Changes in Climate will modify the Geography of Crop Suitability: Agricultural Biodiversity can help with Adaptation

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Abstract

Climate change will cause shifts in areas suitable for cultivation of a wide range of crops. We used current and projected future climate data for ~2055, and the Ecocrop model to predict the impact of climate change on areas suitable for all crops listed in Table 1 of the International Treaty on Plant Genetic Resources for Food and Agriculture and other major staple and cash crops. Most detrimentally affected in terms of reduction of suitable areas for a range of crops will be sub-Saharan Africa and the Caribbean, areas with the least capacity to cope. Conversely, Europe and North America will see an increase in area suitable for cultivation. These regions have the greatest capacity to manage climate change impacts.

To minimize the impacts of these climate and other environmental changes, it will be crucial to breed new varieties for improved resistance to abiotic and biotic stresses is. Plant breeders need to increase their attention to breeding varieties that have greater tolerance to local abiotic stresses such as drought, flooding and extreme temperatures as well as continuing to breed for resistance to pests and diseases. Priorities for breeding should consider the magnitude of the predicted impacts on productivity of the crop, the number of people who depend on the crop and their level of poverty, and the opportunities for significant gains through breeding. Local knowledge of ecological interactions, traditional varieties, and the genetic diversity in the wild relatives of domesticated crops provide rich resources on which to build priority breeding programmes for climate change-tolerant varieties.

1. Introduction

Altered and unpredictable weather patterns can increase crop vulnerability to pests, diseases and the effects of extreme climate events such as high temperatures, droughts and torrential rains. Sequential extremes, such as droughts followed by intense flooding rains, are catastrophic in themselves and are compounded by ecological effects such as the expansion of the ranges of pathogens, diseases, and pests that affect human populations and agricultural production (Rosenzweig et al. 2001).

The impact of climate change on production of various crops varies markedly depending mainly on the region, growing season, the crops and their temperature thresholds. Cereals, oilseed and protein crops depend on temperature and, in many cases, day length, to reach maturity. Temperature increase may shorten the length of the growing period for these crops and, in the absence of compensatory management responses, reduce yields (Porter and Gawith 1999; Tubiello et al. 2000) and change the area of cultivation by rendering unsuitable some currently cultivated areas and suitable, others not currently cultivated.

In this paper, we use the Ecocrop model to project the impact of climate change on selected crops and areas that are currently suitable for growing those crops. We discuss the need for increased attention on breeding varieties that are tolerant of new climate conditions using the rich genetic diversity available in wild species and landraces, and incorporating local knowledge to hone selection of promising varieties for breeding.

2. Broad-brush assessment of climate change impacts on major crops

Crop models are available for only a small percentage of the world's crops. In the absence of mechanistic crop models, the Ecocrop model (http://ecocrop.fao.org/) provides for a simple method to evaluate climate change impacts on a wide range of crops including many less- studied crops. Here we apply Ecocrop to evaluate the impact of climate change on crops that listed in Table 1 of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) plus several other major staples and cash crops (e.g. groundnut, soya, sugar cane). The objective is to identify the crops and regions potentially most afflicted by climate change. More specific analysis of this information can be used to set an agenda for crop improvement to confront these impacts.

The Ecocrop model contains information on the edafo-climatic requirements for 1,200 cultivated species considering optimal conditions and limits to adaptation. Ecocrop is implemented in DIVA-GIS (Hijmans et al. 2005a) and has been interfaced with monthly precipitation and temperature data to permit mapping of suitability on a global scale based solely on climate data. Here we apply Ecocrop to 43 crops (shown in Table 1) using the current climate derived from WorldClim (http://www.worldclim,org, Hijmans et al. 2005b) as a baseline, and two future downscaled GCM outputs (available from http://www.worldclim.org/futdown.htm) based on the HADCM3 model and the CCCMA model for the A2a scenario (widely coined “business as usual”).

A range of statistics are then calculated to examine the global changes in suitability for each crop, the changes in areas suitable for each crop and regional patterns in these changes. Maps are also produced demonstrating the average change in suitability for all crops under each GCM model (Figures 1a and 1b).

