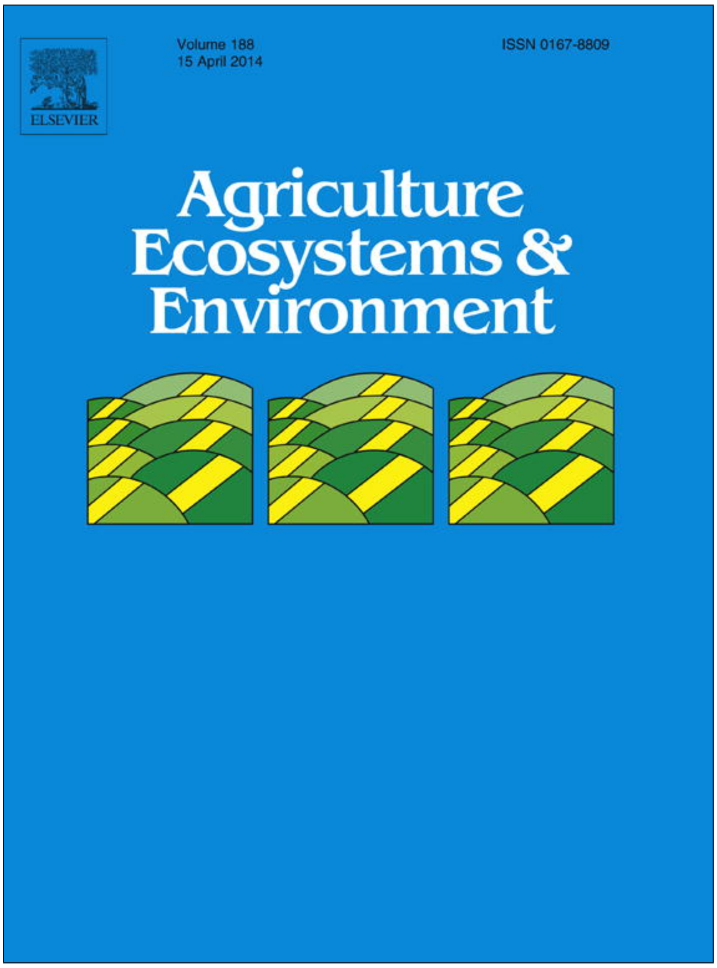
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Impacts of climate change on farm income security in Central Asia: An integrated modeling approach

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ABSTRACT

Increased risk due to global warming has already become embedded in agricultural decision making in Central Asia and uncertainties are projected to increase even further. Agro-ecology and economies of Central Asia are heterogenous and very little is known about the impact of climate change at the sub-national levels. The bio-economic farm model (BEFM) is used for *ex ante* assessment of climate change impacts at sub-national levels in Central Asia. The BEFM is calibrated to 10 farming systems in Central Asia based on the household survey and crop growth experiment data. The production uncertainties and the adaptation options of agricultural producers to changing environments are considered paramount in the simulations.

Very large differences in climate change impacts across the studied farming systems are found. The positive income gains in large-scale commercial farms in the northern regions of Kazakhstan and negative impact in small-scale farms in arid zones of Tajikistan are likely to happen. Producers in Kyrgyzstan may expect higher revenues but also higher income volatilities in the future. Agricultural producers in Uzbekistan may benefit in the near future but may lose their income in the distant future. The negative impacts could be further aggravated in arid zones of Central Asia if irrigation water availability decline due to climate change and water demand increase in upstream regions. The scenario simulations show that market liberalization and improved commodity exchange between the countries have very good potential to cope with the negative consequences of climate change.

1. Introduction

Central Asia covers an area of 400 million hectares, however, only 20% of that is suitable for farming while the rest is deserts and mountainous areas. Nevertheless, agricultural production forms the backbone of Central Asian economies. Agriculture is the main source of export revenues for these countries except the oil rich Kazakhstan and Turkmenistan. The contribution of agriculture to GDP is lowest at 11% in Kazakhstan and highest at 38% in Kyrgyzstan (Bucknall et al., 2003). Cotton exports significantly contribute to the countries' revenues. For instance, cotton fiber exports accounted for about 18% of the total export revenues in Uzbekistan, as of 2004 (CEEP, 2005).

Many aspects of the agricultural sector, including specialization, farm sizes, land ownership and agricultural production efficiency have been undergoing steady transformation since the breakup of the Soviet Union (Pomfret, 2007; Spoor, 2007). Irrational water use during the Soviet Union time have caused several problems in the region including the disappearance of the once fourth largest lake in the world, the Aral Sea (Glantz, 2005). Land degradation as an effect of these improper policies is still a major problem in all Central Asian countries where land salinization affected about 12% of the total irrigated area in Kyrgyzstan, 50–60% in Uzbekistan and even more than 90% in Turkmenistan (Bucknall et al., 2003; CAREC, 2011). Reduction of the cropping areas in the irrigated lands has been observed during the last decades, which often occurs due to land degradation (Kariyeva and van Leeuwen, 2012). Uncertainties during the transition phase combined with land degradation caused high rates of poverty in most of the regions in Central Asia. More than 90% of the population living in the rural areas is defined as poor (<4.30 USD per person per day) according to the recent studies (World Bank, 2009).

Climate change adds additional dimensions to the problems in the Central Asia (CA) region and increases the vulnerability of rural producers (Lioubimtseva and Henebry, 2009). Increasing frequency of droughts is causing serious damage to the livelihoods of rural population in semiarid and arid regions of CA (CAREC,

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2011). Droughts during 2000–2001 and 2007–2008 have shown to be the worst droughts in the history in CA and caused several socio-economic problems (Lioubimtseva and Henebry, 2009). For example, droughts in 2001 and 2008 damaged more than a third of the cropping areas in Tajikistan (Christmann et al., 2009; CAREC, 2011). Furthermore, rainfall is getting heavier and increasing frequency of floods in mountainous regions of CA and the impact is hitting the poorest population the hardest. Rural populations are already suffering from the increasing sequence of extreme events, and projections show even more changes in the future. According to the Intergovernmental Panel on Climate Change (IPCC) predictions (IPCC, 2007b), CA may face declined rainfall during spring, summer and autumn and slightly increased or unchanged precipitation during the winter periods. According to IPCC's fourth assessment report, the temperature in CA may increase by 3.7 °C on average by the end of the century and this is mainly expected to occur during June, July and August, which are the most important months in the vegetation period. Higher temperatures during the vegetation period may cause higher probability of drought risk and declining productivity of agricultural production (IPCC, 2007a).

Existing studies in CA indicate negative effects of weather shocks on the livelihoods of small-scale farmers who are currently operating at a very narrow margin of profits and who lack access to financial resources and technological knowledge in the region (World Bank, 2009; Akramov, 2011).

