Climate Change in the Subtropics: The Impacts of Projected Averages and Variability on Banana Productivity

I. Van den Bergh[1], J. Ramirez[2,3,4], C. Staver[1], D. Turner[5], A. Jarvis[2,3], D. Brown[6]

[1]Bioversity International, Montpellier, France
[2]International Center for Tropical Agriculture
[3]Challenge Program on Climate Change, Agriculture and Food Security, Cali, Colombia
[4]Faculty of Earth and Environment, University of Leeds, Leeds, UK
[5]School of Plant Biology, Faculty of Natural and Agricultural Sciences, University of Western Australia, Crawley, WA, Australia
[6]Bioversity International, Turrialba, Costa Rica

Keywords: *Musa* spp., temperature, rainfall, global climate models, EcoCrop model, homoclimes, climate scenarios.

Abstract

The potential for bananas to produce year round is best expressed when water is abundant and daily temperatures are in the range of 20-30°C. Zones with these conditions produce fruit for the global market. However, banana production, mainly for national markets, has developed in many subtropical areas under less than optimum conditions. Bananas are an important cash crop in southern Brazil, Paraguay and Argentina, in countries of North Africa, the Middle East and southern Africa, and in China and northern India. In these regions, bananas are subject to sub-optimum temperatures and short days. Highly favorable temperatures and long days in the summer may also include short periods of extreme temperatures above 35°C, while rainfall is also highly variable. The effects of climate change on selected subtropical production areas were modeled in a two-step procedure using the EcoCrop model, under current growing conditions and for 2020 and 2050 using a set of 19 IPCC (Intergovernmental Panel on Climate Change) Global Climate Models (GCMs) under the SRES-A2 (business as usual) emission scenario. The modeling showed that current suitability for banana production in the subtropics is much lower than in the tropics with great variation in suitability within the subtropics. Of nine subtropical regions considered, two have improved conditions by 2020s, four are largely unaffected and three have a lower suitability. Our analysis also showed that, in terms of environmental conditions, certain sites are widely represented globally, offering options for technology transfer between sites. Other sites have few similar sites, which means that sites need to be carefully selected for approaches to technology development and transfer. The study leveraged site-specific information with widely available tools to understand potential effects of climate change in the subtropics. However, in order to fully understand the impacts of climate change on banana, the modeling tools used here need to be fully suited for semi-perennial crops to capture the effects of seasonal temperature and rainfall variability on crop cycle length and potential yields.

INTRODUCTION

The potential for bananas to produce year round is best expressed when water is abundant and daily temperatures are in the range of 20-30°C (Simmonds, 1962). Numerous zones with these conditions produce fruit for the global market. However, banana production, mainly for national markets, has developed in many subtropical areas under less than optimum conditions. Bananas are an important cash crop in southern Brazil, Paraguay and Argentina, in countries of North Africa, the Middle East and southern Africa, and in China and northern India where growing conditions are far from uniform throughout the year. In these subtropical regions, bananas are subject to sub-optimum temperatures and short days as well as occasional cold snaps and killing frosts in the winter. Highly favorable temperatures and long days in the summer may also include short periods of extreme temperatures above 35°C. Rainfall is also highly variable, not always synchronized with periods of optimum temperatures, and irrigation is often required.

Temperature and rainfall are expected to change at an unprecedented rate in the coming decades (IPCC, 2007). These changes are very likely to impact *Musa* productivity both directly through changes in the growing environment and the prevalence of pests and diseases and indirectly through relocation of production areas (Ramirez et al., in press). A review of the impacts of climate change on *Musa* crops (Ramirez et al., in press) suggests that future climates (2020s) are expected to be less suitable in more than 70% of the global land areas (mainly tropical areas), but that there could be gains towards the subtropics that could both increase yields and expand areas suitable for *Musa*.

A closer look at the subtropics is of merit for three reasons: (1) this is the region with the most potential gain; (2) the growing conditions of subtropical banana production are highly diverse; and (3) modified parameters for banana growth may apply. To date, only a limited set of studies have dealt with subtropical bananas and climate change. Our objective was to validate the procedure for the estimation of the effect of expected climate changes on banana production in the subtropics using the EcoCrop model to estimate the magnitude of expected changes and the changes in the suitability of selected subtropical regions for banana production given the predicted changes in temperature and rainfall projected by climate change models. We conclude with observations for improving the procedure to estimate the effects of climate change and extrapolate across production zones and homoclimes (areas of similar climate) and the implications for zones with different characteristics.

