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Impact of climate change on wheat productivity in Central Asia

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ABSTRACT

Climate change (CC) may pose a challenge to agriculture and rural livelihoods in Central Asia, but in-depth studies are lacking. To address the issue, crop growth and yield of 14 wheat varieties grown on 18 sites in key agro-ecological zones of Kazakhstan, Kyrgyzstan, Uzbekistan and Tajikistan in response to CC were assessed. Three future periods affected by the two projections on CC (SRES A1B and A2) were considered and compared against historic (1961–1990) figures. The impact on wheat was simulated with the CropSyst model distinguishing three levels of agronomic management. Averaged across the two emission scenarios, three future periods and management scenarios, wheat yields increased by 12% in response to the projected CC on 14 of the 18 sites. However, wheat response to CC varied between sites, soils, varieties, agronomic management and futures, highlighting the need to consider all these factors in CC impact studies. The increase in temperature in response to CC was the most important factor that led to earlier and faster crop growth, and higher biomass accumulation and yield. The moderate projected increase in precipitation had only an insignificant positive effect on crop yields under rainfed conditions, because of the increasing evaporative demand of the crop under future higher temperatures. However, in combination with improved transpiration use efficiency in response to elevated atmospheric CO_2 concentrations, irrigation water requirements of wheat did not increase. Simulations show that in areas under rainfed spring wheat in the north and for some irrigated winter wheat areas in the south of Central Asia, CC will involve hotter temperatures during flowering and thus an increased risk of flower sterility and reduction in grain yield. Shallow groundwater and saline soils already nowadays influence crop production in many irrigated areas of Central Asia, and could offset productivity gains in response to more beneficial winter and spring temperatures under CC. Adaptive changes in sowing dates, cultivar traits and inputs, on the other hand, might lead to further yield increases.

1. Introduction

Global warming and related climate change (CC) may pose a major challenge to agriculture and rural livelihoods in Central Asia, with its five countries Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan and Turkmenistan. However, in view of the little hard data at hand, there is considerable uncertainty about the impact of CC, and the subregion is clearly in need of more climate change-related research (ADB and IFPRI, 2009).

Higher minimum as well as maximum air temperatures has been projected consequences of climate change for the late 21st century in Central Asia (IPCC, 2007). This would raise the water demand of rainfed and irrigated crops in general, but may also increase the risk of heat stress during flowering time of winter and spring crops (wheat, barley) grown in the region. On the other hand, higher temperatures during spring may boost early crop growth of winter crops, lower the risk of severe/late frost damage and thus lead to higher yields.

The projections by Global Climate models (GCMs) of the impact of climate change on precipitation, especially in the high mountain

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regions of the eastern part of Central Asia, are not clear-cut. There is some indication that the northern part of Central Asia (Kazakhstan) may receive more precipitation in the future, while the southern part (Uzbekistan, Turkmenistan) may receive less; the extent of both areas varying in (future) time and space depending on the underlying particular GCM. For certain areas in the center of Central Asia some GCMs project an increase in precipitation while others suggest the opposite. However, the overall changes in precipitation are projected to be rather small (IPCC, 2007). Lioubimtseva and Henebry (2009) reviewed the literature on the vulnerability of the Central Asian countries to climate change. Among others, they examined climate change as projected by IPCC GCMs and concluded that changes in precipitation are small and hardly discernible given the high temporal and spatial variability of precipitation, and that the changes in temperature will be the stronger factor affecting potential vulnerabilities across Central Asia. This is in line with the review of Singh et al. (2011), who estimated the reduction in precipitation for the whole Central Asia to be only about 3%.

Irrigated areas of Central Asia however do not depend so much on the annual precipitation as they depend on river water availability. Yet, snowfall projections and glacier and snow melt in the Pamir Mountains in response to CC are equivocal as well. Consequently, there is uncertainty about the impact of CC on river water availability and seasonality in Central Asia, as the Pamir is the spring of the two major Central Asian Rivers, the Amu Darya and Syr Darya. Up till recently, it was commonly assumed that total glacier ice mass in the Pamir Mountains is shrinking at fast rate. However, latest estimates seem to show that previous projections of glacier melt were too high (Jacob et al., 2012). Even if CC triggered a fast shrinkage of glaciers, the downstream short-term consequences would not be lower but higher water runoff, unless at the same time reduction in snowfall would counterbalance the surplus glacier water input. Nevertheless, CC may have an effect on the seasonality of stream flow. Siegfried et al. (2012), for instance, projected a shift in peak flows, due to earlier snow melt, towards spring and subsequently less water available in early summer in unregulated sub-catchments of the Syr Darya. Overall, however, their results did not point towards a notable change in total annual discharge rates for the coming 40 years. On the other hand, Krysanova et al. (2010) assessing the impact of CC, among others, on the Amu Darya watershed, predicted decreasing annual water availability and increasing frequency and intensity of droughts.

Central Asia comprises a wide range of soils (Sommer and De Pauw, 2011) and agro-ecological zones (De Pauw, 2010). This is not surprising given the dimensions of Central Asia measuring about 2000 km north-south (35 N to 55°N) and almost 2900 km east-west (46°E to 87°E). Coverage of a wide range of altitudes (50–7500 m above sea level) adds to the complex set of agro-ecological zones. Furthermore, the regional differences in terms of dependency on irrigation water for agriculture are large. About 22% (85 Mha) of the total geographic area of Central Asia is under cultivation, whereas roughly 30% of this cultivated land is under irrigation (Celis et al., 2007). Uzbekistan almost fully relies on irrigated agriculture (>80% of the cultivated land), while percent-wise, Kazakhstan has the smallest share of the five countries (<13%). Furthermore, especially Uzbekistan, but also partly the other four Central Asian countries, suffer from land degradation by secondary soil salinization in response to suboptimal irrigation/drainage management and shallow, saline groundwater levels.

Wheat is by far the most important stable crop in Central Asia. An approximate 8.5 Million ha are under wheat in Kazakhstan alone. The Kazak wheat production amounted to 17.1 Mt in 2009 which represents about 2.5% of world total production. The four other Central Asia countries add another 11.5 Mt of wheat annually (FAOSTAT, 2011). Yet, surprisingly little is known about the impact of CC on wheat growth and productivity in Central Asia. Such assessments are often pursued using biophysical simulation tools, such as crop models. White et al. (2011) screened related literature of the past decades and identified 221 peer-reviewed papers that used crop simulation models to examine diverse aspects of how climate change might affect agricultural systems. They could not find a single related paper considering at least one of the five Central Asian countries. Likewise, the reviews of Lioubimtseva and Henebry (2009) and Singh et al. (2011) did not consider studies that dealt with the impact of climate change by means of biophysical (crop) models. Some limited information about the impact of CC on wheat production in Central Asia can be deducted from studies that cover the entire globe. Arnell et al. (2002) studied the consequences of three different climate change scenarios – unconstrained CO_2 emission, stabilization at 750 ppm by 2230, and at 550 ppm by 2170 – on various ecological and economic aspects at global scale. Among others, they used a "suite of dynamic crop growth models" (without detailing further) to simulate the effects of climate change and increasing CO_2 concentrations on the potential yield of major cereal crops. CO_2 levels according to their unconstrained emission scenario would reach around 700 ppm by the year 2100, i.e. similar to the IPCC SRES A1B (IPCC, 2007). In response, estimated changes in national potential long-term mean grain yield by the 2080s were predicted to be in the range of −2.5% to 0% for the whole of Central Asia.

Parry et al. (2004) assessed the effects of climate change on global food production by means of bio-economic modeling. They applied projections of CC of the HadCM3 GCM based on the IPCC SRESs A1FI, A2, B1, and B2. The biophysical impact (temperature, water, CO_2) of CC on the major crops wheat, rice, maize, and soybean was estimated with yield transfer functions based on earlier crop simulation studies (Rosenzweig et al., 1993) with the CERES models for wheat, maize, and rice and the SOYGRO model for soybean. In response to CC, cereal yields of Central Asia – unfortunately lumped together with Russia – were estimated to drop by between 2.5% and 10% (SRES B2a, 2050s: 10–30%) as compared to historic (1990) conditions. The SRES scenarios and the considered future time periods (2020s, 2050s and 2080s) had only a marginal additional distinct impact. Regional variations within countries were not given in the maps published in the study, nor were differences between crops. Iglesias and Rosenzweig (2009) provided the results of a major update of the above-mentioned Parry et al. (2004) study. Country level results are available for download from the internet. Wheat production in Kyrgyzstan, Tajikistan and Uzbekistan was projected to change by +3.6%, +6.9% and +9.9% (same figures for all three countries) in the 2020s, 2050s and 2080s, respectively, under emission scenario A2. For Kazakhstan the changes would be −2.6%, +0.02% and +10.0% for the same periods. The report is inconclusive about how many agro-ecological zones and wheat varieties were considered in Central Asia, but the fact that for Kyrgyzstan, Tajikistan and Uzbekistan exactly the same changes in wheat yields were projected, provides evidence that (at least) for these countries only one 'case' was simulated, probably using identical CC projections.

The International Food Policy Research Institute, IFPRI, made an attempt to simulate the biophysical and economic impacts of climate change at global (0.5° resolution) scale (Nelson et al., 2009). They used the IPCC SRES A2 climate change projections for the year 2050 of the two GCMs NCAR and CSIRO. Year 2000 served as baseline. Biophysical simulations were carried out with the DSSAT modeling suite (Jones et al., 2003). No details about crop model setup, calibration or validation are provided in the report. Furthermore, crop model results for the five crops wheat, rice, maize, soybean and groundnut were either only provides as global averages, or, if disentangle by regions (sub-contents), only for simulations in which the carbon fertilization effect of an elevated atmospheric CO_2 concentration was not considered. The latter seems hardly useful, as there is little doubt about such positive effect; at least for the five simulated crops. And, as it is the raising atmospheric CO_2 concentrations that are largely responsible for a changing climate, the one should not occur without the other. Thus, this report does not provide enough details for "zooming into" regions and assessing the CC impact only for e.g. Central Asia. IFPRI published an update of their 2009 report 1 year later (Nelson et al., 2010) containing some few further details. Global crop modeling of the five mentioned crops was done with only one crop variety each. In other words, the study assumed that wheat (the variety used in the simulations is not mentioned) grown, for instance, in the USA would phenologically and physiologically be 100% identically equal to wheat grown for instance in Africa, Central or South Asia, with no distinctions made between winter and spring wheat, short-season or long-season varieties, high-yielding varieties or traditional land races, etc.; an assumption that needs critical re-evaluation, as it – and some other crudely approximated model settings (not further discussed here) – puts serious doubts on the credibility of the simulations as a whole as well as the range of economic figures deducted thereupon. The updated report now contains percentage yield losses by crop and region with the impact of C fertilization included, but, unfortunately, results for Central Asia are lumped together with Europe.

Fraser et al. (2012) coupled a global hydrological model for identifying regions likely to be exposed to drought, with a biophysical/socio-economic model determining the adaptive capacity of such regions to climate change. This allowed them to identify vulnerability hotspots. Central Asia was not among the hotspots that were designated likely to be both exposed to worse droughts and a reduced capacity to adapt. Only some parts of western Kazakhstan (approximately *Aktobe* province, north of the Aral Sea) were highlighted to have a reduction in adaptive capacity >25%.

No further related studies could be found in the literature. Thus, a detailed biophysical characterization of the impact of climate change on wheat in Central Asia is outstanding.

In conclusion, there is a need to study the effects of CC (a) taking into account the uncertainty in terms of GCM predictions, (b) scaling down to regional levels taking into account the distinct differences in terms of soils, agro-ecological zones and varieties grown, and (c) distinguishing irrigated and rainfed conditions while at the same time considering threats to agricultural production from soil salinization.

This study contributes to filling this gap. Crop growth, water and N-uptake, total aboveground biomass and yield of various wheat varieties grown in selected agro-ecological zones of Kazakhstan, Kyrgyzstan, Uzbekistan and Tajikistan in response to climate change was assessed by means of crop modeling by a team of scientists from the national agricultural research system of these countries and the International Center of Agricultural Research in the Dry Areas, ICARDA.

2. Material and methods

2.1. Study region

2.1.1. Climate

Semi-arid to arid climates prevail in most of the lowland areas of Central Asia. Two major deserts, the Kyzylkum and Karakum, located in the Turan Lowlands occupy a vast area of Central Asia. Broadly speaking, from the north of Kazakhstan southwards temperature increases and precipitation decreases. Thus, in the central and western part of Central Asia, agriculture is only possible with irrigation. Major areas under rainfed agriculture are only found in the very north of Kazakhstan.

The typical climate of the lowlands of Central Asia is shown in Fig. 1 using Shieli as an example.

The climate of the eastern mountainous region of Central Asia is diverse and was characterized as follows: "Influenced by the complex topography in the region, Central Asia's climate is highly variable. Western and central Pamir regions and the western Tien Shan (including north ridge of Fergana valley, Talas, Susamir and Chu valleys) receive the bulk of precipitation during winter and spring seasons. Conversely, eastern Pamir and northern Tien Shan (including Zailiiskiy Alatau) together with the main runoff formation area of the Syr Darya in central Tien Shan have spring-summer maximum precipitation." (Siegfried et al., 2012, p. 3)

2.1.2. Agro-ecological zoning and site selection

Besides data availability, one of the main criteria of selecting suitable sites for this study was their representativeness. This was assured by matching site locations with major agro-ecological zones (AEZ) of Central Asia, which are most suitable for cultivation of wheat as had been identified by De Pauw (2010; Fig. 2 and Table 1).