The results show that the crops likely to suffer significant decreases in suitable areas for their cultivation are typically cold weather crops, including strawberry (32%), wheat (18%), rye (16%), apple (12%) and oats (12%) (Table 1). Twenty-three crops are projected to suffer decreases in suitable area, on average, whilst some 20 crops gain suitable area. Overall, suitable area for crop cultivation is projected to increase. The biggest gains are in areas suitable for pearl millet (31%), sunflower (18%), common millet (16%), chick pea (15%) and soya bean (14%), although many of the gains in suitable area occur in regions where these crops are currently not an integral component of food-security. For example, land area suitable for pearl millet is projected to increase by over 10% in Europe and the Caribbean, yet these levels of increases are not projected for Africa, where the crop is currently widely cultivated.

By region, Europe is projected to experience the largest gain in suitable areas for cultivation (3.7%). Olesen and Grevsen (1993) also predict that, for field-grown vegetable crops in Europe, increasing temperature will generally be beneficial, permitting an expansion of production beyond the presently cultivated areas. Antarctica and North America will also gain suitable area (3.2% and 2.2%

respectively). Sub-Saharan Africa and the Caribbean are projected to suffer a decline in land area suitable for cultivation (-2.6% and -2.2%, respectively), although there is some disagreement on regional impacts between the two models. Both models demonstrate a general trend of loss in suitable area in the Sahel belt, parts of Southern Africa, India and northern Australia, and gains in the northern USA, Canada, and most of Europe (Figures 1). The models differ in the projected impacts on areas of eastern Brazil (HADCM3 predicting significant loss in suitability whilst CCCMA predicting little change), the Himalayas (CCCMA predicting large loss whilst HADCM3 predicting no change), much of Central America (gains predicted in HADCM3 and losses in CCCMA), and south-western Africa (large losses in Angola and Namibia in HADCM3, with no change in CCCMA). However, on the whole the two models agree on the impacts at the crop level ($r^2 = 0.8155$).

The results of the analysis agree with the findings of other researchers (e.g. Fisher et al. 2002) who predict that suitable land and potential production for staple cereal crops will decrease markedly in sub-Saharan Africa and developed nations will see considerable expansion of suitable arable land to higher altitudes and potential to increase production if those lands are brought under cultivation. The paradox is that areas that are currently most food-insecure will be most affected by climate change. These areas have arguably the greatest need for new crop varieties that are tolerant of extreme climate conditions, especially drought, yet they lack the technology and investment in plant breeding. Support for plant breeding is inadequate in most countries and especially in those countries that need it most. A survey of 19 African countries by FAO (2006) showed that financial support for plant breeding in 2005 was lower than it had been in 1985.

Further analysis is needed to identify the socio-economic and cultural importance of the different crops analyzed in order to define the priorities for breeding, which should be based on the magnitude of the predicted impacts on productivity of the crop, the number of people who depend on the crop and their level of poverty, and the opportunities for significant gains through breeding. It may be that some crops are predicted to pass physiological thresholds that cannot be overcome.

3. Breeding climate-resilient varieties

Crop breeders now need to urgently turn their attention to the introduction of drought and heat resistance into crop varieties to reduce losses of yield from climate change impacts and to allow cultivation in areas that are not currently suitable or that will become unsuitable. The large majority of new crop varieties released have been bred for improved resistance to pests and diseases, yet it is claimed that abiotic stress is the primary cause of crop loss, reducing average yields of most major crops by more than 50% (Wang et al. 2003). This proportion will rise with increasing irregularity of climate and frequency of extreme climate events.

Climate is changing at an unprecedented rate and the magnitude of change is highly variable from place to place (Osborn and Briffa, 2005). Therefore, the degree of fit of varieties to environment will vary between regions and over time. Porter et al. (2007) predict that if global temperatures do not increase more than 4^0C over the next century, arable agricultural production can probably adapt to changes in mean global temperature using breeding, selection and management. Plant breeding, however, is a long-term exercise (e.g. 10 years or more for a new cereal variety), and there is usually a lag phase of about 7-8 years between variety development and adoption by farmers (Morris et al. 1994). Further, improved varieties for the future should be adapted to low-input cultivation so that they can be used by resource-poor farmers without the need for inputs that are scarce (such as water) or costly and environmentally damaging (such as chemicals).

