninov coefficient for the future climate, where only monthly mean temperatures were projected.

All the plants have maximum, optimum and minimum temperature limits, which are cardinal temperature points. Especially optimum temperature range is very important, which differs in various crop types; for instance for wheat it is 25 °C. When mean air temperature exceeds this limit, it will be critical for crop to survive. Therefore it is crucially

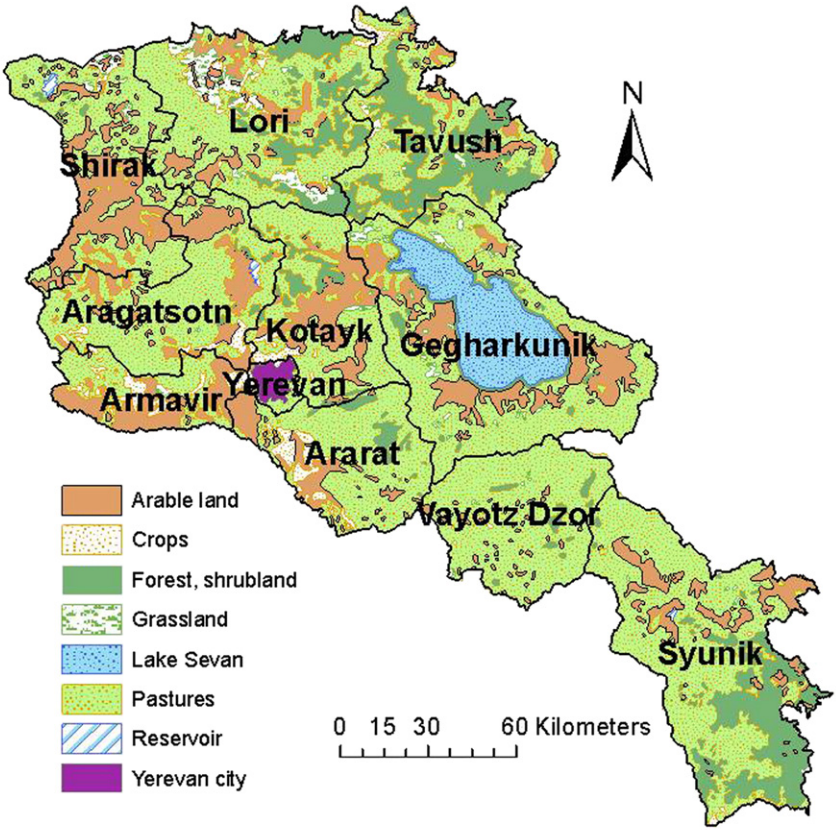


Fig. 2. Land-use classes and eleven states in Armenia.
ASHMS, 2011, modified.

Table 2
Production (in percents) of the main agricultural crops in different states of Armenia.
Source; Statistical Service of Armenia, 2012, modified, Melkonyan and Asadoorian, 2013.

	Production (%)					
States	Grain	Vegetables	Potatoes	Water melons	Fruits and berries	Grape
Aragatsotn	9.5	3.7	6.7	2.4	**18.0**	5.6
Ararat	9.6	**32.1**	5.7	**24.8**	**21.1**	**41.6**
Armavir	**14.1**	**38.0**	7.2	**70.8**	**25.2**	**40.1**
Gegharkunik	**17.6**	5.9	**34.9**		6.2	
Kotayq	5.5	4.7	4.5	0.2	**11.2**	1.3
Lori	6.9	3.3	**18.3**	0.1	3.0	0.2
Shirak	**21.3**	5.3	**10.9**	0.0	1.5	
Syunik	8.7	2.7	5.5	0.4	4.3	0.5
Tavush	5.3	1.6	5.4	0.6	4.6	6.8
Vayots dzor	1.3	1.3	0.7	0.7	3.6	2.2
Yerevan	0.3	1.2	0.3	0.2	1.4	1.9

The highest values are marked in red.

important to estimate heat stress index (f_{HSd}). It was calculated with the following formula (Teixeira et al., 2013):

$$f_{HSd} = \begin{cases} 0.0 \text{ for } T_{day} < T_{crit} \\ \dfrac{T_{day} - T_{crit}}{T_{lim} - T_{crit}} \text{ for } T_{crit} \leq T_{day} \leq T_{lim} \\ 1.0 \, for \, T_{day} \geq T_{lim} \end{cases} \qquad (2)$$

where T_{day} is the daily average temperature (°C), T_{crit} is the critical temperature threshold (for wheat 27 °C is taken) and T_{lim} is the limit temperature threshold (for wheat 40 °C is taken).

