The Effect of Climate Change on Global Potato Production

Robert J. Hijmans

International Potato Center (CIP), Apartado 1558, La Molina, Lima 12, Peru.
Email: rhijmans@uclink.berkeley.edu

ABSTRACT

The effect of climate change on global potato production was assessed. Potential yields were calculated with a simulation model and a grid with monthly climate data for current (1961-1990) and projected (2010-2039 and 2040-2069) conditions. The results were mapped and summarized for countries. Between 1961-1990 and 2040-2069 the global (terrestrial excluding Antarctica) average temperature is predicted to increase between 2.1 and 3.2 C, depending on the climate scenario. The temperature increase is smaller when changes are weighted by the potato area and particularly when adaptation of planting time and cultivars is considered (a predicted temperature increase between 1 and 1.4 C). For this period, global potential potato yield decreases by 18% to 32% (without adaptation) and by 9% to 18% (with adaptation). At high latitudes, global warming will likely lead to changes in the time of planting, the use of later-maturing cultivars, and a shift of the location of potato production. In many of these regions, changes in potato yield are likely to be relatively small, and sometimes positive. Shifting planting time or location is less feasible at lower latitudes, and in these regions global warming could have a strong negative effect on potato production. It is shown that heat-tolerant potato cultivars could be used to mitigate effects of global warming in (sub)tropical regions.

RESUMEN

Se estudió el efecto del cambio climático en la producción global de la patata. Los rendimientos potenciales fueron calculados con un modelo de simulación y una rejilla con datos mensuales de clima para las condiciones actuales (1961-1990) y proyectadas (2010-2039 y 2040-2069). Los resultados fueron presentados en mapas y resumidos por países. Se predice que entre 1961-1990 y 2040-2069 la temperatura media global (en áreas terrestres excepto la Antártica) aumentará entre 2.1 y 3.2 C, dependiendo del escenario climático. El aumento de la temperatura es más pequeño cuando los cambios son ponderados con el área del cultivo de la patata y particularmente cuando se considera la adaptación de la época de siembra y de los cultivares (se predice un aumento de la temperatura entre 1 y 1.4 C). En este período, la producción potencial global de la patata disminuye de 18% al 32% (sin adaptación) y de 9% al 18% (con adaptación). En latitudes mayores, el calentamiento global podría conducir a cambios en la época de siembra, el uso de cultivares más tardíos, y cambio de los lugares donde se produce patata. En muchas de estas regiones, los cambios en la producción de la patata serían relativamente pequeños, y a veces positivo. Los cambios en la época de siembra o de los lugares de producción son menos factibles en latitudes más bajas, en estas regiones el calentamiento global podría tener un fuerte efecto negativo en la producción de la patata. Se muestra que se podrían utilizar cultivares con tolerancia al calor para atenuar el efecto del calentamiento global en regiones (sub)tropicales.

INTRODUCTION

It is likely that the currently observed trend of global warming, which has been 0.6 C ± 0.2 since 1900, will continue and that the average global temperature will increase by between 1.4 and 5.8 C over the period 1990 to 2100 (Houghton et al. 2001). The impact of this type of climate change will probably lead to a decrease in crop productivity, but with important differences between regions (Rosenzweig and Liverman 1992; McCarthy et al. 2001).

Accepted for publication 17 April 2003.
ADDITIONAL KEY WORDS: Adaptation, heat tolerance, geographic information systems, GIS, potential yield, simulation, *Solanum tuberosum*.

The effects of climate change on crop production can be complex. Depending on the temperature regime and the crop, high temperatures can lead to low yields due to increased development rates and higher respiration. However, a short growth cycle can also be beneficial, e.g., to escape drought or frost, and the use of late-maturing cultivars could offset the effect of high development rates. In environments where low temperatures now limit production, global warming could lead to a beneficial lengthening of the growing season and temperatures close to optimal for assimilation. Moreover, global warming is related to the increase of atmospheric CO_2 concentration, which is likely to increase crop yields, particularly when water limits crop production (Nonhebel 1993).

Potato is grown in many different environments, but it is best adapted to temperate climates (Haverkort 1990). At high temperatures (above 17 C; Stol et al. 1991) tuberization diminishes (Reynolds and Ewing 1989a). Potato is also frost sensitive, and severe damage may occur when temperature drops below 0 C (Hijmans et al. 2003). Various authors have used simulation models to study the effect of global warming on potato production. Higher temperatures are predicted to increase potato yields in England and Wales (Davies et al. 1996), Scotland (Peiris et al. 1996) and Finland (Carter et al. 1996), primarily because of a longer growing season. However, an overall yield decrease was predicted for the USA (Rosenzweig et al. 1996).