There is very limited research available on the impact of climate change on agro-ecosystems and analysis of the adaptation strategies in response to the growing urgency in Central Asia (Christmann and Aw-Hassan, 2011). Especially developing integrated assessment tools are becoming very important in order to analyze environmental, economic and social trade-offs in adaptation options in Central Asia (Lioubimtseva and Henebry, 2009). The current knowledge of the economic impacts of climate change on agricultural production in CA is limited in the existing literature at global levels (Cline, 2007; Nelson et al., 2009, 2010), and is very limited in the literature at national or sub-national levels (World Bank, 2009; Mirzabaev, 2013). One of the first few assessments was done for the Syr Darya river basin (one of the transboundary river basins in CA) by Savoskul et al. (2004) which addressed the adaptive measures to cope with increased drought or flooding but mainly based on the data of crop yields taken from global and regional level models rather than considering parameters observed in CA. The research focus of further studies in the region was analyzing the impact of a changing climate on crop yields and natural resources (Ososkova et al., 2000; Chub, 2007; Spectorman and Petrova, 2008; Siegfried et al., 2012). There have been no studies investigating the economic consequences of these biophysical changes at sub-national levels while taking into account adaptive capacity of agricultural producers to the best of our knowledge. Therefore, this study aims at filling this gap in the region through assessing the impact of climate change at the farm level in CA. Additional contributions of this study are the use of the data based on extensive farm surveys, field trials and inclusion of the risk coping behavior of the decision makers in representative farms in the analysis.

2. Modeling approaches to assess the impact of climate change

Available literature broadly distinguishes three types of quantitative assessment methods of climate change impact analysis: Ricardian models, agronomic models and agro-ecological zoning studies (Cline, 2007; World Bank, 2009). The Ricardian model is one of the most widely used methods that is based on the econometric analysis of climate change impact on economic indicators (e.g. income or revenues). Flexibility of this approach is that the scale of the analysis (on farm or regional levels) can be selected depending on data availability. Another advantage of this approach is that it enables the drawing of conclusions based on empirical observations derived from long term historical records (or cross sectional data), which already includes adaptation adjustments of the decision makers (Mirzabaev, 2013). However, availability of long-term data is often difficult in developing countries, especially when smaller production units (e.g. farm level) are considered. Using national or regional level observations may disregard differences in the levels of sensitivity by farm types (e.g. subsistence vs. commercial) (Weersink et al., 2002). Furthermore, this approach may face some difficulties in foreseeing the impact of climate change on agricultural productivity in the far future, especially under changing technology levels and increasing CO_2 concentrations.

In contrast, agronomic models could be very suitable to capture complex effects of climate change on crop productivity. This complexity could be well taken into account using agronomic models such as CropSyst and DSSAT (Jones et al., 2003; Stockle et al., 2003). These models are well-known tools used to analyze the impact of biophysical environment, management practices and climate variation on crop yields. The usefulness of crop simulation models to predict yields have been proven to a large extent and the assessment of farm level impact of climate change is already well investigated with these models. However, one of the disadvantages of this model for impact assessment is the consideration of management as exogenous which disregards the decision makers' adaptation behavior (Schönhart et al., 2011). The impact of climate change on agricultural producers is very much dependent on available adaptation options (Gibbons and Ramsden, 2008) especially in irrigated systems such as those that exist in Central Asia (Kariyeva and van Leeuwen, 2012).

Decision makers' adaptive behavior could be considered in the well-known integrated models often known as bio-economic farm models (BEFM) when analysis are conducted at farm levels (Janssen and van Ittersum, 2007; van Delden et al., 2011). Integrated models are capable of simultaneous consideration of bio-physical changes and management decisions in different farming systems, which makes this approach suitable for analyzing the impacts of climate change on whole farm or sector levels (Keating and McCown, 2001). Additional advantage of integrated models is the possibility of combining agro-ecological zoning approaches (Cline, 2007; World Bank, 2009) since these models could be made spatially explicit (Schönhart et al., 2011). Integrated models give an opportunity of analyzing complex functional relationships between agro-ecological characteristics (e.g. soil type and fertility) and farm level decision making (e.g. input use, technology choice) under climate change scenarios. This makes integrated models very attractive for *ex ante* assessment of scenarios (e.g. climate, policy, technology) even with restricted data availability (Weersink et al., 2002; Thornton, 2006; Janssen and van Ittersum, 2007; Schönhart et al., 2011). Consideration of the uncertainties associated with climate change projections plays an important role in *ex ante* assessment of climate change impact (Iglesias et al., 2010).

Clear superiority of these three approaches over the other does not exist and selection of one of these models can be decided based on the objective of the study and data availability. Since this study aims to investigate the impact of climate chance of agricultural producers in the far future considering adaptation options we consider bio-economic modeling framework suitable to our context.

3. Data and methods

3.1. Integrated model

A bio-economic farm model (BEFM) with risk component is calibrated for 10 representative farm types in four Central Asian

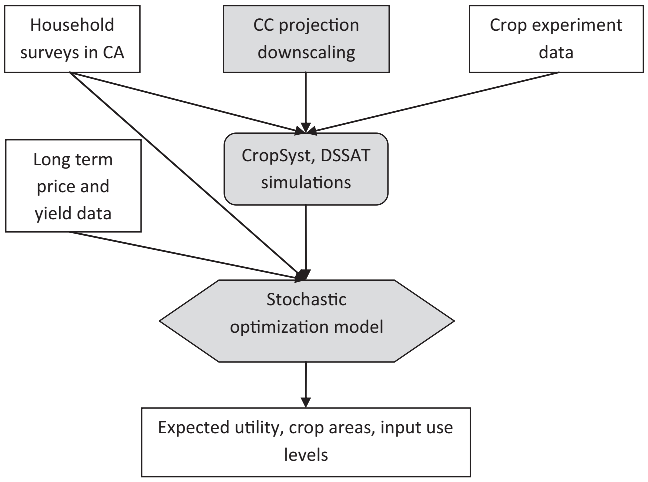

Fig. 1. Bio-economic farm model (BEFM) components. *Note:* CC – climate change and CA – Central Asia.

countries (Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan) with different agro-ecological and socio-economic characteristics. We consider the impact of climate change on three main crops which have crucial importance for the rural economies and food security in CA. Cotton is included in this study as it is the main export crop in Uzbekistan, Tajikistan and Kyrgyzstan (Pomfret, 2007). Average share of cotton in total crop area in some regions of CA reaches up to 40–50% (Bobojonov et al., 2013). Potato and wheat are also included due to their importance in food security and farm income. Wheat is the main export crop in Kazakhstan and is also essential for food security reasons in the entire region (Ali et al., 2005).

Climate change scenarios are spatially downscaled to the local levels (De-Pauw, 2012). The crop simulation models then use these downscaled scenarios (Fig. 1). This combination allows consideration of impacts of climate change on the productivity of different crops. These crop simulation models are calibrated with the crop experiment data as well as actual farm management practices collected from farm surveys. The results of the crop simulation models (yields) were then used in a farm-level stochastic-optimization model in order to identify the climate change impact of farm income volatility and potential of different management options to improve farm income (Fig. 1).

3.2. Farm surveys and representative farms

We have identified 10 representative farms for Central Asia (Kazakhstan, Uzbekistan, Tajikistan and Kyrgyzstan) according to agro-ecological and socio-ecological diversity of the regions in Central Asia. Water availability is the main climatic factor constraining crop growth in Central Asia and aridity zones (AZ) are considered one of the main factors characterizing agro-ecological diversity (Fig. 2) within the country according to farming system and bio-economic modeling studies (e.g. Dixon et al., 2001; Breisinger et al., 2013). Moreover, we distinguish similar AZ in different countries as different farming systems due to socio-economic differences such as farm size, land tenure and agricultural policies between the counties (Pomfret, 2007; Spoor, 2007).

