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ORIGINAL ARTICLE

Potential impacts of early twenty-first century changes in temperature and precipitation on rainfed annual crops in the Central Andes of Peru

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Abstract Smallholder agriculture in the Central Andes of Peru is based to large extent on rainfed cropping systems, is exposed to climatic risks and is expected to respond sensitively to increasing temperatures and shifts in the precipitation regime. Here, we examine the potential implications of early twenty-first century climate change scenarios for the cultivation of potato, maize, wheat, barley and broad bean, five annual crops that account for 50 % of the cultivated area in the Department of Cusco and Apurímac and provide the dietary backbone for a large share of the local population. The scenarios disclose a regionally coherent increase in temperature of the order of 1 °C but overall only moderate changes in growing season precipitation by 2030. A simple crop model is used to assess the effects of these changes on crop phenology and development. The results show earlier harvest dates, shorter cropping seasons and, in a few cases, a slightly higher risk of planting failure in the near future. This suggests that a better understanding of changes in the precipitation regime at the onset of the cropping season is required to evaluate short-term needs and possibilities for adaptation. However, as the scenarios are highly uncertain, these conclusions should be verified.

Keywords Climate change · Temperature · Precipitation · Annual crops · Central Andes · Rainfed agriculture

Introduction

Agriculture in Latin America is currently undergoing important structural changes and becoming increasingly oriented toward the production of agricultural commodities for the global market. Yet, in many areas of the South American continent, including the Andes, agriculture is still predominantly practiced at a subsistence level. This goes along with high levels of poverty, a human and social problem affecting a significant percentage of the rural population (Berdegué and Fuentealba 2011).

Low productivity levels in agriculture and poverty are also characteristic of Cusco and Apurímac, two political Departments in the Central Andes of Peru in which more than 70 % of the population has a rural background and more than 50 % of the population can be considered as indigent (INEI 2010, 2013a). With <30 % of the agricultural area being irrigated (INEI 1994), crop production is for the most part rainfed and relies on traditional techniques. Farmers have often to cope with losses caused by abnormal climatic conditions (Altieri and Koohafkan 2008; Jarvis et al. 2011; Sietz et al. 2012). Common for this area are seasonal droughts, frosts and late season warm weather spells (Frère et al. 1975; Gilford et al. 1992; Quevedo et al. 2006). Crop production is further threatened by pests and diseases (Perez et al. 2010).

In the Central Andes of Peru, declining trends in rainfall but positive tendencies for intense rainfall events and

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consecutive dry days have already been observed in the past (Haylock et al. 2006, as reported in Magrin et al. 2007) and are expected to continue in the future (Sanabria et al. 2009; Urrutia and Vuille 2009; Minvielle and Garreaud 2011; Thibeault et al. 2012). In addition, some evidence has been found that yield development of important cereals could already have weakened as a consequence of past trends in climate (Lobell et al. 2011). Clearly, climate change is perceived with concern in the Central Andes of Peru, and this calls for regional impact assessments that can deliver the scientific baseline for implementing adaptation.

An example of regional impact assessment for the Peruvian highlands is the study of Sanabria and Lhomme (2013). In this study, a simple process-oriented model of crop phenology and growth (Lhomme et al. 2009) was applied to examine the possible effects of climate change on potato cropping. Changes in monthly mean temperature, precipitation, relative humidity, solar radiation and reference evapotranspiration as projected for 2071–2100 by the HadRM3P regional climate model were taken as a starting point for the evaluation. The results suggested a range of impacts, including earlier planting dates, shorter crop cycles and higher potato yield deficits, calling the attention on the consequences of climate change for agricultural policy and adaptation.

The present study is meant to complement the earlier analysis by Sanabria and Lhomme (2013) by examining the implications of regional scale scenarios for the growing conditions of potato, maize, wheat, barley and broad bean (an important source of proteins). These are crops that, in Cusco and Apurímac, account for a large fraction of the cultivated area and are expected to respond sensitively to climate change (Jarvis et al. 2011).

Analogously to Sanabria and Lhomme (2013), the focus is primarily on examining the implications of changes in monthly temperature and precipitation for crop-water requirements and water availability and the effects of water stress on crop yields. Because in reality climate interacts with soil and management in a number of ways, this can only provide an incomplete view on how crops may respond to climate. Still, it can be argued that the approach deliver useful insights (Steduto et al. 2012), as demonstrated for the Andean region in other studies exploiting a similar setup (e.g., Garcia et al. 2007; Geerts et al. 2009).

The present analysis differs from the study conducted by Sanabria and Lhomme (2013) both in terms of geographic focus and time frame. Regarding the former, we focus on the Departments of Cusco and Apurímac rather than Puno, as this was the area selected for the implementation of the Program on Climate Change and Adaptation in Peru (PACC, Programa de Adaptación al Cambio Climático en el Perú) (Salzmann et al. 2009), an initiative in which the present study was embedded. Five weather stations were considered to represent some of the main cropping areas within these two departments. While it is clear that five weather stations are not sufficient for provide a detailed representation of an area that extends over 300 km in longitude and 400 km in latitude, one has to bear in mind that the density of the meteorological network in the Central Andes of Peru is overall relatively modest (see e.g., Fig. 1 in Schwarb et al. 2011).

Concerning the time frame, we consider projections valid for 2030 rather than 2085 on the ground that assessment for the short term is necessary to build awareness, improve preparedness and promote the process of adaptation. In short, these were the goals PACC. Within this program, regional climate change scenarios for Cusco and Apurímac were developed by Acuña et al. (2012), and these were adopted for our analysis. The climate change scenarios refer to the A1B emission scenario rather than the A2 and B2 emission scenarios used by Sanabria and Lhomme (2013). Although the choice of emission scenario can, in principle, have repercussions in terms of impacts, we believe that it is not critical with respect to the time frame of the present study (2020–2039), since differences in atmospheric greenhouse gas abundances and corresponding radiative forcing are still reasonably contained within this time horizon (Nakicenovic and Swart 2000; IPCC 2001).

Materials and methods

Study area and crops

The Departments of Cusco and Apurímac are located in the Central Andes of Peru. They extend approximately from 71.25 to 73.50°W, and from 13.00 to 14.75°S (Fig. 1) and cover altitudes above 2,900 m.a.s.l., if one excludes the region in the north of Cusco that is located within the Amazonian basin. Temperature fluctuates between −8 and 20 °C, and annual precipitation ranges from 500 to 1,000 mm, with more than 70 % of the precipitation falling during austral spring and summer (October to March). Frost events are relatively frequent, as are seasonal droughts.

Although it is often assumed that precipitation variability and extreme precipitation conditions are called upon by the El Niño-Southern Oscillation (ENSO), in practice only a weak linkage is implied by the statistical analysis of precipitation records from the Central Andes (Nickl 2007; Lagos et al. 2008).