Crops require tolerance to different abiotic stresses depending on where they are grown. Rice, for example, thrives in waterlogged soil and can tolerate submergence at levels that would kill other crops, is moderately tolerant of salinity and soil acidity, but is highly sensitive to drought and cold (Lafitte et al. 2004). Adapting crop varieties to local ecological conditions will reduce risk due to climate change; however, varieties improved for cultivation in one region could be adopted for cultivation elsewhere, where they would face the same abiotic and biotic stresses. Rice varieties that were initially bred for resistance to chilling temperatures in Nepal, for example, were successfully adopted in Bangladesh (Sthapit and Wilson 1992).

Diversity in species, varieties and practices has permitted agriculture to withstand moderate change in climate over the past 10,000 years. Over centuries of observation and selective breeding, farmers' practices have given rise to traditional varieties that are well adapted to local environmental conditions. Farmers use indicators of abiotic stress tolerance that could assist selection of local breeding material to combine tolerance traits with relatively high yield and desirable market traits of modern varieties. Blending the resistance traits of traditional varieties through modern plant breeding will ensure that new varieties are bred to suit specific requirements of local conditions and communities.

4. Crop wild relatives – key sources of resistance genes

The wild plants related to traditional and modern crops harbour an abundant supply of resistance genes. Crop wild relatives (CWR), which include crop ancestors as well as other related species, have been used for crop improvement for over 100 years (Plucknett et al. 1987). Crop wild relatives have saved the agricultural industry millions of dollars, directly and indirectly, by improving crop resilience to biotic and abiotic stresses. Using CWR in breeding improved crop varieties has mainly concentrated on integrating resistance to pests and disease. A review of the use of wild relatives in breeding by Hajjar and Hodgkin (2007) showed that breeding for improved tolerance to abiotic stresses such as drought, extreme temperature and soil salinity has been the exception but that such tolerance traits were increasingly being incorporated.

Crop wild relatives can improve climate tolerance in crops yet, due to climate change, these very genetic resources may themselves be under threat of extinction in the wild. Jarvis et al. (in press) modeled the impact of climate change on wild peanuts, potato and cowpea and found that up to 61% of peanut species, 12% of potato species, and 8% of cowpea species could become extinct within 50 years. Many of these species have already provided important genetic traits for the improvement of domestic crops.

Conservation of crop wild relatives and traditional varieties is needed to ensure that diversity is available to meet the demands of agricultural production under changing and unpredictable climatic conditions. Crop wild relatives are under-represented within genebanks, and under-researched for use in crop improvement. Increasing threats to natural habitats and farming systems make it imperative to collect, conserve and characterize the inter- and intra-specific diversity of wild relatives in order to mitigate against the biotic and abiotic stresses caused by climate change.

6. Conclusions

Areas suitable for cultivation of a wide range of the world's most important crops will shift as a result of climate change. Overall, suitable areas will increase, but most affected by loss of area will generally be regions that are already struggling from the impacts of irregular and extreme climate events. Regions such as Europe, Antarctica and North America stand to gain additional area for cultivation. At the crop level, 23 crops are predicted to gain suitable area while 20 are predicted to lose, including the cereals wheat, rye and oats. Further analysis is needed to identify priority species and areas to target for climate adaptation strategies, particularly for improved climate change- tolerant varieties. Plant breeders now need to focus on the future as well as the present, and evaluate the vast genetic resources in genebanks and in the wild that hold potential for adaptation of major crops to a changing climate The rich species and genetic diversity that exists in landraces and wild species should be exploited and local knowledge used to guide crop and variety selection. Adapting crops to climate conditions will allow cultivation to continue on current areas as well as taking advantage of new suitable areas.

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Figure 1. Average changes in suitability based on the HADCM3 model (top) and CCCMA model (bottom). Blue indicates increase in suitability, and red indicates reduction in suitability.