Heat stress intensity index values are summarized then and averaged throughout the thermal-sensitive period (TSP), when $T_{day} > T_{crit}$ (Eq. (3)).

$$f_{HS} = \frac{\sum_{j=1}^{TSP} (f_{HSd})}{TSP} \qquad (3)$$

Further, heat intensity index has been calculated for the future climate (for two RCP scenarios) to evaluate the extent of crop sensitivity increase in the future.

As mentioned above, one of the most important parameters for crop planting under rainfed conditions is water balance (precipitation–potential evapotranspiration) (Bannayan et al., 2011b). Further the AMBAV/AMBETI model was used to calculate soil temperature, soil humidity (field capacity) at 5 and 10 cm depths, and potential evapotranspiration under different crop covers (here only winter wheat is used) considering the relevant processes of heat, water and vapor transport in the soil–crop–atmosphere including water losses during irrigation (Löpmeier, 1994). The model was developed by German Weather Service to give recommendations for effective irrigation for different soil types (in this study the soil types were taken from GIS of Armenian Weather Service). Within the model, Penman–Monteith formula is used to simulate water balance in the crop–soil-system. Soil water dynamics are simulated using a mechanistic model based on the Richards equation, while the soil water characteristics and hydraulic conductivity functions are described by pedotransfer functions. The coefficients are recalculated to obtain field capacities and wilting points. The reduction of evaporation and transpiration is calculated from soil water potentials and resistances representing the plant roots.

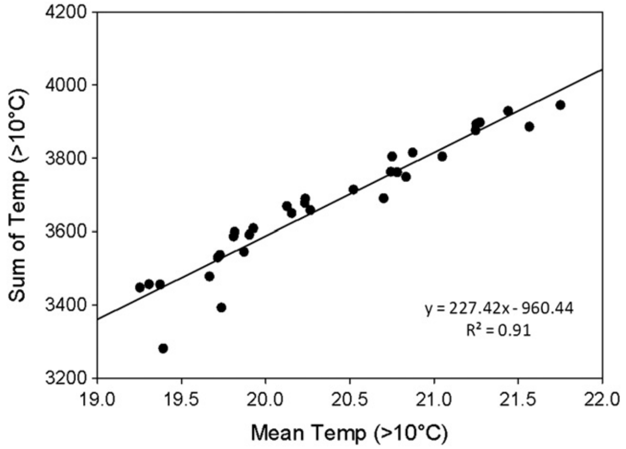


Fig. 3. Regression between mean air temperature and sum of temperature, when temperature was larger than 10 °C (April–October) in Armavir (1966–2010).

Required input parameters are hourly data of air temperature, relative humidity, cloud cover, amount of precipitation, wind speed and global radiation. Incoming and outgoing short- and long-wave radiations were received from CM SAF (The Satellite Application Facility on Climate Monitoring, 2013) database.

In macroeconomic model used here market equilibrium is defined when demand (dependent on prices, public income) and supply (dependent on prices and meteorological parameters) curves intercept returning the equilibrium price and quantity of the products (wheat flour and bread are considered as the main products of winter wheat) (Melkonyan and Asadoorian, 2013). Projecting temperature and precipitation with different models for different scenarios, Selyaninov ratio is also projected gaining new market equilibrium dependent on climate (all the other economic parameters are remained constant). Hence, new market equilibrium with potential economic loss due to unfavorable weather conditions in the context of climate change is evaluated.

5. Results

Agricultural production is influenced by factors, like irrigation system, technologies (mechanization), pest weed and diseases, nutrients, and the most important climate (temperature increase, precipitation decrease, frequency of droughts, etc.). Within the frames of the given study only climate will be analyzed due to the limited access to the other parameters. In the first part, the overall picture of the agrometeorological parameters (both measured and modeled) is presented and their impact on crop production is evaluated. In the second part, projection of future climate (2011–2040) and vulnerability of economic production with the help of macroeconomic model are estimated.

5.1. Climate impact on crop production: agrometeorological resources in the current climate

The analysis of air temperature trend showed that average air temperature increased from 4.65 °C to 5.5 °C throughout the whole territory of Armenia during the period of 1966–2010. In Fig. 4 mean air temperature trend for the different stations grouped for altitude a.s.l. is presented. It can be seen that the sharpest increase (0.04 K/year; from 8 °C to 11 °C on the left axis) occurred at the mid-altitudes (up till 1500 m), where the main agricultural production is concentrated, making crop production more vulnerable.

