chapter 9

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chapter 9

An assessment of global banana production and suitability under climate change scenarios

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main chapter messages

- Even with temperature increases of 3 °C by 2070, conditions globally will continue to be highly favorable for banana production. Increasing annual temperatures will make conditions more favorable for banana production in the subtropics and in tropical highlands. Through 2070 land area suitable for bananas will increase by 50%.

- Production cycles from planting to harvest will be shorter due to an accelerated rate of leaf emission, but water demand will increase by 12-15%. Selected banana areas expected to surpass seasonal temperatures above 30 °C may be lost for banana production by 2050.

- Specific cultivar groups such as East African highland bananas merit special studies. Their special suitability to tropical highland conditions indicates that their cultivation area may expand to higher elevations. However, growers in lower elevation areas may need to substitute other cultivars as temperatures increase.

- Even though increasing temperatures are not unfavorable for banana, they may be unfavorable for perennial and annual crops with which bananas are often grown. Farm households growing crops such as coffee, with banana as a secondary crop, may abandon banana when they abandon coffee because of climate change.

- Additional analyses are needed to quantify the effects of extreme weather events and the implications for banana productivity and management. More analyses are also required to better understand the impacts on pest and disease dynamics for banana and tropical crops.

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1. Introduction

Banana and plantain are among the top ten crops globally in area, yield and calories, occupying seventh or eighth place depending on the category. The diverse set of cultivar groups making up banana and plantain are a source of income, food supply and dietary diversity for millions of rural and urban households throughout the tropics and subtropics. Banana is also a major export crop, the most widely consumed fruit, generating income and employment for millions of households. Unlike many other crops, which have crop cycles of 3-5 months, banana is a semi-perennial crop with a crop cycle nearly a year long under optimum conditions and even longer with lower temperatures or more erratic water supply. The vulnerability of the crop to climate change is an important consideration, demanding specific tools suited to banana growth habit and crop cycle.

Bananas and plantains figure among the top ten crops worldwide, ranking behind maize, rice, wheat, cassava, and potatoes, but ahead of sorghum, millet and sweet potatoes. The group comprising banana and plantain, unlike many of the other top ten crops, is made up of a diverse set of cultivar groups, each with a different genetic makeup, not just varieties of a single species. This diversity adds an additional dimension to any analyses of this crop. Nearly half of global production is the Cavendish group, which is the most important banana in world trade, followed by cooking bananas of diverse types, other dessert bananas and finally plantains (Table 1).

Although banana is considered a tropical crop, needing a uniform warm and rainy climate year-round, in practice bananas are grown throughout the tropics and subtropics. Bananas are found in

table 1

Banana production in tonnes by cultivar group and region for 2011

Tonnes	Cooking bananas		Dessert bananas		Total
	Plantain AAB group	Highland bananas + ABB + other ABB +AAA+AA	Cavendish	Gros Michel & others	
North America	0	1 000	8 000	100	9 100
South America	5 664 779	416 491	12 479 463	3 927 750	22 488 483
Central America	783 830	63 835	7 551 531	81 500	8 480 696
Caribbean	1 061 898	669 130	1 125 518	199 930	3 056 476
West and Central Africa	8 981 861	758 796	2 349 174	485 342	12 575 173
East Africa	944 716	12 574 031	2 726 439	874 516	17 119 702
North Africa & Middle East	1 031	135 879	1 969 375	71 871	2 178 156
Asia	2 130 774	10 726 630	32 034 984	12 942 172	57 834 560
Oceania	1 286	530 043	674 681	259 556	1 465 566
Europe	2	20	422 641	30	422 693
World Total	19 570 177	25 875 855	61 341 806	18 842 767	125 630 605

Source: Fruitrop, 2011

southern Europe, northern Africa, Pakistan, northern India and China at their northern extreme and in Argentina, Paraguay, South Africa and Australia at their southern extreme. They are also grown in the tropics into mid-altitudes of higher than 1 500 metres above sea level in the Andes, Himalayas, Kilimanjaro and the East African Highlands.