In Cusco and Apurímac, the cultivated surface amount to about 365,000 and 165,000 ha, respectively, of which a large fraction is at high elevations (MINAG 2013a). In Cusco, coffee represents the most important crop by agricultural area but its cultivation is limited to the Amazonian lowlands. In Apurímac, potato, maize, wheat, barley and broad bean

Fig. 1 Geographic map of the study region showing the location of the Departments of Apurímac and Cusco within Peru (inset), and the position of the meteorological stations considered for the analysis (see list in Table 1). The two stations of Granja Kcayra (northernmost station on the map) and Chuquibambilla (on the lower right) were included as they were used by Baigorria et al. (2004) to develop the parameterization of solar radiation adopted in the present analysis

account for 80 % of the cultivated surface (mean value for the year 2007–2011) (MINAG 2013a). In Cusco, the share of these crop by surface is of 45 % (MINAG 2013a).

To better take advantage of the altitudinal diversity of agricultural environments and taking into account the thermal and water requirements of different crops, it is common practice to grow crops and/or varieties of the same crop in different altitudinal belts (Tapia 1997). In relation to the five crops considered for the present analysis, the following can be observed:

- Potato. The Andean variety “Ccompis” (*Solanum tuberosum* ssp. *Andigenum*) (Alvarez and Repo 1999; Tapia and Fries 2007) is cultivated between 3,400 and 3,800 m.a.s.l. (Tapia and Fries 2007) and is characterized by a growing cycle of 150 to 160 days (Frère et al. 1975; Gómez et al. 2008).
- Maize. The local variety dubbed “Cuzco” *(Zea mays amilaceo)* is cultivated in principle between 2,400 and 3,300 m.a.s.l., but above 2,800 m.a.s.l. only in areas that receive sufficient rainfall (Salhuana 2004). This variety is characterized by a growing cycle of approximately 200 days.
- Barley and wheat. Local varieties of barley (*Hordeum vulgare* L) and wheat (*Triticum* spp) are grown between 3,000 and 3,800 m.a.s.l and between 2,000 and 3,500 m.a.s.l., respectively (Frère et al. 1975; INIA 2005). They are characterized by growing cycles of around 120 and 140 days, respectively.
- Broad bean. The local variety called “blanca” (*Vicia Faba* L) is cultivated between 3,500 and 3,850 m.a.s.l. (Horqque 1989). It is characterized by a growing cycle of approximately 180 days.

Climatic data and scenarios

Observed climatic data

Daily climatic data covering the period 1990–2009 were extracted from the database maintained by the Peruvian Weather Services (Servicio Nacional de Meteorología e

Hydrología del Perú—SENAMHI) for the following sites (Fig. 1):

- in Apurímac, Andahuaylas (13° 39′ S, 73° 22′ W, 2,866 m.a.s.l) and Chalhuanca (14° 20′ S, 73° 10′ W, 2,850 m.a.s.l.);
- in Cusco, Cay Cay (13° 36′ S, 71° 42′ W, 3,150 m.a.s.l.), Sicuani (14° 15′ S, 71° 14′ W, 3,574 m.a.s.l.) and Yauri (14° 49′ S, 71° 25′ W, 3,927 m.a.s.l.).

The five stations were selected to represent five of the main agricultural areas of this region:

- in Apurímac, the provinces of Andahuaylas (~250,000 ha of agricultural surface) and Amayaraes (~160,000 ha);
- in Cusco, the provinces of Paucartambo (~32,000 ha), Espinar (~15,000 ha) and Canchis (~10,000 ha) (INEI 1994).

Meteorological variables considered for the analysis were daily minimum, maximum and mean temperature, precipitation amounts, relative humidity, wind speed and sunshine duration. Since solar radiation (R_S) is not routinely observed at these stations, it was estimated from sunshine duration (n) using the Ångström–Prescott equation (Allen et al. 1998):

$$\frac{R_S}{R_a} = a_S + b_S \frac{n}{N} \tag{1}$$

where R_a represents the extra-terrestrial solar irradiance (in units of MJ m^{-2} day^{-1}), N is the astronomical day-length, and a_S and b_S are coefficient that need to be calibrated. For Peru, this has been done by Baigorria et al. (2004) for 14 actinometric stations. Based on this study, numerical values ($a_S = 0.376$ and $b_S = 0.364$) valid for Granja Kcayra (14° 19′ S, 71° 31′ W, 3,219 m.a.s.l.; Fig. 1) were taken to model solar radiation at Andahuaylas, Chalhuanca and Cay Cay, whereas numerical values ($a_S = 0.395$ and $b_S = 0.384$) valid for Chuquibambilla (14° 28′ S, 70° 26′ W, 3,971 m.a.s.l.; Fig. 1) were assumed to model solar radiation at Sicuani and Yauri.

All data were subject to quality check and homogenization following Schwarb et al. (2011). To obtain complete records needed on input to the crop model, missing values were replaced with the corresponding climatological long-term mean values.

Reference evapotranspiration

Apart from knowledge of temperature and precipitation, estimates of the so-called reference evapotranspiration (ET_0) are required to run the crop model ("Crop simulation model" section). According to Allen et al. (1998), the reference evapotranspiration is defined as the water vapor flux from a standard grass vegetation (12 cm tall) not short of water. In the standard approach, ET_0 is calculated using a parameterized version of the Penman–Monteith equation (see also Garcia et al. 2003, 2004). The equation reads:

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G)\; + \;\gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta\; + \;\gamma\,(1 + 0.34 u_2)} \tag{2}$$

where R_n is the net radiation, G the soil heat flux, γ the psychrometric constant, T the daily mean temperature, u_2 the wind speed at 2 m height, e_s the saturation vapor pressure as a function of temperature and e_a the actual vapor pressure.

For the evaluation of Eq. (2) under current conditions, net radiation, soil heat flux, as well as saturation and actual vapor pressure were computed using formulas discussed in Allen et al. (1998). For estimating ET_0 under future climatic conditions, net radiation, relative humidity and wind speed were assumed unchanged relative to today's climatic conditions. Only e_s and e_a were allowed to adjust in response to the increase in minimum and maximum temperature specified by the scenarios (see "Climate change scenarios" and "Present and future climate" sections).

Climate change scenarios

Climate scenarios targeting the 2030s (nominal mean time for 2020–2039) were developed from the output of two climate model experiments that were carried out at 20 km × 20 km horizontal spatial resolution, assuming atmospheric greenhouse gas concentrations as in the A1B emission scenario (Nakicenovic and Swart 2000). Details concerning the two experiments can be found in Acuña et al. (2012).