To be able to assess vulnerability of crop production towards climatic parameters for each state of Armenia, the meteorological data for separate stations should be averaged within the states, because of the fact that crop data are given only for states as entity without any further distinguishment. Hence the meteorological data can be averaged neither according to the height of the stations (they may lie in different states), nor by stations over the state (due to height differences). For that reason temperature, precipitation and relative humidity profiles have been built according to the altitudes of the stations (Fig. 5; temperature is only shown).

As it can be seen in Fig. 5, the correlation between temperature and station height is significantly high ($r = 0.96$, $\alpha = 0.05$); the temperature gradient is 0.66 K/100 m (this result is further used to correct temperature projections received from different models). The dependence of precipitation on station height (not shown here) is also good, even though not too high ($r = 0.66$, $\alpha = 0.05$), which is not the case for relative humidity and for the other meteorological parameters like wind speed and direction (not shown here). Hence, to be able to average the meteorological parameters for the states and find their relationship with crop production, Geographic Information System (GIS) tools have been applied. Two layers of GIS — one with political districts and stations (topographic map) and the other one with grain and grape production have been extracted, so that the weighted average height only for the regions suitable for grain and grape production was calculated. The stations, the height of which corresponded to the calculated weighted average height of the corresponding region were taken as representative stations. Hereafter multiple regression analysis (crop production dependence on meteorological parameters) has been carried out on the basis of the data from the representative stations; crop production is taken as a dependent variable and air temperature, precipitation, relative humidity, wind speed, wind direction as independent variables (Table 3; only grain production in the state of Ararat is shown). The multiple correlation coefficient is 0.84; comparable results were received for grape production at the other stations within different states as well.

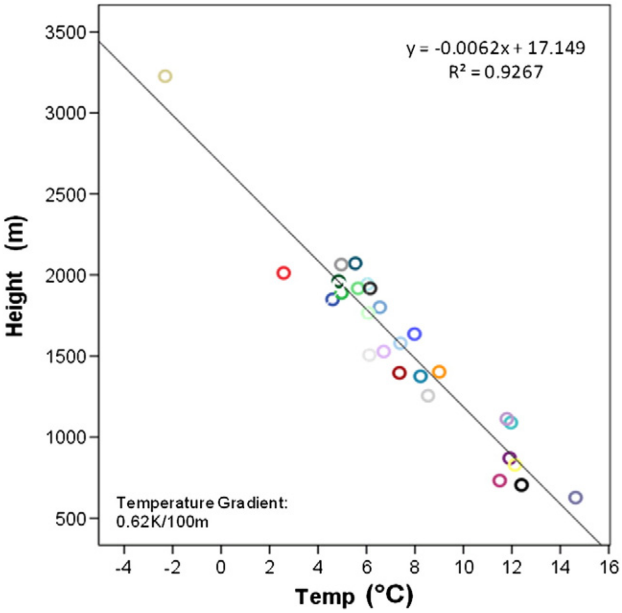


Fig. 5. Temperature dependence on height for different stations (mean values for 1966–2010).

Even though approximately 84% of the whole variance of crop production can be explained with the meteorological parameters, these results are not satisfying (low significance niveau), keeping in mind the fact that not only meteorological parameters (involved in Table 3) are correlated with each other (problem of multicollinearity), but also other parameters important for crop production, like evapotranspiration, soil moisture and soil temperature should also be examined for developing an effective irrigation system through examining the water balance important for the dry climate with limited water resources.