A farm/household survey with a total sample of 1591 was conducted in the representative farming systems during the years 2009–2010. The survey covered both family farms (household plots) as well as commercial farms (*fermers*). The stratified random selection procedure was applied to select several villages from these representative provinces for the abovementioned 10 agro-ecological zones. The number of villages selected from each AZ was determined by the number of farms and agricultural areas used for crop production by different producer types. After identifying the number of villages per AZ, random sampling was used to identify the names of the villages from an available list of villages. Collected data included household characteristics and farm level production characteristics (e.g. farm size, fertilizer use, irrigation practices, input use and fertilizer availability) as well as climate change perceptions. This household data was the main source of information for the identification of representative farms (Table 1) and BEFM calibrations.

One representative farm with average production endowments (e.g. farm size, input use) from each farming systems is selected for calibrating the bio-economic model (Table 1). The study considers two representative medium size farms in Uzbekistan (34.1 ha in the semiarid, 27.1 ha in the arid zone). Three farm types in Kazakhstan were selected: a representative farm with 28 ha of land in the arid zone, 77 ha in the semiarid and 773 ha in the sub-humid zone (including some agricultural areas in humid zones). In the north, the large scale grain cooperatives are predominant with small vegetable plots given to the cooperative workers for subsistence production or others rented out to rural people living in the area. Northern zones produce the largest share of wheat in Kazakhstan and play a very important role for food security in Central Asia (Petrick et al., 2013).

The model is calibrated for a small representative farm of 5.1 ha in the semiarid zones of Kyrgyzstan. Potatoes and wheat producing farm also with 5.1 ha is modeled in the sub-humid areas (including some humid areas) of Kyrgyzstan. The model is calibrated for a farm with 2.1 ha in the humid zone (including per-humid areas) of Tajikistan. Similarly a farm growing wheat, cotton and potato on 4.6 ha in the semiarid zone of Tajikistan is modeled. The selected farm in arid region also have 4.1 ha of land.

3.3. Climate change scenarios

A1b and A2 greenhouse gas emission scenarios of Intergovernmental Panel on Climate Change (IPCC) care considered in the analyses (IPCC, 2007b). There are 23 General Circulation Models (GCM) available and each of them could be used under different emission scenarios. From these GCMs, 7 most realistic/advanced models were used to downscale precipitation, minimum, maximum and mean temperature changes under these scenarios for different future time periods by GIS modeling team (De-Pauw, 2012). The downscaling was implemented by overlaying coarse-gridded GCM change fields into current high-resolution climate grids (Delobel et al., 2010). The main advantage of this method is that it yields results close to the observed situation, even in areas with complex topography, and directly generates climate surfaces (De-Pauw, 2012). This downscaling method provided absolute deviation of monthly temperature (ΔT) and relative deviation of monthly sum of precipitation (ΔP) from historic data. The temperature and precipitation is expected to increase (Table 2) in all considered farming systems but the magnitude of changes very much differs among the farming systems.

Downscaled climate change scenarios were used in crop simulation models in order to determine the yield change under climate change scenarios. Average of 7 GCMs are considered for each considered farming system under A1b and A2 scenarios for two different future time periods (2010–2040 and 2070–2100) in the scope of this study. Since crop models require daily time step data, stochastic weather generators (WGs) are commonly used for estimating daily data. The LARS-WG (Semenov and Barrow, 1997) was chosen as the most suitable weather generator for Central Asian climate for producing the required daily step data (Sommer et al., 2013).

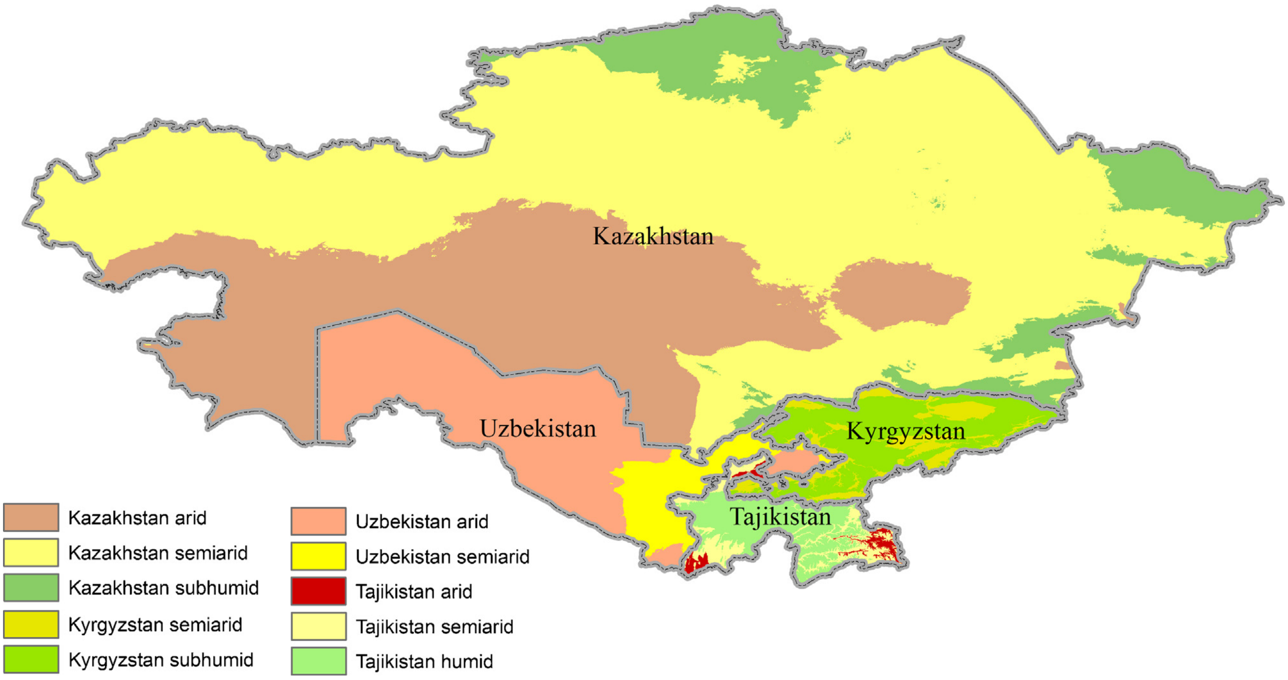

Fig. 2. Representative farming systems in Central Asia. Adapted from De-Pauw (2012) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Table 1
Representative farm characteristics.

Country	AEZ	Farm size, ha	Family size	Fertilizer (N) use per hectare, kg/ha	Land ownership
Kazakhstan	Arid	28	4.1	134.4	Private
	Semiarid	77	5.7	52.3	Private, cooperative
	Sub-humid	773	6.2		Private, cooperative
Kyrgyzstan	Semiarid	5.1	5.6	136.3	Private
	Sub-humid	5.1	5.1		Private
Tajikistan	Arid	4.1	7.3	119.5	State, private
	Semiarid	4.6	7.8	43.5	State, private
	Humid	2.1	8.2	166.7	State, private
Uzbekistan	Arid	27.1	6.7	138.4	Leased
	Semiarid	34.1	5.9	120.2	Leased

Source: Household surveys.