All these studies on potato were conducted for small regions at high latitudes and their results are difficult to extrapolate to other regions. In this paper, some of the possible effects of climate change on potato production are studied at the global level. A simulation model was used to calculate potential potato yield for the current climate and for projected future climates in 2010-2039 and 2040-2069, using seven climate scenarios from five different climate models. The goal of the paper is to identify regions where there is likely to be a strong decline in productivity due to the increase in temperature, and to determine the extent to which heat-tolerant potato cultivars would be useful to mitigate the effect of climate change in those regions. Only the effect of changes in temperature and solar radiation was considered and not the effect of changes in rainfall, of increased levels of atmospheric CO_2, or of increased ultraviolet radiation. The results are presented in relation to the current global distribution of the potato crop.

MATERIALS AND METHODS

Climate Data

Average monthly climate data for 1961-1990 (hereinafter referred to as "current climate"), and for climate change from that period to 2010-2039 and to 2040-2069 were used. For the current climate, data from New et al. (1999) were used; for the

TABLE 1—*Climate scenarios used in this study*[1].

Scenario	Institute	Code	Forcing details[2]	Original resolution in degrees	Solar radiation[3]	Min. and max. temperature
I	Canadian Centre for Climate Modelling and Analysis	CGCM1[4]	GS	3.75 x 3.75	Yes	Yes
II	Australian Commonwealth Scientific and Industrial Research Organisation	CSIRO-Mk2	GG	5.625 x 3.214	Yes	Yes
III	Australian Commonwealth Scientific and Industrial Research Organisation	CSIRO-Mk2	GS	5.625 x 3.214	Yes	Yes
IV	German Climate Research Centre	ECHAM4	GG	2.8125 x 2.8125	Yes	Yes
V	US Geophysical Fluid Dynamics Laboratory	GFDL-R15	GS	7.5 x 4.5	Yes	No
VI	UK Hadley Centre for Climate Prediction and Research	HadCM2 (4)	GG	3.75 x 2.75	No	Yes
VII	UK Hadley Centre for Climate Prediction and Research	HadCM2 (4)	GS	3.75 x 2.75	No	Yes

[1]Data supplied by the Intergovernmental Panel on Climate Change Data Distribution Center (1999)

[2]Climate change model forcing details: GG = Greenhouse Gas; GS = Greenhouse Gas and Aerosols. All scenarios used assume an increase of 1% atmospheric CO_2 per annum (IS092a).

[3]Yes – data were present; No – data were absent. If solar radiation data were absent these were calculated from extraterrestrial radiation and cloud cover. If minimum and maximum temperature were absent these were calculated from mean temperature (see text). Parameters for these calculations were taken from the current climate in a grid cell.

[4]Mean of four ensembles (identical model experiments performed with the same historical changes and future changes in greenhouse gases, but initiated from different points on the control run).

projected future climate, seven scenarios from five climate models were used (Table 1). The projected change in climate was superimposed on the current climate to create projected climate surfaces for 2010-2039 and 2040-2069 (further refereed to as 2010-39 and 2040-69, respectively). Daily temperature and radiation data were derived by linear interpolation between the monthly averages. All datasets were resampled (statistically disaggregated by interpolation) to a 1 by 1 degree resolution, using IDRISI software (Clark Labs, Worcester, MA, USA) (the data for the current climate were available at a 0.5 by 0.5 degree resolution and were aggregated).

Global average temperatures for the current climate and for all scenarios were calculated for terrestrial cells only (16,862 cells), without considering Antarctica, taking the size of each square degree grid cell into account (the size of the one square degree cells decreases with increasing latitude).

Simulation Model

The LINTUL simulation model as described by Stol et al. (1991) and Van Keulen and Stol (1995) was used to calculate potential yield. The model has a temperature-dependent development of the canopy (green ground cover). Biomass production is the product of the fraction green ground cover, incident solar radiation and radiation use efficiency.

Stol et al. (1991) estimated tuber yield as a temperature-dependent percentage of the total biomass accumulated during the growing season. In this study, however, the relative allocation of biomass to tubers was calculated on a daily basis. Relative allocation to the tubers is initially 0%. After a thermal time threshold is reached, relative allocation starts increasing linearly with thermal time until the next threshold after which 100% of new biomass goes to the tubers. The values of these parameters were estimated so that harvest index of a mature crop is 80% under normal circumstances (no frost or heat stress), as in the original model. This procedure avoids overestimating yield for a crop with prematurely killed foliage due to frost, or for a crop for which the end of the growing season is very warm, and hence has a lower harvest index than would be expected from the average temperature during the growing season. The absolute allocation of biomass to the tubers is also dependent on daily average temperature: it decreases above 15 C and becomes zero at an average temperature above 28 C (Stol et al. 1991). A heat-tolerant potato cultivar was defined by shifting this curve two degrees.

In the adapted model, radiation use efficiency (RUE) was made dependent on daily average temperature, following Kooman (1995) and Kooman and Haverkort (1995). RUE is highest (2.9 g MJ^{-1} (PAR)) between 15 and 21 C and zero below 2 C and above 34 C, with intermediate values in between. Decrease of RUE at high temperatures is due to increasing respiration (Kooman and Haverkort 1995). Radiation (PAR) above 12 MJ (PAR) m^{-2} day^{-1} was not considered, to account for light saturation (Kooman and Haverkort 1995).