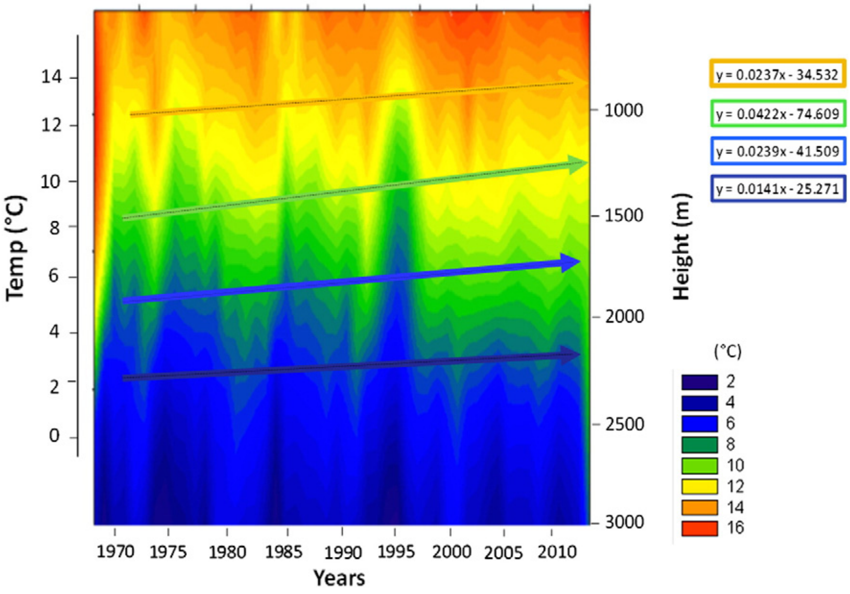


Fig. 4. Mean annual temperatures at the stations with different heights a.s.l. (1966–2010) and their time trend (on the left axis).

Table 3
Grain production in dependence on sown area and meteorological parameters in Ararat (western state of Armenia; R^2 of the multiple regression analysis is 0.84 with 95 % significance).

	Grain production in Ararat						
Years	Grain production (t)	Sown area (ha)	Sum temp (° C)	Sum prec (mm)	Rel hum (%)	Wind speed (m/s)	Wind direction (°)
1990	5392	3306	4766	327	61	1.8	172
1991	7704	4344	4435		62	1.7	177
1992	6099	4602	517	306	61	1.7	172
1993	17,049	9655	4336	311	62	1.2	126
1994	14,111	8540	4698	336	62	1.2	139
1995	11,620	7205	4865	323	60	1.4	152
1996	13,155	6907	4911	324	60	1.4	143
1997	14,908	9285	4530	327	60	1.4	168
1998	21,884	13,102	5076	300	57	1.5	177
1999	24,055	13,712	4059	335	59	1.5	181
2000	22,232	13,728	4872	331	54	1.4	180
2001	19,706	13,913	4956	318	59	1.0	149
2002	20,101	13,038	4742	297	59	1.1	157
2003	18,359	11,849	4641	322	61	1.3	168
2004	22,556	12,497	4765	321	60	1.7	178
2005	21,421	12,481	4789	311	63	1.7	172
2006	14,766	9408	5010	307	63	1.5	139
2007	13,003	6516	4693	336	64	1.2	140
2008	10,614	5456	5083	311	60	1.1	134
2009	9943	5120	4686	324	65	1.0	129
2010	8583	4880	5128	227	62	0.8	109

For that reason potential evapotranspiration, soil moisture (field capacity), and soil temperature at the depth of 5 cm were calculated with the help of the AMBAV/AMBETTI model and together with precipitation sum, Selyaninov hydrothermal ratio and SPI are presented on the monthly basis during the vegetative period in Fig. 6.

Fig. 6 shows that the wettest months are April and May, when precipitation sum reaches its maximum value (45 mm); SPI and Selyaninov ratio vary between -0.8 and 1 and 0.2 and 1, respectively. Relatively high sum of potential evapotranspiration (maximum 150 mm in July) accompanied with extremely less precipitation sum (low Selyaninov and SPI indices, too) and high temperatures (25 °C in average) reflects the negative water balance in the region (potential evapotranspiration–precipitation). High soil temperature (max 17 °C during summer months) and less soil moisture (40% at the field capacity) are the result of this dryness.

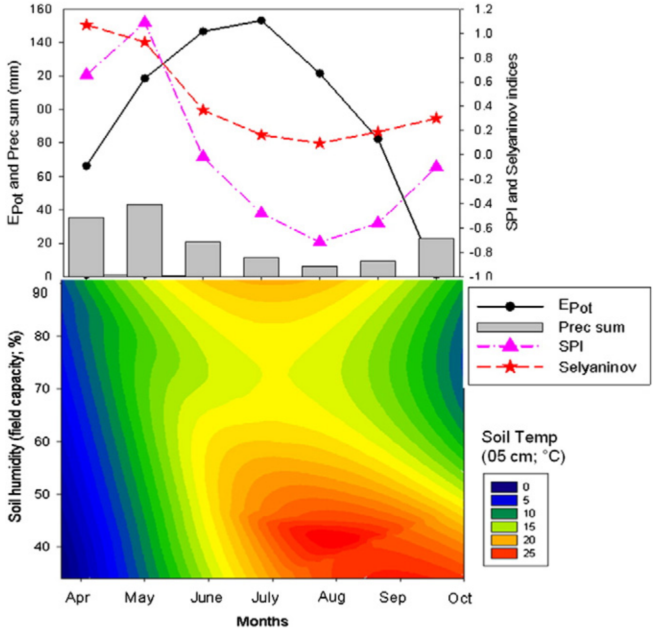


Fig. 6. Available field capacity (%), soil temperature in 5 cm depth, precipitation sum, SPI, Selyaninov index, potential evapotranspiration in Armavir state, Armenia during the vegetative period of 2007–2010 (calculated with the model AMBAV; DWD).