The first experiment refers to simulations with version 3.2 of the Weather Research and Forecasting model (WRF 3.2, Wang et al. 2012). WRF has been run operationally for weather prediction at SENAMHI since 2008. In 2010, version 3.2 was installed in collaboration with the Max Planck Institute for Meteorology (Hamburg, Germany) for conducting a climate change experiment, which was driven with lateral boundary conditions obtained from a run with the ECHAM5-OM global model.

The second experiment refers to simulations with version 3.2 of the high-resolution, global climate model developed by the Meteorological Research Institute/Japan Meteorological Agency (MRI/JMA TL959L60) (Noda et al. 2008).

The ability of the two global models involved in this study to reproduce the dominant large-scale circulation patterns over South America was examined by Acuña et al. (2012) and for MRI/JMA by Vergara et al. (2007),Vergara and Scholz (2010) and Blázquez and Nuñez (2013). Both

ECHAM5-OM and MRI/JMA were found to perform satisfactorily with respect to the position and evolution of both the Bolivian High and the Inter-Tropical Convergence Zone (ITCZ), although ECHAM5-OM tended to put the ITC more to the south than observed.

The high-resolution version MRI/JMA has also been found to provide a reasonable representation of the Andean orography, with a Pearson correlation coefficient of ~0.6 between the observed elevation at 45 stations situated in the Peruvian highlands and the corresponding one assumed by the model (Vergara et al. 2007).

It has been argued that use of a 20 km × 20 km mesh in climate model experiments can improve the simulation of regional climates in complex topography (Mizuta et al. 2006; Solman 2013). For the Central Andes of Peru, however, comparison of meteorological fields simulated by both WRF 3.2 and MRI/JMA with observations reveals the presence of substantial biases. For temperature, there is a cold bias of −3 °C (austral summer) to −4 °C (austral winter) in the WRF 3.2 experiment and of −8 °C (austral summer) to −3 °C (austral winter) in the MRI/JMA experiment. For precipitation, the relative bias is as a rule negative in the WRF 3.2 experiment, ranging from −10 to −100 %, but positive in the MRI/JMA experiment, exceeding in some cases and/or months 100 %. Regarding the MRI/JMA experiment, these findings are in line with those obtained by Mizuta et al. (2006, 2012) and Blázquez and Nuñez (2013). Overall, the present results are also consistent with the biases disclosed for an ensemble of regional climate models by Solman et al. (2013).

Because large systematic errors preclude the direct use of climate model outputs as input to crop models, daily data for 2020–2039 were developed following Déqué (2007) by imposing additive (temperature) or multiplicative (precipitation) climate change factors onto the observed daily weather data (see also Wilby et al. 2009). As in Lhomme et al. (2009), change factors were computed on a calendar month basis as differences (temperature) or ratios (precipitation) of climatological mean fields as simulated for 2020–2039 and 1990–2009. Change factors obtained separately from the outputs of WRF 3.2 and MRI/JMA were averaged to produce mean change factors.

Crop simulation model

The effects of climate on crop growth and yield were estimated using the simple crop model developed by Lhomme and Katerji (1991) and Lhomme et al. (2009). At the core of the model is the implementation of the procedures developed by the Food and Agriculture Organization (FAO) of the United Nations for estimating crop-water requirements (Allen et al. 1998) and water stress effects on yield (Doorenbos and Kassam 1979; Steduto et al. 2012).

The model operates on a daily time step. It requires daily mean temperature (T), daily precipitation (P) and reference evapotranspiration (ET_0) as inputs, and delivers planting date, harvesting date, length of the growing season, number of interrupted growing cycles, potential dry-matter production and relative yield deficits on output.

A full simulation cycle consists of the following five steps:

- Calculation of the planting date. Within a pre-defined potential sowing window [DOY_1, DOY_2], the crop is planted whenever a minimum amount of precipitation (P_{so}) has occurred during a given number (N_{so}) of consecutive days. This is a standard approach for estimating the sowing date in semi-arid areas under rainfed agriculture (e.g., Stern et al. 1982; Sivakumar 1988)
- Determination of crop phenology. The models accounts for four developmental stages (initial, crop development, mid-season and late season) that are expressed as a function of the so-called thermal time, i.e., the running sum of growing degree-days (GDD_1, GDD_2, GDD_3 and GDD_4). The latter are calculated by subtracting a base temperature T_b from the minimum of daily mean temperature T and cutoff temperature T_c:

$$GDD = \max\left[\min(T, T_c) - T_b, 0\right] \tag{3}$$

- Evaluation of potential dry-matter accumulation. As detailed in Sanabria and Lhomme (2013), potential dry-matter production is assumed proportional to the total amount of solar radiation received during the various growing stages (Monteith 1972). The proportionality factor accounts for the climatic efficiency of radiation (i.e., the ratio between photosyntetically active and solar radiation), the stage-specific biological conversion efficiency of the crop (i.e., the radiation use efficiency) and the interception of solar radiation as a function of the leaf area index. The leaf area index is assumed to linearly increase during early development, remain at a constant value during mid-season and linearly decrease to zero during the late season (see also Allen et al. 1998).
- Evaluation of the actual evapotranspiration. Given an estimate of the reference evapotranspiration ET_0, the model first evaluate potential crop evapotranspiration as $ET_c = K_c \times ET_0$, allowing the crop coefficient K_c to assume different values for the initial, crop development, mid-season and late season stages (Allen et al. 1998). Actual evapotranspiration is then calculated as $ET_a = K_{ws} \times ET_c$, where K_{ws} is a water stress factor that depends on soil water availability. Following

Table 1 Management, crop and soil parameters

Parameter	Symbol	Site	Potato	Maize	Wheat	Barley	Bean
Earliest sowing date	DOY_1	Andahuaylas	289	289	320	320	289
		Chalhuanca	320	–	289	320	–
		Cay Cay	294	259	–	–	294
		Sicuani	294	259	275	320	259
		Yauri	–	–	–	306	–
Latest sowing date	DOY_2	Andahuaylas	320	320	350	350	320
		Chalhuanca	350	–	320	350	–
		Cay Cay	325	289	–	–	325
		Sicuani	325	289	304	350	289
		Yauri	–	–	–	335	–
Minimum precipitation amount for sowing	P_{so} (mm)	Andahuaylas	12	9	10	10	10
		Chalhuanca	10	–	10	10	–
		Cay Cay	7	6	–	–	7
		Sicuani	11	6	6	10	6
		Yauri	–	–	–	10	
Minimum number of consecutive wet days for sowing	N_{so} (days)	all sites	3	3	3	3	3
Thermal time for							
Initial stage	GDD_1 (°C)		230	100	210	180	160
Development stage	GDD_2 (°C)		510	540	690	750	510
Mid-season stage	GDD_3 (°C)		200	535	650	500	170
Late season stage	GDD_4 (°C)		350	650	110	90	800
To maturity	GDD (°C)		1,290	1,825	1,660	1,520	1,640
Temperature base	T_b (°C)		2	6	0	0	1
Total available water							
Minimun value	TAW_n	all sites	10	10	10	10	10
Maximun value	TAW_x	Andahuaylas	50	50	40	40	60
		Chalhuanca	60	–	40	40	–
		Cay Cay	60	60	–	–	60
		Sicuani	60	60	40	40	60
		Yauri	–	–	–	40	–
Yield response factor	K_y		1.1	1.25	1.05	1.05	1.15
Crop coefficient							
Initial stage	K_{c1}		0.4	0.4	0.4	0.4	0.50
Mid-season stage	K_{c2}		1.15	1.15	1.15	1.1	1.15
Late season stage	K_{c3}		0.75	1.05	0.3	0.9	1.10