The production and consumption of the different groups vary geographically. Cavendish is concentrated in Asia and Latin America and the Caribbean, while cooking bananas are found primarily in Asia (India, Indonesia and the Philippines) and East Africa. Other dessert bananas are found primarily in Asia and Latin America. Plantains are concentrated in West and Central Africa and Latin America, but production is also found in East Africa and Asia.

The effects of climate change on agriculture have been proposed in terms of both productivity and the risk of disruption of production, with implications for food security and income for millions of households worldwide. The increase in average temperature that characterizes climate change is likely to generate an increase in the frequency and severity of extreme and moderate weather events resulting in additional episodic losses. This converts into increased vulnerability in agriculture over the medium and long term unless measures are taken to strengthen the resilience of production systems.

This study examines the effects of climate change on banana. The study also contributes to the global effort to build the response capacity of sectors linked to commodities of global importance. The study's main objectives are to:

1. Quantify the effects of climate change on growing conditions for banana globally;
2. Estimate the impacts of climate change on indicators of banana productivity;
3. Estimate the potential effects of climate change on the primary banana leaf disease;
4. Identify major changes in potential areas gained and lost in subtropical and tropical highlands and tropical lowlands due to climate change for 2030, 2050 and 2070.

2. Climatic zones suitable for banana production

To classify areas according to a range of suitability criteria for banana production, a spatial modelling procedure was developed and implemented in ArcGIS (Esri Inc.), using Esri Model Builder. Actual Mean Monthly Temperature and Precipitation (Spatial resolution: – 5 kilometre (km) – 2.5 arc-min) were used for the global classification analysis found in the portal WorldClim (Hijmans *et al*., 2005).

Three categories of lands were identified in the initial round of analysis (see Table 2 for key temperature parameters for banana growth). Areas not suitable for banana production were defined as areas having three or more months with temperatures below 13 °C. Globally suitable areas were classified into tropical and subtropical banana production areas. Tropical areas have a relatively uniform average monthly temperature throughout the year, while subtropical areas were considered those which have a difference between the warmest and coolest months of greater than 8 °C (as well as with fewer than three months below 13 °C).

For both the tropics and subtropics, subcategories were identified based on average annual temperature, total annual rainfall and length of the dry season (Table 4). A month is considered dry if it has less than 60 mm precipitation. Three categories of average annual temperature were identified: 13-18 °C, 18-24 °C and >24 °C. While banana will survive in the 13-18 °C range, leaf emission is very slow and a stem may take over two years to flower. Assuming no water limitations, in the 18-24 °C range, planting to harvest will generally take between 12 months and 24 months, while in the >24 °C range, a stem will produce a bunch in less than one year. For assessing total annual rainfall, four categories were proposed: <900 mm, 900-1500 mm, 1500-2500 mm and >2500 mm. Depending on length of dry season, banana may suffer growth limitations at below 1500 mm/year of rainfall, while if rainfall is above

table 2

Key temperature parameters for banana growth

Temperature (°C)	Effect of temperature on banana growth
47	Thermal danger point, leaves die
38	Growth stops
34	Physiological heat stress starts
27	Optimum mean temperature for productivity
13	Minimum mean temperature for growth, field chilling
6	Leaf chlorophyll destruction
0	Frost damage, leaves die

this amount conditions for growth are more favourable. Two categories for length of dry season are used: three months or fewer with less than 60 mm of monthly rainfall (i.e. “dry”) and more than three dry months. The combination of total annual rainfall and length of dry season provides an indication both of viability for banana growth without irrigation and of the conditions for leaf diseases. With fewer than three dry months and greater than 150 mm/month of rainfall, banana grows well year-round without irrigation. Such conditions are also more favourable for leaf diseases.