For each grid cell, the model was run for 12 planting times (with planting at the first day of each month) and for five maturity classes of potato, representing different cultivars with early to late senescence. This was repeated for the heat-tolerant potato. Maturity classes used were 1000, 1200, 1400, 1600, or 1800 Cd, expressed as the temperature sum (thermal time) between emergence and harvest, with a base temperature of 2 C. The optimal planting time for a location (grid cell) was determined after the simulations, selecting the month/cultivar combination that led to the highest yield. Average temperature during the optimal planting time was calculated for each grid cell. To distinguish between the effect of changes in radiation and in temperature, the model was also run for the projected climate, while using radiation data for the current climate.

Current and projected potential yield were compared for two cases: with and without adaptation. Adaptation is narrowly defined as changes in the month of planting or in the maturity class of the cultivar. This is sometimes referred to as "autonomous adaptation" in the sense that these are inexpensive and can be carried out at the farm level (McCarthy et al. 2001). In the case of "without adaptation," potential yield for projected conditions is calculated for the combination of cultivar and month of planting that gave the highest yield for the current climate. In the case of "with adaptation," the highest yield is taken from the 60 (5 cultivars × 12 months) months of planting/cultivar combinations for the projected climate scenarios. Hence, in this latter case, the month of planting and cultivar type in a location (grid cell) can be different for current and future climates.

Maps and Potato Distribution Data

For each grid cell, the mean potential yield (over all climate scenarios) was compared with the yield as calculated for the current climate. Maps were made of changes in potential yield for the "with adaptation" and "without adaptation" cases for the 2010-39 and the 2040-69. Results were also summarized on maps indicating the potential contribution to yield of heat-tolerant potatoes.

The maps only include data for the current areas with potato production according to a global 1-degree grid described by Hijmans (2001) (7004 cells with potato area; 42% of the global land area excluding Antarctica). These potato distribution data were also used to weigh changes in temperature and yield by potato area. Such potato-area-weighted results were obtained by multiplying the grid of potato area with the grids of current and projected temperature and yield, and dividing these by the total global potato area. Thus, in the aggregate results, the weight of an area (grid cell) with, for example, 10,000 ha of potatoes would be twice that of an area with 5,000 ha. Results were summarized for countries with more than 100,000 ha of potato area. Average change in yield and the percentage of grid cells where climate change would lead to higher yields was calculated for these countries.

RESULTS

Temperature

According to the climate scenarios considered in this study, the increase in global average temperature will be between 1.2 and 1.8 C in the 2010-39 and between 2.1 and 3.2 C in 2040-69 (Figure 1). This increase is higher than the predicted temperature change weighted by potato area, which is between 0.9 and 1.7 C for 2010-39 and between 1.6 and 3.0 C for 2040-69. When no adaptation of cultivar type and month of planting is allowed between current and future conditions, the potato-area-weighted average temperature change during the potato-growing period is only a little lower than the average temperature change over the whole year (averaged over all climate scenarios a difference of 0.1 C for 2010-39 and 0.2 C for 2040-69). When adaptation of the planting time and cultivar choice is allowed, however, average temperature change during the potato-growing period is much lower than change over the whole year: between 0.6 and 1.1 C for 2010-39 and between 1.0 and 1.4 C for 2040-69 (Figure 1).

Yield

When no adaptation is allowed, overall simulated global potato yields decrease between 10% and 19% in 2010-39, and between 18% and 32% in the 2050s (Figure 2). With adaptation, yields still go down but the decrease is about 40% less: between 5% and 11% in 2010-39 and between 9% and 18% in 2040-69. Adaptation typically consists of a shift of one or two months of the planting time and the use of cultivars that have later foliage senescence in terms of thermal time.

These global aggregate data mask differences between regions. Although simulated potato yields decrease in most regions where the crop is currently grown (Figures 3 and 4), the magnitude of change differs sharply between potato produc-

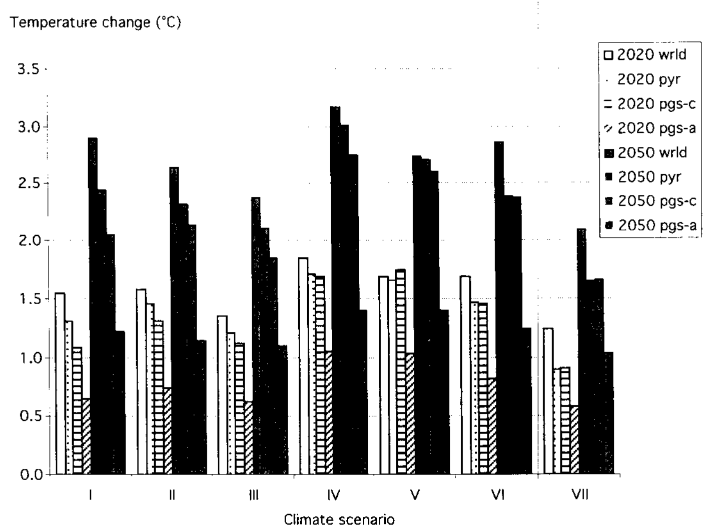

FIGURE 1.
Average projected temperature change in 2010-39 and 2040-69, relative to the current climate, for seven climate scenarios (see Table 1). For the whole year and world (wrld; the terrestrial areas except Antarctica); the whole year weighted by potato area (pyr); during the potato growing season without adaptation (pgs-c); and during the potato growing season with adaptation (pgs-a).