3.4. Crop yield simulation under climate change

CropSyst and DSSAT models are used to assess the impact of climate change on crop yields in Central Asia (Jones et al., 2003; Stockle et al., 2003). These models were calibrated for each of these countries and selection of the locations is done according to the importance of the farming systems in production of wheat, cotton and potato. Data on crop experiments conducted by national research institutes in Central Asia was obtained in order to calibrate the crop simulation models (Kato and Nkonya, 2012; Sommer

Table 2
Model scenarios, mean annual temperature and precipitation changes to the baseline scenario.

	A1b (2010–2040)		A2 (2010–2040)		A1b (2070–2100)		A2 (2070–2100)	
	Temp., °C	Percip., mm	Temp., °C	Percip., mm	Temp., °C	Percip., mm	Temp., °C	Percip., mm
Kazakhstan								
Arid	1.3	8.4	1.4	9.3	3.6	11.5	4.4	5.3
Semiarid	1.3	12.9	1.4	16.5	4	27.7	4.8	19.8
Sub-humid	1.3	10	1.5	16	4.2	25.3	5.1	11.9
Kyrgyzstan								
Semiarid	1.3	6.6	1.4	8.4	3.6	22.7	4.2	19.3
Sub-humid	1.3	8.1	1.4	10	3.6	36.5	4.2	36.3
Tajikistan								
Arid	1.3	6.2	1.5	8.3	3.7	9.7	4.3	2.7
Semiarid	1.4	8.6	1.5	21	3.8	13	4.4	7.3
Uzbekistan								
Arid	1.3	7.7	1.3	12.6	3.5	12.7	4.1	10.4
Semiarid	1.3	14.9	1.4	18	3.6	25.4	4.2	17.1

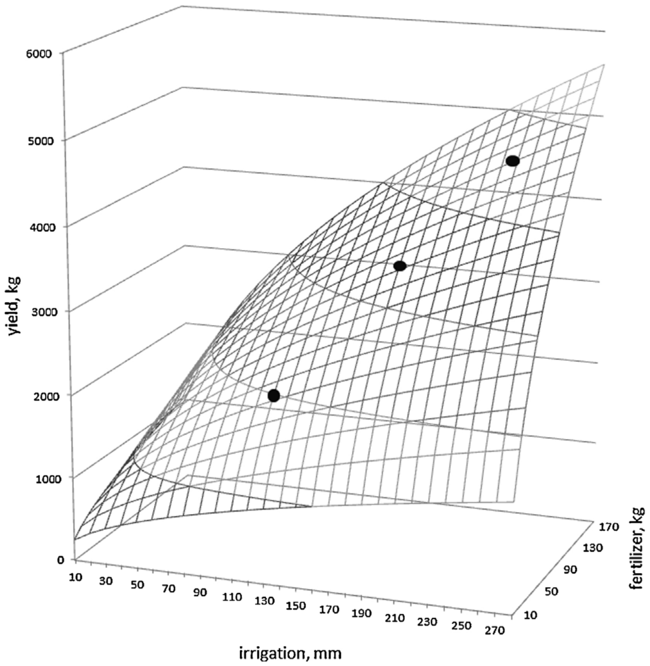

Fig. 3. Illustration of CropSyst yield simulation for different irrigation and fertilizer use in the example of wheat.

et al., 2012). The production of wheat was simulated by CropSyst (Sommer et al., 2012) while production of cotton and potato were simulated by DSSAT model (Kato and Nkonya, 2012). Crop yields under these scenarios for the years of 2011–2040 (near future) and 2071–2100 (far future) were analyzed with the help of CropSyst and DSSAT models. The selection of these models was determined by two independent modeling teams according to data availability and their experience in a certain platform (Kato and Nkonya, 2012; Sommer et al., 2012).

The CropSyst model was calibrated with the experimental data with different fertilization rates and irrigation practices (Sommer et al., 2012). Calibrations of crop models were implemented with at least three years of daily weather records and crop growth experiment data conducted at national research stations in selected farming systems. After the calibration of the crop models, crop yields under different management options were simulated for the abovementioned scenarios and time periods. In order to reduce the dimensionality problem, the CropSyst modeling team has selected three management options as presented in Fig. 3. Mean yield and standard deviation of yield for these three management options for all locations and climate change scenarios were available from crop simulation results. These three input use bundles are hereafter named as low, average and high input intensive management options (see Supplementary Material). Only one planting date for each farming system is considered in the crop yield simulations (Sommer et al., 2013).

DSSAT model was calibrated to simulate different mineral fertilizer and organic fertilizer (manure) levels (Kato and Nkonya, 2012). Irrigation water for cotton and potatoes were kept constant in levels observed in the farming systems. An example of crop model mean yield and yield volatilities is given in Tables 3 and 4 in the case semiarid farming systems in Uzbekistan.

The mean yield and volatilities differ between the crops as well as the climate change scenarios (Tables 3 and 4). Similar information was obtained for all considered farming systems together input use for each of those management options (see Supplementary Material for detailed info). Those yields estimated by crop models used in the optimization process are explained in more detail below.

3.5. Expected value-variance estimations

In farm economics, it is not only important to look at the variability of yields and prices associated with climate uncertainties, but also covariance between them. Omitting this, in turn, may cause over/under estimation of impact depending on crops and farm types considered. For example, the negative effects of lower yields are moderated or reversed if there is strong negative correlation between prices and yields. The reduction in farm benefits may be very limited due to a natural hedging effect (i.e. yield and price risk cancels each other) under these circumstances. However, considerable decline in the benefits could be observed in the regions where there is no negative price correlations observed. Furthermore, crop diversification effect is one of the important aspects that also need to be considered for multiple crop farms. These aspects could be well captured when selecting stochastic modeling framework.

In this study, the expected value-variance (EV) framework approach is used as one of the commonly used approaches to analyze risk associated with different agricultural decisions such as crop allocation and input use levels (Hazell and Norton, 1986; Ingersoll, 1987; Hardaker and Lien, 2010). In the EV approach, the choice of activities or enterprises with the highest utility for the farmer is determined taking into account the variability of utilities and their covariance across different crop enterprises. The EV can be used to analyze the impact of climate change and the resultant farmer responses especially with regard to area allocation and resource use decisions. The BEFM model determines optimal cropping area allocation and optimal input use levels under different climate scenarios. The main criteria for identification of the optimal mix of activities are the expected income and variance of income of each type of activity. The model objective function which maximizes the expected utility (EU) (also known as certainty equivalent, CE) as considered in many bio-economic models in the past (e.g. Börner et al., 2007) and given by:

$$\max\ \mathrm{EU} = E(Y) - \frac{\lambda}{2}V(Y) \qquad (1)$$

$$\text{Subject to } B_j \geq \sum_{i=1}^{n} a_{ji}H_i \qquad (2)$$

where $E(Y)$ represents the total expected income (expected returns minus costs) of the farm, $V(Y)$ is the variance of the income and λ is a parameter that represents the coefficient of absolute risk aversion, B_j is the availability of jth resource (e.g. fertilizer, irrigation water), a_{ji} is input use coefficient for crop i, and H_i is the area under each crop. The EU according to Eq. (1) can be used as a measure of risk free income and the option with a higher EU is preferred to one with a lower EU. The constraints in the model are estimated from the household survey data, which represent physical constraints of resources associated with agro-climatic (e.g. water) as well as socio-economic (e.g. lack of fertilizer due poor service sector) factors. Mean and standard deviation of yields, prices and their stochastic dependencies are the main parameters used in the estimation of $E(Y)$ and $V(Y)$ (see Supplementary Material for detailed info).