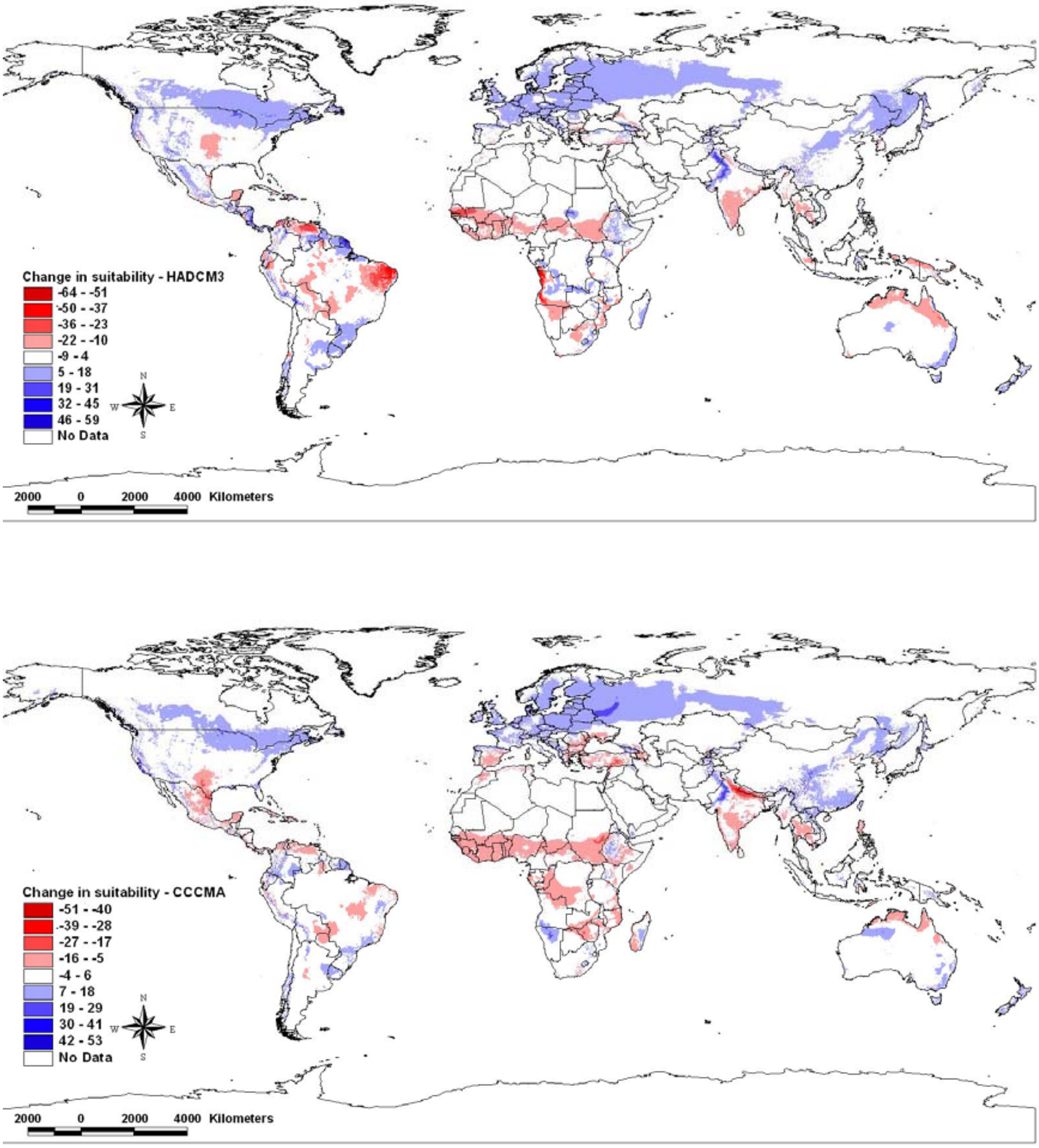

Table 1. Impacts of climate change on the area suitable for cultivation of ITPGRFA Table 1 crops and other important staples and cash crops, based on projections using the HADCM3 and CCCMA models under the A2a scenario