Altogether 18 sites were selected. These cover whole Central Asia, except Turkmenistan, and are located in the above-mentioned AEZs (Table 2). Five sites were under rainfed management while the rest received either full irrigation or supplemental irrigation adjusted according to seasonal precipitation. Table 2 also shows the 14 wheat varieties used in the experiments that built the basis for crop model calibration.

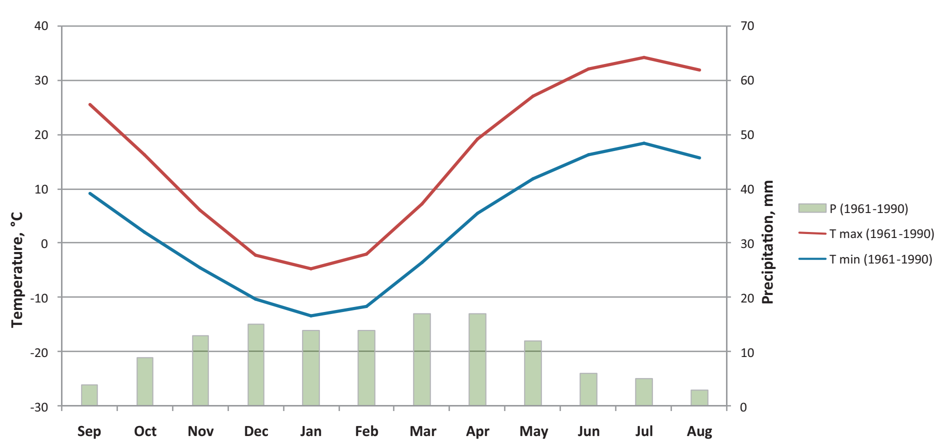

Fig. 1. Monthly precipitation and monthly mean maximum and minimum temperature of Shieli (44°06′N, 66°54′E, altitude: 151 m) located in the Shieli district of Kyzyl Orda province in Southern Kazakhstan; data are averages of 30 years of daily records of temperature, and monthly average of precipitation (1961–1990); courtesy of Hydrometeorological Service of Uzbekistan (Uzgidromet), Tashkent, Uzbekistan.

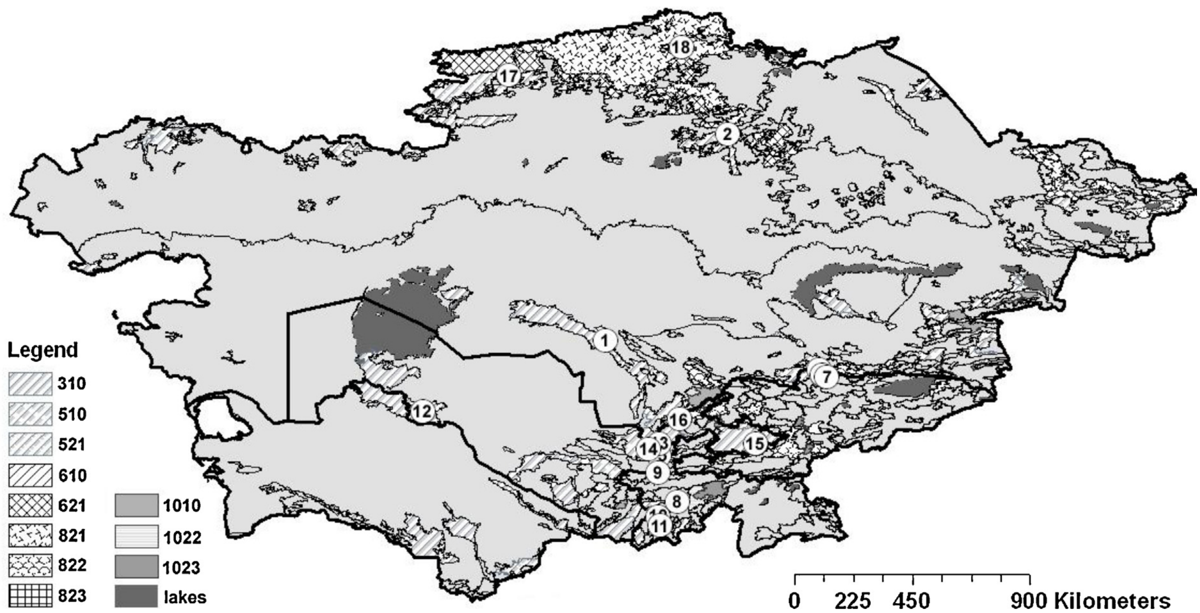

Fig. 2. Agro-ecological zones suitable for cultivation of wheat in Central Asia (De Pauw, 2010), and sites selected for the study (number 1–18).

2.1.3. Soils

Soils of Central Asia are diverse. Xerosols and Yermosols, followed by Kastanozems, Solonetz and Lithosols with rock outcrops occupy the largest area in Central Asia. Sand dunes prevail in the Kyzylkum and Karakum deserts of the south. A map showing the major soil associations can be found in Sommer and De Pauw (2011).

Soils of the selected sites were described in regard to their physical conditions (soil texture, soil bulk density and soil water retention characteristics) and soil chemistry (soil organic matter, mineral N and, if applicable, soil salinity). Soil water retention characteristics and soil bulk density were not available for all sites. Therefore, to provide for a homogenous site description, soil water retention characteristics, namely field capacity, permanent wilting

Table 1
Brief description of agro-ecological zones of Central Asia according to De Pauw (2010) suitable for cultivation of wheat.

AEZ	Description	Countries (in order of abundance)
310	Irrigated wheat in an arid climate with cold winter and hot summer	Uzbekistan, Kazakhstan, Tajikistan
510, 521	Irrigated or rainfed wheat in a semi-arid climate with cold winter and mostly warm summer	Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan
610, 621	Irrigated or rainfed wheat in mostly semi-arid climate with mostly cold winters and mild summer	Kazakhstan, Kyrgyzstan
821, 822, 823	Rainfed wheat in sub-humid climate with cold winters and mild summer	Kazakhstan, Kyrgyzstan, Uzbekistan
1010, 1022, 1023	Irrigated or rainfed wheat in a humid climate with cold winters and mild summers	Kazakhstan, Tajikistan, Kyrgyzstan, Uzbekistan

Table 2
Selected sites their respective agro-ecological zones (AEZ) and varieties grown, annual precipitation (historic simulations) and irrigation management.

Country	Site name	Wheat variety	AEZ	# on map	Annual precipitation (mm)	Irrigation
Kazakhstan	Astana	*Saratovskaya 29*	521	2	395	Rainfed
	Kostanay	*Saratovskaya 29*	521	17	362	Rainfed
	Petropavlovsk	*Saratovskaya 29*	821	18	426	Rainfed
	Shieli	*Almaly*	310	1	247	Suppl.
Kyrgyzstan	Daniyar	*Intensivnaya, Asyl*	510	6	481	Suppl.
	KyrNIIZ	*Adyr*	510	7	481	Suppl.
	Uchkhoz	*Kyal*	510	3	422	Suppl.
	ZhanyPakhta	*Adyr*	510	4	481	Rainfed
Tajikistan	Bakht	*Jagger*	510	11	300	Suppl.
	Faizabad	*Navruz*	1032	8	855	Rainfed
	Khorasan	*Navruz*	510	10	300	Rainfed
	Shahristan	*Navruz*	532	9	438	Suppl.
	Spitamen	*Kazakh.-10*	510	5	320	Suppl.
Uzbekistan	Akaltyn	*Polovchanka*	510	13	349	Suppl.
	Akkavak	*Mars, Kroshka*	510	16	461	Suppl.
	Khorezm	*Kupava*	310	12	137	Full irrig.
	Kushmanata	*Dustlik*	510	14	421	Suppl.
	Kuva	*Kroshka*	310	15	277	Full irrig.

Table 3
Soils of the selected sites and main physical and chemical characteristics (0–1.0 m); sites where shallow groundwater affected crop growth are indicted by √.

Site	Soil type(s)	Soil texture	SOM (g/kg)	Mineral N (kg ha^{-1} m^{-1})	Soil salinity (dS m^{-1})	Shallow groundwater influence?
Astana	HK	L, CL, SCL	14.1	160	1	
Kostanay	EF, CC	C, CL	27.6	47	2.6	
Petropavlovsk	HC	SC, C	27.1	36	1.9	
Shieli	EF, TY	SL, SCL	14.8	138	5.8	
Daniyar	L, K, HX	SL, SCL	11.1	78	n.d.	√
KyrNIIZ	L,	SL	8.5	72	n.d.	
Uchkhoz	L, K, HX	SL, SCL	16.6	79	1.3	√
ZhanyPakhta	EG	SL	8.5	59	n.d.	
Bakht	S, CG, CX	SL	6.6	61	n.d.	
Faizabad	L	SL, L	13.1	128	n.d.	
Khorasan	L, CX	SCL, CL	10.6	65	n.d.	
Shahristan	L	SL	7.4	97	n.d.	
Spitamen	CX	SL	6.6	69	n.d.	
Akaltyn	CX	SL	6.7	106	21	√
Akkavak	CX, EG	SL	5.4–6.4	71–109	0.5	
Khorezm	CG	L	4.8	101	11.5	√
Kushmanata	CX	SL	5.8	88	4.2	√
Kuva	CX, CG	SCL, SL	11.6	87	10.5	√

HK = Haplic Kastanozem, EF = Eutric Fluvisol, CC = Calcic Chernozem, HC = Haplic Chernozem, TY = Takyric Yermosol, L = Lithosol, K = Kastanozems, HX = Haplic Xerosol, EG = Eutric Gleysol, S = Solonchak, CG = Calcic Gleysol, CX = Calcic Xerosol, L = Loam, CL = Clay loam, SCL = Silt clay loam, C = Clay, SL = Silt loam; n.d. = not determined (salinity not an issue).

point, saturated hydraulic conductivity and soil bulk density were estimated for all sites with the pedo-transfer functions of Saxton and Willey (2006) using soil texture and organic matter content as input parameters. Table 3 provides an overview of soil characteristics of the selected sites.

2.1.4. Wheat cropping

In Central Asia all three types of wheat are grown, i.e. winter wheat, facultative wheat and spring wheat. The latter is grown mainly in the north of Kazakhstan, and its growth period, i.e. the time from planting to harvest, with 90–110 days, is among the shortest worldwide. The growth period of winter wheat and facultative wheat, on the other hand, is 210–270 days. Irrigation and fertilizer applications vary greatly between regions, whereas rainfed wheat usually receives much less fertilizer than irrigated wheat given the much lower yield potential (Gupta et al., 2009).

2.2. Crop model

The CropSyst model (Stockle et al., 2003), version 4.15.05, was used to simulate the impact of climate change on wheat. This crop model has been applied successfully under a range of climatic conditions and for a variety of annual crops, such as maize, barley, rice, sorghum, potato, alfalfa and cotton. Crop modeling of wheat accounts for most of the published simulation studies with CropSyst. This comprises studies on durum wheat in northern Syria (Pala et al., 1996), winter and spring wheat in Washington State in the USA (Pannkuk et al., 1998), as well as winter wheat in Italy (Bechini et al., 2006), the Turkish Central Anatolia Plateau (Benli et al., 2007) and northwest Uzbekistan (Djumaniyazova et al., 2010). CropSyst had also been applied for the assessment of potential impacts related to climate change on wheat in Italy (Tubiello et al., 2000), Australia (Anwara et al., 2007), Switzerland (Torriani et al., 2007), 13 countries around the Mediterranean Sea (Giannakopoulos et al., 2009), Egypt (El Afandi et al., 2010), Tunisia (Temani, 2010) and Syria (Sommer, 2011), which may be an indication for some proven reliability of the model. Moreover, the main selection criterion for CropSyst was its ability to simulate the climate change relevant aspects temperature, water and CO_2. In a nutshell, in CropSyst elevated levels of CO_2 increase the radiation and water use efficiency, and decrease canopy conductance (see Tubiello et al., 2000 for further details). CropSyst is also capable of considering the impact of shallow (saline) groundwater and soil salinity on crop growth. Additionally, its automatic irrigation module allowed for a convenient assessment of the impact of CC on irrigation water demands.

2.3. Crop model calibration

For each of the selected sites at least 3 years of observations on the growth and yield of wheat were available for crop model calibration. These observations were part of a number of previous national research studies on the agronomic impact of varying N-fertilizer and/or, if applicable, irrigation water inputs or agronomic management (tillage, crop rotation).

CropSyst was setup in the following way:

The Penman–Monteith method (analogous to Allen et al., 1998) was chosen for estimating reference crop evapotranspiration. In addition to the basic weather parameters, precipitation, solar radiation, minimum and maximum temperature, this method requires daily time-step information on relative humidity and wind speed. As has been demonstrated by McAneney and Itier (1996), the Penman–Monteith method is most preferable over the Priestley–Taylor method to determine potential evapotranspiration (ET_{pot}), as the Priestley–Taylor method is error-prone during times when the aerodynamically driven evaporative demand contributes a major share to ET_{pot}. In the semi-arid to arid environment of the lowland of Central Asia this is consistently the case during late spring and summer times.

For simulating soil water dynamics, the finite difference method of CropSyst was applied that builds on the Richards equation and the Campbell (1985) model to describe soil water retention and hydraulic conductivity. This method allows the simulation of upward movement of water, which is an important aspect at sites with shallow groundwater.

Furthermore, the nitrogen (N) routine was enabled, i.e. the simulation of all N-related dynamics including crop N-uptake and stress, soil N-turnover and nitrate leaching.

The (soil) organic matter and N-turnover was simulated with CropSyst's single organic matter, straw and manure residue pool with carbon decomposition module (Stöckle et al., 2007; Kemanian and Stöckle, 2010) using default settings.