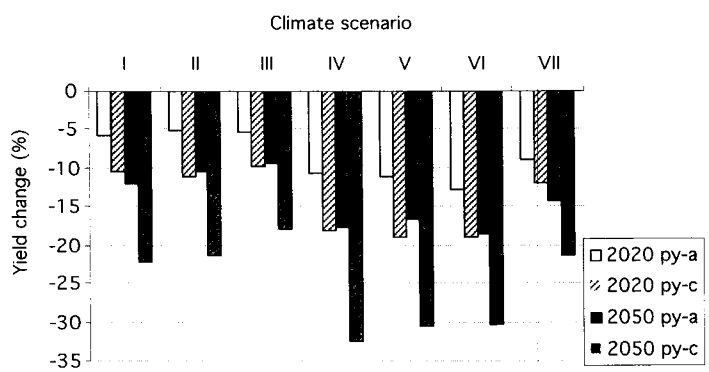

FIGURE 2.
Average change in potential potato yield, weighted by area, for 2010-39 and 2040-69, relative to the current climate, for seven climate scenarios (see Table 1). Without adaptation (py-c); and with adaptation (py-a).

tion regions, and is strongly dependent upon whether adaptation is considered or not (compare Figures 3B and 4A and Figures 3C and 4B). Without adaptation, calculated decrease in potential yield is large (> 25%) for many regions, particularly in 2040-69 (Figure 3C). When adaptation is allowed, the effect on yield is lower, except for regions in the tropics.

Changes in yield can in most cases be attributed to temperature change alone (in 90% of the grid cells, radiation contributed less than 10% of the change in yield). Although in some restricted regions changes in yield are strongly influenced by changes in radiation, sometimes induced by changes in cloudiness, but more often because of a shift in planting time.

The moderating effect of adaptation on the temperature during the growing period, and hence on yield, is illustrated in Figure 4C. In some regions, the temperature during the potato-growing period will likely decrease with global warming! (Because higher temperatures will allow a winter crop). Yet in other regions temperature is projected to increase by more than 2 C.

In general, potato-growing regions in the (sub)tropics will suffer the largest decline of potential potato yield, and there is not much scope for adaptation in these regions. Note, however, that some of the worst hit regions (yield decline > 50%) have only very little potato area (Figure 3A). A region with a large potato area and a strong predicted yield decline is a zone from southeast Europe through Russia and Kazakhstan. The regions where global warming would not be a very serious problem, or might be beneficial for potato yield, are mostly at high latitudes, such as regions in Canada, Russia (Siberia), and Scandinavia, where global warming will result in longer (frost-free) growing periods, or at high altitudes in the tropics, such as in the cold

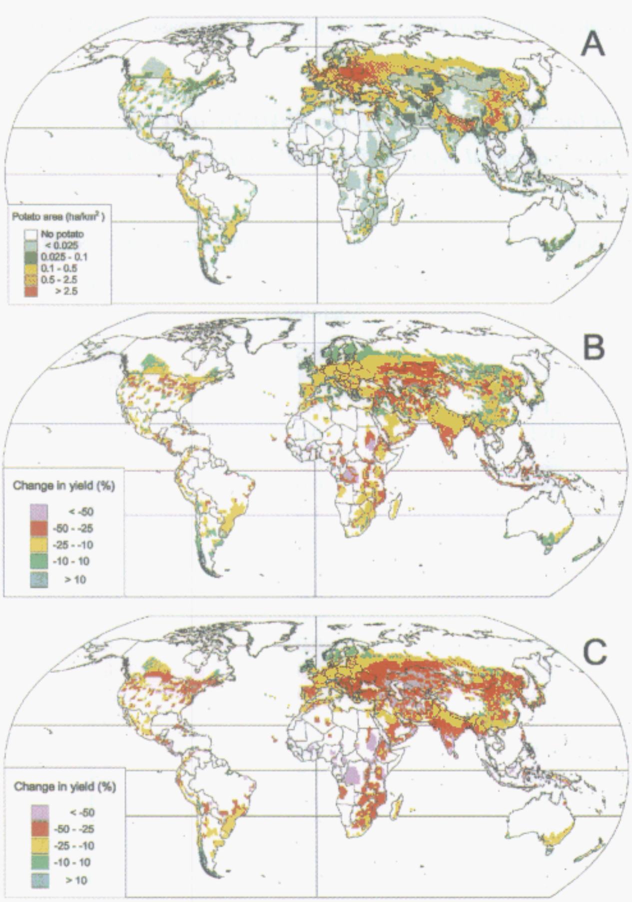

FIGURE 3.
(A) Global potato distribution (source: Hijmans 2001); and average change in potential potato yield due to climate change, without adaptation, for (B) 2010-39 and (C) 2040-69.