Based on these parameters, the current suitability for banana cultivation can be mapped and quantified (Figure 1, Table 3). Currently across the globe the land area not suitable for banana – 140 million square kilometres – is far larger than the tropical and subtropical lands suitable for banana. Potential banana lands in the subtropics and tropics are split about evenly, with around 40 million square kilometres in each climatic region.

For the subtropics, the vast majority of lands (36 million km^2) receive less than 900 mm of rainfall annually (Figure 2, Table 5) and over half of these also experience annual temperatures between 13-18 °C. These lands are suitable for banana only with special practices. Around seven million square kilometres in the subtropics offer more favourable rainfall and temperature conditions for banana.

For the tropics, in terms of temperature, all lands are suitable except high elevations, which represent only about two million square kilometres (Table 5). Suitable areas in terms of temperature and rainfall, including the extremely wet zones with over 2500 mm rainfall, represent around 30 million square kilometres. This can be contrasted with a current area under banana and plantain production of 126 000 square kilometres (calculated based on 10 tonnes/hectare approximate yield).

3. Climate change impacts through 2070 on areas of climatic zones for banana suitability

The impact of climate change on the land area for agroclimatic zones was also mapped and quantified using climate change projections based on data from the Climate Change, Agriculture and Food Security (CCAFS) data portal (Ramirez and Jarvis, 2008) with a resolution of five kilometres. Projections were done for 2030, 2050 and 2070, assuming scenario A2 and the average of 20 general circulation models (GCMs). Tropical and subtropical areas are combined in this analysis, although shown separately in Table 5.

Over the projected period, the most important banana-growing areas will increase substantially in area (Figure 2). Zones 131, 231, 331 and 431 will all increase substantially in area. In each of

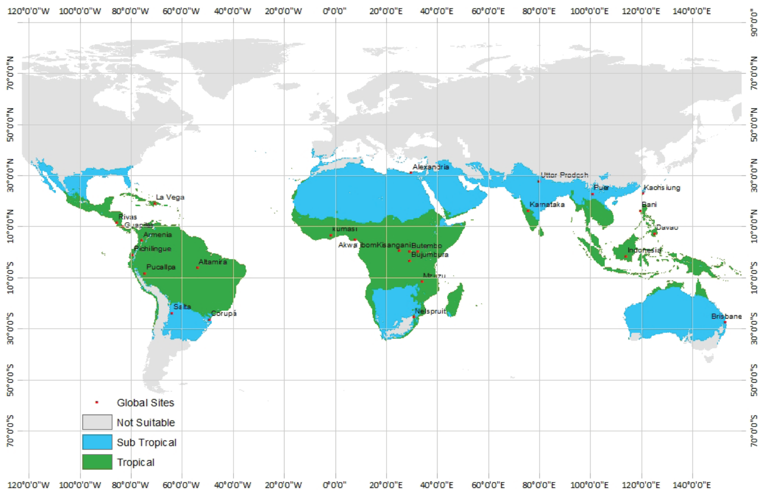
table 3

Total area (in km^2) for three categories of suitability for banana currently and with climate change

Category	Current	2030	2050	2070
Not Suitable	141 224 300	134 962 475	132 472 650	130 299 200
Subtropical	41 201 350	40 346 450	40 194 675	39 829 175
Tropical	43 189 025	46 952 150	49 593 750	52 132 700

figure 1

Current global distribution, showing unsuitable, subtropical and tropical regions for banana



the rainfall regimes (represented by the first digit in Table 5), there is a decline in the areas with cooler temperatures (represented by second digit of 1 (13-18 °C)) and an increase in higher temperatures (represented by second digit of 2 or 3 (18-24 °C or >24 °C)). Table 5 also highlights a new category, 141, to identify those areas which will be subject to excessively high temperatures (>35 °C for at least three months per year). These areas first appear in 2050 and increase substantially by 2070, although they make up only a small percentage of area suitable for banana.