A dash indicates that the given crop is not cultivated at the given location

Lhomme et al. (2009), the latter is determined by solving the soil moisture balance of a single soil layer representing the bulk of the rooting zone. Details can be found in Sanabria and Lhomme (2013).

- Computation of the relative yield deficit. In a final step, the relative yield deficit is calculated on the basis of the crop-water production function described by Doorenbos and Kassam (1979). For the purpose at hand, the function can be put in the following form:

$$1 - \frac{Y_a}{Y_m} = K_y\left(1 - \frac{\sum ET_a}{\sum ET_c}\right) \tag{4}$$

Here, Y_m and Y_a are the potential and actual yield, K_y is the yield response factor and summation of ET_a, and ET_c, is carried out over the four developmental stages.

Model parameters and ancillary data

Values of all relevant model parameters can be found in Table 1. For potato and maize, base temperature and growing degree day thresholds (T_b and GDD_1, GDD_2, GDD_3, GDD_4 and GDD, respectively) were specified based on data collected by SENAMHI in field experiments conducted in the Department of Puno and Apurímac between 2000 and 2008. Base temperature and growing degree day thresholds for bean were inferred from those published by Confalone et al. (2010), while they were specified following Miller et al. (2001) and Bauer et al. (1993) for barley and wheat, respectively.

Concerning the potential sowing window, earliest and latest planting dates (DOY_1 and DOY_2 in Table 1) were estimated using unpublished data by SENAMHI and the agricultural calendar available from the Ministry of Agriculture (MINAG 2013b). Taking into account that our projections refer to the 2030s, the same potential sowing window was assumed for both the baseline period (1990–2009) and for the future time window (2020–2039).

Values of P_{so} and N_{so} were specified based on the literature (Stern et al. 1982; Sivakumar 1988) and previous studies from Peru (Alarcón Velazco 1991) and Bolivia (Garcia et al. 2007). In addition, we conducted a sensitivity analysis with daily rainfall data for each the five study locations. The results (not shown) indicated that increasing N_{so} to 5 or 10 days (cf. Sanabria and Lhomme 2013) would lead to an unrealistically high rate of planting failure. Setting N_{so} top 3 days (Table 1) for all crops can therefore be considered as a practical compromise.

Minimum and maximum water storing capacity of the soil (TAW_n and TAW_x in Table 1) were defined on the basis of estimates obtained from the analysis of a series of soil profiles sampled by SENAMHI in Cusco and Apurímac (unpubl. data), of which 7 were collected in Chahuanca, 6 in Andahuaylas, 9 in Cay Cay, 8 in Sicuani and 15 in Yauri. These estimates are consistent with the soil properties published by IGN (1989) and MINAG (2013c).

Finally, values of the crop coefficient for the initial, mid-season and late season stages of development (Kc_1, Kc_2 and Kc_3, respectively) were specified according to Doorenbos and Kassam (1979).

Results

Present and future climate

The precipitation regime of the study region is characterized by distinct wet and dry seasons, with the former broadly corresponding to the months of October–April and the latter corresponding to the months of May–September (Fig. 2. See also Garreaud 2009). An increase in monthly amounts with altitude is suggested by the stations' data in January, February and March (Fig. 2).

At the regional scale, temperature in Cusco is on average higher than in Apurímac. The annual cycle of temperature at higher elevations has a larger amplitude, as revealed by comparing the curves for Cay Cay, Sicuani and Yauri in Fig. 2. Accordingly, the difference in monthly mean temperature between austral summer and winter is of only a few °C at Andahuaylas, Chalhuanca and Cay Cay, but is close or slightly exceeds 5 °C at Sicuani and Yauri.

Growing season ET_0 is higher at Yauri and Sicuani than at Cay Cay. Otherwise, the annual course of ET_0 follows the progression of temperature and solar radiation, with minimum values during the austral winter (June, July and August) and maximum values during austral summer (December, January and February).

Changes in monthly temperature and precipitation simulated individually by WRF 3.2 and MRI/JMA are plotted in Figs. 3 and 4. As can be seen from these figures, for temperature there is a good agreement between the results of the two climate model experiments, with a warming of about 1 °C in austral summer and slightly exceeding 1 °C in autumn and early winter. Systematic differences of the order of 0.5–1 °C are nevertheless apparent at Sicuani, with WRF 3.2 projecting a significantly stronger increase in temperature than MRI/JMA.

Concerning precipitation, relative changes projected for the rainy season at Andahuaylas, Chalhuanca, Cay Cay and Sicuani are comparatively small in both scenarios. More pronounced negative changes are simulated for Yauri (a location in the south of Cusco) by WRF 3.2, but not MRI/JMA.

Changes in monthly temperature, precipitation and reference evapotranspiration obtained from averaging the outputs of WRF 3.2 and MRI/JMA are presented in Table 2 and illustrated in Fig. 2. In this average scenario, annual mean temperature is projected to increase from +0.9 °C at Sicuani to +1.3 °C at Andahuaylas and Yauri. The increase is more distinct with respect to the dry season (June through October) than regarding the rain season (December through April), and more pronounced for minimum temperature than for maximum temperature. At first sight, the greater increase in minimum temperature could be interpreted as a sign that the risk of frost is likely to decrease in the future. However, as the appearance of frost damages in crops is a complex problem, this issue needs to be examined more thoroughly with appropriate tools (e.g., Lhomme and Vacher 2002), crop specific indicators (Snyder and de Melu-Abreu 2005) and taking into account processes by which crops such as wheat can potentially become more tolerant to the effects of freezing (e.g., Forbes and Watson 1992).

Changes in precipitation are geographically more diverse, as already noticed. For Andahuaylas, Chalhuanca and Cay Cay, i.e., the three stations located at lower altitudes, changes during the rainy season are small and positive. For Yauri and Sicuani, mean changes are negative throughout the year.