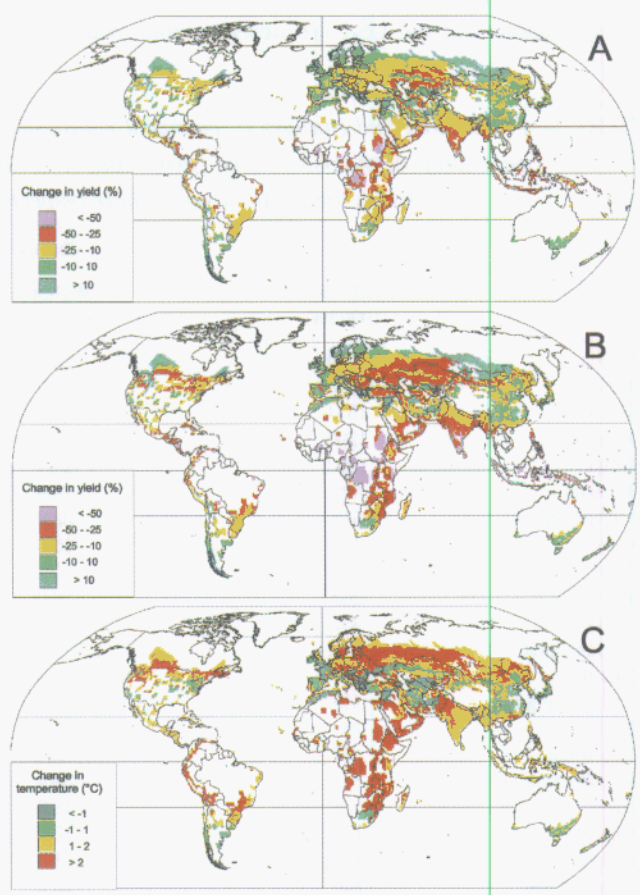

FIGURE 4.
Average changes in potential potato yield due to climate change, with adaptation, for (A) 2010-39 and (B) 2040-69; and (C) predicted temperature change during the growing season, for 1961-90 to 2040-69, with adaptation.

highland region of the Peruvian/Bolivian Altiplano. In these regions there is much land that is currently climatically unsuitable for potato production that will become suitable with global warming. Adaptation is particularly important in parts of southern China where higher temperatures increase the opportunity for winter cropping. These findings are further illustrated by the averages broken down by country (Table 2).

Results by Country

When adaptation is not considered, most of the major potato-producing countries would suffer great losses in potential potato yield. Bolivia is the only country where potential yield would increase without adaptation, and with adaptation it is predicted to increase a staggering 77%. In most other major potato-producing countries, adaptation mitigates a large part of the climate-change-induced yield loss. In Iran, for example, yield loss decreases from –48% to –13%. China, Peru, Russia, and the USA are other notable examples of countries were adaptation could mitigate much of the negative effects of global warming. When considering adaptation, Bangladesh, Brazil, Colombia, and Ukraine have the largest decrease in potential yield (more than 20% in 2040-69). The percentage of area (grid cells) with yield increase (Table 2) reflects the possibility to mitigate the effect of climate change by shifting the location of production within existing potato growing regions. It is particularly high (>30%) in Argentina, Canada, China, Japan, UK, Russia, and Spain.

Heat Tolerance

The current value of increased heat tolerance would be rather small (less then 5% increase in potential yield in most regions), except for some regions in the lowland tropics, with little potato area (Figure 5). However, this situation changes notably with climate change. In 2010-39 and 2040-69 heat tolerance would increase potential yields by more than 5% in most potato production zones. Potential yield increase would be over

TABLE 2—*Potato area and changes in potential potato yield induced by climate change in the 2040-59, and the percentage of the potato area (grid cells) in a country where potential potato yield will increase. Yield changes are weighted by the potato area in their respective grid cells.*

Country	Potato area (1000 ha)	Change in potential yield (%)		Areas with yield increase (% of cells)	
		Without Adaptation	With Adaptation	Without Adaptation	With Adaptation
China	3430	-22.2	-2.5	8.5	30.7
Russia	3289	-24.0	-8.8	12.4	48.4
Ukraine	1534	-30.3	-24.8	0.0	2.7
Poland	1290	-19.0	-16.1	0.0	2.4
India	1253	-23.1	-22.1	0.4	2.0
Belarus	692	-18.8	-16.6	0.0	0.0
United States	548	-32.8	-5.9	1.4	20.1
Germany	300	-19.6	-15.5	0.0	0.0
Peru	263	-5.7	5.8	8.3	13.9
Romania	262	-26.0	-9.9	0.0	19.2
Turkey	207	-36.7	-17.1	0.0	10.4
Netherlands	181	-20.0	-10.9	0.0	0.0
Brazil	177	-23.2	-22.7	0.0	0.0
United Kingdom	169	-6.2	8.1	50.0	57.1
France	168	-18.7	-6.9	4.5	29.9
Colombia	167	-32.5	-30.6	4.5	4.5
Kazakhstan	165	-38.4	-12.4	2.3	9.4
Iran	161	-48.3	-13.3	0.0	21.4
Canada	155	-15.7	4.6	17.9	55.5
Spain	142	-31.4	-6.6	0.0	37.5
Bangladesh	140	-25.8	-24.0	0.0	0.0
Bolivia	131	8.4	76.8	22.6	29.0
Lithuania	126	-13.7	-9.2	0.0	0.0
Argentina	115	-12.9	0.5	11.4	35.2
Nepal	115	-18.3	-13.8	0.0	16.7
Japan	102	-17.4	-0.9	8.8	41.2