MATERIALS AND METHODS

The analysis had five stages: (i) identification of current banana areas by means of expert consultation, (ii) calibration of a model and modeling of the suitability of current banana production areas, (iii) modeling of expected suitability (i.e. 2020, 2050) and changes in suitability of subtropical banana production areas, (iv) analysis of changes in yearly seasonality, and (v) identification of homoclimes and discussion of options for transfer of technology.

Cultivated Areas and Identification of Key Sites

Regional banana experts were consulted through face-to-face meetings, telephone or email, to select sites via Google Earth or by manually drawing polygons over a map. These areas and sites were digitized and transformed to polygon and point-type GIS-compatible formats and used in all the analyses. We then selected nine sites that are important for subtropical production of bananas: southern coastal China (SCC), southern non-coastal China (SNC), Northernmost India (NIN), northern Morocco (NMO), Canary Islands (CIS), Mozambique-South Africa border (MSB), Formosa province, Argentina (FOR), Paraguay (PRY) and southern Brazil (SBR).

Current and Future Climate Data

Current climate data were derived from WorldClim (Hijmans et al., 2005, http://www.worldclim.org). Monthly maximum, minimum and mean temperatures and total monthly precipitation data were gathered at 30 arc-seconds spatial resolution and aggregated to 5 arc-minute using bilinear interpolation to reduce computational time.

We downloaded monthly time series of temperature and precipitation data for the baseline period (20th century) and projections of future climate for the 21st century for the SRES-A2 (business as usual) emission scenario, at original GCM resolutions for 19 different coupled GCMs used in the IPCC Fourth Assessment Report (PCMDI, 2007; IPCC, 2007; Jarvis et al., 2010). Using the complete GCM time series, for each of the GCMs, months and variables, we calculated the 30-year running average over the baseline period (1961-1990), and over two future periods: 2020s (2010-2039) and 2050s (2040-2069). Deltas (i.e. future - baseline climatology) were calculated for each GCM and then applied to the climates represented in WorldClim (at 5 arc-minutes) in a process called disaggregation (Ramirez and Jarvis, 2010). We finally obtained a set of 38 disaggregated future climate scenarios for use in the modeling, each of which represent a different period predicted by each of the 19 available GCMs.

Model Calibration and Parameterization

We adopted the EcoCrop model as described in Beebe et al. (in press). The model uses mean and minimum monthly temperature and monthly precipitation data to evaluate the climatic suitability of a location for a crop. To calibrate the model parameters, we extracted the annual mean temperature and total annual rainfall for all the identified banana production sites. Based on the frequency distribution of these data, supported by a literature review, and using an iterative process for refining the thresholds of suitability by means of visual inspection of results, we tuned the ecological parameters of the crop.

Subtropical bananas are generally adapted to seasonal climates and low temperatures at certain times of the year (Fig. 1). We found that bananas cannot grow with monthly minimum temperatures below 0°C (Tkill), they stop growing below 12°C (Tmin) or above 33°C (Tmax), and they have optimum growth between 17.5 and 26.3°C (Topmin and Topmax, respectively). Rainfed subtropical banana crops fail due to drought if they receive less than 200 mm/year (Rmin) or due to waterlogging if they receive more than 4,000 mm/year (Rmax), yet they grow optimally if rainfall is between 900 and 1,760 mm/year and soil drainage is good.

Model Implementation and Seasonal Changes in Selected Sites

The model was applied over the baseline climate data and over each of the 38 future disaggregated climate scenarios. The changes in suitability of the 19 models were averaged and the coefficient of variation (n = 19) was computed. We identified the areas currently limited by temperature and/or by precipitation. We then analyzed the changes in suitability in the nine selected subtropical production sites and the uncertainty based on changes in individual GCMs.

For each of the selected key sites, we extracted current and predicted monthly maximum, minimum and mean temperatures and total monthly rainfall and examined the changes in seasonality throughout the year to identify issues and opportunities for production of bananas.

Homoclimes of Banana Production: Potential for Targeting Crop Technology

Changes in crop technology need to be taken into account to capture adaptation potential with changing climates. We used Homologue TM (Jones et al., 2005) to identify areas that are climatically similar to each of our nine selected sites through a probability surface ranging from

0 to 1 for each pixel. Based on an average probability map, we then calculated the percentage of the total area in the aggregated map that was identified as a homoclime of the specific site. We calculated areas above 0.25, 0.50, 0.75 and 0.90 probabilities for each of the site probability surfaces as an index of each site's potential for technology transfer.