Canopy growth was simulated based on leaf area index (LAI) development. The transpiration use efficiency (TUE) was described with a TUE-curve model of CropSyst. This model comprises TUE (g biomass/kg H_2O) when atmospheric vapor pressure deficit is 1 kPa and a scaling coefficient for the TUE regression power function (Kemanian et al., 2005).

Soil freezing, snow accumulation and melting, and crop sensitivity to cold temperatures (potential frost damage) was also simulated.

For sites where soil salinity and/or shallow (saline) groundwater was an issue, CropSyst's soil salinity and shallow groundwater routine was enabled. In these cases the soil solution (salt) osmotic potential for 50% yield reduction was set to −504 kPa and the salinity tolerance (Van-Genuchten) exponent to 3, following figures on salt tolerance of crops for wheat published in the FAO Soils Bulletin 39 (Abrol et al., 1988). Shallow groundwater dynamics entered the model as observed on-site.

CropSyst considers the impact of high, detrimental temperature during anthesis, by calculating a harvest index (HI) reduction factor (0–1). HI is reduced linearly with the accumulation of thermal degree time above a threshold of 31 °C during anthesis, analogous to the empirical relationship presented by Ferris et al. (1998).

A range of CropSyst parameters were subject to change during model calibration: thermal times, expressed as growing degree days (GDD) from planting to flowering and maturity, were adjusted to match the observed dates, whereas, for the sake of closest possible match, also the base temperature and the cutoff temperature were optimized. Furthermore, all wheat cultivars were simulated to be photoperiod sensitive (long-day plants). Enabling this setting allowed for a closer simulation of the observed key phenological stages of flowering and crop maturity as compared to considering cultivars to be photoperiod insensitive. The optimum mean daily temperature for growth was left at its default value of 10 °C. As far as required in-season data were available, the TUE at VPD equal 1 kPa, the specific leaf area and the leaf/stem partition coefficient were calibrated by fitting the simulated LAI and aboveground biomass (AGB) to observation. If such data were unavailable, mentioned CropSyst parameters were kept at default values or were modified only within very reasonable limits to match observed final AGB and yield data. Unstressed harvest index (HI) data were taken from the optimal (control) treatments of the trials. Other important parameters, such as the radiation use efficiency, were kept at CropSyst defaults.

2.4. Climate change scenarios

Climate change scenarios comprised the IPCC (2007) SRES scenario A1B and A2 and distinguished three different futures, namely *immediate-future* (2011–2040), *medium-term future* (2041–2070) and *long-term future* (2071–2100). ICARDA's GIS-unit (De Pauw and co-workers) provided regionally downscaled climate change (CC) maps for Central Asia derived from seven most realistic/most advanced GCMs. These then were averaged into one single set of data for each site, future period and SRES scenario. In detail, CC weather data were available in form of absolute deviation of monthly temperature (ΔT) and relative deviation of monthly sum of precipitation (ΔP) from historic data (reference period of 1961–1990).

To produce multi-year climate change data at daily time scale, which is required for crop modeling, the stochastic weather generator (WG) *LARS-WG* (Semenov and Barrow, 1997) was used. Using available meteorological data of the period 1961–1990, *LARS-WG* was applied to generate historic stochastic daily time-step weather data. Furthermore, using ΔT and ΔP data as inputs, CC weather data were produced for the above-mentioned three future periods and SRES scenarios.

Once calibrated to a certain local climate, *LARS-WG* can generate as many years of data as required, whereas each year represents – randomly within the stochastic limits defined during calibration – the climate of the underlying data set/location and period. In general, it is usually assumed that at least 30 years of weather data are needed to draw statistically sound conclusions on the impact of a certain climate on, for instance, crop growth.

LARS-WG's outputs are limited to maximum and minimum temperature, solar radiation and precipitation. However, to calculate the Penman–Monteith reference crop evapotranspiration, in addition, minimum and maximum relative humidity and wind speed data are required. For estimating these missing parameters, the *ClimGen* WG (Stockle et al., 1999) as part of the CropSyst modeling suite was used. *ClimGen* is capable of producing stochastically generated weather data from existing daily data. Relative humidity data are generated from linear regression equations that relate observed daytime and night time dew point temperatures to observed air temperatures, as well as from similarly derived, so-called aridity indices. Wind speed data are generated without correlation to any of the other climate variables, using a Weibull distribution function, with the Weibull α and β parameters calculated on a monthly basis using existing data.

Using this combination of WGs, daily weather data for the historic period as well as for six CC scenarios (two emission scenarios times three future periods) were generated for each site, whereas each data set comprised 50 years.

2.5. Agronomic management scenarios

Studying the effect of a changing climate on wheat yields, besides the climate impact itself, the considered, underlying agronomic management practice may attenuate or amplify CC impact. To draw a realistically ample picture, we considered the range of existing differences in agronomic management of wheat in Central Asia by defining three different business-as-usual (BAU) agronomic management scenarios. These took into account when wheat is planted, whether, when and how much irrigation water or fertilizer is applied, and what other important field operations (tillage, salinity management) are usually carried out.

BAU management scenarios for each location were based on information acquired by a socio-economic survey where interviews with the heads of altogether 282 farm households in selected provinces of Tajikistan, Uzbekistan and the Republic of Karakalpakstan were done (Bobojonov et al., 2012). This survey provided us with statistics on dates of planting, irrigation, N-fertilizer use and field cultivation (tillage), which were complemented with national recommendations developed by National Ministries of Agriculture and National Research Institutes for Uzbekistan, Tajikistan, Kyrgyzstan and Kazakhstan. BAU scenarios took into account fertilizer (N) application amounts and timing, and irrigation water application (amounts, rates, moisture stress thresholds for application, and timing). Given the comparably minor (direct) impact of field cultivation on yields, simulated tillage operations were the same in all three scenarios following common practice in each province. Also, to keep the total number of simulations and thus the complexity of results at a manageable/digestible level, we only considered one (average) planting date for each site, and did not interlace the three irrigation and fertilizer levels. Thus, for each site, BAU management scenarios were categorized into:

– *Poor irrigation and fertilizer management* = what the lower 25% farmers do;
– *Average irrigation and fertilizer management* = what 50% of the farmers do;
– *Optimal irrigation and fertilizer management* = what the upper 75% farmers do.

Distinction of the three levels of N-fertilizer application was based on log-transformed observed province data rounded to the

Table 4
Irrigation management for sites that were simulated as receiving "automatic" irrigation; differences in maximum allowable depletion of plant-available water largely reflect differences in soil water retention characteristics.

Site	Management	Fixed pre-sowing irrigation amount (mm)	Automatic irrigation			
			Maximum allowable depletion (%)	Depletion observation depth (m)	Minimum daily application (mm)	Maximum daily application (mm)
Shieli	Sub-opt.	100	95	1	30	120
	Average	100	90	1	30	100
	Optimal	100	80	1	30	70
Daniyar	Sub-opt.	40	No further irrigation			
	Average	50	66	0.8	35	150
	Optimal	60	33	0.8	35	150
KyrNIIZ	Sub-opt.	20	No further irrigation			
	Average	40	66	0.8	35	150
	Optimal	60	33	0.8	35	150
Uchkhoz	Sub-opt.	30	No further irrigation			
	Average	40	66	0.8	35	150
	Optimal	60	33	0.8	35	150
Bakht	Sub-opt.	60	95	1	30	120
	Average	60	85	1	30	100
	Optimal	60	80	1	30	70
Shahristan	Sub-opt.	/	86	1	30	120
	Average	/	48	1	30	100
	Optimal	/	35	1	30	70
Spitamen	Sub-opt.	/	86	1	30	120
	Average	/	48	1	30	100
	Optimal	/	35	1	30	70
Akaltyn	Sub-opt.	100	40	1	30	75
	Average	100	40	1	30	75
	Optimal	100	40	1	30	70
Akkavak	Sub-opt.	70	86	1	30	120
	Average	60	48	1	30	100
	Optimal	50	35	1	30	70
Kushmanata	Sub-opt.	70	65	1	30	90
	Average	70	60	1	30	75
	Optimal	70	55	1	30	60

next decadic number. In regard to the definition of the three irrigation management levels, a different strategy was followed. Only for the fully irrigated Uzbek sites Khorezm and Kuva, levels were derived from observed patterns. For the other sites, irrigation application, apart from a start-up irrigation, was not fixed (by dates and amounts), but derived automatically by the model, based on decision rules taking into account the soil moisture regime, i.e. soil water depletion rate and thus indirectly crop water stress (Table 4). The decision rules were slightly changed when moving from poor to average and optimal management. As compared to optimal, the simulated poor irrigation management would allow for a stronger depletion of plant-available soil water and a higher single irrigation rate, or in other words, applying more water less frequently. The average management would range in-between these two. Regarding the latter, Akaltyn was an exception from the rule, because test simulations had revealed that the influence of shallow groundwater basically nullified differences in irrigation management. Therewith optimal irrigation management not necessarily would mean a larger total amount of irrigation water applied in a single season. We favored decision rules over static amounts and times, because these mimic better the adaptive behavior of farmers, especially in regions where irrigation is supplemental, i.e. applied only when precipitation is insufficient. Another advantage of simulating automatic irrigation is that the resulting irrigation amounts could be used as direct measure of the impact of CC in terms of irrigation water requirements.

The fully irrigated Khorezm and Kuva sites received a fixed seasonal total amount of between 355 and 410 mm and 215 and 345 mm, respectively, applied in three to five irrigation events spread over early March until late May; the better the management the more frequent the application.

2.6. Statistical evaluation

Simulated yields of all sites were subject to analysis of variance using version 14 of the *GenStat* software. The following factors were considered: *Period* (historic, immediate-future, medium-term future, long-term future), *Emission scenario* (none, A1b, A2), and *BAU-level* (suboptimal, average, optimal). The 50 years of simulations were considered as replications. As *Period* and *Emission scenario* were partially aliased, a nested design was included in the ANOVA in which historic-none was compared against the six distinct CC scenarios (immediate-future-A1B, immediate-future-A2, medium-term-future-A1B, ...). Thus, we were able to compare whether a CC-affected future would result in yields that are different from historic yields, whether agricultural BAU management had any effect and whether differences could also be attributed to the two considered Emission Scenarios.

The goodness of the fit of simulated and observed yield and AGB was expressed by calculating the root mean square error (RMSE) and the relative RMSE (RRMSE), where

$$\mathrm{RMSE} = \sqrt{\frac{\sum(\mathrm{Observed}_i - \mathrm{Simulated}_i)^2}{n}}$$

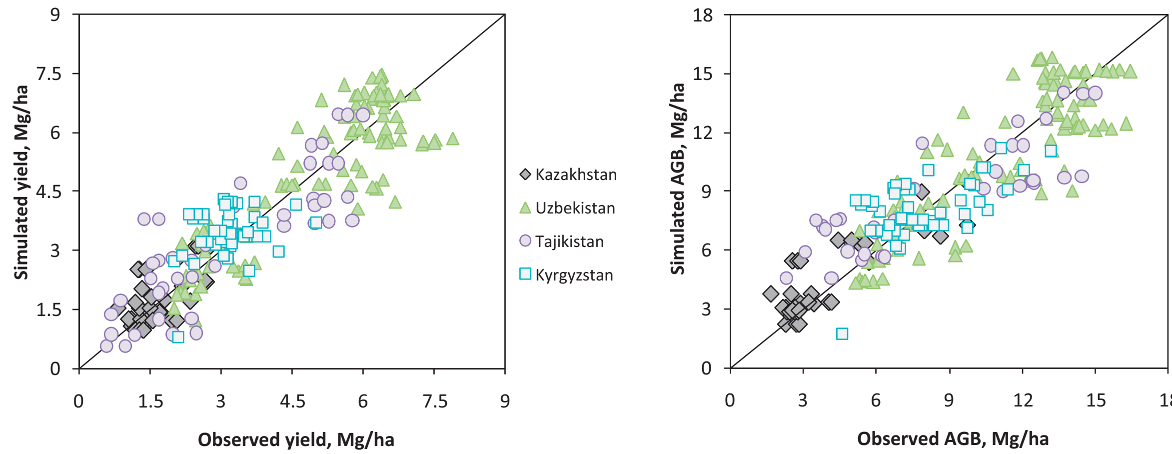

Fig. 3. Simulated grain yield and aboveground biomass (AGB) vs. observed grain yield and AGB of all Central Asian sites and years of simulations (historic data set).

$$\text{RRMSE} = \frac{\sqrt{\sum(\text{Observed}_i - \text{Simulated}_i)^2/n}}{\sum \text{Observed}_i/n} \times 100$$

3. Results

3.1. Crop model calibration

Across all sites and years of available data set, crop model calibration resulted in an acceptable accuracy of simulation. The RMSE between observed and simulated yields and AGB was 0.83 and 1.79 Mg/ha, the corresponding RRMSE was 22.1% and 20.0%, respectively (Fig. 3). Fig. 3 illustrates that there was no tendency of over- or under-prediction of observed yields and AGB towards the lower or upper end of yields or AGBs, i.e. an overall adherence to the 1:1 line. The CropSyst crop physiological and phenological model settings are provided in Table A1.

3.2. Climate change projections

The relative change in precipitation was rather limited across all sites and futures, rarely exceeding 10%. For most of the sites CC resulted in a moderate increase in precipitation (Fig. 4). Shahristan and Kushmanata were two sites where GCMs projected a minimal decrease in precipitation. No precipitation trend was visible for Khorasan, Faizabad and Bakht. Khorezm was projected to benefit the most in terms of relative increase in precipitation, but as the annual precipitation amount was only 137 mm historically (Table 2), absolute changes were small.