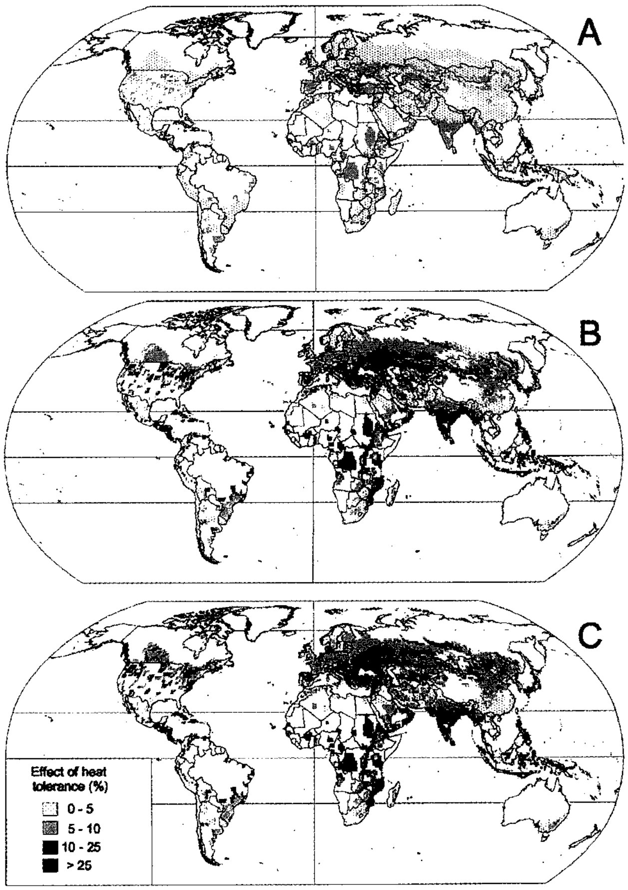

FIGURE 5.
The effect of increased heat tolerance (a 2 C shift in the temperature-tuberization curve) on potential potato yield, for (A) 1961-90, (B) 2010-39, and (C) 2040-69.

10% in many zones, particularly in the tropics, but also in a large stretch in eastern Europe and west Asia, and in parts of the USA and Canada. In these northern regions, both adaptation and heat tolerance would be important to allow for high yields.

DISCUSSION AND CONCLUSIONS

Because of increases in temperature, future potato yields could decrease in many regions. In some regions, mainly in temperate regions, yield decline can partly be avoided through adaptation. Yields may even go up at high latitudes because of a lengthening of the growing season. In some regions, such as in parts of Algeria, Morocco, China, and South Africa, yield may increase because a warmer climate would allow growing a winter crop (instead of an autumn or spring crop).

There is not much scope for adaptation of potato production in the tropics, where there is little temperature variation during the year, and in the warmer parts of the subtropics, where potatoes are already grown in the coolest season. In much of the tropical highlands of Africa, temperature is relatively high and stable throughout the year. In the river plains in India and Bangladesh, potato is a winter crop already grown in the coldest season and climate change might slow the impressive expansion of potatoes in Asia (Walker et al. 1999) that is otherwise expected to continue (Scott et al. 2000). Warm summers can become problematic in many regions with continental climates, such as in Kazakhstan.

The differences between the results obtained when adaptation is taken into account or not, show how there can be important differences between general global climate change and the climate change that a particular crop will experience. These differences were due to adaptation of cultivars and planting time. It should be noted, however, that in practice some of these "autonomous" types of adaptation may be not that straightforward. The planting season of a crop also depends on other factors like other crops (particularly in production systems with multiple cropping), water availability, pests and diseases, and markets. Moreover, cultivars with a maturity that is better adapted to a changed climate may exist, but are perhaps not available to farmers in a specific region, or they may not have good market value. Many potato cultivars are photoperiod sensitive, and this might decrease the temperature sensitivity of their development rate. Changes in the planting time also lead to changes in the photoperiod, and these have not been taken into account.

The identification or the development of potato cultivars with increased heat tolerance appears to be important to cope with climate change. Heat tolerance in this context refers to the effect of temperature on tuberization. Potato tuber initiation and development are much more sensitive to high temperature stress than photosynthesis (Reynolds and Ewing 1989a; see also Ewing and Struik 1992). Given the long time it takes to develop new potato cultivars, breeding programs should take future climate change into account. Breeding populations could be tested in warmer environments similar to the projected climate of the regions for which they are being bred. Heat tolerance has been found in wild potato species (e.g., Reynolds and Ewing 1989b) and progress in selecting and breeding for heat tolerance in cultivated potato has been reported in the literature (Khanna 1966; Levy 1984; Van der Zaag and Demagante 1988; Tai et al. 1994).