RESULTS

Current and Predicted Future Climatic Suitability of Areas for Banana Production

Based on current temperature and rainfall data, overall suitability for banana production in the subtropics is much lower than in the tropics (Fig. 2a). Within the subtropics, suitability varies greatly. Among the nine subtropical sites selected for detailed analysis, several had reasonably high suitability (PRY, FOR, MSB and SCC), while others have very low suitability (NIN, SNC, SBR, NMO, CIS). Rainfall is the most limiting factor (Fig. 2b), except in PRY, FOR and SBR.

Changes in expected suitability in 2020s vary by site with three sites largely unaffected by expected changes (MSB, CIS and NMO), four disadvantaged (NIN, PRY, FOR and SCC) and two more favorable for banana production (SBR and SNC) (Fig. 3), and these trends are shown to continue in the projection for 2050s (Fig. 2c,d and Fig. 3). This suggests that the subtropics are characterized not by one but a number of climate types for banana with differing outcomes due to climate change. The level of uncertainty in the predictions increases from the tropics to the subtropics (Fig. 2e).

Seasonal Variations in Current and Predicted Future Climate in Selected Sites

Seasonality of temperature and rainfall is found in all the subtropical sites and will continue for both 2020s and 2050s (Fig. 4). Temperature is expected to rise throughout the year at all sites. Rainfall is expected to decrease in some seasons at some sites and to increase in other seasons or sites, although a significant variation is attributed to the different GCMs.

In China, SCC is currently reasonably well suited to banana production; SNC is less suited due to winter temperatures below 12ºC during 2-3 months per year. Winter rainfall is low, especially in SCC. In both sites, temperature will increase throughout the year, which will reduce banana injury due to winter chilling, but in SCC, summer temperatures above 33°C will become limiting.

Banana production in SBR is currently limited by winter temperatures below the minimum threshold. Climate change will bring an increase in temperature, as well as in rainfall.

For MSB, both winter temperatures and summer temperatures remain within a suitable range, though rainfall is inadequate in the winter season. Expected changes in rainfall are minimal, and the slight increase in temperature will not greatly affect banana production.

NMO and CIS are currently dry sites, especially in the period of high temperatures. Summer temperatures do not exceed Topmax in the Canary Islands and Tmax in northern Morocco. Winter temperatures remain above the lower limit 12ºC in the Canary Islands, but can go down to about 5ºC in northern Morocco. Because of their dry climate and low winter temperature, both sites depend on irrigation and increasingly on protected environments (Table 1). Temperature will increase in the future in NMO and stay fairly constant in the CIS.

For FOR and PRY (represented by PRY in Fig. 4), current temperature ranges are maintained more or less between Tmin and Tmax. Rainfall is low in the winter months when temperatures are also low; however, both sites could experience a slight increase in rainfall mainly during the winter months. More significantly is the expected increase in temperature that could push summer temperature over the suitable maximum.

In NIN, a dry period from November to April and high temperatures well above Tmax during the last months of the dry season limit suitability. Rainfall is projected to go up in the rainy season but stay more or less the same in the dry season, whilst temperature is expected to increase throughout the year. Suitability for banana production is expected to decrease.

Homoclimes of Banana Production: Potential for Future Crop Technology Targeting

The analysis showed the similarity between the aggregate map of tropics and subtropics and the nine study sites. NIN is the site with the highest potential for transferability of technologies to other sites, with 49% of the total aggregated area being a homoclime with a probability threshold above 0.1 (Table 2), followed by FOR (41%), PRY (38%) and MSB (14%). CIS and NMO appear as areas with a very low proportion of homoclimes. Most sites already use irrigation, but more efficient systems may be shifted from one homocline to another. Irrigation is also used to cool plants during periods of excessively high temperatures. Technology of protective structures is likely to be transferred to new areas not currently growing bananas.

DISCUSSION AND CONCLUSIONS

Our analysis of the impacts of climate change on selected subtropical production areas needs to be discussed in terms of the strengths and weaknesses of the modeling procedure itself and the implications for adaptation to climate change in subtropical regions.