In terms of changes of annual average temperatures, across all sites the impact of CC was quite homogenous, with an increase of about 1 °C towards the immediate future, 2–2.5 °C medium-term and 3.3–4.5 °C in the long-term future; the latter showing some distinct differences between the A1B and A2 SRES scenario, namely A2 resulting in approximately 0.5 °C higher annual temperatures than A1B.

3.3. Climate change impact

3.3.1. Yield

Based on the defined business-as-usual scenarios and the projected changes of climate in response to the emission scenarios A1B and A2 as well as for three futures

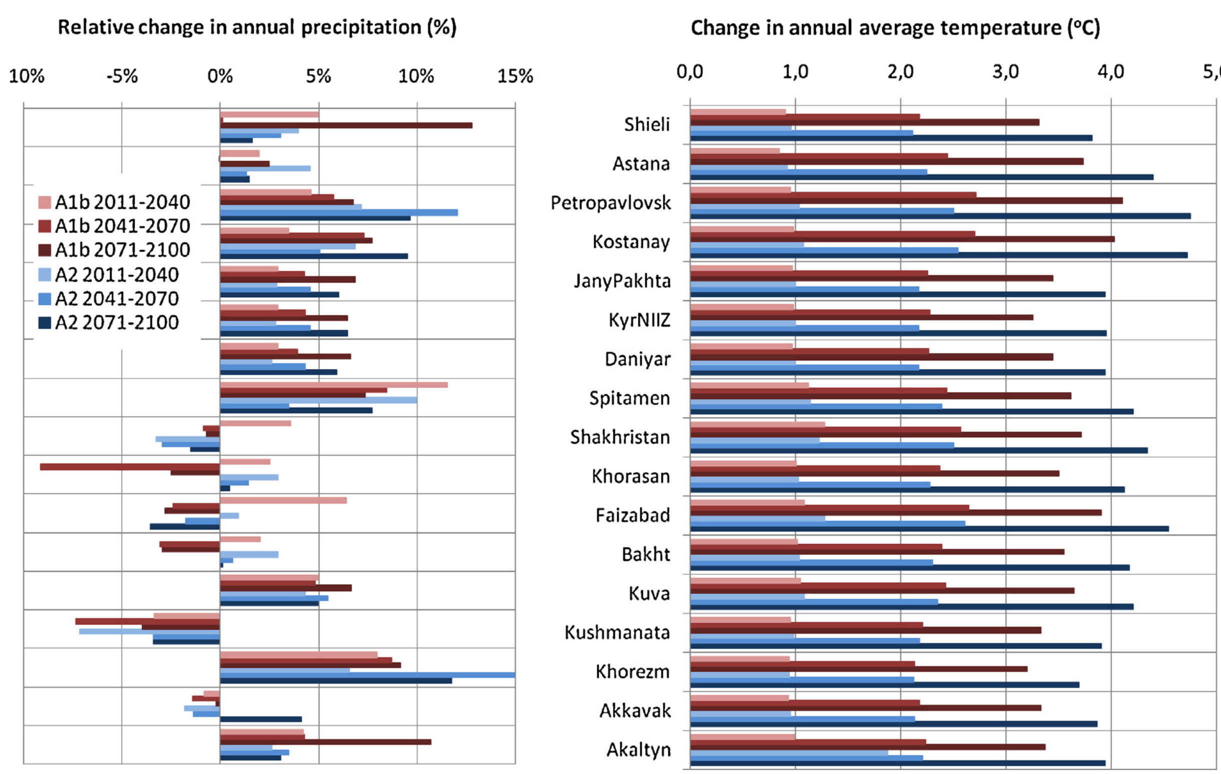

Fig. 4. Simulated relative change (%) in annual precipitation and absolute change (°C) in annual average temperature for the three future periods and the two SRES scenarios.

Table 5
Impact of climate change on wheat productivity at different sites in the four Central Asian countries Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan; N = negative, P = positive impact, – no significant change; yield increases (last three columns) refer to the average yields of the three different futures and two different emission scenarios in relation to historic yields.

Country	Site	CC impact on yield Management level			Change of yield across all Mgmt. levels		
		Suboptimal	Average	Optimal	%	Mg/ha	
Kazakhstan	Astana	–	–	–	5	0.11	n.s.
	Kostanay	P	–	–	5	0.11	*
	Petropavlovsk	P	P	–	15	0.32	*
	Shieli	–	–	P	10	0.31	*
Kyrgyzstan	Daniyar	–	P	P	10	0.33	*
	KyrNIIZ	–	–	P	14	0.42	*
	Uchkhoz	–	–	–	0	−0.01	n.s.
	ZhanyPakhta	P	P	P	24	0.54	*
Tajikistan	Bakht	–	–	P	4	0.15	*
	Faizabad	–	P	P	26	0.44	*
	Khorasan	P	P	P	27	0.47	*
	Shahristan	P	P	P	14	0.5	*
	Spitamen	N	N	–	−3	−0.09	*
Uzbekistan	Akaltyn	–	P	P	25	0.47	*
	Akkavak	–	–	P	9	0.43	*
	Khorezm	P	P	P	22	1.3	*
	Kushmanata	–	–	–	1	0.03	n.s.
	Kuva	P	P	P	18	0.75	*

* Indicates significance at $p < 0.05$.

(immediate, medium-term and long-term), annual grain yields of the 14 different wheat varieties and the 18 sites located in the major agro-ecosystems of Central Asia were simulated. Subsequently, results were compared with yields simulated under identical soil and management conditions but based on generated historic weather data.

Only at Khorasan (Tajikistan) the two emission scenarios significantly differed in terms of impact on yields across the three different futures and three management levels. Historic grain yield averaged to 1.75 Mg/ha, while under SRES A1B and A2 the average projected yield was 2.13 and 2.31 Mg/ha, respectively, with a least significant difference (LSD) equal to 0.10 Mg/ha (A1B vs. A2) and 0.15 Mg/ha (Historic vs. A1B or A2). Thus the impact of the two SRES scenarios was notable but differences were small. For all other sites, climatic differences as projected under A1B and A2 emission scenario were not discernible by their effects on grain yield.

Averaged across the two emission scenarios and three futures, only at Spitamen (Tajikistan) climate change had a negative impact on crop yields. At three sites climate change had no impact, whereas at all other sites the projected change in climate led to an increase in yields (Table 5). Most of the yield increases were comparably small ranging between about 0.1 and 0.5 Mg/ha. Similar was the case for percent increases that for whole Central Asia averaged to 12%, ranging between 4% and 27%. The yield increase of the fully irrigated variety *Kupava* grown in Khorezm with on average 1.3 Mg/ha was the only exceptional case.

There was no significant impact of CC on crop yields at Astana site in northern Kazakhstan (Figs. A1–A4). Similarly, the impact of CC at Kostanay site was limited to the suboptimal management simulations in four out of six simulated futures. The CC impact on yields was significant for Petrapavlovsk, but the average increase was only 0.32 Mg/ha. Astana, Kostanay and Petrapavlovsk are three rainfed cropping sites, where the major growth-limiting factor is water, and the projected slight increases in rainfall were offset largely by an increase in evaporative demand. Increased N-fertilizer application – the only “improvement” in crop management simulated under rainfed conditions – had only a small (but significant) impact on crop yields under historic as well as CC conditions. Shieli, the fourth Kazakh site was under irrigation, where increased temperatures in response to CC during early

Table 6
Average change in days from emergence to reach maturity of the different wheat varieties, comparing the three different futures, immediate (I), medium-term (M) and long-term (L) future, with historic conditions and the two emission scenarios, A1B and A2.

Country	Site	Variety	Change in days from emergence until maturity					
			A1B			A2		
			I	M	L	I	M	L
Kazakhstan	Astana	*Saratovskaya 29*	−5	−9	−11	−5	−9	−12
	Kostanay		−3	−5	−7	−3	−6	−7
	Petropavlovsk		−5	−12	−15	−5	−11	−16
	Shieli	*Almaly*	−1	−3	−5	−1	−4	−7
Kyrgyzstan	Daniyar	*Asyl*	−5	−10	−16	−4	−10	−18
		Intensivnaya	−5	−10	−16	−4	−10	−18
	KyrNIIZ	*Adyr*	2	3	1	3	3	0
	Uchkhoz	*Kyal*	−4	−8	−12	−3	−8	−14
	ZhanyPakhta	*Adyr*	−3	−6	−9	−2	−6	−11
Tajikistan	Bakht	*Jagger*	−4	−7	−11	−3	−8	−14
	Faizabad	*Navruz*	−6	−11	−16	−5	−11	−19
	Khorasan		−3	−6	−9	−3	−6	−11
	Shahristan		−4	−7	−12	−4	−8	−14
	Spitamen	*Kazakh.-10*	−4	−8	−13	−4	−8	−15
Uzbekistan	Akaltyn	*Polovchanka*	−3	−5	−8	−1	−5	−10
	Akkavak	*Mars*	−1	−3	−4	−1	−3	−5
		Kroshka	−4	−8	−13	−4	−8	−15
	Khorezm	*Kupava*	−4	−7	−12	−3	−8	−13
	Kushmanata	*Dustlik*	−3	−7	−10	−3	−7	−12
	Kuva	*Kroshka*	−5	−10	−15	−5	−10	−18

growth triggered a higher biomass production and thus higher yields. Analogous to the rainfed sites, this increase in yield potential could only materialize under optimally managed conditions, i.e. sufficient water and N-fertilizer supply. Further noteworthy for Kazakhstan is the tendency of a downward trend of yields from immediate to long-term future at Astana, Kostanay and Petropavlovsk site, which was due to an increased occurrence of extreme, detrimental temperatures during flowering.

CC impact trends were similar for the two varieties *Asyl* and *Intensivnaya* grown at Daniyar site in Kyrgyzstan, with no impact under suboptimal management conditions and positive impact increasing toward the long-term future under average and optimal management (Fig. A2). The two varieties differed in terms of absolute simulated yields, whereas *Asyl* was higher yielding. A trend towards higher yields in a CC future was also found at KyrNIIZ site, clearly visible under optimal management conditions. However, year-to-year variability was higher (witnessed by a larger LSD) than in Daniyar, and a significant CC impact could only be shown for the medium-term (optimal management only) and long-term future; not, however, under average management, A2.

Uchkhoz was one of the few sites where nitrate leaching out of the rooting zone in response to fast downward movement of irrigation water and a shallow groundwater table, and subsequent N-stress was one of the major growth constraints. This influence did offset a positive impact of CC on crop growth, as more rainfall also meant more leaching. On the other hand, a significant CC impact on wheat grown at ZhanyPakhta site, which was the only Kyrgyz rainfed site, was detected. Thus, ZhanyPakhta with over 500 mm of annual rainfall was not comparable to the much dryer rainfed sites in northern Kazakhstan.

Bakht and Spitamen where the only Tajik sites, where a significant negative impact of CC on wheat yield was simulated under suboptimal (Spitamen) and average (Bakht) management conditions for at least some of the projected CC futures (Fig. A3). The reason was an increased loss of nitrate out of the rooting zone and a subsequent slight increase in N-stress under the given soil (N-levels) and management conditions. Yet, decreases in yields were rather negligible and could be offset if N-fertilizer rates were increased and irrigation practices changed toward applying less amounts more frequently, as was simulated under optimal management. In this case, the impact of CC rendered positive at Bakht or without influence at Spitamen site. A positive impact of CC was also simulated for the two rainfed sites Faizabad and Khorasan and for the irrigated site Shahristan. For the latter a relative yield decrease under emission scenario A1B was visible moving from medium- to long-term future.

All sites in Uzbekistan were under full or supplemental irrigation. Yields steadily increased from historic times until long-term future in response to CC at Akaltyn, Khorezm and Kuva sites (Fig. A4). Akaltyn was the comparably lowest yielding site in Uzbekistan (overall mean grain yield: 2.23 Mg/ha), which was caused by the combined impact of a highly saline soil (compare Table 3), relatively cold winters (frost damage) and risk of nitrate leaching in spring after snow melt. Here, CC only diminished the detrimental effect of frost damage. Khorezm was the highest yielding sites of all simulated countries, environment and sites, and CC had the largest positive impact. On the one hand, this was related to the fact that *Kupava* grown in Khorezm obviously is a modern, high-yielding variety with a significant positive response to inputs (water, fertilizer). Also, as compared to Akaltyn, soil salinity at the Khorezm site was much lower. Finally, simulations showed that the positive impact of CC on winter temperatures in Khorezm triggered a vigorous plant establishment in late autumn and higher and faster biomass accrual in spring. Akkavak yields peaked in the medium-term future, and then decreased in the long-term future, overall however then being still higher or equal than historic yields. Overall, the variety *Kroshka* was slightly higher yielding than *Mars*. Even though there was a negative yield trend visible from historic to the long-term future, climate change had no significant impact on yields at Kushmanata site (exception: A2, long-term future under optimal management).

3.3.2. *Vegetation period*

The length of the life cycle of a cereal crop, i.e. the vegetative and reproductive phenological stages, is governed by the accumulation of growing degree days (GDDs, expressed in °C-days). Consequently, in response to warmer temperatures in a CC future, the life cycle – planting until maturity – of all 14 wheat varieties shortened considerably. Management practices (fertilizer and irrigation water application) did not have any effect on the life cycle of the simulated wheat varieties. Even the suboptimal management practices to some extent resulted in water or N-stress, this was not severe enough to trigger a shortening of growing period. The latter is a well-known stress-avoidance strategy of many cereals under extreme drought stress.