In addition to adaptation, there could be a shift of location of potato production because of the general trend of potato production to move towards areas of high productivity (Walker et al. 1999). There could be shifts between existing production zones in a country and also toward zones where there is currently no potato production (cf. Leemans and Solomon 1993). In some (tropical) highland regions, potato area could expand into higher zones (e.g., into the Puna and Paramo zones of the Andes). There would also be considerable potential for potato area expansion in Russia and Canada, but whether this is likely to happen depends on many factors outside the scope of this paper.

The direct effect of increased atmospheric CO_2 concentration on crop growth was not accounted for. Summarizing three studies on the effect of doubling of CO_2 on potato yield, Rosenzweig and Hillel (1998) calculated an expected 51% yield increase. Miglietta et al (1998) found a 40% increase, but recent research in multiple locations across the European Union found an average yield increase of 20% (De Temmerman et al. 2000). However, the magnitude and persistence of this effect under field conditions is highly uncertain.

Accounting for the effect of CO_2 could obscure the prospect of exploiting the increase of CO_2 for crop production. Instead of asking to what extent increased levels of CO_2 may compensate for negative temperature effects, we should try to avoid yield decline due to temperature change, and attempt to benefit from the possibly positive effect of CO_2 on yield.

Unlike in previous studies, detailed crop distribution data were used to interpret the results of this study. This avoided giving too much weight to yield changes in regions with relatively little potato area. Instead of climate data for a limited number of weather stations, as used in most studies of the impact of climate change on crop production (e.g., Rosenzweig and Parry 1994), a comprehensive grid was used in this study. Using monthly climate data on a grid instead of daily weather data may mask the effect of extreme weather events on crop production. Yet this does not seem to be very important for this study because, with the exception of frost incidence, potato (and the model used) is not highly sensitive to short time fluctuations of the weather.

To improve this study, variation between cultivars in the effect of temperature on tuberization, and the current geographic spread of these cultivars, could be considered. It would be difficult to accommodate all this type of variation in a global study. A next step would be to zoom in to priority regions and evaluate the effect of climate change while taking into account peculiarities of local cropping systems (rotations with other crops, the presence of multiple potato cropping seasons), cultivars used, production constraints, and market demands. In studies of smaller regions it will also be easier to include the effect of (changes in) rainfall, taking into account the degree to which the crop is irrigated. However, for such studies more would need to be known about the interaction of drought stress and increased levels of CO_2 on potato growth.

Whether changes in potential yield accurately reflect changes in actual yield is also uncertain. There can be many other factors that diminish potato yield, such as lack of water and nutrients, and damage from pests and diseases. For example, the range of the Colorado potato beetle in Europe is expected to increase with global warming (Jeffree and Jeffree 1996). In Finland, the area infected with the potato cyst nematode, and losses caused by this pest are expected to increase (Carter et al. 1996). The longer growing season would lead to increased late blight problems and fungicide use (Kaukoranta 1996). These findings support a sustained investment in knowledge-intensive technologies such as integrated pest management and in breeding for potatoes with pest and disease resistance, in addition to an increased emphasis on breeding and selection for heat tolerance.

ACKNOWLEDGMENTS

I thank the International Potato Center for funding this research and Meredith Bonierbale, Louise Fresco, Martin Kropff, John Stares, Tom Walker, and anonymous reviewers for comments on earlier versions of this paper.

LITERATURE CITED

Carter TR, RA Saarikko, and KJ Niemi. 1996. Assessing the risks and uncertainties of regional crop potential under a changing climate in Finland. Agr Food Sci Finland 5:329-350.

Davies A, T Jenkins, A Pike, J Shaq, I Carson, CJ Pollock, and MI Parry. 1996. Modelling the predicted geographic and economic response of UK cropping systems to climate change scenarios: the case of potatoes. Aspects Appl Biol 45:63-69.

De Temmerman L, M Bindi, J Craigon, A Fangmeier, A Hacour, H Pleijel, K Vandermeiren, V Vorne, and J Wolf. 2000. Changing Climate and Potential Impacts on Potato Yield and Quality. Veterinary and Agrochemical Research Centre, Tervuren, Belgium.

Ewing EE, and PC Struik. 1992. Tuber formation in potato: induction, initiation and growth. Hort Rev 14:89-198.

Haverkort AJ. 1990. Ecology of potato cropping systems in relation to latitude and altitude. Agr Syst 32:251-272.

Hijmans RJ. 2001. Global distribution of the potato crop. Am J Potato Res 78:403-412.

Hijmans RJ, B Condori, R Carillo, and MJ Kropff. 2003. A quantitative and constraint-specific method to assess the potential impact of new agricultural technology: the case of frost resistant potato for the Altiplano (Peru and Bolivia). Agr Syst. 76: 8g5–g11.