Long-term prices at country level are compiled from international (e.g. FAO) and national statistical committees. Farm level prices were available from the household survey for 2010. Country level prices were adjusted to the farm gate prices in the estimation of mean and variance of prices used in the model. Variable and fixed costs are estimated from household survey data. Variable costs include machinery (including fuel), fertilizer, water and labor costs. Fixed costs include depreciation costs of machinery, buildings and tax payments.

Table 3
Crop yields under different management options and climate change scenarios in semiarid zones of Uzbekistan, ton ha^{-1}.

Crop	Management option (input use level)	Baseline	A1b (2010–2040)	A1b (2070–2100)	A2 (2010–2040)	A2 (2070–2100)
Cotton	Low	3.27	3.33	2.08	3.52	1.63
	Average		3.6	1.56	3.92	1.06
	High		3.79	2.35	4.03	1.73
Potatoes	Low	18.9	21.41	23.38	21.47	22.11
Wheat	Low	2.83	2.88	3.27	2.88	4.01
	Average	4.3	4.36	4.87	4.42	5.45
	High	5.44	5.69	6.37	5.73	6.87

Source: Sommer et al. (2012) and Kato and Nkonya (2012).

Mean and variance of yields are obtained from the results of the crop simulation models for each crop under different crop management options discussed in the previous section.

The optimization model is calibrated by adjusting the risk aversion parameter λ in Eq. (1). The reason behind this calibration procedure is to identify the risk aversion of the decision maker which motivates him/her to diversify cropping patterns to secure revenues. The model is calibrated to the observed crop allocation in each of the agro-ecological zones.

3.6. Assumptions and limitation of the study

The representative farms considered in the study are assumed to be commercial farms and no constraint associated with household consumption demand is considered. Furthermore, only one farm type per farming system is considered and no differentiation between subsistence and commercial farm is elaborated. All farms are assumed to be price takers and no price changes associated with their production decisions are considered. The mean and variance of output prices used in the climate change simulations are estimated from historical observations. Furthermore, no adjustment to input prices are made due to the lack of data related to future input price changes in the region.

Occurrences of rare events are considered on the base of current probabilities which might be one of the shortcomings of this study. Additionally, simulated yields under climate change scenarios do not consider any impact of changing diseases and pests in the future. Furthermore, the static nature of the model does not consider any accumulation effect of climate change over the years. The study does not provide information about the effect of technology changes as well as changes in crop varieties in the future. Further information needs to be obtained in order to adjust model parameters to potential improvements of technologies and the crop varieties considered in the study.

4. Results and discussion

4.1. Climate change impact on representative farms

The mean yields of wheat and potatoes in semiarid Uzbekistan will increase under all management options, but the yield of cotton will decline. Volatility of wheat and potato yields will slightly decline in the future, but volatility of cotton yield is expected to increase, especially under the A2 scenario in the far future. The expected gross margin of potato is very high when compared to other crops due to high yields of potato (Table 5).

The optimal cropping patterns simulated under climate change scenarios for the representative farm in semiarid Uzbekistan are presented in Table 5.The high share of cotton and wheat area against their low economic returns (even negative in some cases) could be explained by the minimum area constraint introduced to reflect the procurement systems in Uzbekistan (Bobojonov et al., 2010; Djanibekov et al., 2013). This quota must be fulfilled by all farmers regardless of their risk aversion levels in order to maintain farming licenses issued by local authorities (Veldwisch and Spoor, 2008). Therefore alternative crops are grown in very limited areas despite their high economic returns (Bobojonov et al., 2013). The returns from the state ordered crops are very low and can be even negative in some future scenarios (Table 5).

Allocation of crop areas presented in Table 6 change across climate change scenarios depending on gains (or losses) in the expected utility (EU) from growing these crops under the different scenarios. Furthermore, it can also be noted that there are changes in crop areas under different management levels. The main factors determining the changes in EU are mean and variance of crop yields, the volatility as well as the production costs under the different management practices. Furthermore, selection of crop areas and the best management options are also influenced by the availability of irrigation water and fertilizers in the representative farm.

Each of the crops considered in the model could be planted with three management options. If returns from one input level decline, farmers have a choice to change farming practices to more input intensive technology or to change crop acreages. It should be noted that cotton production has shifted from high input use management options to less intensive input use options. The main reason for that could be explained by the increasing area of wheat production with more intensive management options. Thus, less fertilizer and water was available for growing cotton with intensive input levels. These are the kind of trade-offs farmers will face to optimize their resources use, especially under climate change. Similar results were also reported by several studies where, due to the differential in marginal returns, farmers often used the subsidized fertilizer obtained for cotton on other high return crops (Veldwisch and Spoor, 2008).

Expected income (without considering risk) per hectare in semiarid regions of Uzbekistan is equal to USD 786 under the base case scenario. A slight increase of expected income is seen in the A1b scenario in both time periods and in the A2 scenario during the period 2010–2040. However, there is a decline to USD 690 ha^{-1} in the A2 scenario during the period 2070–2100. The results demonstrate that expected income will not be lower than the current level in the near future (2010–2040), but could be expected to decline in the late future (2070–2100) in the semiarid regions of Uzbekistan. However, the previous two statements require further qualification in terms of changing risk in the future. Fig. 4 demonstrates increasing variance in all scenarios which may indicate higher risk in the future. The figure reveals that expected farm income may increase in the near future, but farming business will also become more risky which is mainly due to increasing variation of yields caused

Table 4
Crop yield volatilities (coefficient of variation) under different management options and climate change scenarios in semiarid zones of Uzbekistan.

Crop	Management option (input use level)	Baseline	A1b (2010–2040)	A1b (2070–2100)	A2 (2010–2040)	A2 (2070–2100)
Cotton	Low	0.11	0.14	0.21	0.10	0.23
	Average		0.17	0.27	0.14	0.31
	High		0.14	0.23	0.09	0.24
Potatoes	Low	0.32	0.29	0.22	0.29	0.25
Wheat	Low	0.46	0.49	0.48	0.47	0.34
	Average	0.31	0.34	0.37	0.33	0.27
	High	0.22	0.25	0.27	0.24	0.21

Source: Sommer et al. (2012) and Kato and Nkonya (2012).

Table 5
Expected gross margins under different management options and climate change scenarios in semiarid zone of Uzbekistan, USD ha^{-1}.