This broad overview of suitability based on temperature and rainfall indicates that lands suitable for banana production will continue to be widely available for banana-growing in the subtropics and tropics even with climate change. However, there will be an increase in climatic zones with higher temperatures and the appearance of areas not suitable due to extended periods of extremely high temperatures. This suggests that if temperatures continue to increase beyond 2070, more areas in the tropics may be lost for banana production due to excessively high temperatures.

table 4
Agroclimatic zones

	<900 mm (1)				**900-1500mm (2)**			
> 3 dry months (1)	13-18 °C (1)	18-24 °C (2)	>24 °C (3)	>35 °C (4)	13-18 °C (1)	18-24 °C (2)	>24 °C (3)	>35 °C (4)
	111	121	131	141	211	221	231	241
	<900 mm (1)				**900-1500mm (2)**			
< 3 dry months (2)	13-18 °C (1)	18-24 °C (2)	>24 °C (3)	>35 °C (4)	13-18 °C (1)	18-24 °C (2)	>24 °C (3)	>3 5°C (4)
	112	122	132	142	212	222	232	242
	1500-2500 mm (3)				**>2500 mm (4)**			
> 3 dry months (1)	13-18 °C (1)	18-24 °C (2)	>24 °C (3)	>35 °C (4)	13-18 °C (1)	18-24 °C (2)	>24 °C (3)	>35 °C (4)
	311	321	331	241	411	421	431	441
	1500-2500 mm (3)				**>2500 mm (4)**			
< 3 dry months (2)	13-18 °C (1)	18-24 °C (2)	>24 °C (3)	>35 °C (4)	13-18 °C (1)	18-24 °C (2)	>24 °C (3)	>35 °C (4)
	312	322	332	342	412	422	432	442

4. Climate change projections for 24 banana-growing areas in Latin America, Africa and Asia

To further explore the implications of climate change for banana-growing, we identified 24 sites where banana is an important crop, located in contrasting climatic zones in Latin America, Africa and Asia (Table 7). Eight sites were chosen from each major continent, with no more than two sites per country. These sites represent 13 of the climatic zones in Table 5. They include seven subtropical sites, five tropical highland sites, six wet/dry tropical sites and six wet tropical sites (see Figures 3-6 for the different groupings and their projected climate change). For each site, changes in average temperature and monthly rainfall were projected for 2030, 2050 and 2070, using data from the CCAFS database portal (Ramirez and Jarvis, 2008) with a resolution of five kilometres. Projections assume scenario A2 and an average of 20 GCMs.

The subtropical sites (Figure 3) show a marked difference between a cooler season when minimum temperatures are as low as 10 °C and a high sun season with elevated temperatures. Two sites have extremely high temperatures in the summer season – Salta, Argentina and Uttar Pradesh, India – with temperatures ranging above 40 °C, especially for 2050 and 2070. Rainfall is highly variable for the different sites. Some sites have highly uniform rainfall distribution from month to month, while others receive a major part of the annual rainfall in only a few months. The projections for the next decades show little major change in monthly rainfall distribution.

For the tropical highland sites (Figure 4), temperatures are quite uniform throughout the year, except for the site in China, which is a

table 5

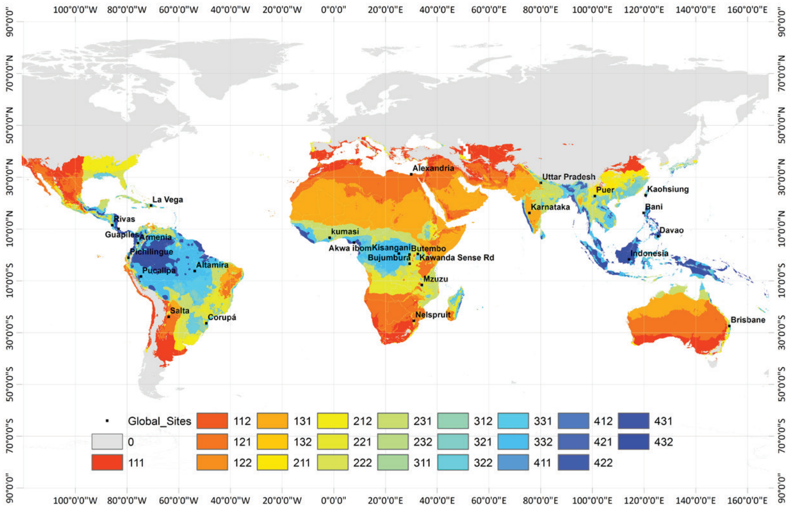
Changes in area (in km²) in climatic zones for banana in subtropical and tropical regions for climate change projections through 2070