We considered in more detail the days required for the crop to complete emergence until maturity (DEM), as this is the period where the crop is exposed to environmental factors such as low (frost) and high temperatures, as well as water and N-stress. This period shortened for all sites, increasingly from immediate to long-term future (exception: KyrNIIZ; Table 6).

The considered emission scenarios had a minor additional influence, whereas the A2 scenario further shortened DEMs, as these scenario projects higher future temperatures than the A1B scenario. In comparison to the historic conditions DEMs shortened on average across all sites by 3, 7, 11 (A2 scenario: 12) days for immediate, medium-term and long-term future, respectively.

KyrNIIZ site (variety *Adyr*) was an interesting exception from this rule: at KyrNIIZ planting is usually done between late October and mid-November (1 November in the simulations), and emergence occurs about 4–5 weeks later, after 175 °C-days. Given the considerably higher temperatures in November in a climate change-affected future, emergence shortened by about 15 days from the historic period to the long-term future. The overall growth period (planting – maturity) however shortened less, meaning that the period in-between (emergence – maturity) increased slightly. *Adyr* was also used for ZhanyPakhta simulations. The above-mentioned effect however did not manifest itself there, because planting is done some 2 to 3 weeks earlier (15 October in the simulations) and plants emerge earlier not benefiting from increased November temperatures in a CC future.

3.3.3. *Minimum temperatures during vegetative growth*

Climate change and the related increase in temperature affected the early vegetative growth positively. The increase in the average daily temperature (T_{avg}) during vegetative growth (emergence until flowering) across all sites was 0.8 °C (range: 0.6–1.0 °C), 1.7 °C (1.4–2.4 °C) and 2.9 °C (2.2–4.1 °C) for the immediate, medium-term and long-term future, respectively. Not only average, but also extreme minus temperatures during winter deemphasized in response to CC, as is illustrated in Table 7 by the 5% percentile of minimum temperature (T_{min}). The three Kazakh spring wheat sites, Astana, Kostanay and Petropavlovsk located in the

Table 7
Average temperature (T_{avg}) and the lower 5% percentile of the minimum temperatures (T_{min}) during vegetative growth of all sites across the two emission scenarios for historic (H) period as well immediate (I), mid-term (M) and long-term futures; H = historic, I = immediate, M = medium-term, L = long-term future.

Country	Site	T_{avg} during vegetative growth				5% percentile of T_{min}			
		H	I	M	L	H	I	M	L
Kazakhstan	Astana	19.9	20.9	22.3	24.0	8.5	9.4	10.7	12.3
	Kostanay	20.8	21.6	22.9	24.3	8.8	10.0	11.1	12.6
	Petropavlovsk	19.0	19.8	21.2	22.7	8.0	8.7	10.0	11.3
	Shieli	2.2	2.9	3.7	4.7	−18.5	−17.6	−16.4	−15.0
Kyrgyzstan	Daniyar	4.9	5.6	6.5	7.6	−13.4	−12.4	−11.3	−9.9
	KyrNIIZ	4.5	5.2	5.9	7.0	−14.1	−13.1	−12.0	−10.6
	Uchkhoz	4.9	5.6	6.5	7.6	−13.5	−12.5	−11.4	−10.0
	ZhanyPakhta	4.4	5.1	6.0	7.1	−13.7	−12.7	−11.6	−10.2
Uzbekistan	Akaltyn	6.2	7.1	7.7	8.7	−10.0	−9.1	−8.1	−7.0
	Akkavak	8.1	8.9	10.0	11.3	−6.8	−5.9	−4.8	−3.4
	Khorezm	6.3	6.9	7.7	8.5	−10.0	−9.0	−8.2	−7.2
	Kushmanata	7.8	8.4	9.3	10.3	−7.4	−6.8	−5.8	−4.7
	Kuva	6.4	7.1	8.1	9.2	−8.9	−7.9	−6.8	−5.4
Tajikistan	Bakht	8.5	9.1	10.1	11.2	−4.0	−3.4	−2.1	−0.8
	Faizabad	7.2	8.0	9.0	10.2	−5.6	−4.8	−3.4	−2.0
	Khorasan	10.0	10.7	11.7	12.8	−3.8	−3.1	−1.8	−0.5
	Shahristan	5.9	6.7	7.6	8.6	−9.8	−8.8	−7.6	−6.4
	Spitamen	8.9	9.7	10.5	11.6	−4.5	−3.5	−2.5	−1.3

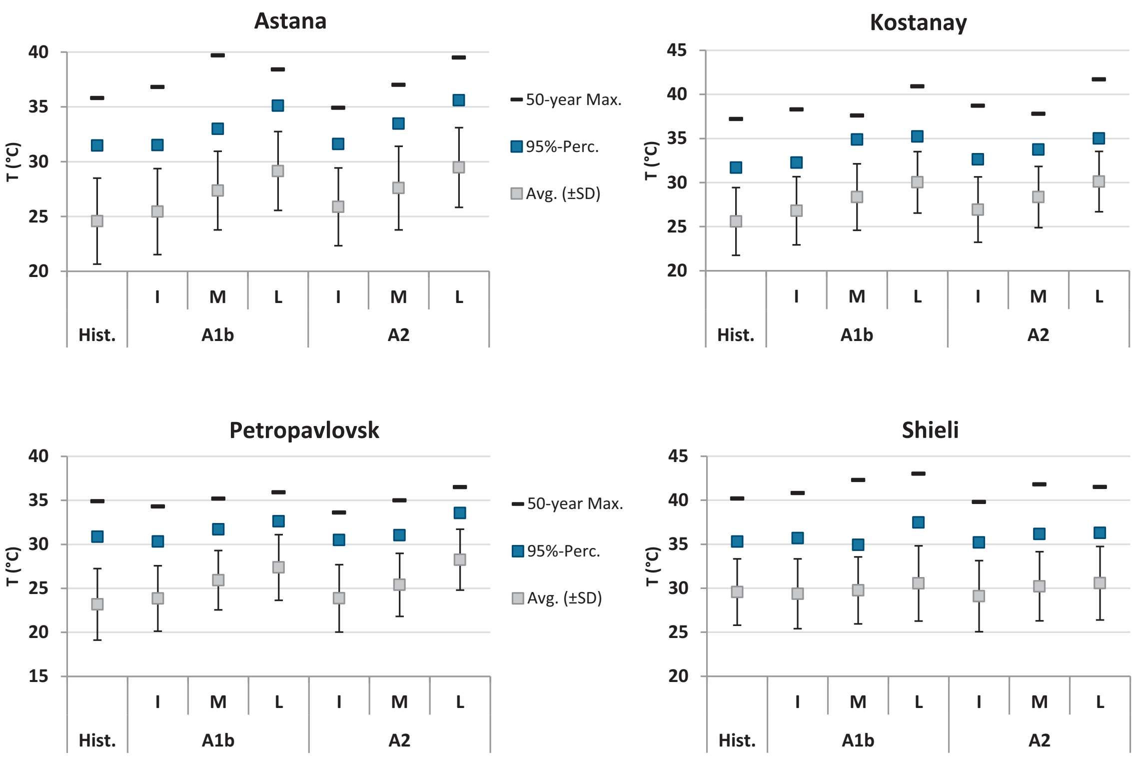

Fig. 5. Maximum temperature during flowering of the four Kazakh sites Astana, Kostanay, Petropavlovsk and Shieli; I = immediate, M = medium-term, L = long-term future.

north of Central Asia, were clear discernible from the remaining sites where winter wheat or facultative wheat is planted in autumn.

The consequence in general of such warmer winters and spring was less frost damage and faster early crop growth.

3.3.4. Maximum temperatures during flowering

Average maximum temperatures (T_{max}) during flowering of the spring wheat variety *Saratovskaya 29* increased considerably from the historic period to the long-term future at Astana, Kostanay and Petropavlovsk sites (Fig. 5). The average T_{max} however did not surpass 30 °C, and in less than 3 of the 50 simulated years (=95% percentile) went beyond 35 °C on a single day.

At Shieli located in southern Kazakhstan, where facultative wheat is grown, T_{max} during flowering was slightly below 30 °C historically and increased by about 1 °C towards the long-term future. T_{max} was above 35 °C for 1 day in more than 3 of the 50 simulated years already historically, and this share also increased; less so under A2 because the cropping cycle was shorter and flowering shifted backwards further into the comparably cooler early spring.

A similar trend towards an increase of T_{max} during flowering was also observed for most of the other sites (Figs. A5–A7). At all Kyrgyz sites and Bakht, Shahristan (both Tajikistan), Akaltyn and Akkavak (both Uzbekistan) T_{max} was comparably low and very rarely (~once every 50 years), if ever, above 35 °C. 95%-percentiles of T_{max} at flowering at Khorasan, Spitamen (both Tajikistan) and Khorezm (Uzbekistan) sites where above 35 °C already historically (Khorasan and Khorezm) or surpassed this temperatures towards the long-term future (Spitamen), meaning that detrimentally high temperatures during flowering would become more problematic at these sites. Faizabad, on the other hand, is the only site where CC triggered a decrease in T_{max} during flowering. Faizabad had the biggest impact of CC on the shortening of life cycle, and therefore flowering was predicted to occur much earlier during the season when temperatures were also still comparably colder irrespectively of an increase in temperatures in response to CC.

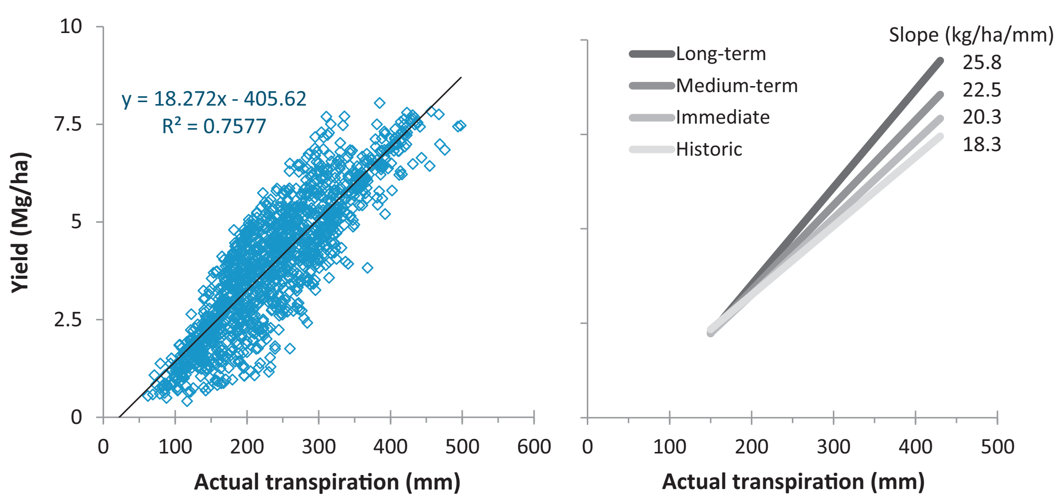

Fig. 6. Left: relationship between grain yield and actual transpiration of all Uzbek sites across the three managements under historic climatic conditions (linear regression equation based on kg/ha); right: linear regression equations describing the relationship between grain yield and actual transpiration of all Uzbek sites across the three management conditions under historic climatic conditions and for the immediate, mid-term and long-term future.

3.3.5. Irrigation requirements

As expected, for most of the supplementary irrigated sites, the three implemented irrigation management levels were clearly discernible in terms of resulting total seasonal irrigation amounts. Overall CC had little effect on irrigation water demand. Given the moderate increases in precipitation (compare Fig. 4) in response to CC, irrigation water demand reduced slightly, but not significantly given the high year-to-year variation, at the majority of the sites. Likewise, the two emission scenarios were not clearly (and significantly) discernible in regard to their impact on irrigation requirements. In terms of irrigation amounts, the reductions in irrigation water requirement were rather moderate and in most cases below 30 mm per season. The only exception was Spitamen with a 151 mm reduction per season – 381 mm historically to 231 mm in the long-term future under SRES A2 and optimal management conditions.

3.3.6. Water use efficiency (CO_2 response)

Not surprisingly, a strong correlation between simulated actual transpiration and biomass and yield formation was observed, as is exemplarily shown for all Uzbek sites under historic climatic conditions (Fig. 6, left). The correlation could be well described by a linear regression equation, in which the slope of the equation reflects the transpiration use efficiency (TUE) with the unit kg/ha/mm.

The increase in atmospheric CO_2 concentration as the major driver of CC in the two SRES, was considered in the simulations by enabling the CropSyst-intrinsic CO_2 sub-routine, which influences radiation use efficiency and transpiration use efficiency. As a consequence, the linear regression equations changed. For example for all Uzbek sites combined, the slope increased from 18.3 kg/ha/mm under historic (CO_2) conditions to 25.8 kg/ha/mm in the long-term future (Fig. 6, right). Converted into grain yields, transpiring 300 mm of water, Uzbek wheat would yield 5.08 Mg/ha under historic conditions, but 6.1 Mg/ha in the long-term future; a plus of 20%. The influence of the two emission scenarios on TUE was small, with wheat under A2 exhibiting a slightly higher TUE than under A1B.

4. Discussion

Eighteen sites were considered in this study, which reflected all major agro-ecological zones of Central Asia suitable for wheat cultivation; rainfed (spring) wheat production predominating in the north of Kazakhstan and irrigated cropping in the more arid south of Central Asia. Results revealed rather complex interactions between a range of agronomic factors (irrigation fertilizer application), wheat varieties under study, biophysical site-specific attributes (groundwater, soil salinity), factors related to climate change (warmer winters, hotter flowering periods) and interrelated crop phenological/growth characteristics, such as a shortening of cropping period or a shift in time of flowering. Varying levels of agronomic management added to the complexity. Our simulation results thus – even though unprecedented in terms of magnitude of considered impact factors – provide only a snapshot of the vast possible scenarios addressing the impact of CC. We believe that the complexity of presented results is a strong indication for the necessity to improve global-scale CC impact studies in terms of crop varieties considered, presumed agronomic management and abiotic conditions.