As presented in Fig. 6 and Table 4, all these parameters are significantly correlated with each other, showing that the model results (soil moisture and temperature, potential evapotranspiration and LAI) are reliable being in perfect accordance with measured data (air temperature, precipitation, relative humidity, calculated SPI, Selyaninov hydrothermal ratio). With these results the AMBAV model was verified for the first time for the mountainous dry region of South Caucasus showing the wide use opportunities of the model on the one hand and on the other hand the application of output data for Armenia, where except classical meteorological data, agricultural parameters are lacking.

This kind of information is very important for farmers to organize the planting. For instance, when the field capacity is equal to the water content in the soil, this period is the start of vegetative period or crop growing season (Bannayan et al., 2011a). Generally this period corresponds to the period when the mean temperature is larger than 10 °C (Alexandrov and Hoogenboom, 2000). Analysis shows that the sum of temperatures (>10 °C) increased from 2410 °C to 2827 °C in Armenia, making 9.26 °C/year growth rate (1966–2010). Due to this temperature increase starting dates of crop stages occur earlier, the duration of stages is even shortened (Eitzinger et al., 2010; Finger et al., 2011). Having a look at the time trend of vegetation period in Armenia (Fig. 7) it can be seen that the sum of temperature larger than 10 °C increased significantly (8.9 °C per year) and the mean temperature (>10 °C) did so, too (0.02 °C per year). The date when the temperature exceeded 10 °C for the first time in the year was transformed into the day after the year beginning (for instance 01 March was set to 60). As shown Fig. 7, the vegetation period occurs now significantly earlier (0.3 days per year). If in the beginning of the research period (60s, 70s) the start of vegetative period was in April, now it is in March. This information is important for multiple harvest possibility during a year.

5.2. Estimation of crop production loss: macroeconomic assessment

If in the previous section agroclimatic resources of Armenia (both measured and modeled) together with their impact on crop production were presented, here climate projections in the future and economic loss in agricultural sector (using macroeconomic model) are analyzed.

For assessment of agricultural vulnerability macroeconomic model has been used firstly to estimate crop loss due to drought episodes and then to model this loss, when temperature increase is projected (the climate change signal was too weak and chaotic to conclude changes in precipitation). Four GCMs (ACCESS-G, CNRM-CM5.1, MPI-ECHAM 5 and GFDL 2.0) for two scenarios (RCP 4.5 and RCP 8.5) have been used (Table 5) to estimate temperature changes for the period of 2011–2040 (April–October). This near future period was chosen due to the fact that economic and political parameters might change too drastically and unforeseeably in the longer time period.

Modeled data were verified comparing them with measured data of the stations nearby the corresponding grid cell, realizing also correction of height according to the temperature gradient presented in Fig. 5.

Having the future signal of monthly mean air temperature (precipitation projection is not useful, due to the low resolution of the models and high topographic variation of the region) the sum of temperature during vegetative period (using the regression equation of Fig. 3) and hence also Selyaninov hydrothermal coefficient (Eq. (1)) have been calculated for the near future climate. If the sum of temperature during the vegetative period in 1971–2000 was 3762 °C, it will increase to 4126 °C (using the mild scenario) and 4201 °C (using the severe scenario) during the period of 2011–2040; therefore the Selyaninov hydrothermal ratio will decrease from 0.50 to 0.46 (RCP 4.5) and 0.45 (RCP 8.5) holding the precipitation sum constant.

Table 4
Correlation coefficients among SPI, Selyaninov hydrothermal ratio, potential evapotranspiration, air temperature, relative humidity, soil temperature at 5 and 10 cm depths, soil moisture (field capacity).