Houghton JT, Y Ding, DJ Griggs, M Noguer, PJ van der Linden, D Xiaosu, K Maskell, and CA Johnson (eds). 2001. Climate Change 2001. The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change Data Distribution Center. 1999. Providing climate change and related scenarios for impact assessment. CD-ROM. Version 1.0. Climate Research Unit, University of East Anglia, Norwich, UK.

Jeffree CE, and EP Jeffree. 1996. Redistribution of the potential geographical ranges of mistletoe and Colorado beetle in Europe in response to the temperature component of climate change. Funct Ecol 10(5): 562-577.

Khanna ML. 1966. Breeding potato cultivars tolerant to higher thermoperiods. Current Sci 35(6): 143-144.

Kaukoranta T. 1996. Impact of global warming on potato late blight: Risk, yield loss and control. Agr Food Sci Finland 5:311-327.

Kooman PL. 1995. Yielding ability of potato crops as influenced by temperature and daylenght. PhD thesis, Wageningen Agricultural University. Wageningen, Netherlands.

Kooman PL, and AJ Haverkort. 1995. Modelling development and growth of the potato crop influenced by temperature and daylength: LINTUL-POTATO. *In*: AJ Haverkort and DKL MacKerron (eds), Potato Ecology and Modeling of Crops under Conditions Limiting Growth. Kluwer Academic Publishers, Dordrecht, Netherlands. pp. 41-60.

Leemans R, and AM Solomon. 1993. Modeling the potential change in yield and distribution of the Earth's crops under a warmed climate. Climate Res 3:79-96.

Levy D. 1984. Cultivated *Solanum tuberosum* L. as a source for the selection of cultivars adapted to hot climates. Trop Agr 61(3): 167-170.

McCarthy JJ, OF Canziani, NA Leary, DJ Dokken, and KS White, 2001. Climate Change 2001. Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

Miglietta F, V Magliulo, M Bindi, L Cerio, FP Vaccari, V Loduca, and A Peressotti. 1998. Free air CO_2 enrichment of potato (*Solanum tuberosum* L.): development, growth and yield. Global Change Biol 4:163-172.

New M, M Hulme, and P Jones. 1999. Representing twentieth-century space-time climate variability. Part I: development of a 1961-1990 mean monthly terrestrial climatology. J Climate 12:829-856

Nonhebel S. 1993. The importance of weather data in crop growth simulation models and assessment of climatic change effects. Ph.D. thesis, Wageningen Agricultural University, Wageningen, Netherlands.

Peiris DR, JW Crawford, C Grashoff, RA Jefferies, JR Porter, and B Marshall. 1996. A simulation study of crop growth and development under climate change. Agr For Meteorol 79:271-287.

Reynolds MP, and EE Ewing. 1989a. Effects of high air and soil temperature stress on growth and tuberization in *Solanum tuberosum*. Ann Bot 64(3): 241-247.

Reynolds MP, and EE Ewing. 1989b. Heat tolerance in tuber bearing *Solanum* species: A protocol for screening. Am Potato J 66(2): 63-74.

Rosenzweig C, and D Hillel. 1998. Climate Change and the Global Harvest: Potential Impacts of the Greenhouse Effect on Agriculture. Oxford University Press, New York.

Rosenzweig C, and D Liverman. 1992. Predicted effects of climate change on agriculture: A comparison of temperate and tropical regions. *In*: SK Majumdar (ed), Global Climate Change: Implications, Challenges, and Mitigation Measures. The Pennsylvania Academy of Sciences, Philadelphia. pp. 342-61.

Rosenzweig C, and ML Parry. 1994. Potential impact of climate change on world food supply. Nature 367:133-138.

Rosenzweig C, J Phillips, R Goldberg, J Carroll, and T Hodges. 1996. Potential impacts of climate change on citrus and potato production in the US. Agr Syst 52(4): 455-479.

Scott GJ, MW Rosegrant, and C Ringler. 2000. Global projections for root and tuber crops to the year 2020. Food Policy 25(5): 561-597.

Stol W, GHJ de Koning, AJ Haverkort, PL Kooman, H van Keulen, and FWT Penning de Vries. 1991. Agro-ecological characterization for potato production. A simulation study at the request of the International Potato Center (CIP), Lima, Peru. CABO-DLO, Report 155.

Tai GCC, D Levy, and WK Coleman. 1994. Path analysis of genotype-environment interactons of potatoes exposed to increasing warm-climate constraints. Euphytica 75(1-2): 49-61.

Van der Zaag P, and AL Demagante. 1988. Potato (*Solanum* spp.) in an isohyperthermic environment. 3: Evaluation of clones. Field Crops Res 19:167-181.

Van Keulen H, and W Stol, W. 1995. Agro-ecological zonation for potato production. *In*: AJ Haverkort and DJL MacKerron (eds), Potato Ecology and Modeling of Crops under Conditions Limiting Growth. Kluwer Academic Publishers, Dordrecht, Netherlands. pp. 357-372.