The 5-steps procedure followed leverages site-specific information with widely available tools to provide an initial understanding of climate change in the subtropics. A step-by-step review indicates where future work is needed to reduce uncertainties in the results:

(1) Expert mapping to identify banana production areas is a rapid and reliable means of obtaining knowledge that is not available in the literature. It requires minimal resources and takes advantage of local experience and knowledge. When production areas are compact, mapping is quite straightforward; however, when spread over a large area, expert knowledge may introduce imprecision in results;

(2) Available climate data can be readily accessed and manipulated, but the density of stations is variable and extrapolation difficult for identifying climatic conditions for specific localities;

(3) Parameterization of certain atmospheric processes is still highly inaccurate and predictions of e.g. rainfall are highly uncertain, particularly in the tropics and subtropics, weakening the reliability of climate change models and crop suitability projections;

(4) The EcoCrop model which is at the heart of the analysis introduces a number of uncertainties: (a) The calibration of the model and inspection of suitability surfaces rely on both the knowledge of the modeler(s) and crop expert(s) and the quality of the data that are being gathered and used. Here, we have checked the suitability surfaces against our own knowledge and against known distributions of the crop; (b) The model is for rainfed production, while many subtropical production areas are only possible with irrigation. Areas of low suitability without irrigation may be quite suitable with irrigation, especially due to dry air conditions which reduce foliar diseases; (c) For perennial crops such as bananas, rainfall and temperatures during the growing season are equal to the annual rainfall and temperature, which results in neglecting the seasonality of annual climates, a serious limiting factor for subtropical bananas. Modifications to take into account seasonality are needed to make EcoCrop more useful for banana and to improve the relationship between our climatic suitability rating and the resulting gross yield obtained in banana fields.

Subtropical banana production faces low temperatures, drought and occasionally excessive high temperatures. Our analysis showed that overall suitability in the subtropics is projected to increase, particularly in more northern or southern areas, with increase in suitable areas. Banana growers in the nine study sites already use diverse technologies to overcome temperature and water limitations, including annual planting, protective structures and most commonly irrigation. The most serious challenge for future production in these sites is short periods of excessively high temperatures which deform bunches and damage leaves, a factor in 6 out of the 9 sites studied. Increasing overall temperatures will bring benefits during the winter period. However, weather volatility, not covered in current models, but mentioned among climate change trends, may also increase, indicating that cold snaps and frosts may continue to be a risk. The projected trends in rainfall patterns vary. Even in places where rainfall does not decrease, if temperature rises, water demand will also increase. In areas with limited rainfall and a high demand for irrigation, technologies for greater water efficiency will be needed.

The substitution of cultivars with greater tolerance to drought and temperature extremes is a promising measure. Although subtropical banana production depends primarily on Cavendish cultivars with local selection for more adapted lines, genetic improvement can be expected to make a contribution to adaptation. Wild species diversity is currently underutilized in breeding programs (INIBAP, 2006; Vuylsteke et al., 1993; Wong et al., 2002; Oselebe et al., 2006), even though some of them hold useful traits, including tolerance to cold (*Musa sikkimensis*, *Musa basjoo*, *Musa thomsonii*) and drought (*Musa balbisiana*, *Musa nagensium*) (Bakry, 2010). Genetic screening and genome mapping of wild species and landraces by means of novel and less resource-consuming methods (Lam et al., 2010) are needed both for drought tolerance and low/high temperatures. This can be expected to result in germplasm with tolerances to drought and other abiotic factors and adequate market conditions.

The homoclime analysis showed that large areas of the subtropics have characteristics similar to the nine areas studied. This suggests considerable scope for production to expand in subtropical areas, to higher altitudes, regions with a more favorable rainfall distribution (either wetter or drier) or regions with increasing minimum temperatures provided summer temperatures do not surpass the maximum temperature for the crop. Refining the homoclime procedures demonstrated here has potential to contribute to national strategy building and to more efficient technology generation targeted to different types of climatic conditions.

References

Bakry, F. 2010. These proceedings.

Beebe, S., Ramirez, J., Jarvis, A., Rao, I.M., Mosquera G, Blair, M. and Bueno, J.M. Genetic adjustments to changing climates: Common bean. In: S. Yadav, B. Redden, J.L. Hattfield and H. Lotze-Campen (eds.), Crop Adaptation to Climate Change. Wiley-Blackwell. In press.

Hijmans, R.J., Cameron, S.E., Parra J.L., Jones, P.G. and Jarvis, A. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25:1965-1978.

INIBAP. 2006. Global Conservation Strategy for *Musa* (Banana and Plantain). International Network for the Improvement of Banana and Plantain, Rome, Italy.

Intergovernmental Panel on Climate Change. 2007. IPCC Fourth Assessment Report: Climate Change 2007, IPCC, Geneva.