Crop	Management option	Baseline	A1b (2010–2040)	A1b (2070–2100)	A2 (2010–2040)	A2 (2070–2100)
Cotton	Low	196.8	215.3	−215.9	283.6	−369.9
	Average		217.1	−484.2	328.4	−654.9
	High		313.9	−183.8	400.2	−395.4
Potatoes	Low	3783.4	4514.4	5122.3	4532.0	4737.8
Wheat	Low	128.8	135.8	197.2	136.2	319.1
	Average	327.6	335.6	415.0	345.5	512.5
	High	481.4	519.6	626.5	526.3	710.8

Table 6
Allocation of crops with different management options, semiarid zone Uzbekistan, ha.

Crop	Management option	Baseline	A1b (2010–2040)	A1b (2070–2100)	A2 (2010–2040)	A2 (2070–2100)
Cotton	Low	18.8	9.0	17.4	7.8	17.8
	Average		7.5		8.6	
	High		2.2	1.4	2.4	0.9
Potatoes	Low	4.8	4.9	5.0	4.9	4.9
Wheat	Average		1.1	0.6	1.4	
	High	10.6	9.0	9.8	8.8	10.5

by climate change. Therefore, farmers may gain less utility, as shown by low EU, in some of the scenarios due to increased variance in farm income.

Similar simulations were also carried out for the remaining nine farming systems in CA. Only average yield and expected utility changes are reported for the remaining farming systems in this paper (see Supplementary Material for the detailed model outputs). The direction of change in arid regions of Uzbekistan is also similar to the semiarid zones, but the magnitude of change differs. The model simulations have shown that utility of the farmers in arid regions of Uzbekistan will be higher (compared to the baseline) under all scenarios except scenario A2 for the period of 2070–2100. Magnitude of increase especially is higher under the A1b scenario in the far future. Prolongation of the vegetation period and carbon fertilization created favorable conditions to increase the productivity of crops and therefore higher yields as presented in Fig. 5.

However, higher temperature projections under the A2 scenario during the period of 2070–2100 reduce cotton yields caused mainly by increased water stress under this scenario. Therefore, the EU per hectare is expected to decline by more than 15% under the A2 scenario in the far future (Table 7).

Fig. 6 maps the changes in EU in representative crop growing farms in all considered farming systems under different scenarios. These maps are presented for a better visualization of the results as well as for identifying the areas which require more attention in terms of policies for increasing climate resilience. However, the maps are valid only for crop growing farms in these zones and does not include changes in profits of livestock farms and gardeners. Nevertheless, the changes in other farming systems may also develop in similar directions due to high and positive covariance between the revenues of farms located in the same AZ.

The green areas in the figures show the areas where farm income is expected to increase under climate change scenarios. In contrast, red areas show the regions where farm income is expected to decline. The arid regions of Uzbekistan, located in the southwest of Central Asia (see Fig. 2 for the location of the countries and AZs). It can be seen that arid regions of Uzbekistan often appeared with green colors in all scenarios except in A2 for the years 2070–2100 presented (lower right panel in Fig. 6).

From Table 7 it can be seen that farmers in arid zones of Kazakhstan (the central and western location of CA in Fig. 6) might expect utility gains from climate change in the future. Furthermore, expected increases in temperature and precipitation may create more favorable growth condition and higher yields in this farming system.

The semiarid zone covers the largest area in Kazakhstan where cereals are the main crops grown. Furthermore, vegetable production also plays an important role for food security especially in small-scale farms and rural households. Cotton is also produced in the southern regions with semiarid climate in the neighboring areas of Uzbekistan.

Model results have shown that climate change is expected to have a positive effect on agriculture in sub-humid zones of Kazakhstan. Increasing temperatures and rainfall are likely to create favorable conditions for agricultural production. As shown by Table 7, this increases crop yields, which is very likely to also increase farm income in the future.

The expected utilities of farms will stay at the same level with the base scenario in the near future under both emission scenarios in the semiarid zones of Kyrgyzstan. However, expected utility is expected to increase slightly in the far future under both gas emission scenarios due to increased yield of wheat in this region. However, variance of income is also expected to increase in this region which may cause more uncertainties in decision making.

Similar to the semiarid regions, the expected utility of farmers increased under future scenarios in the sub-humid areas of Kyrgyzstan. Especially the increase in

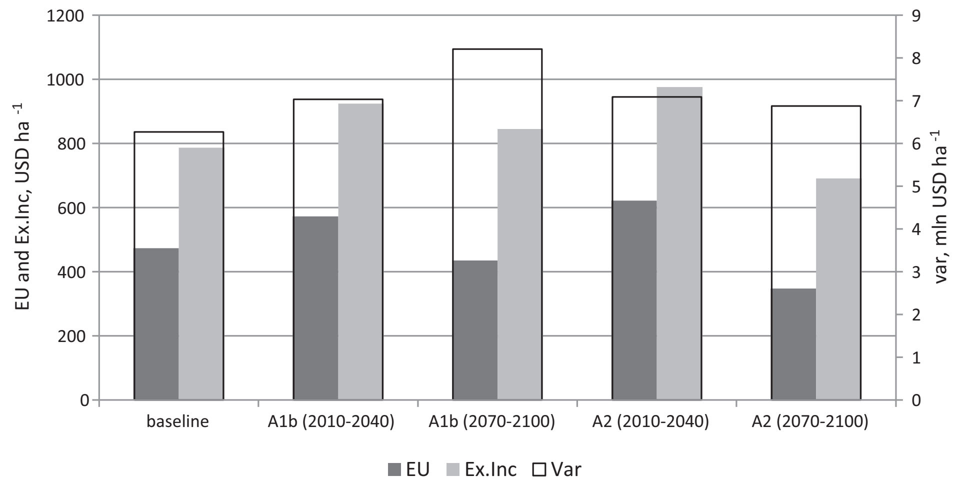

Fig. 4. Expected utility, expected income and variance change in the representative farm under different scenarios (semiarid, Uzbekistan).