Value	Subtropical					Tropical				
	Current	2030	2050	2070		Current	2030	2050	2070	
0	0	1 350	1 750	1 875	+					
111	1 907 000	1 202 500	775 525	542 900	-	616 725	382 125	253 025	183 900	-
112	4 450	3 375	12 575	16 950	+	3 975	3 400	1 475	1 275	-
121	17 749 650	15 634 075	13 442 900	11 594 125	-	2 495 050	1 638 800	1 234 875	933 800	-
122	3 400	1 200	3050	17 175	+	9 700	2 975	4 225	3 050	-
131	16 018 350	21 161 325	25 159 125	28 595 100	+	4 653 925	5 556 050	6 085 825	6 333 975	+
132	0	0	0	25	+	3 600	5 425	4 950	5 325	+
141	0	0	225	30 700	+	0	0	0	17 975	+
	35 682 000	38 002 475	39 393 400	40 796 975	+	7 783 000	7 588 775	7 584 375	7 479 300	-
211	251 325	266 700	241 575	205 875	-	326 900	199 475	126 225	85 100	-
212	472 000	229 150	171 200	159 975	-	82 800	57 375	49 450	50 450	-
221	1 384 225	1 299 950	1 370 450	1 319 475	-	4 449 025	2 900 100	2 138 425	1 234 025	-
222	1 067 550	1 580 275	1 842 650	1 962 050	+	772 075	355 225	232 675	151 400	-
231	1 756 375	2 299 825	2 600 575	3 034 800	+	6 807 200	8 279 450	8 957 925	9 626 725	+
232	24 225	74 700	168 725	241 200	+	601 775	916 975	943 325	1 065 850	+
	4 956 000	5 750 600	6 395 175	6 923 375	+	13 400 000	12 708 600	12 448 025	12 213 550	-
311	89 900	69 950	51 825	38 025	-	78 375	32 575	17 475	8 650	-
312	166 950	106 700	69 300	51 200	-	182 175	109 200	81 500	63 275	-
321	760 350	602 375	521 200	445 975	-	1 167 375	561 550	374 200	275 825	-
322	808 575	1 237 050	1 491 850	1 707 725	+	1 669 025	829 525	620 600	494 750	-
331	404 525	764 225	1 087 850	1 372 525	+	2 930 250	3 813 325	4 377 875	4 755 450	+
332	14 425	25 875	107 600	250 525	+	8 185 925	8 539 500	8 319 750	7 963 500	-
	2 245 000	2 806 175	3 329 625	3 865 975	+	14 213 000	13 885 675	13 791 400	13 561 450	-
411	17 200	11 725	8 825	7 275	-	800	2 300	2 525	1 400	+
412	3 225	2 625	2 375	3 150	-	98 825	76 000	64 125	55 375	-
421	128 850	103 875	94 850	86 600	-	56 125	41 575	31 275	25 700	-
422	31 975	33 625	39 025	42 600	+	792 950	506 150	393 100	312 050	-
431	116 025	190 700	257 125	317 800	+	384 025	421 500	457 500	494 250	+
432	5 750	21 200	35 600	50 600	+	4 830 875	5 115 850	5 422 300	5 686 100	+
	303 000	363 750	437 800	508 025	+	6 164 000	6 163 375	6 370 825	6 574 875	+