	SPI	Selyaninov	Epot	Air temp	Rel hum	Soil temp (05 cm)	Soil temp (10 cm)	Soil moisture
SPI	1							
Selyaninov	0.87	1						
Epot	−0.64	−0.70	1					
Air temp	−0.66	−0.80	0.98	1				
Rel hum	0.83	0.70	−0.82	−0.74	1			
Soil temp (05 cm)	−0.53	−0.66	0.95	0.99	−0.69	1		
Soil temp (10 cm)	−0.49	−0.62	0.95	0.98	−0.68	0.99	1	
Soil moisture	0.70	0.74	−0.92	−0.92	0.82	−0.91	−0.92	1

This information has been used in the macroeconomical model (developed by Melkonyan and Asadoorian, 2013) to assess the vulnerability of agroeconomic sector towards climate change in the near future.

In the economic model market equilibrium is set when demand and supply curves intercept determining the equilibrium price and quantity of the product (here flour and bread are taken, as the main products of winter wheat). The demand curve is defined to be dependent on market price and public income, whereas the supply curve is dependent on market price and climatic conditions. To describe climatic conditions Selyaninov index is taken involving both temperature and precipitation. A positive correlation between supply and Selyaninov coefficient implies that, with better climatic conditions (efficient precipitation and not too high temperatures), the grain production increases and vice-versa.

In order to estimate constant elasticities from the demand and supply models the natural logarithmic transformations were taken and the following models are obtained:

$$\text{Demand}: \ \ln Q_D = 9.26\text{–}0.3 \ln P\text{–}0.1 \ln I + \varepsilon \tag{4}$$

$$\text{Supply}: \ \ln Q_S = 4.52 + 0.3 \ln P + 0.2 \ln w + \varepsilon \tag{5}$$

where Q_D and Q_S are the demanded and supplied quantities of the product, P is the price, I is the public income, w is the Selyaninov coefficient and ε is the stochastic error term with the usual properties. For validating the model, mean values of the corresponding variables for the period of 2001–2010 were used and the equilibrium (*) price and quantity of wheat flour and bread in Armenia ($\text{Ln } P = 5.68$, hence $P^* = 292$ Armenian Drams; $\text{Ln } Q = 6.1$; $Q^* = 445$ thousand tonnes) were obtained (Melkonyan and Asadoorian, 2013). The demand and supply curves are given in Fig. 8, where the market equilibrium represents the interception of them.

Very short fluctuations in these variables will lead to changes along the curves (up or down from equilibrium price). The drought event of the year 2006 can be taken as this kind of short-term change, when the quantity supplied in the market was $e^{6.07}$ (or 436 thousand tonnes). The surface area of the triangle received after projecting this quantity both on the demand (the point coordinates are 6.07; 5.75) and supply (the point coordinates are 6.07; 5.53) curves and connecting these interception points with the initial equilibrium point (the point coordinates are 6.1; 5.68) (Fig. 8) represents the economic welfare loss due to a specific drought event occurred in 2006. This economic welfare ('deadweight') can be evaluated in the following manner (as the surface area of the triangle represented above):

$$½ \left(e^{5.75}–e^{5.53}\right) \cdot \left(e^{6.1}–e^{6.07}\right). \tag{6}$$

In contrast to short-term fluctuations in any variable, the consistent changes of one of the parameters will move the whole curve either to the right (if, for instance, climate conditions become more favorable for the supply) or to the left side (if Selyaninov coefficient decreases as a result of increased temperature or decreased precipitation). Since the model calculations showed that Selyaninov coefficient will significantly decrease (from 0.5 to 0.45), the supply curve will synchronically be removed to the left side by $e^{0.3}$ (Fig. 9). This magnitude was found by calculating the $\text{Ln}Q_D$ according to Eq. (5), replacing w (Selyaninov coefficient) by 0.45 instead of current climatic conditions, where $w = 0.50$. Solving Eq. (5) for P, which is $e^{5.74}$ (or 306 Armenian Drams) we find the new equilibrium (B_1).

As it can be seen, the consistent worsening of the climatic conditions causes economical loss in agricultural sector (here winter wheat) and in