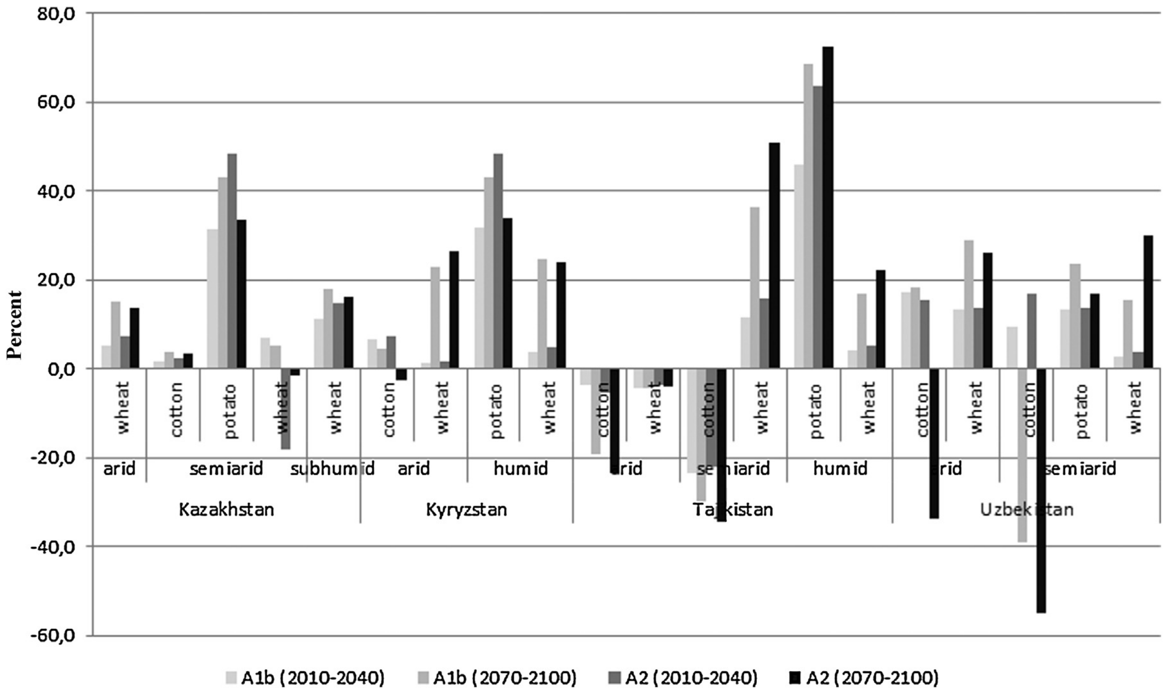

Fig. 5. Crop yield changes under average input use levels compared to the baseline scenario.

expected utility is very significant in late future scenarios due to the increase in wheat yields in the AZ.

The yield of wheat is expected to increase in the future as simulated by the CropSyst model based on climate change projections in the semiarid zone of Tajikistan (Sommer et al., 2012). In contrast, cotton yields are expected to decline in these zones according to the DSSAT results. Increased wheat yields will have positive impacts on overall expected utility of farmers in the semiarid zone of Tajikistan.

Similar to semiarid regions, humid zones of Tajikistan may also benefit from climate change especially in the far future scenarios. Expected farm utility may increase up to 50% in the later future scenarios due to increased crop yields. Model results are very different, though, for the arid zones and the semiarid zones of Tajikistan. Climate change might reduce expected utility by more than 30% in the late future in the arid zones. This is mainly due to expected decline of yields of all crops in the arid zones of Tajikistan.

In overall, there are already several geographical patterns that could be detected in both emission scenarios. For example, northern regions of Kazakhstan may benefit from increasing temperature and rainfall patterns. In contrast, arid regions of Uzbekistan and Tajikistan may be affected by water stress due to increasing temperatures.

4.2. Impact of water scarcity on farm revenues

Several studies have investigated the water availability under climate change scenarios and indicated flow decline of 5–30% in Amu Darya and Syr Darya rivers, the most important irrigation water sources in Central Asia (Ososkova et al., 2000; Savoskul et al., 2004; Chub, 2007; CAREC, 2011; Swinnen and Herck, 2011; Siegfried et al., 2012). We have considered the maximum level of 30% reduction predicted by these studies in order to account for predicted water use increase associated with increased water demand (e.g. construction of water dams) in the upstream regions (Eshchanov et al., 2011; Siegfried et al., 2012).

Observed current (mean) income (i.e. baseline scenario) presented in Table 7 is considered to be 100% and changes of expected income in other scenarios are presented relative to the baseline scenario. The results presented in Table 8 show that the expected income will drop in most of the AZs if 30% less water will be available at the farm level when compared to the situation without additional irrigation water restrictions. Sharp drops in expected utility are observed in both farm types in Uzbekistan under reduction of irrigation water availability. Thus, a very high level of welfare loss can be observed due to amplified effects of reduced crop yields combined with irrigation water reduction. Reduced irrigation water availability may force farmers to reduce the area of high value water intensive crops and increase the area of crops with less water demand. The expected utility may decline even drastically under water scarcity condition under A2 scenario in the far future in both farming systems in Uzbekistan.

There is also some decline observed in the expected utility under conditions of lower levels of water availability in arid and semiarid farming systems in Kazakhstan. However, the decline of the expected utility is not as drastic as observed in the case of Uzbekistan. Execrated rainfall increases in the largest part of Kazakhstan may offset the negative impact of reduced irrigation water availability in the future. Expected reduced irrigation water supply should not create much concern in the humid zones of Kazakhstan since the importance of irrigation is very limited due to favorable rainfall conditions.

There will be negative changes in the expected utility under A1b and A2 scenarios in the near future in semiarid regions in Kyrgyzstan. Reduction of irrigation water supply might reduce expected farm utilities about 15% under these scenarios. However, there are no negative shifts observed for sub-humid regions due to lower irrigation water demand compared to the semiarid zone. A similar pattern of change

Table 7
Expected utility in the baseline and relative changes (in percent) under climate change scenarios.

		Baseline, USD ha^{-1}	A1b (2010–2040)	A1b (2070–2100)	A2 (2010–2040)	A2 (2070–2100)
Kazakhstan	Arid	365.3	9.8	25.4	15.2	20.4
	Semiarid	553.6	19.1	28.8	18.8	21.3
	Sub-humid	129.2	38.9	77.7	47	74.5
Kyrgyzstan	Semiarid	512.1	0.8	26.3	0.4	30.2
	Sub-humid	662.8	9.7	33.9	18.5	32.3
Tajikistan	Arid	534.1	−16.9	−29.5	−21.8	−34.6
	Semiarid	111.1	52.9	122.3	61.2	153.2
	Humid	372.7	50.2	56	30.8	49.9
Uzbekistan	Arid	418.2	48.2	66.7	48.3	−15.6
	Semiarid	472.9	21	−8.2	31.4	−26.6