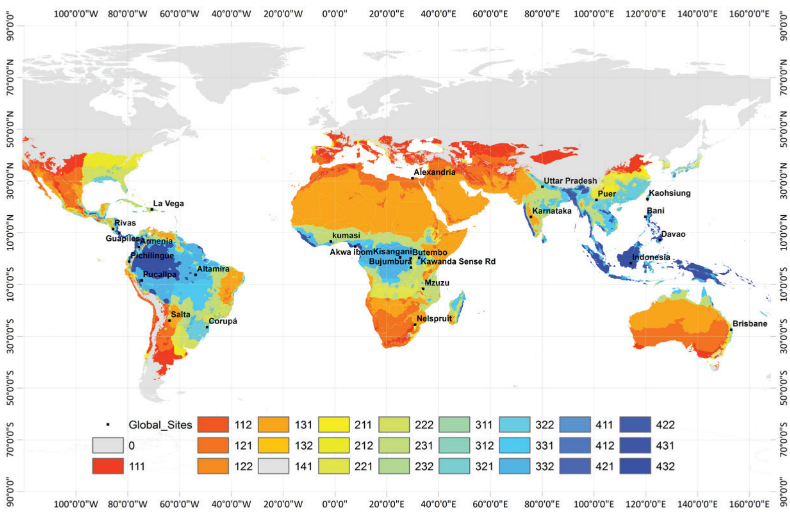
figure 2

Map showing changing distribution for climatic zones for banana suitability (Table 4) A: Current, B: 2050

A: Current



B: 2050



highland area (1300 metres above sea level), although subtropical in location. For the China site, winter temperatures are limiting for banana growth, although according to climate change projections, the winter cold will be moderated. Temperatures in the other sites – even by 2070 – range between 15 and 30 °C, well within the acceptable parameters for banana growth. Several sites will shift to the agroclimatic zone which has temperatures >24 °C. Rainfall distribution varies from site to site. Sites such as Kawanda, North Kivu and Armenia have no dry months, while the other sites have seasonal dry periods. The monthly rainfall distribution is not projected to change over the period studied.

For the remaining two blocks of sites, wet/dry tropics (Figure 5) and wet tropics (Figure 6), average temperatures are projected to increase over the next 50 years by over 3 °C, from 25 °C to 28 °C, but remain largely within a favourable range of 25-30 °C. Maximum temperatures will reach the danger zone for banana in the India site by 2070, although even for current production, occasional heat waves may cause damage to new banana plants and to emerging bunches. On average, rainfall is not highly variable, except for the sites in Central America and the Caribbean, where rainfall is projected to decline by 2050 and 2070.

Five of the 24 sites will shift agroclimatic categories due to temperature change over the period from the present to 2070: Kawanda, Uganda; Butembo, Democratic Republic of the Congo (DRC); Mzuzu, Malawi; Salta, Argentina; and Armenia, Colombia (Table 6). These sites will shift from an 18-24 °C temperature range to a >24 °C temperature range. Three sites will shift the climatic zone to which they are mapped due to rainfall changes: Rivas, which will become drier; Kawanda, which is projected to become wetter; and La Vega. In La Vega several months hover right around the limit of 60mm/month, which is considered the difference between a dry month and a wet month and thus changes the length of the dry season based on rainfall.

In summary, based on this analysis of 24 sites:

- All sites demonstrate the linear increase in temperatures – average as well as minimum and maximum temperatures – which has made climate change a concern for humankind.
- Only three sites show trends towards extremely high temperatures – two in India and one in Argentina – which may limit banana growth.

table 6

Shift in agroclimatic zone for sites showing change in category with climate change (other sites unchanged)