Our results showed that, in part, the simulated optimal management could offset potentially negative impacts of climate change (example: Bakht and Spitamen). This means that better agronomic management already nowadays constitutes a tool for addressing potential threats of CC. Changing the time of planting and fertilizer and irrigation application, adjusting input amounts, or adopting resource conserving agronomic management practices, such as Conservation Agriculture – all of which were not further considered in our study – may add to this toolbox of opportunities. Further in-depth (modeling) studies are required to investigate their CC adaptation potential. A few aspects of CC, however, may not easily be addressed by changing only agronomic management. Shrinking irrigation water resources, for example, may only be coped with up to certain extent. Adapting irrigation management to 30–40% reduction in irrigation, as has been published by Perelet (2007) as the most drastic decline in water availability, is a big challenge, especially if drainage infrastructure is suboptimal and secondary soil salinization a constant threat. Especially Uzbekistan, but also parts of Turkmenistan and Kazakhstan, suffer from land degradation by secondary soil salinization in response to suboptimal irrigation and drainage management and shallow, saline groundwater levels. While currently salinity is affecting crop growth and yield to an extent that may still be considered tolerable, the agro-ecology/soil productivity level of the affected production areas is highly unstable and therewith extremely vulnerable to any change in climate and irrigation water availability (Forkutsa et al., 2009). A CC future with less irrigation water may render a significant area under full irrigation no longer suitable for cropping.

Similar is true for hotter temperatures during flowering and associated sterility of flowers. Our simulations show that in some areas under spring wheat in the north (Astana) and in the south (Khorasan) of Central Asia CC will bring notably hotter temperatures during flowering. Crop breeders may be able to address the issue by targeted breeding for improved heat-tolerant varieties or shortening of the vegetative period; but only up to a certain physiological limit. This means that CC may lead to a shift of agro-ecozones, rendering wheat cropping impossible in some regions in the long-term future.

However, despite all threats associated with CC, our results show that for the whole of Central Asia for the winter/spring crop wheat the increase in temperature in response to CC is the most important factor that leads to earlier and faster crop growth, biomass accumulation and yield. Higher winter–spring temperatures also mean less frost damage contributing to the beneficial impact of CC. Increasing atmospheric CO_2 levels add further to increased biomass production and yield.

The moderate increase in rainfall had only a minor, insignificant, positive impact on crop yields under rainfed conditions, because of the increasing evaporative demand of the crop under higher future temperatures. However, in combination with an improved transpiration use efficiency in response to elevated atmospheric CO_2 concentrations, a slight reduction in irrigation water requirements was simulated for those sites where irrigation management was “automatic”, i.e. taking into consideration the soil moisture regime when scheduling irrigation events. Overall, the reduction in irrigation water requirement was small, and thus hardly notable given the considerable year-to-year variation in precipitation.

Our study did not tackle the likelihood of increased future abundance of pest and diseases. This because neither is there enough scientific evidence available on the issue for Central Asia, nor are biophysical models mature enough to produce trustworthy/useful prediction of the impact of pest and diseases on crop growth.

It is noteworthy that an overall shorter life cycle did not negatively affect biomass accrual and yield. Often a short(er)-season variety is lower yielding than a long-season variety, because the crop has less time for photosynthesis and biomass buildup. In Central Asia, however, simulations revealed that a potentially negative effect of a shorter life cycles in a CC-affected future was more than counter balanced by more favorable growth conditions in early (higher temperatures) and late spring (higher temperatures and a positive effect of elevated atmospheric CO_2 concentrations).

Furthermore important is the fact that CC differences as projected under A1B and A2 emission scenario were not discernible by its effect on grain yield on 17 of the 18 sites. In part, this was because climatic differences were small for the immediate and mid-term futures and only notable in the long-term future. Then, however, detrimentally high temperatures during flowering and the CO_2 fertilization effect counterbalanced.

Averaged across the two emission scenarios and three futures, yields increased in response to the projected CC at 14 of the 18 sites. The overall increase averaged across all sites and futures and management scenarios was 12%. This is higher than comparable results presented by Iglesias and Rosenzweig (2009, −2.4% to +10.0%, details see introduction), and contradicting the loss of grain yields predicted by Parry et al. (2004; −2.5% to −10%) and Arnell et al. (2002; −2.5% to 0%).

Yields were simulated to decrease – very moderately though – at only one site, Spitamen (Tajikistan). Spitamen was among the sites with the relatively highest increase in annual rainfall (∼7% on average), which resulted in an increased loss of nitrate out of the rooting zone and a subsequent slight increase in N-stress under the given soil (N-levels) and (poor) management conditions. These results however have to be considered with care, as simulation of nitrate movement in soils can only roughly approximate reality, when real observation for an in-depth site/soil specific model calibration are absent as was the case for Spitamen. To provide a firmer answer, more detailed field studies and subsequent model simulations need to be carried out. Similar is true for the precise simulation of the impact soil salinity – historically as well as under CC – which was shown to influence yields at Akaltyn site.

Positive responses of crop yields to climate change have also been predicted by Eitzinger et al. (2003) using CERES-Wheat for the semi-arid growth condition at two sites, one in southeastern Czech Republic and another one in northeastern Austria. They compared historic climate with CC scenarios projected by three IPCC GCMs. The averaged scenario comprised an average annual change in temperature of +3.0 °C and an increase in annual precipitation of 3.9%. Assuming an increase of the atmospheric CO_2 concentrations to 660 ppm, Eitzinger et al. (2003) predicted notably higher yields on both sites compared to historic (1985–1993) conditions. At the same time – similar to our results – crop transpiration and water stress dropped significantly in response to a simulated increase in water use efficiency and reduced total potential evapotranspiration caused by shortened growing period.

CropSyst proved an efficient tool for simulating the impact of CC. It contains routines for addressing all relevant/important CC aspects, such as CO_2 response, frost damage and heat stress during flowering. The latter in version 4.15.05 was still hard-coded which omitted the possibility to isolate and quantify the impact of this effect by comparing simulations with enabled against simulation with disabled heat-stress-during-flowering routine.

For regions with groundwater influence it is paramount to be able to capture the influence of shallow groundwater and its contribution to crop water uptake as well as secondary soil salinization; as we did for 6 of the 18 study sites. This aspect was repeatedly overlooked in earlier studies (e.g. those of Nelson et al., 2009, 2010) using biophysical models that lack a groundwater and/or salinity routine. It is unclear how this affected the quality of earlier predictions for a region like Central Asia with almost 50% of the irrigated areas affected by salinization (Bucknall et al., 2003).

5. Conclusions

The overall simulated impact of climate change on wheat productivity in Central Asia is positive. A warmer climate explains most of this positive impact; CO_2 fertilization adds to it. Too hot temperatures during flowering (flower sterility) will become a problem in the long-term future in some, mostly southern, areas and in the spring wheat areas of northern Kazakhstan. However, the picture is not unduly dramatic, and targeted crop breeding towards temperature tolerance in combination with improved agronomic management (shifting planting dates) may be able to tackle the issue.

Irrigation water requirements do not increase under CC. However, already the current situation of excessive irrigation and subsequent secondary soil salinization being a constant threat to agricultural production demands for an improved irrigation and drainage management. Therefore, further research should address options for improved irrigation management; this also in light of the observed risk of increased N loss out of the soil by leaching in response to higher and more intensive precipitation.

Development of adaptation options to CC was part of the original objectives of the study. However, given the generally positive impact of CC on wheat productivity in Central Asia, there remains little to be argued about adaptation needs for farmers.

The above-said is only valid for a future in which irrigation water availability (snowfall/melt in the mountains) does not substantially decrease. Our simulations did not cover such scenarios given the fact that the GCMs on average rather predicted slightly increasing rather than decreasing precipitations under CC. Therefore, it seems very much required to couple crop modeling of irrigated crop production in Central Asia with hydrological/climatological estimates of snowfall and snow melt in the mountains and the impact of climate change.

This study does not constitute a true spatial CC assessment, but is based on biophysical point-scale simulations in key AEZs of Central Asia. To carry out such regional/spatial assessment, a comprehensive set of information (maps) would be needed, such as about distribution of wheat varieties, or at least current land use, regional agronomic management practices, as well as soil and weather data suitable for daily time-step crop model simulations at spatial scale.

Acknowledgments

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Appendix A.

Table A1

Table A1
Summary of CropSyst crop physiological and phenological model settings for all considered wheat varieties; for the sake of conciseness only those parameters are shown which were subject to change during model calibration; for all other parameters CropSyst default values were used.

Location		Variety	Base temperature (°C)	Cutoff temperature (°C)	Accumulated growing degree days (°C-day)						Leaf area duration (°C-day)	Specific leaf area, SLA ($m^2\ kg^{-1}$)	Leaf/stem partition coefficient, SLP	Transpiration use efficiency when VPD is at 1 kPa (g/kg)	Scaling coefficient of TUE regression (power function)	Unstressed harvest index (HI)	Sensitivity to water and N stress during flowering (0–1.5)	Sensitivity to water and N stress during grain filling (0–1.5)	Duration of grain filling period (unstressed; days)	Sensitivity to temperature stress during flowering	Maximum rooting depth (m)
					From seeding to emergence	To maximum rooting depth	From seeding to end of vegetative growth	From seeding to flowering	From seeding to beginning grain filling	From seeding to maturity											
Kazak.	Kostanay, Petropavlovsk, Astana	*Saratovskaya 29*	0	22	325	925	958	958	1020	1412	900	20	1.8	5	0.45	0.49	0.1	0.1	20	0.5	1.3
	Shieli	*Almaly*	2	23	155	550	583	583	638	1300	630	19	1.8	5.5	0.45	0.48	0.55	0.55	32	0.5	1
Kyrgyzstan	KyrNIIZ, ZhanyPakhta	*Adyr*	0	22	175	450	580	590	645	1450	700	20	2	5	0.45	0.46	0.5	0.5	38	1	1.4
	Daniyar	*Asyl*	2	23	115	480	485	485	540	1310	700	22	1.8	5.5	0.45	0.45	1	1	20	1	1.3
	Daniyar	*Intensivnaya*	2	23	115	425	430	430	490	1300	700	22	1.8	5.5	0.45	0.46	1	1	20	1	1
	Uchkhoz	*Kyal*	2	23	95	470	470	497	550	1080	620	22	2	5	0.45	0.46	0.5	0.5	25	1	1.25
Tajikistan	Shahristan, Khorasan, Faizabad	*Navruz*	0	20	70	500	621	621	680	1050	600	20	1.8	5	0.45	0.45	0.6	0.6	18	0.6	1.2
	Bakht	*Jagger*	1	21	145	450	460	460	570	1112	650	21	1.8	5	0.4	0.46	0.1	0.3	27	0.5	1.1
	Spitamen	*Kazakhskaya-10*	1	22	150	750	750	765	830	1530	830	22	1.7	5	0.45	0.46	0.25	0.25	33	0.5	1.1
Uzbekistan	Khorezm	*Kupava*	3	25	94	440	507	507	590	1040	740	20	2	5.1	0.45	0.46	0.3	0.2	21	1	1.1
	Kuva, Akkavak	*Kroshka*	2	23	135	450	461	461	600	1135	700	24	1.6	5.9	0.45	0.47	0.5	0.5	13	0.7	1
	Akaltyn	*Polovchanka*	2	22	182	490	500	500	620	1218	600	18	1.6	5	0.45	0.43	0.6	0.6	29	1	0.9
	Kushmanata	*Dustlik*	−1	19	102	580	580	605	700	1125	690	22	1.6	5	0.45	0.48	0.5	0.5	19	0.5	1.4
	Akkavak	*Mars*	1	21	160	570	570	580	680	1060	700	22	1.8	5	0.45	0.48	0.5	0.5	17	1	1.3