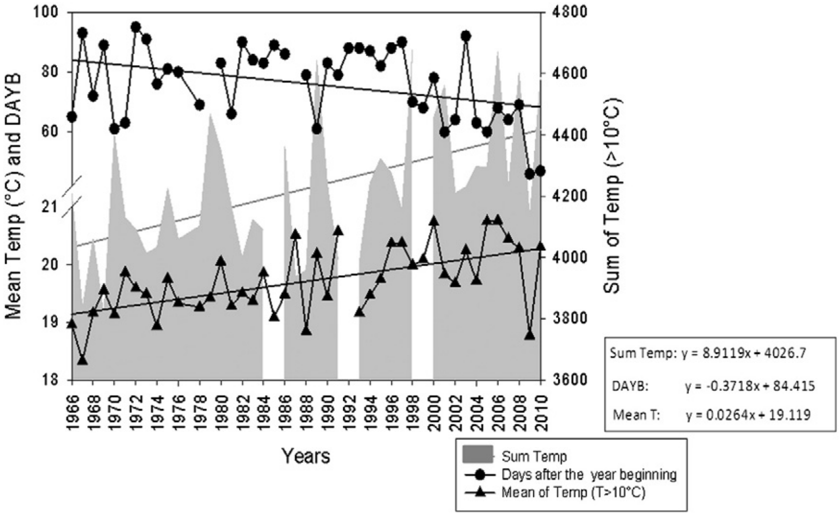


Fig. 7. Time trend of sum of temperatures (>10 °C), mean temperatures (>10 °C), and the days after the year beginning when the temperature exceeded 10 °C at the station Artashat (state Ararat; western state of Armenia).

Table 5
Mean air temperature changes in 2011–2040 in comparison to the period of 1971–2000 for four models (ACCESS; MPIM; CNRM and GFDL) using two scenarios (RCP 4.5 and RCP 8.5).

Models	Scenarios	
	(RCP 4.5)	(RCP 8.5)
ACCESS	1.46	1.84
MPIM	1.74	1.83
CNRM	1.60	1.29
GFDL		2.75
Mean	*1.6*	*1.93*

public welfare, increasing the prices of vitally important product (grain and bread), simultaneously decreasing the production quantity. Calculating the heat stress index (Formulas (2)–(3)), it was seen that in Armenia crop sensitivity is medium ranging between 0.05 and 0.15 (it was 0.11 in the driest south-west region) in the current climate. If we consider mean temperature increase by 1.6 °C (RCP 4.5 scenario) and 1.92 °C (RCP 8.5 scenario), then this index will increase to 0.15 and 0.16, respectively, making the crop production highly sensitive towards temperature. (The sensitivity ranges are given in Teixeira et al., 2013.)

The crop production damage caused by increased temperature can be replaced by adaptation mechanisms, like starting the planting earlier getting a double-harvest chance. Fig. 7 showed that during the last decades the vegetative period occurred earlier (in average it was 76 days after the year beginning, means around March 15) by 0.3 days a year. If we use temperature projection scenarios included in Table 5, and use the regression equation of Fig. 7, it can be seen that the sum of temperature during the vegetative period increases from 3762 °C to 4126 °C (using the mild scenario) and to 4201 °C (using the severe scenario) during the period of 2011–2040. Therefore, the start of vegetative period will occur 8 days earlier than in the current climate (in average it will occur 68 days after the year beginning, means early March, instead of mid-March).

6. Discussion and conclusion

Worldwide agriculture accounts for about 40% of the world's ice-free land use, between 70 and 90% of water consumption, and is responsible for about 60% of greenhouse emissions (FAO, 2009). Because of growing resource constraints, environmental pressures, and higher costs for some inputs, growth in global agricultural products has been above 2% per year over the past several decades, but it's projected to slow to 1.7% per year over the next decade (Green, 2012). Besides, given the fact that agriculture is the most important sector at the local scale too, the emphasis of the given study is given to this sector. On the basis of the trend analysis of harvest and meteorological parameters during the last two decades, crop dependence on climate parameters, structured analysis of all agrometeorological parameters, assessment of drought indices and evaluation of crop production vulnerability towards current and future climate are the main goals of the given study. The simulation of agroclimatic resources has been carried out implementing the AMBAV/AMBETI model (German Weather Service) which later on might be applied as a fundament for improving insurance systems in Armenia (used in Melkonyan and Asadoorian, 2013). This model has been validated for the first time in a complex terrain of Armenia, including important input data like soil type, texture and thickness for various crop types. Reliable results on agrometeorological data, like potential and actual evapotranspiration, leaf area index, soil temperature and humidity at the depths of 05 and 10 cm are obtained. These data are not measured in the country (only at very limited number of stations), which made it impossible to analyze the effectiveness of irrigation systems with very sparse water resources. Mainly grain production has been analyzed in this paper given the fact that not only population's access to cereal production reduces the risk of hunger and poverty, but also grain needs the highest water requirements (also irrigation requirements) having 52% share in the whole crop production requiring irrigation. Therefore, the crucial subject in agriculture is availability of water resources, where input–output efficiency should be calculated. Water management in Armenia is an important task due to the lack of water resources which will become even more crucial within the frames of climate change convention on desertification. For that reason different drought indices (SPI and Selyaninov hydrothermal ratio, heat stress index) have been calculated. It was shown that in the current climate Armenian crop production is sensible to temperature in the medium range (heat stress index is 0.11), which is in very good accordance with Teixeira et al. (2013), but in the future climate the exposure will be significantly higher (0.16). By using a crop analysis model (AQUACROP) FAO has shown that in the future climate water (irrigation) requirements of the grain and fruits in Armenia will rise up by 19–22% and 19–23%, respectively which is also in good accordance with the results of the given study.