Finally, scenarios relative to the reference evapotranspiration are again coherent across sites, with more

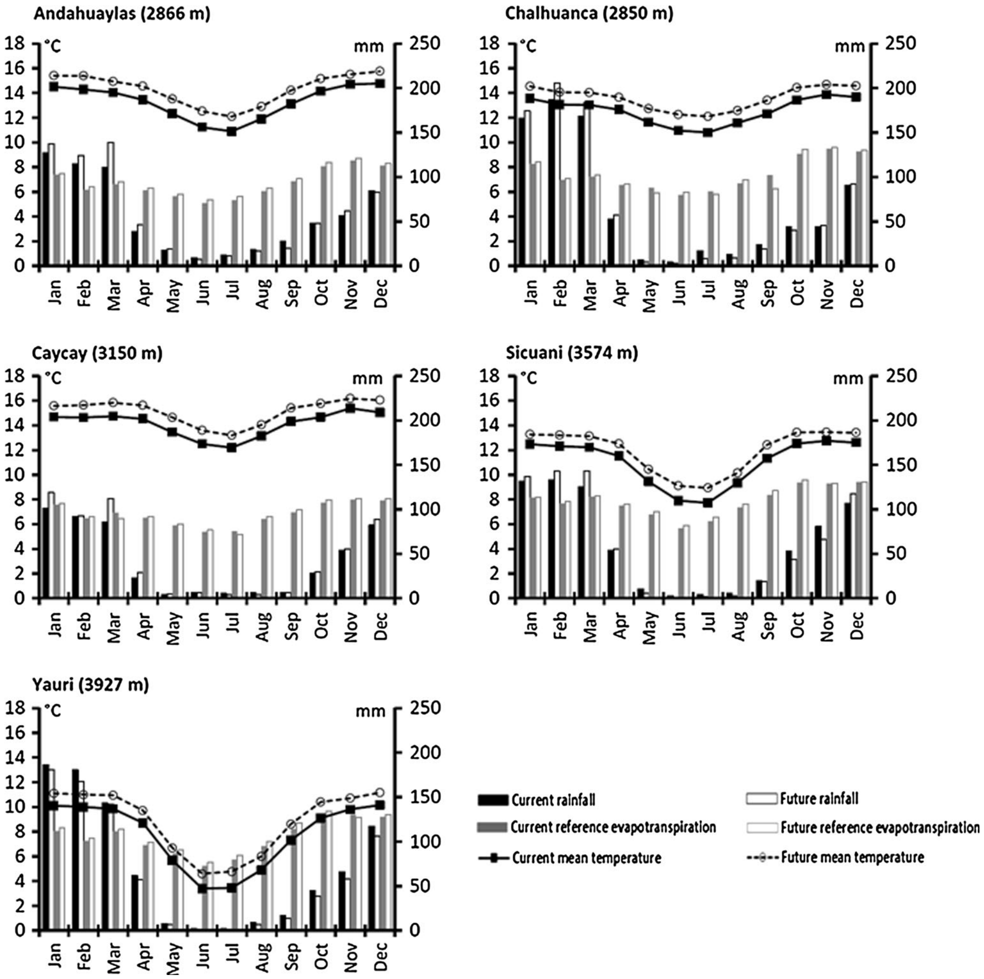


Fig. 2 Seasonal course of temperature (*lines*), precipitation (*black bars*) and reference evapotranspiration (*gray bars*) at (*top* to *bottom*, *left* to *right*) Andahuaylas, Chalhuanca, Cay Cay, Sicuani and Yauri, under present (1981–2010, continuous *lines* and *full bars*) and future climatic conditions (2016–2045, *dashed lines* and *empty bars*)

moderate shifts of between +0 and +3 % during December to March and more pronounced shifts of +3 to +6 % during June to September.

Potential impacts on crops

Crop model outputs relative to crop establishment, development and yield are summarized in Table 3. Several features are worth noting. There is little difference in planting dates between baseline period and future scenario except for slight, but not significant shifts found for a few crops at Sicuani. In view of a similar temperature increase at all sites (~ +1 °C during the crop season), earlier maturity dates are simulated for the scenario at all sites and for all crops.

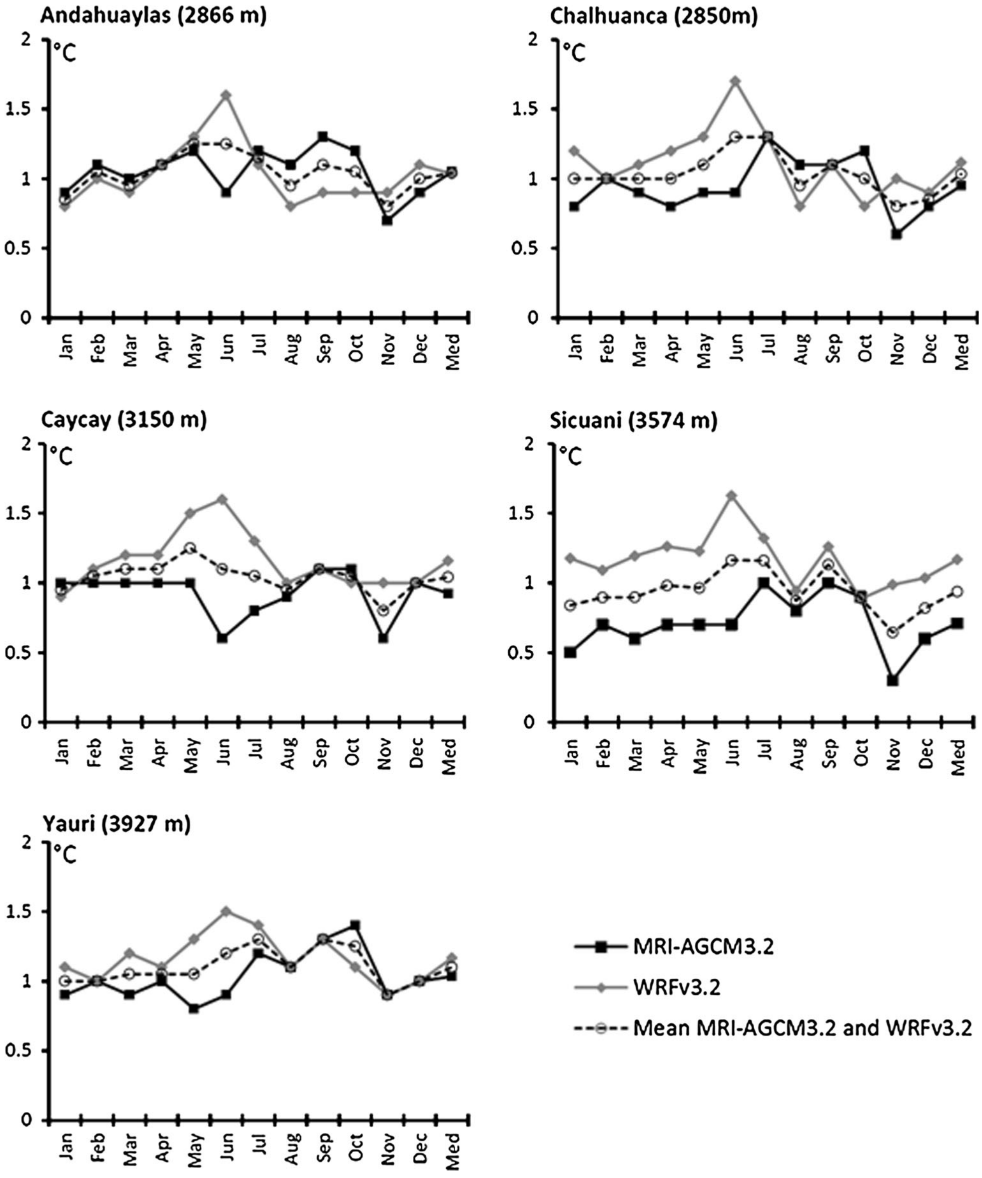
The percentage of years for which the conditions required for crop establishment at sowing are not fulfilled varies considerably across sites and crops. Crops such as potato, with relatively high water requirements during the initial stage of development, display higher planting failure rates than more tolerant crops already under current conditions. Since average changes in monthly precipitation amounts projected for September and October are only minimal, planting failure rates simulated under future conditions are comparable those simulated for present-day climate.