Crop	Species	ITPGRFA Table 1	Change in Suitable Area HADCM3 (%)	Change in Suitable Area CCCMA (%)
Apple	*Malus domestica* Borkh.	Y	-21.38	-3.42
Asparagus	*Asparagus officinalis* L.	Y	-5.18	1.37
Banana	*Musa accuminata* Colla	Y	-4.25	-0.67
Barley	*Hordeum vulgare* L.	Y	-2.53	5.60
Bean	*Phaseolus vulgaris* L.	Y	-15.01	0.00
Sugar Beet	*Beta vulgaris* L. v *vulgaris*	Y	-5.45	8.86
Breadfruit	*Artocarpus altilis* (Park.)	Y	-3.21	1.47
Carrot	*Daucus carota* L.	Y	-10.44	-2.18
Cassava	*Manihot esculenta* Crantz.	Y	-5.67	0.26
Chick pea	*Cicer arietinum* L.	Y	13.91	16.95
Coconut	*Cocos nucifera* L.	Y	-0.43	4.19
Coffee	*Coffea arabica* L., *Coffea canephora* Pierre	N	-14.97	-7.27
Cotton	*Gossypium hirsutum* L.	Y	11.17	14.31
Cowpea	*Vigna unguiculata* unguic. L	Y	2.71	6.13
Cocoyam	*Colocasia esculenta* (L.) S.	Y	-17.52	-6.61
Eggplant	*Solanum melongena* L.	Y	-5.03	-1.92
Faba bean	*Vicia faba* L.	Y	3.78	12.21
Finger millet	*Eleusine coracana* (L)Gaertn	Y	-5.06	1.31
Grass pea	*Lathyrus sativus* L.	Y	-0.98	10.81
Groundnut	*Arachis hypogaea* L.	N	5.91	10.58
Lemon	*Citrus limon* (L.) Burm. f.	Y	-14.41	-5.17
Lentil	*Lens culinaris* Medikus	Y	3.00	10.12
Maize	Zea mays L. s. mays	Y	5.34	7.80
Common millet	*Panicum miliaceum* L.	N	18.19	14.17
Oat	*Avena sativa* L.	Y	-21.46	-2.79
Oil palm	*Elaeis guineensis* Jacq.	N	-6.00	-2.42
Sweet orange	*Citrus sinensis* (L.) Osbeck	Y	-0.41	4.50
Pea	*Pisum sativum* L.	Y	-8.93	-3.61
Pigeon Pea	*Cajanus cajan* (L.) Mill ssp	Y	-0.94	2.94
Plantain	*Musa balbisiana* Colla	Y	-6.72	-3.05
Potato	*Solanum tuberosum* L.	Y	-3.55	6.80
Pearl millet	*Pennisetum glaucum* (L)R.Br.	Y	31.28	31.46
Rice	*Oryza glaberrima* Steud., *Oryza sativa* L. s. japonica, *Oryza sativa* L. s. indica	Y	-3.34	-1.10
Rye	*Secale cereale* L.	Y	-25.72	-6.22
Sorghum	*Sorghum bicolor* (L.) Moench	Y	8.42	9.01
Soya bean	*Glycine max* (L.) Merrill	N	13.31	13.99

Crop	**Species**	**ITPGRFA Table 1**	**Change in Suitable Area HADCM3 (%)**	**Change in Suitable Area CCCMA (%)**
Strawberry	*Fragaria x ananassa* (D.) G.	Y	-39.25	-24.33
Sugar Cane	*Saccharum officinarum* L.	N	-3.64	1.23
Sunflower	*Helianthus annuus* L v macro	Y	16.20	19.02
Sweet Potato	*Ipomoea batatas* (L.) Lam.	Y	-0.44	4.69
Tannia	*Xanthosoma sagittifolium* L.	Y	-5.80	0.40
Wheat	*Triticum aestivum* L.	Y	-30.86	-4.48
Yam	*Dioscorea dumetorum* (K.) P., *Dioscorea opposita* Thunb., *Dioscorea trifida* L., *Dioscorea alata* L., *Dioscorea esculenta* (L.) B., *Dioscorea bulbifera* L., *Dioscorea rotundata* Poir., *Diocorea cayenensis* Lam.	Y	-2.01	-1.49