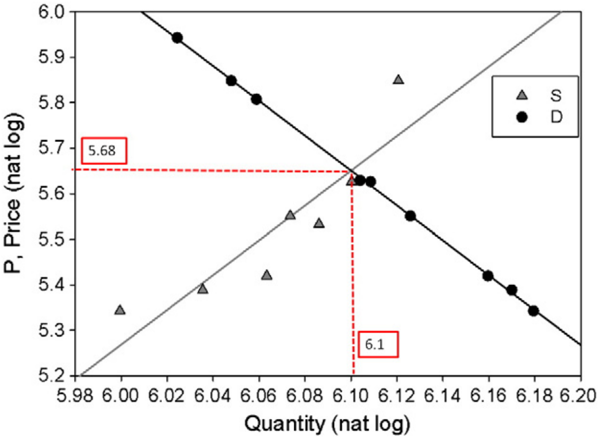


Fig. 8. Demand and supply of wheat flour and bread; market equilibrium, Armenia (Melkonyan and Asadoorian, 2013).

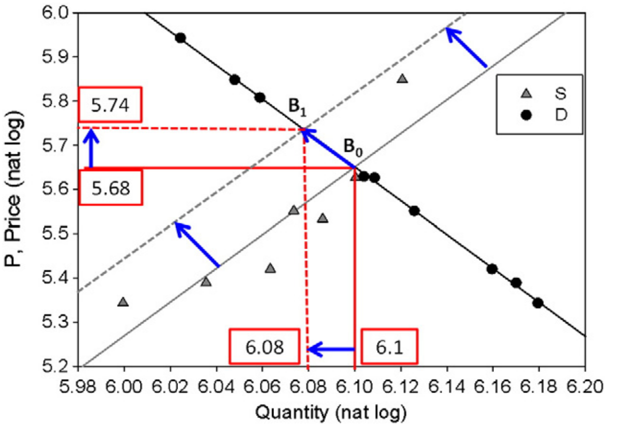


Fig. 9. Demand and supply of wheat flour and bread; market equilibrium for the current climate (B_0) and for the near future climate (B_1), Armenia.

Mathematical modeling of economic efficiency and evaluation of economic loss due to drought events have been realized in the frames of this research study. For that reason market equilibrium (equilibrium price and quantities) for flour and bread (as the main products of winter wheat) was defined by modeling supply and demand curves. The former one was defined to be dependent on climatic conditions (Selyaninov hydrothermal ratio, which is a function from temperature and precipitation sum during the vegetative period). Further, having climate projections for the future climate (2011–2040), crop production vulnerability can be predicted for the future climate as well giving important information for implementing adaptation mechanisms. IPCC defines adaptation as adjustments in ecological, social or economic systems in response to actual or expected climatic stimuli and their effects. Selecting the appropriate adaptation measures needs to consider net economic benefit, timing the benefits, distribution of benefits, and consistency with developing objectives (Rosengrant et al., 2008; Green, 2012). Adaptation is assistance for farmers to make decisions such as timing of planting, choice of crops and crop varieties (a shift towards more valuable crop varieties requiring less irrigation), application of fertilizers, herbicides, pesticides and increasing the effectiveness of irrigation system (use of micro-irrigation, like sprinkle and drop irrigation, which makes currently only 0.07% of the irrigation system). In this analysis it was shown that the start of the planting will occur eight days earlier in the future climate. This information together with other adaptation means, like improvement of irrigation system, building water reservoirs, and introduction of drought resistant crops, will probably cover the economical damage caused by dry weather conditions. But to be able to assess the exact sum of economical coverage, it is necessary to know how much expenses are required for these adaptation mechanisms, which is very hard to estimate due to the fact that agricultural sector is not centralized in Armenia, but it is a subject of small private farms, which have only limited resources and access to the global markets.

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