Jarvis, A., Ramirez, J., Anderson, B., Leibing, C. and Aggarwal, P. 2010. Scenarios of climate change within the context of agriculture. In: M.P. Reynolds (ed.), Climate Change and Crop Production. CAB International.

Jones, P.G., Cock, J.H. and Diaz, W. 2005. Homologue, beta Version. CD-ROM. CIAT. Cali, Colombia.

Oselebe, H.O., Tenkouano, A. and Pillay, M. 2006. Ploidy variation of *Musa* hybrids from crosses. African Journal of Biotechnology 5(11):1048-1053.

PCMDI. 2007. IPCC Model Output. http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php (accessed 26 September 2009).

Ramirez, J. and Jarvis, A. 2010. Disaggregation of Global Circulation Model Outputs. Decision and Policy Analysis Working Paper No. 2. CIAT. http://gisweb.ciat.cgiar.org/GCMPage/docs/Disaggregation-WP-02.pdf

Ramirez, J., Jarvis, A., Van den Bergh, I., Staver, C. and Turner, D. Chapter 20: Changing climates: Effects on growing conditions for banana and plantain (*Musa* spp.) and possible responses. In: S. Yadav, B. Redden, J.L. Hattfield and H. Lotze-Campen (eds.), Crop Adaptation to Climate Change. Wiley-Blackwell. In press.

Simmonds, N.W. 1962. Evolution of the Bananas. Longmans, London, UK.

Vuylsteke, D., Ortiz, R. and Ferris, S. 1993. Genetic and Agronomic Improvement for sustainable production of plantain and banana in Sub-Saharan Africa. African Crop Science Journal 1(1):1-8.

Wong, C., Kiew, R., Argent, G., Set, O., Lee, S.K. and Gan, Y.Y. 2002. Assessment of the validity of the sections in *Musa* (Musaceae) using AFLP. Annals of Botany 90:231-238.

Tables

Table 1. Characteristics of eight subtropical banana production areas.

Zone	Latitude/ longitude	Area (Hectares)	Production (tonnes)	Technology	Principal cultivars
NIN	23-30 N/75-90 E	180,000	5,000,000	Open, irrigation	Cavendish, Mysore, Silk
SCC/SNC	18-28 N/102-118 E	300,000	8,000,000	Open, partial protection, irrigation	Cavendish
NMO	30 N/10 W	4,500	215,000	Full protection, open, irrigation	Dwarf Cavendish
CIS	28 N/16 W		400,000	Full protection, open, irrigation	Dwarf Cavendish
PRY	25 S/54 W	8,000	58,000	Open	Cavendish
FOR	25 S/60 W	9,400	151,000	Open, irrigation	Cavendish
SBR	26-29 S/50 W	53,000	943,000	Open, irrigation	Cavendish
MSB	20-25 S/30-35 E	14,000		Open, irrigation	Cavendish

Southern coastal China (SCC), southern non-coastal China (SNC), Northernmost India (NIN), northern Morocco (NMO), Canary Islands (CIS), Mozambique-South Africa border (MSB), Formosa province, Argentina (FOR), Paraguay (PRY) and southern Brazil (SBR).

Table 2. Proportion of areas that are homoclimes of each selected site and proportion of homoclimes to which technology can be transferred above different probability thresholds.

Location	Area	Area above	Area above	Area above	Area above

	(%)	p = 0.25 (%)	p = 0.50 (%)	p = 0.75 (%)	p = 0.90 (%)
MSB	14.2	55.5	24.2	8.1	2.4
SCC/SNC	6.6	62.7	33.8	15.1	5.8
NIN	48.9	58.8	31.1	14.6	6.6
PRY	38.3	58.1	26.6	8.8	3.2
FOR	41.1	54.4	23.6	8.2	2.8
NMO	0.4	60.2	31.0	15.3	7.1
SBR	2.3	57.7	27.8	9.6	3.9
CIS	0.2	55.4	19.2	4.7	2.1

Southern coastal China (SCC), southern non-coastal China (SNC), Northernmost India (NIN), northern Morocco (NMO), Canary Islands (CIS), Mozambique-South Africa border (MSB), Formosa province, Argentina (FOR), Paraguay (PRY) and southern Brazil (SBR).