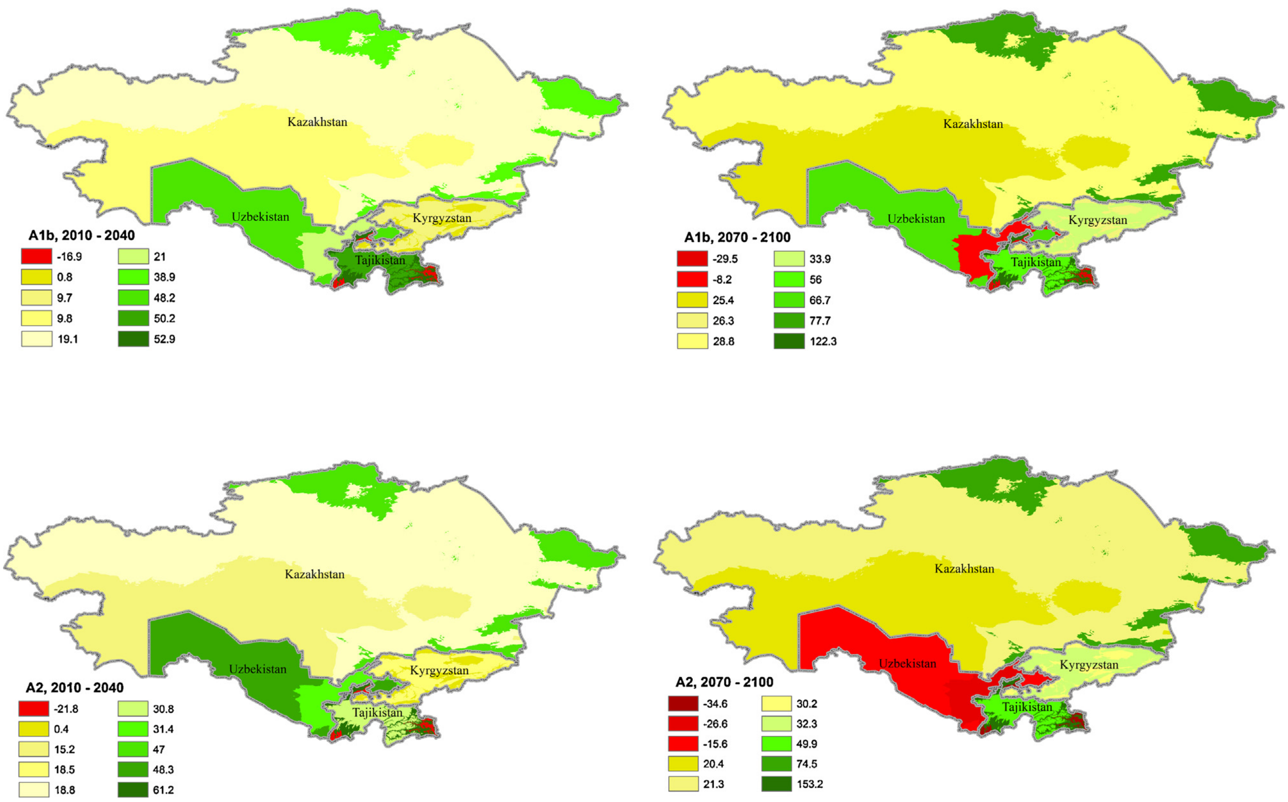

Fig. 6. Percentage changes of expected utility to the baseline scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 8
Percentage changes of expected utility under water scarcity to the baseline scenario, in percentage.

		A1b (2010–2040)	A1b (2070–2100)	A2 (2010–2040)	A2 (2070–2100)
Kazakhstan	Arid	−11.6	1.7	−5.4	0.1
	Semiarid	3.2	11.1	2.7	4
	Sub-humid	38.9	77.7	47	74.5
Kyrgyzstan	Semiarid	−14.6	7.3	−14.5	11.3
	Sub-humid	5.6	24.6	14.3	22.4
Tajikistan	Arid	−28	−30.1	−30.7	−34.6
	Semiarid	49.5	122.3	58.8	153.2
	Humid	17.1	29.5	13.2	30
Uzbekistan	Arid	14.7	25.5	15.1	−57.5
	Semiarid	10.7	−25.5	21.2	−42.6

is also identified in the arid zone in Tajikistan. Negative impacts of climate change are further intensified in both scenarios in the near future when water availability is expected to decline.

The results under a water scarcity scenario show that farmers in arid regions are very vulnerable to risk associated with irrigation water availability. A slight reduction of farm level irrigation water may cause significant decline of farm level revenues. High water demand of crops associated with hot and dry climates is expected to further increase in the future, which makes the profitability of agricultural production more vulnerable to water availability changes. Therefore, increasing the efficiency of irrigation water use and developing drought

Table 9
Changes of expected utilities under market integration to the baseline scenario, in percentage.

		A1b (2010–2040)	A1b (2070–2100)	A2 (2010–2040)	A2 (2070–2100)
Kazakhstan	Arid	10.6	24.7	17.2	23.2
	Semiarid	2.7	9.1	2.1	1.8
	Sub-humid	63.7	105.3	72.4	101.7
Kyrgyzstan	Semiarid	17.1	18.9	14.8	18.6
	Sub-humid	22.7	43.5	31.1	41.7
Tajikistan	Arid	199.6	190.4	190	178.1
	Semiarid	61.8	116.4	69	139
	Humid	44.5	43.4	21.3	36.3
Uzbekistan	Arid	327.5	339.4	324.5	122.5
	Semiarid	229.3	106.6	258.3	65.7

tolerant varieties of crops are very important strategies for dry regions of Central Asia.

4.3. Climate change impact under market liberalization

Political and ethnic disputes in CA are causing serious constraints to trade between the countries (FAO and WFP, 2010). Restrictions in commodity trade between the countries prevent farmers from planting crops according to their comparative advantages and obtaining increased revenue with the available resources. Furthermore, trade limitation is not only related to agricultural commodities but also limits agricultural input exchange between the countries. Therefore, salient price differences in input and output prices in CA countries exist (see Supplementary Material). This scenario investigates how market integration will impact farm revenues under climate change scenarios.

Agricultural commodity and input prices are expected to be similar in all four countries under this scenario. Only the price of cotton is treated differently in the simulations due to selling cotton to the world market. The price levels observed in Kazakhstan and Tajikistan are used for Uzbekistan and Tajikistan in the case of cotton as considered in similar studies (Bobojonov et al., 2010; Djanibekov et al., 2013). All other model parameters remain the same in the previous scenario.

The results (Table 9) show that farmers in Uzbekistan and Tajikistan will particularly benefit from such policy in the future. Thus income gains from market integration will offset negative impacts of climate change. There were no large gains observed in Kazakhstan and Kyrgyzstan since farmers already receive competitive market prices in those countries. However, some gain was still observed which offset income decline under climate change. Thus, the results of this simulation show that political measures such as market liberalization could increase risk coping potential of farmers under climate change. However, the careful interpretation of results in light of model assumptions and limitation is still needed. The model does not consider the impact of changing income levels and consumption patterns on input and output prices which require careful interpretation of the results of this scenario. Further research is also required on the potential impact of changing world market prices on regional prices under climate change scenarios.

5. Conclusions

Climate change impacts on agricultural systems in Central Asia differ depending on agro-ecological zones and socio-economic aspects. Farmers in Uzbekistan will benefit from climate change due to more favorable weather conditions for crop growth in the near future (2010–2040). However, revenues are expected to decline in the late future (2070–2100) due to increasing temperatures and increasing risk of water deficit, especially if availability of irrigation water declines.

There might be a slight increase of expected revenues in semi-arid zones of Kazakhstan. Some increase in revenues also is also expected in arid areas of Kazakhstan which will not increase the farmers' utility due to expectation of higher variances in crop yields associated with climate uncertainties. In contrast, farmers in sub-humid zones are expected to benefit from increasing temperature and precipitation.

Impact of climate change on income of Kyrgyz farmers in semi-arid zones will be neutral in the near future, but expected to be positive in the late future. Farmers in sub-humid zones of Kyrgyzstan will probably have higher expected income under all emission scenarios in near and late future scenarios. However, this might not increase their utilities since additional gain is prone to increased risk associated with weather extremes.

In Tajikistan, impact of climate change is crop specific. Wheat revenues may not change in the future, but income from cotton will decline due to drop in yields if current levels of management are maintained. Potato farmers may receive higher revenues in the future as yields are expected to increase. Overall, the impact of climate change is positive in semiarid and humid zones of Tajikistan, but producers in arid regions may suffer from losses under climate change scenarios.

Scenario simulations with the condition of market liberalization show great potential for policies to enable producers to mitigate negative consequences of climate change, especially in Tajikistan and Uzbekistan.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2014.02.033.

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