Relative yield deficits are appreciable already under current climatic conditions at all sites, ranging between 10 and 35 %, 30 and 50 %, 10 and 25 %, 10 and 15 % and 30 and 40 % for potato, maize, wheat, barley and bean, respectively. For all sites, yield deficits simulated under future climatic conditions are only marginally higher than those simulated under baseline conditions.

Discussion

The potential impacts of changes in temperature and precipitation on rainfed crop production in Cusco and Apurímac were assessed on the basis of a new set of climate change scenarios valid for 2020–2039. As already mentioned, the time frame of our scenarios differs considerably from the late twenty-first century time horizon targeted in previous studies (e.g., Urrutia and Vuille 2009; Sanabria

Fig. 3 Changes in temperature for (top to bottom, left to right) Andahuaylas, Chalhuanca, Cay Cay, Sicuani and Yauri as simulated individually by WRF 3.2 (*gray diamonds* and *lines*), MRI/JMA (*black squares* and *lines*) and as an average of the two sets (*empty circles* and *dashed lines*). Shown is the absolute difference in monthly mean temperature between 2020–2039 and 1990–2009

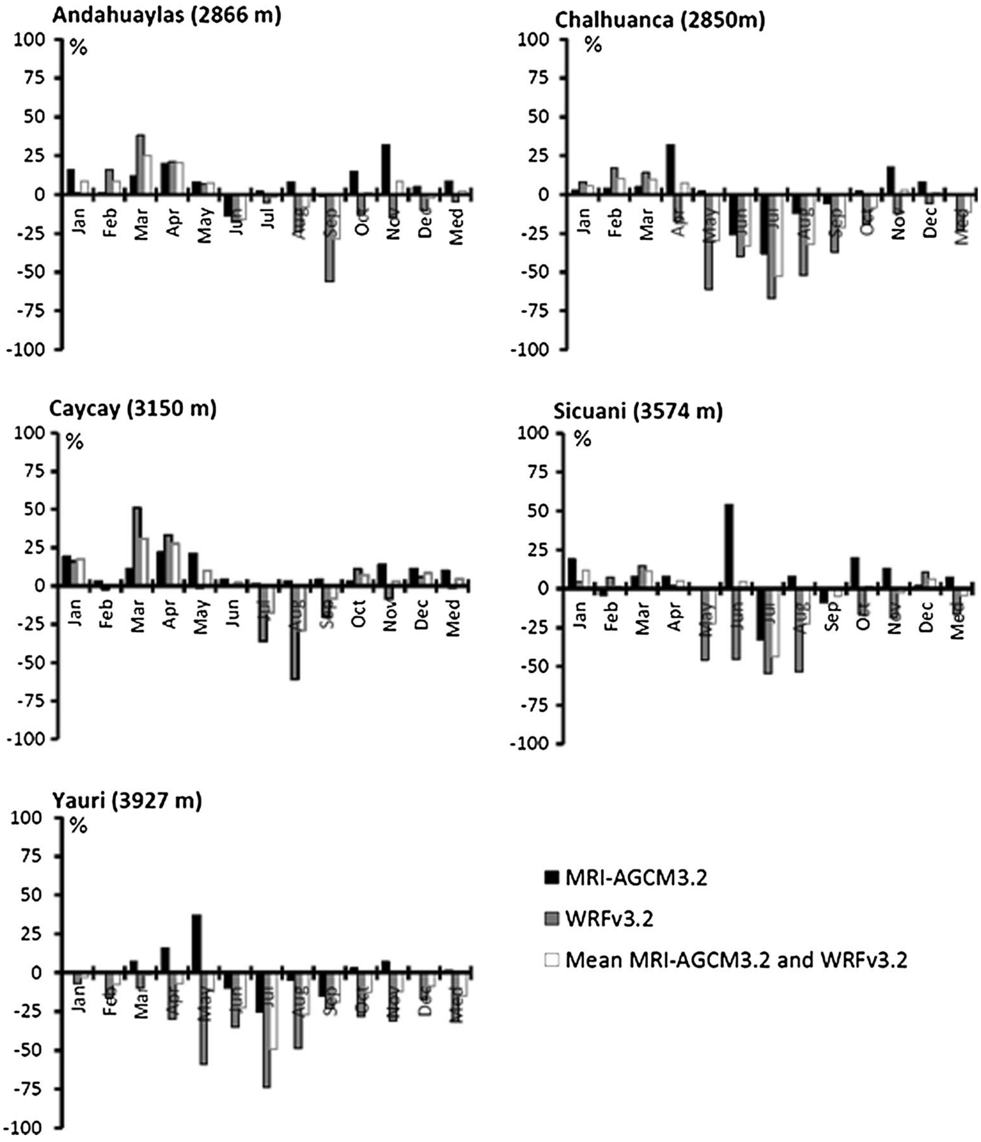


and Lhomme 2013) and implies overall weaker impacts than disclosed in earlier assessments. As a rule, on the time scale considered in our study, the only appreciable impacts are those related to the changes in temperature, i.e., earlier maturity dates and shorter crop cycles.