Figures

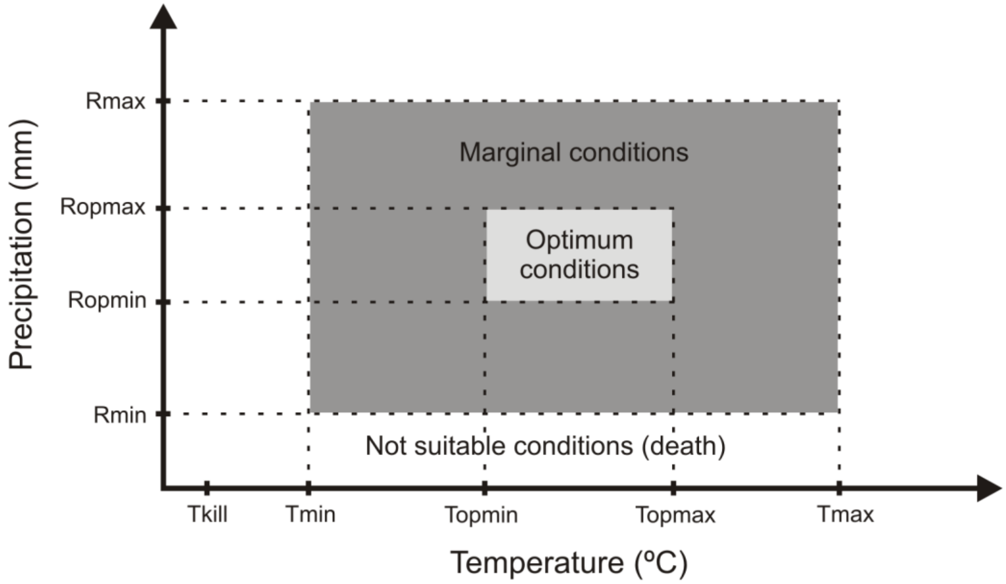

Fig. 1. Ecological parameters required for a single Ecocrop run and the way they interact: White area is deemed as unsuitable, dark gray area ranges from very marginally suitable to very suitable, and light gray area is the main ecological niche of the crop.