Figs. A1–A7

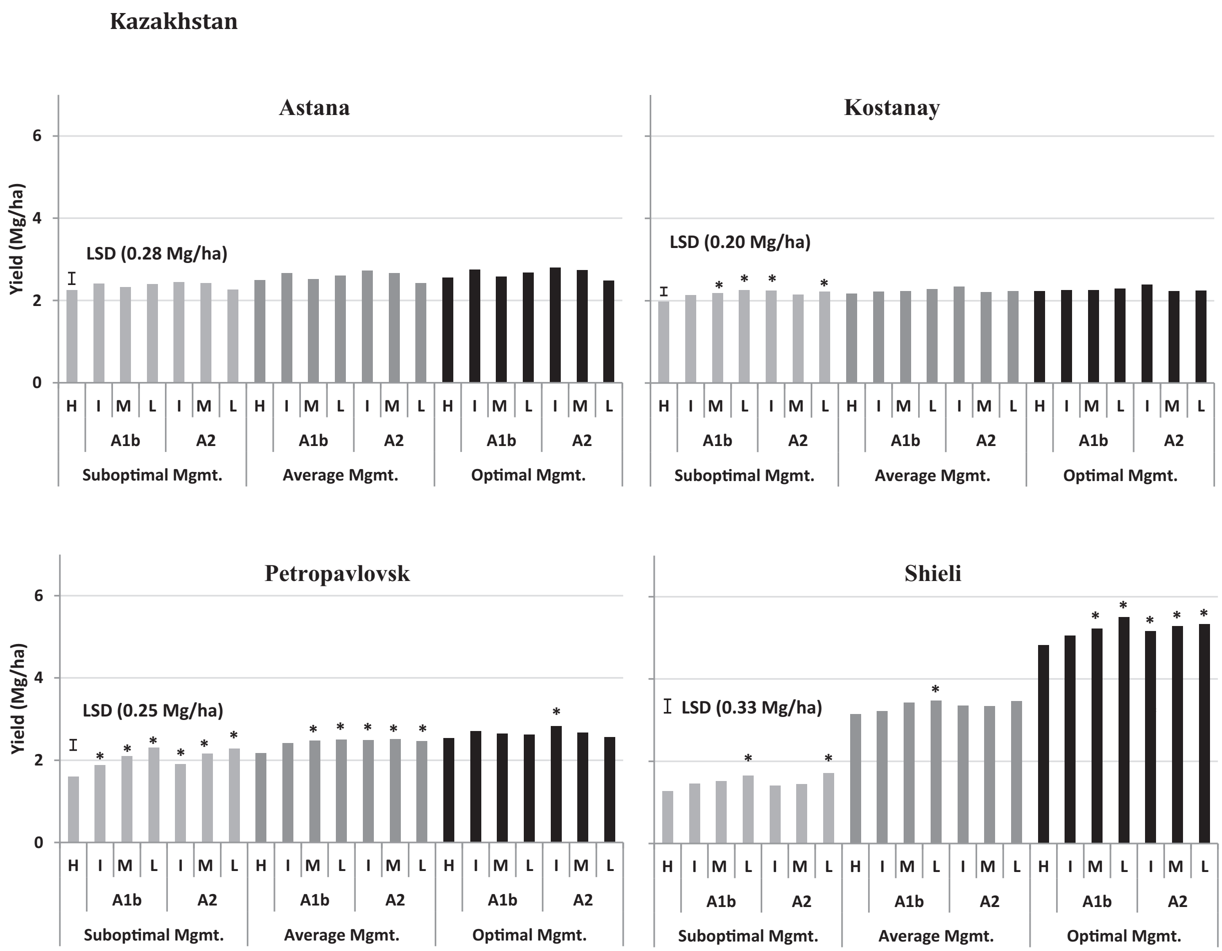

Fig. A1. Yield in response to suboptimal, average and optimal agronomic management and climate change of the four Kazakh sites: Astana, Kostanay, Petropavlovsk and Shieli; H = historic, I = immediate, M = medium-term, L = long-term future; asterisks denote significant changes as compared to Historic.

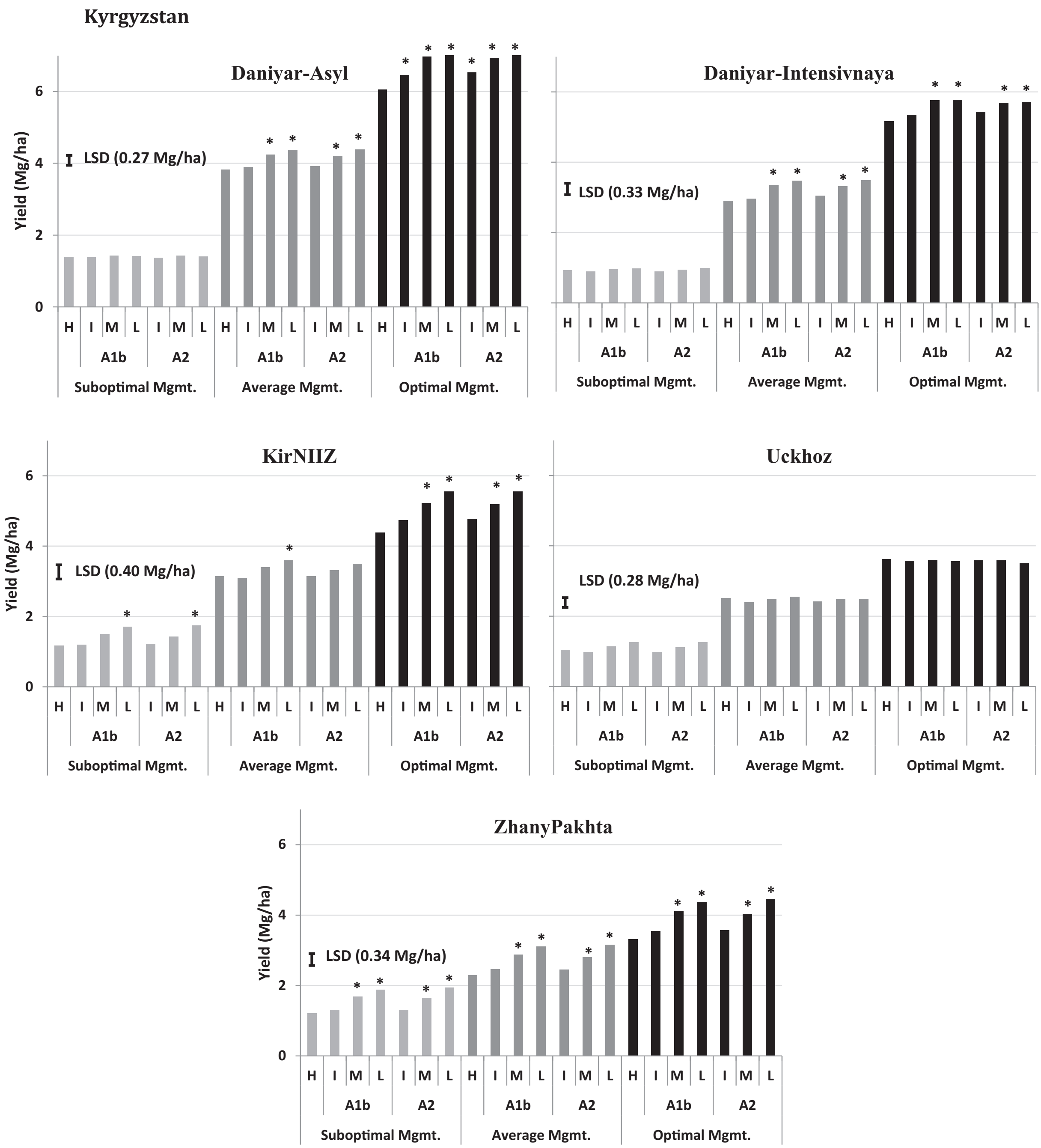

Fig. A2. Yield in response to suboptimal, average and optimal agronomic management and climate change of the four Kyrgyz sites: Daniyar (variety *Asyl* and *Intensivnaya*), KyrNIIZ, Uchkhoz and ZhanyPakhta; H = historic, I = immediate, M = medium-term, L = long-term future; asterisks denote significant changes as compared to Historic.

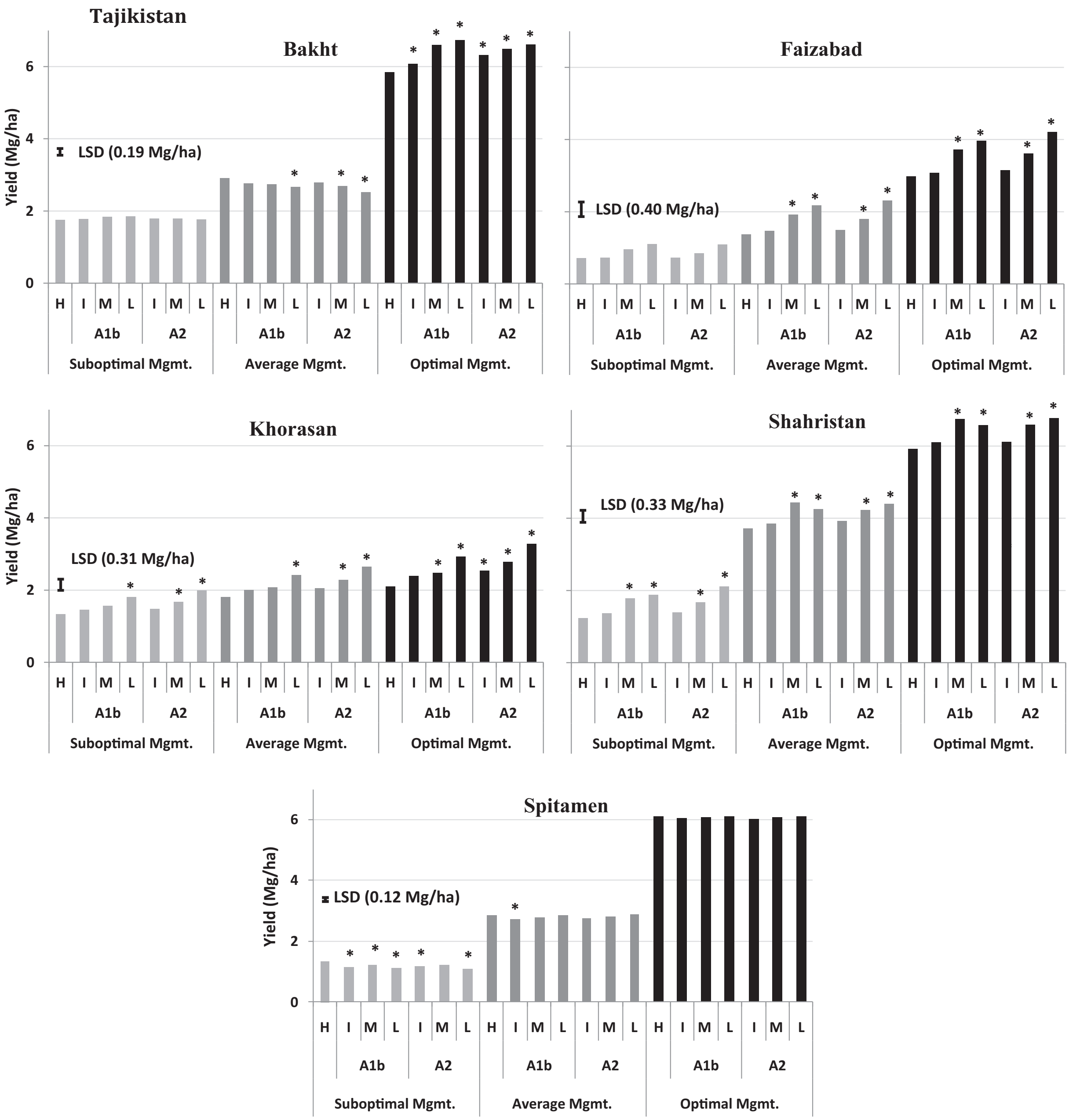

Fig. A3. Yield in response to suboptimal, average and optimal agronomic management and climate change of the five Tajik sites: Bakht, Faizabad, Khorasan, Shahristan and Spitamen; H = historic, I = immediate, M = medium-term, L = long-term future; asterisks denote significant changes as compared to Historic.

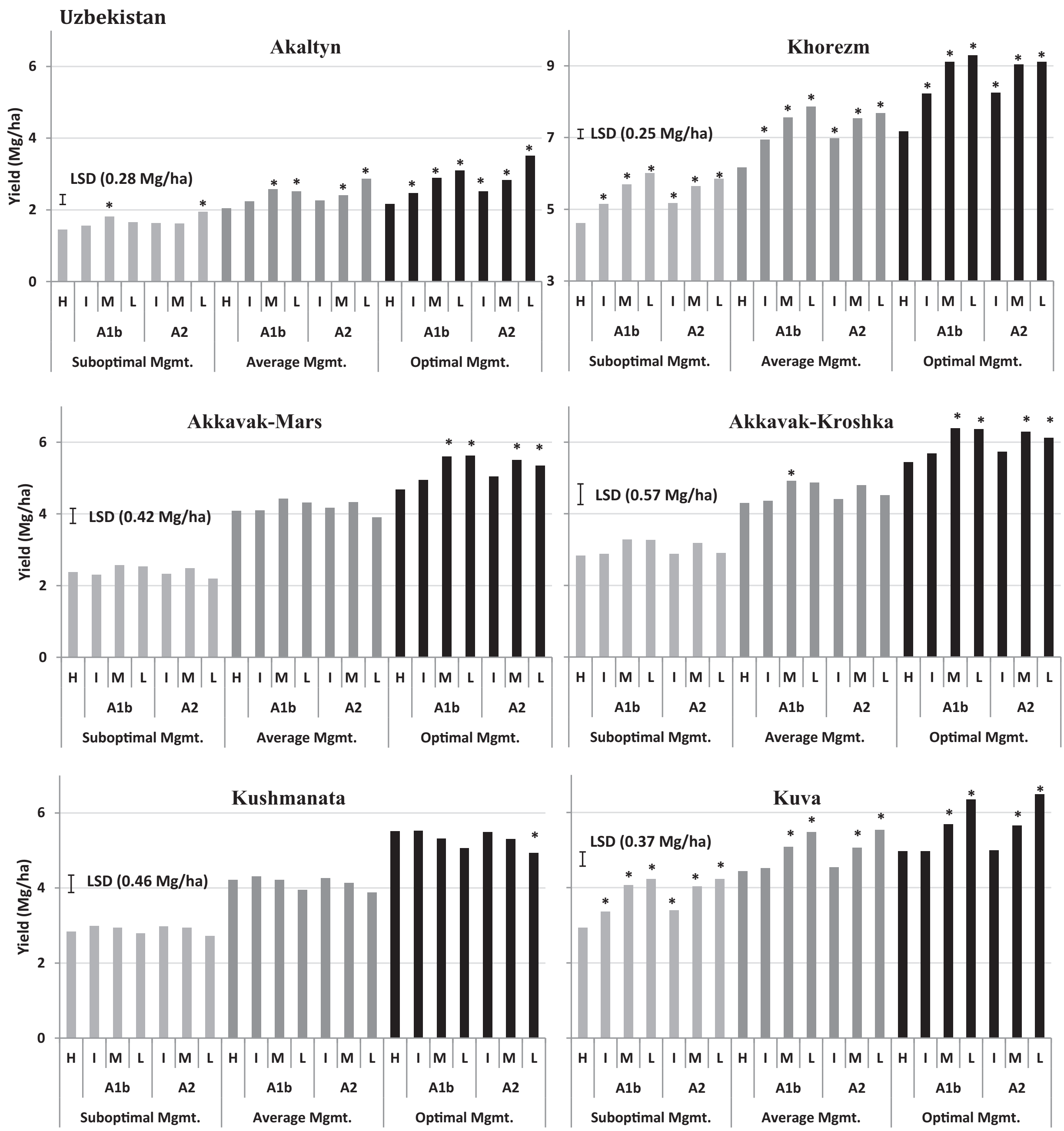

Fig. A4. Yield in response to suboptimal, average and optimal agronomic management and climate change of the five Uzbek sites: Akaltyn, Khorezm, Akkavak (variety *Mars* and *Kroshka*) Kushmanata and Kuva; H = historic, I = immediate, M = medium-term, L = long-term future; asterisks denote significant changes as compared to Historic; note the different *y*-scale for Khorezm.