On the other hand, the slightly higher risk of planting failure found for Sicuani in relation to potato and wheat could be taken as a sign that changes in precipitation patterns can become of concern already in the near future, at least on a regional level. Unfortunately, the precipitation scenarios available for our study (Acuña et al. 2012) only included changes in mean monthly amounts and did not address changes in the frequency of rainy days. In our approach, the latter is the crucial piece of information for the determination of the onset of the rainy season, implying that more detailed scenarios are needed to more firmly examine the impacts of changes in the precipitation regime. In practice, resolving the climate change signal on a daily basis could have been tackled with more sophisticated approaches to downscaling (Wilby et al. 2009), but this was beyond the goals set for the present study by the Program on Climate Change and Adaptation in Peru (PACC).

Regarding precipitation, we noticed that the information available from the two climate change scenarios considered for this study was not always coherent. In relation to temperature, the differences in projected changes appear to be systematic, with MRI/JMA suggesting a smaller temperature increase than WRF 3.2, which could be due to increased cloudiness or other factors. In any case, as impacts on crops were assessed only with respect to a mean scenario, care is needed in interpreting the results. In

Fig. 4 Same as Fig. 3 but for the relative change in precipitation. Shown with *gray bars* are the projections from WRF 3.2 experiment, in *black* those from the MRI/JMA experiment, and with *empty bars* the average of the two sets



general, high uncertainty levels and large differences between individual scenarios are recurrent features in compilations of climate change projections for the Andean region (cf Boulanger et al. 2010; Solman 2013; Solman et al. 2013), which points to the necessity to deal more comprehensively with this issue in extensions of the present work.

Other shortcomings are evident in the setup adopted for the present study. For instance, we only took into account changes in the long-term mean climatic constraints, disregarding possible changes in climate variability. However, knowledge of changes in inter-annual variability is essential in the context of risk analysis (Sivakumar and Motha 2007). This goes along with a better understanding of those aspects of the large-scale atmospheric circulation that ultimately shape the precipitation regime of the Peruvian highlands (cf. e.g., Garreaud and Aceituno 2001; Garreaud 2009; Acuña et al. 2012; Thibeault et al. 2012).

To improve the current level of understanding, a better hold on the possible role played by the ENSO is necessary (Jarvis et al. 2011). There is no doubt that the influence of ENSO on agriculture is of concern for many countries of Latin America. For Peru as a whole, 17 % of the losses in the agricultural sector recorded in 1998 have been attributed to the 1997–1998 episode (ECLAC 2010). Earlier investigations have proposed that the precipitation regime of the Central Andes of Peru is only weakly controlled by the ENSO (Lagos et al. 2008) but this conclusion remains to be verified.

From a modeling perspective, a recent examination of the performance of the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al. 2012) models over tropical South America has shown that about half of the

Table 2 Monthly climate change factors for daily mean (ΔT), minimum (ΔT_{min}) and maximum (ΔT_{max}) temperature, precipitation (ΔP) and reference evapotranspiration (ΔET_0)

Station	Altitude	Variable (units)	January	February	March	April	May	June	July	August	September	October	November	December
Andahuaylas	2,866	ΔT (°C)	*0.9*	*1.1*	*0.9*	*1.1*	1.2	1.3	1.2	1.0	1.1	*1.0*	*0.8*	*1.0*
		ΔT_{min} (°C)	*1.1*	*1.0*	*1.0*	*1.1*	1.4	1.2	1.1	0.9	1.1	*0.9*	*0.9*	*1.1*
		ΔT_{max} (°C)	*0.6*	*1.1*	*0.9*	*1.0*	1.1	1.4	1.3	1.1	1.0	*1.1*	*0.7*	*0.9*
		ΔP (%)	*8*	*8*	*25*	*20*	7	−16	−2	−8	−28	*1*	*9*	*−2*
		ΔET_{o} (%)	*1*	*4*	*3*	*3*	3	5	5	4	3	*4*	*2*	*2*
Chalhuanca	2,850	ΔT (°C)	*1.0*	*1.0*	*1.0*	*1.0*	1.1	1.3	1.3	1.0	1.1	*1.0*	*0.8*	*0.9*
		ΔT_{min} (°C)	*1.2*	*1.2*	*1.2*	*1.3*	1.3	1.4	1.2	0.9	1.1	*0.9*	*1.0*	*1.2*
		ΔT_{max} (°C)	*0.8*	*0.8*	*0.8*	*0.7*	0.9	1.2	1.4	1.0	1.1	*1.1*	*0.6*	*0.5*
		ΔP (%)	*5*	*10*	*9*	*8*	−29	−33	−52	−32	−21	*−9*	*3*	*1*
		ΔET_{o} (%)	*2*	*2*	*2*	*1*	3	4	5	4	4	*4*	*1*	*1*
Cay Cay	3,150	ΔT (°C)	*0.9*	*1.0*	*1.1*	*1.1*	1.2	1.1	1.0	0.9	1.1	*1.1*	*0.8*	*1.0*
		ΔT_{min} (°C)	*1.1*	*1.1*	*1.2*	*1.3*	1.6	1.2	1.1	0.8	1.2	*1.0*	*1.0*	*1.1*
		ΔT_{max} (°C)	*0.7*	*0.9*	*0.9*	*0.9*	0.9	0.9	0.9	1.0	1.0	*1.1*	*0.6*	*0.9*
		ΔP (%)	*17*	*0.4*	*31*	*27*	10	2	−18	−29	−8	*7*	*3*	*8*
		ΔET_{o} (%)	*1*	*2*	*2*	*2*	2	3	3	3	3	*3*	*1*	*2*
Sicuani	3,547	ΔT (°C)	*0.8*	*0.9*	*0.9*	*1.0*	1.0	1.2	1.2	0.8	1.1	*0.9*	*0.7*	*0.8*
		ΔT_{min} (°C)	*1.1*	*1.0*	*1.1*	*1.2*	1.1	1.2	1.1	0.9	1.1	*1.0*	*0.9*	*1.2*
		ΔT_{max} (°C)	*0.5*	*0.7*	*0.6*	*0.8*	0.8	1.1	1.2	0.8	1.1	*0.8*	*0.4*	*0.5*
		ΔP (%)	*11*	*2*	*11*	*5*	−22	4	−44	−23	−4	*2*	*−2*	*6*
		ΔET_{o} (%)	*0*	*2*	*1*	*2*	3	4	5	3	4	*2*	*0*	*0*
Yauri	3,927	ΔT (°C)	*1.0*	*1.0*	*1.1*	*1.0*	1.0	1.2	1.3	1.1	1.3	*1.3*	*0.9*	*1.0*
		ΔT_{min} (°C)	*1.2*	*1.0*	*1.3*	*1.1*	1.1	1.2	1.3	1.0	1.2	*1.2*	*1.0*	*1.2*
		ΔT_{max} (°C)	*0.9*	*1.0*	*0.9*	*1.0*	0.9	1.2	1.3	1.2	1.4	*1.3*	*0.9*	*0.8*
		ΔP (%)	*−3*	*−7*	*−1*	*−7*	−11	−22	−49	−27	−19	*−13*	*−12*	*−9*
		ΔET_{o} (%)	*3*	*3*	*2*	*3.5*	4	5	6	5	6	*5*	*3*	*2*