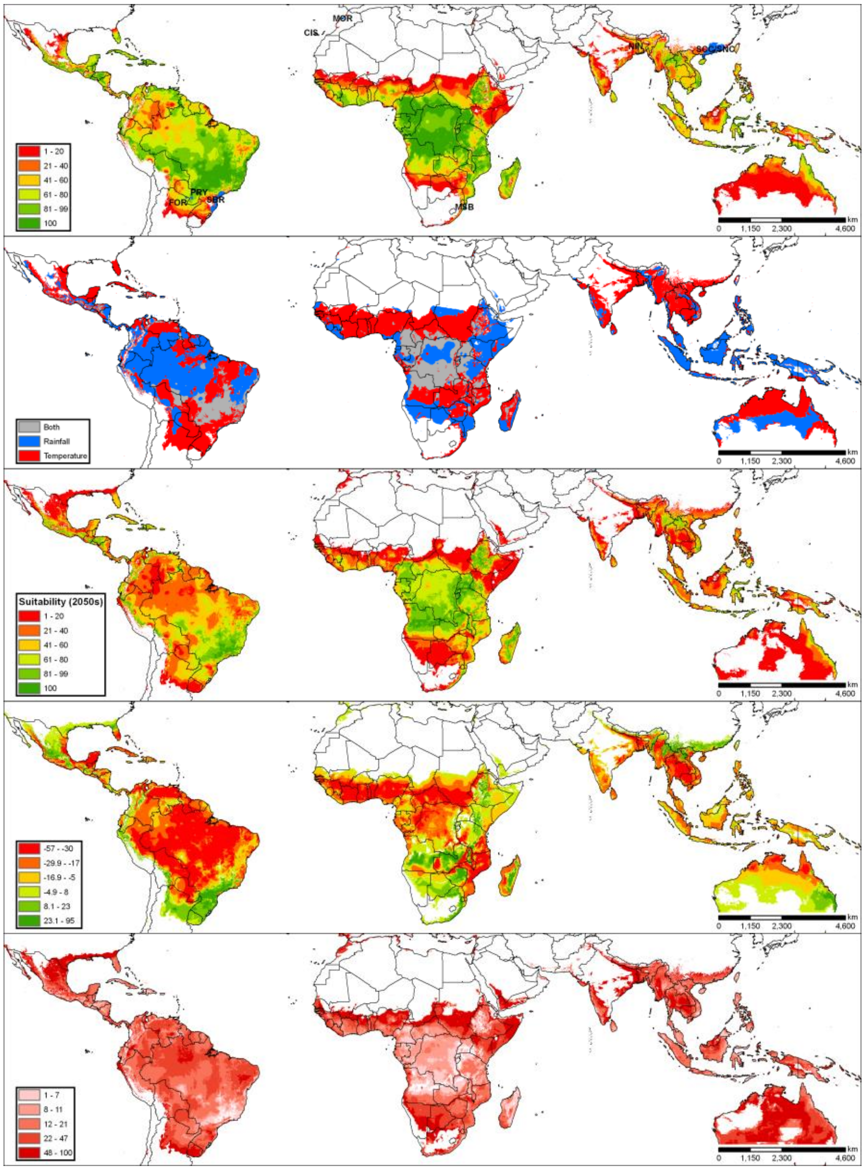

Fig. 2. (a) Current suitability for banana production; (b) Limiting factor (blue for precipitation and red for temperature); (c) Future suitability by 2050s as average of 19 GCMs; (d) Change in suitability by 2050s as average of 19 GCMs; (e) Suitability change coefficient of variation by 2050s.

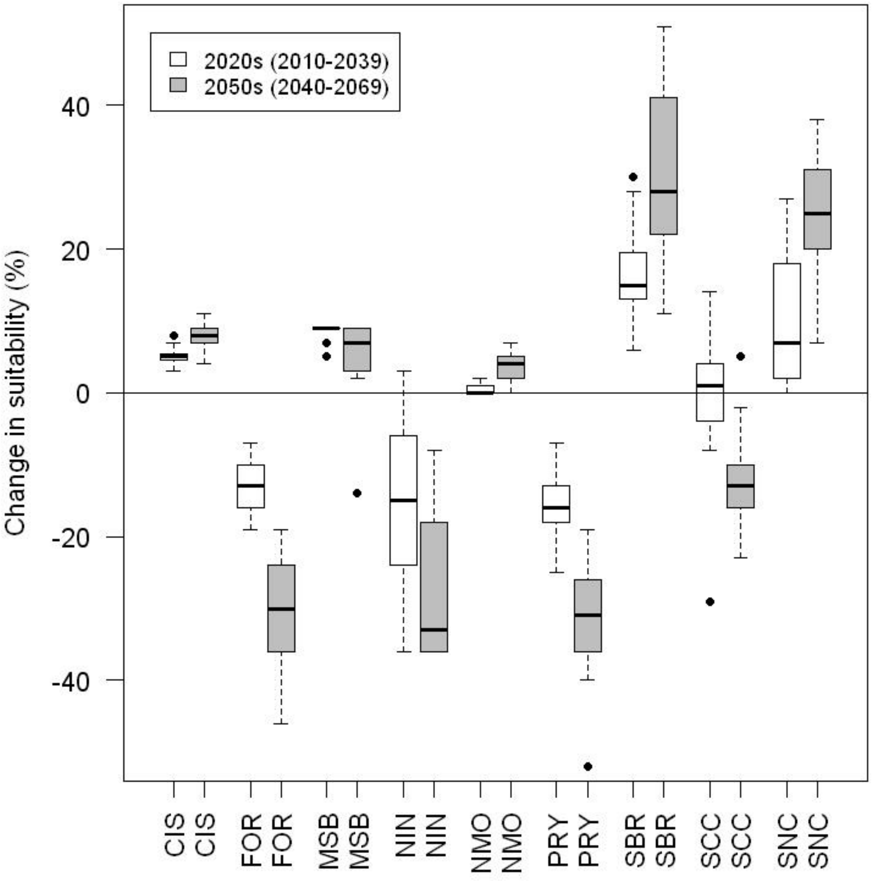

Fig. 3. Changes in suitability (2020s, 2050s) with respect to the baseline suitability (present climates) for selected key production sites as given by the different GCMs included in the analyses.

In each box: the short horizontal thick line indicates the median, the upper and lower hinges of the box represent the 1st and 3rd quartiles, the upper and lower notches indicate maximum and minimum values respectively, and the points are outliers (Tukey, 1977).

Southern coastal China (SCC), southern non-coastal China (SNC), Northernmost India (NIN), northern Morocco (NMO), Canary Islands (CIS), Mozambique-South Africa border (MSB), Formosa province, Argentina (FOR), Paraguay (PRY) and southern Brazil (SBR).