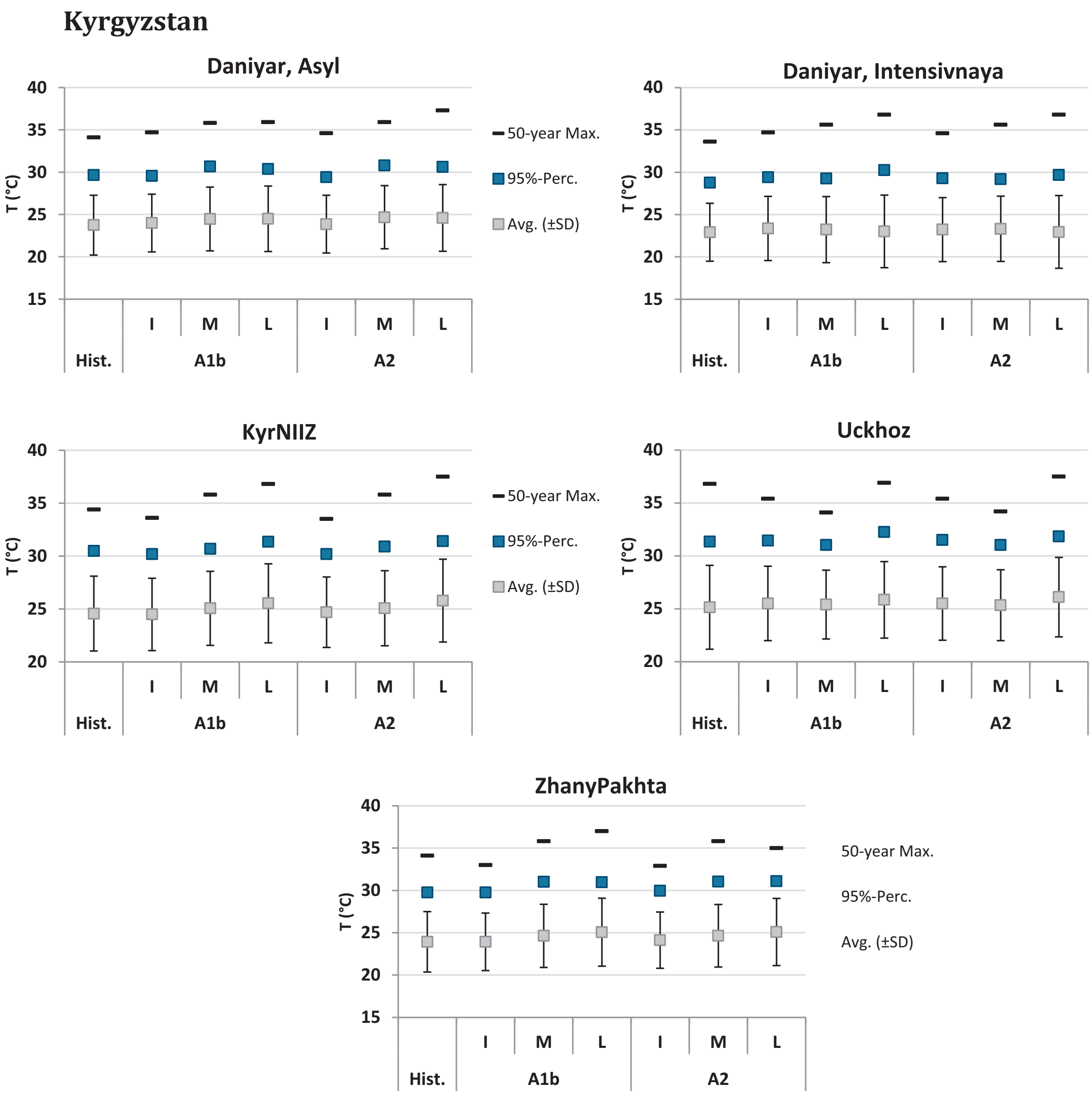

Fig. A5. Maximum temperature during flowering of the four Kyrgyz sites: Daniyar (variety *Asyl* and *Intensivnaya*), KyrNIIZ, Uchkhoz and ZhanyPakhta; I = immediate, M = mid-term, L = long-term future.

Tajikistan

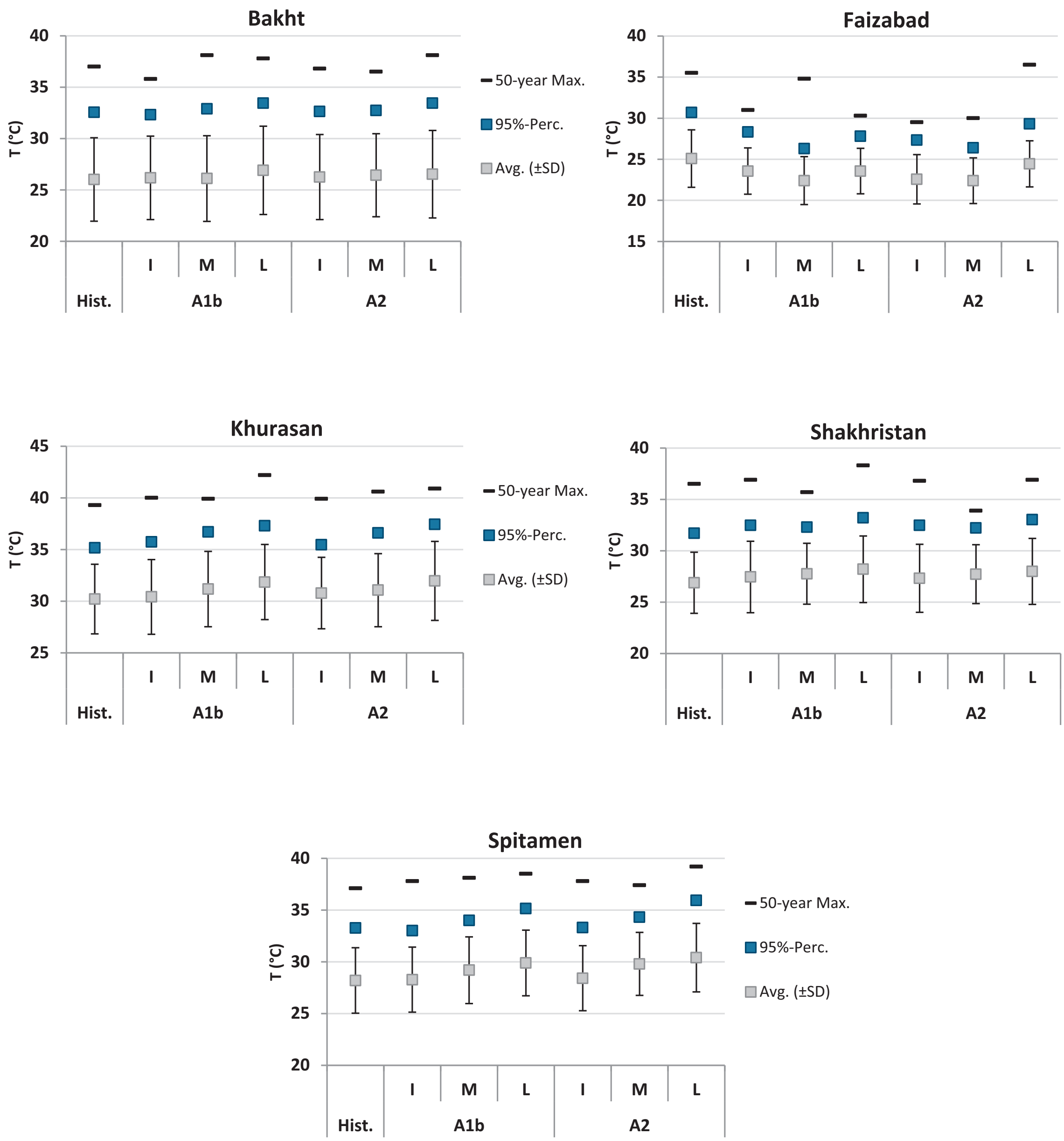

Fig. A6. Maximum temperature during flowering of the five Tajik sites: Bakht, Faizabad, Khorasan, Shahristan and Spitamen; I = immediate, M = mid-term, L = long-term future.

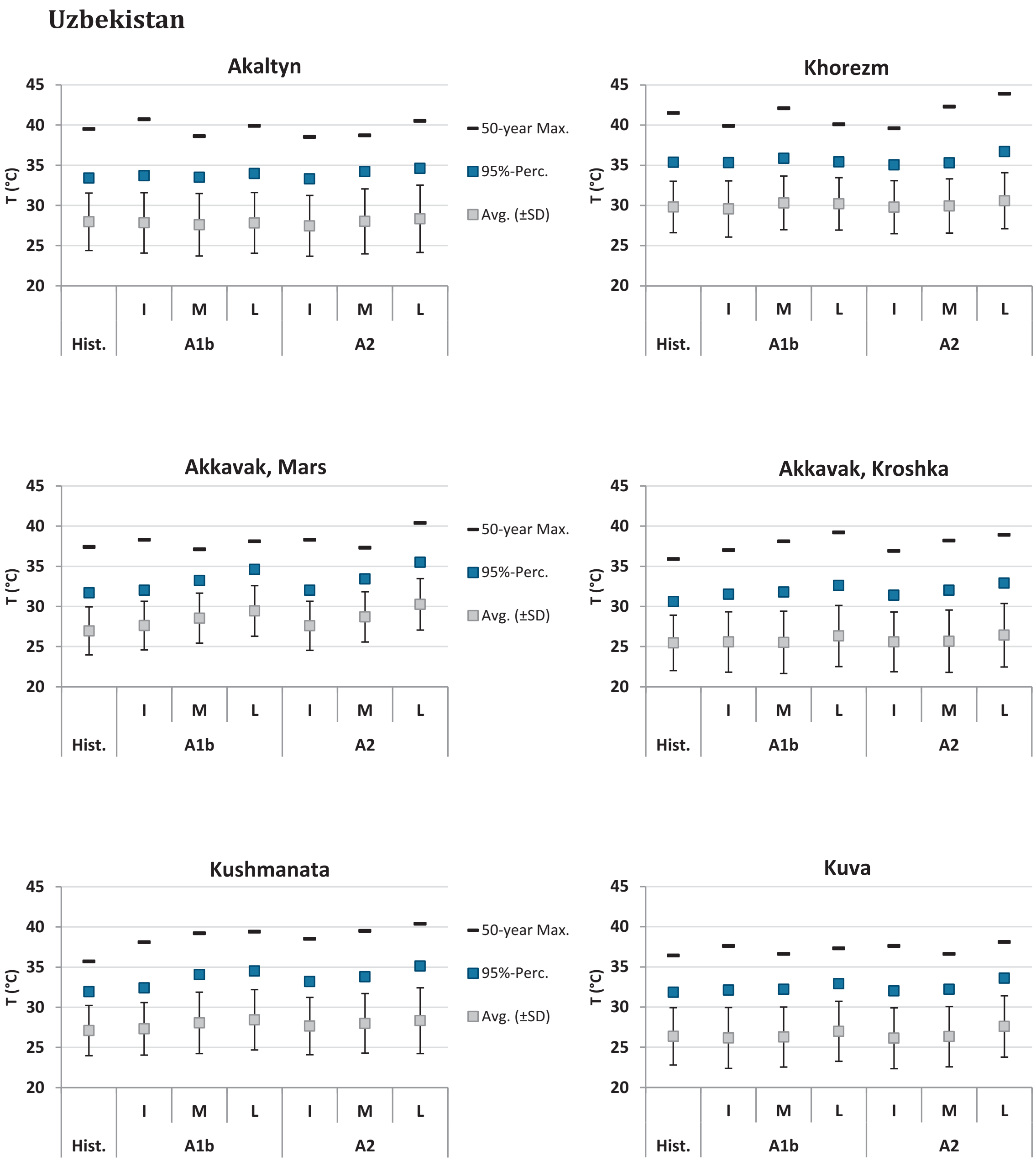

Fig. A7. Maximum temperature during flowering of the five Uzbek sites: Akaltyn, Khorezm, Akkavak (variety *Mars* and *Kroshka*), Kushmanata and Kuva; I = immediate, M = mid-term, L = long-term future.

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