For temperature the anomalies are given as an additive factor, for precipitation and reference evapotranspiration as a relative difference (in %). Values represent the arithmetic average of the climate change signals simulated by ECHAM5-OM/WRF 3.2 and MRI/JMA TL959L60, respectively. Values for the average rainy season are italics

Table 3 Results of the crop model simulations for current and future climatic conditions

Crop	Station	Planting time (day of the year)			Harvest time (day of the year)			Crop cycle length (days)			Risk of planting failure (%)			Yield deficit (%)		
		Current	Future	Δ	Current	Future	Δ	Current	Future	Δ	Current	Future	Δ	Current	Future	Δ
Potato	Andahuaylas	298	298	*0*	24	18	*−6*	91	85	*−6*	5	5	*0*	29	31	*2*
	Chalhuanca	331	331	*0*	64	58	*−6*	98	92	*−6*	5	5	*0*	9	9	*0*
	Cay Cay	303	303	*0*	26	21	*−5*	88	83	*−5*	16	16	*0*	34	32	*−2*
	Sicuani	299	302	*−3*	45	35	*−10*	111	98	*−13*	0	5	*5*	17	16	*−1*
	Yauri	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Maize	Andahuaylas	297	297	*0*	59	51	*−8*	127	119	*−8*	0	0	*0*	30	30	*0*
	Chalhuanca	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Cay Cay	277	276	*−1*	36	28	*−8*	124	117	*−7*	21	21	*0*	51	50	*−1*
	Sicuani	272	272	*0*	54	45	*−9*	147	139	*−8*	5	5	*0*	35	32	*−3*
	Yauri	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wheat	Andahuaylas	327	326	*−1*	79	73	*−6*	117	112	*−5*	0	0	*0*	11	15	*4*
	Chalhuanca	300	300	*0*	69	51	*−18*	134	116	*−18*	11	16	*5*	26	29	*3*
	Cay Cay	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Sicuani	284	289	*−5*	53	49	*−4*	134	126	*−8*	5	11	*6*	22	21	*−1*
	Yauri	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Barley	Andahuaylas	327	326	*−1*	69	59	*−10*	107	98	*−9*	0	0	*0*	11	14	*3*
	Chalhuanca	331	331	*0*	82	74	*−8*	116	108	*−8*	5	5	*0*	8	8	*0*
	Cay Cay	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Sicuani	325	328	*−3*	84	77	*−7*	124	114	*−10*	0	0	*0*	9	7	*−2*
	Yauri	314	314		104	89	*−15*	155	140	*−15*	0	0	*0*	14	14	*0*
Bean	Andahuaylas	298	298	*0*	47	41	*−6*	114	108	*−6*	0	0	*0*	30	31	*1*
	Chalhuanca	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Cay Cay	303	303	*0*	50	43	*−7*	112	105	*−7*	16	16	*0*	38	36	*−2*
	Sicuani	272	272	*0*	39	31	*−8*	132	125	*−7*	5	5	*0*	35	35	*0*
	Yauri	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Changes (Δ) are italics. All numbers are multi-year average dates, number of days or rates (mean values for 1990–2009 in the baseline and for 2020–2039 in the scenario). A dash indicates that the given crop is not cultivated at the given location models tend to overrate the influence of teleconnections on precipitation (Yin et al. 2013). In general, the capability of current climate models to simulate the ENSO should undergo close scrutiny. This is important given that there is still considerable uncertainty concerning the ability of current climate models to simulate the response of ENSO to global warming (Latif and Keenlyside 2009).

With regard to crop modeling, in our study potential, impacts of changes in temperature and precipitation were addressed with the help a simple model that manifestly cannot offer the same capabilities as more sophisticated tools such CropSyst (Stöckle et al. 2003), DSSAT (Decision Support System for Agrotechnology Transfer; Jones et al. 2003) or APSIM (Agriculture Production System Simulator; Keating et al. 2003). Apart from the fact that even complex models are probably not up to the task in many respects (cf. e.g., Rötter et al. 2011; AgMIP 2013), the question of whether a simple model can capture the reality of crop farming in terms of environmental constraints and management remains a pertinent one.

In our case, the choice of a simple model was primarily motivated by (a) the lack of detailed data that would have been needed for the setup, calibration and verification of more sophisticated tools, (b) the fact that in the study area agriculture is still largely practiced without technical assistance (INEI 2013b), and (c) the fact that adoption of the FAO methodology has proven very useful in studies addressing similar questions in a comparable geographic context (e.g., Garcia et al. 2007; Geerts et al. 2009).

Our assessment neglected the direct and indirect effects of increased atmospheric CO_2 concentrations on crop growth and yield. It is well known that crops can benefit from increased CO_2 concentrations both from increased assimilation and from improved water use efficiency (Larcher 2003; Vanuytrecht et al. 2012). Depending on emission scenario, atmospheric CO_2 concentrations are expected to reach between 450 and 650 ppm by 2040–2050 (IPCC 2001; van Vuuren et al. 2011). For this range of CO_2 concentrations, water productivity is expected to improve by perhaps 15 to 20 % as a result of increase in biomass production and decrease in seasonal evapotranspiration (Vanuytrecht et al. 2012). Model extensions to include the direct and indirect effects of increased atmospheric CO_2 concentrations should therefore be addressed with priority in the future.

Conclusions

Agriculture in the highlands of Peru is considerably exposed to climate variability and change, and this is of concern for a rural population that is already afflicted by poverty. In the present investigation, we showed that for the near future the consequences of climate change on crop production could be limited and manageable provided that shifts in precipitation patterns during the rainy season are small, as suggested by the two scenarios used for the analysis. In view of the various limitations of the current approach, this conclusion remains to be verified. Clearly, a more comprehensive analysis based on an improved database (in terms of both climatic data and agricultural information), a larger number of climate change projections, spatially explicit scenarios and scenarios addressing changes in the rainfall characteristics at the daily scale (duration of wet and dry spells, transition probabilities, daily precipitation intensity) is required to develop a minimal scientific baseline for informing adaptation.

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