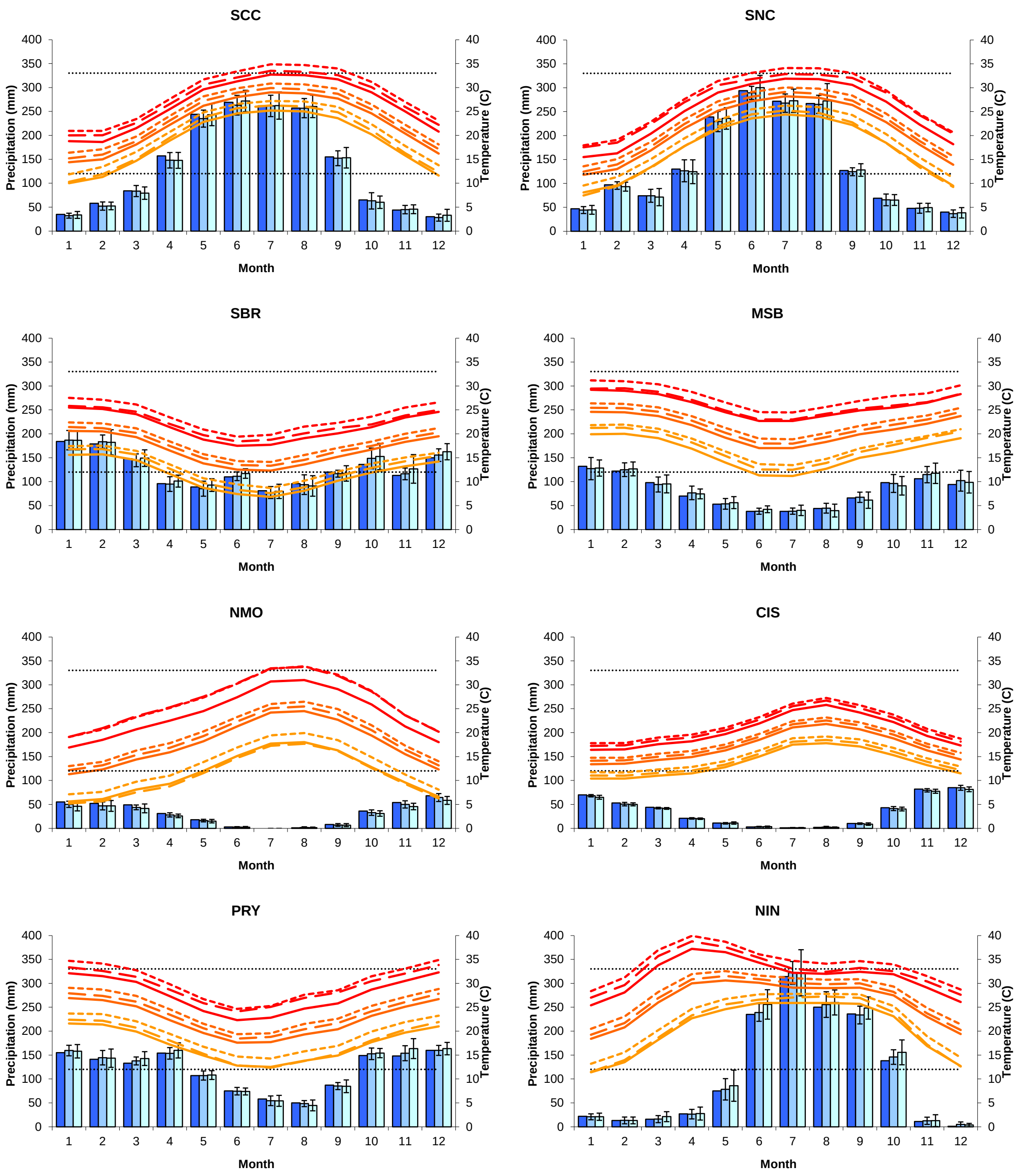

Fig. 4. Current and expected future (2020s, 2050s) monthly climates for selected sites.

Lines for temperature: Continuous lines show baseline data, long-dashed lines show prediction for 2020s and short-dashed lines show prediction for 2050s. Yellow lines are minimum temperatures, orange lines mean temperatures and red lines maximum temperatures. Short-dashed horizontal black lines represent maximum absolute temperature (Tmax, upper line) and minimum temperature (Tmin, bottom line) at which the crop grows.

Bars for precipitation: Left bars are baseline data, center bars are 2020s and right bars are 2050s. Deviation lines on top of the bars indicate standard deviations over the average of 19 GCMs (only shown for precipitation).

Southern coastal China (SCC), southern non-coastal China (SNC), Northernmost India (NIN), northern Morocco (NMO), Canary Islands (CIS), Mozambique-South Africa border (MSB), Formosa province, Argentina (FOR), Paraguay (PRY) and southern Brazil (SBR).