Region	Country	Town	Current	2030	2050	2070
Africa	Uganda	Kawanda	222	222	322	332
Africa	DRC	Butembo	312	322	322	322
Africa	Nigeria	Akwa Ibom	432	432	432	432
Africa	Malawi	Mzuzu	321	331	331	331
Africa	DRC	Kisangani	332	332	332	332
America	Argentina	Salta	121	121	131	131
America	Colombia	Armenia	322	322	322	332
America	Dominican Rep.	La Vega	222	221	221	221
America	Nicaragua	Rivas	331	231	231	231

table 7

Agroclimatic zone for selected sites grouped by zones

Zone	Region	Country	City/Province	Town	Longitude	Latitude
121	Africa	South Africa	Nelspruit	Nelspruit	30.97	-25.47
121	America	Argentina	Salta	Salta	-63.86	-23.92
131	Asia	India	Bagalkot	Karnataka	75.69	16.19
222	Africa	Uganda	Kampala	Kawanda	32.52	0.41
222	America	Dominican Rep.	La Vega	La Vega	-70.71	19.06
222	Australia & Oceania	Australia	Queensland	Brisbane	153.02	-27.47
231	Africa	Burundi	Bujumbura	Bujumbura	29.36	-3.38
231	Asia	India	Uttar Pradesh	Uttar Pradesh	80.12	27.81
232	Africa	Ghana	Kumasi	Kumasi	-1.60	6.69
312	Africa	DRC	Kivu Norte	Butembo	29.28	0.13
321	Africa	Malawi	Mzuzu	Mzuzu	34.07	-11.64
321	Asia	China	Yunnan	Puer	100.99	22.78
322	America	Brazil	St. Catarina	Corupá	-49.30	-26.44
322	America	Colombia	Quindío	Armenia	-75.72	4.53
331	America	Nicaragua	Rivas	Rivas	-85.64	11.51
331	America	Ecuador	Los Rios	Pichilingue	-79.46	-1.10
332	Africa	DRC	Kisangani	Kisangani	25.18	0.53
332	America	Peru	Ucayali	Pucallpa	-74.58	-8.38
332	Asia	Philippines	Davao Region	Davao	125.46	7.22
421	Asia	Taiwan	Kaohsiung	Kaohsiung	120.66	23.06
431	Asia	Philippines	Bani	Bani	119.86	16.24
432	Africa	Nigeria	Akwa Ibom	Akwa Ibom	7.86	4.80
432	America	Costa Rica	Guapiles	Guapiles	-83.26	10.04
432	Asia	Indonesia	Cent. Kalimantan	Palangkaraya	114.26	-1.70

- In most sites the rainfall distribution during the year and the amount of rainfall per month are quite stable from the present through 2030, 2050 and 2070. The sites in Central America and the Caribbean are projected to experience declines in monthly rainfall, while sites in Uganda and Burundi show a tendency to increase.

5. Changes in potential productivity for 24 key banana-growing areas in Latin America, Africa and Asia for 2030, 2050 and 2070

The analysis in the previous section is based on general growing conditions for banana and provides an overview of the effects of average climate change. Diverse tools have been used to convert the general requirements for growth into more quantified effects. For example, niche modelling, such as with Maxent, Bioclim and Ecocrop, has been used in many different crops. Ecocrop has been used in banana (van den Bergh *et al*., 2012). Models such as Ecocrop use annual data for temperature and rainfall which limits their applicability for crops that have a 12- month cycle and that may use irrigation.

To establish a quantitative index of the effects of changing temperature and water availability on banana growth, we developed a calculation using monthly temperature and rainfall. Leaf emission rate is a key variable in banana productivity, because the rate of leaf emission is closely correlated to the length of the vegetative cycle and the development time from one bunch to the next for each banana mat. Leaf emission rate is highly influenced by temperature and available water. Three calculations were carried out: 1) effect of temperature alone, measured by growing degree days (GDD); 2) thermal development units (TDU), in which GDD are reduced by excess or insufficient available soil water for optimum growth; and 3) water deficit, based on a water balance using natural rainfall and optimum crop needs. All three calculations were carried out for current conditions and 2030, 2050 and 2070.

5.1 Method to estimate banana GDD and TDU

The basic concept of GDD is that plant development will occur when temperatures exceed a base temperature and cease when a non-lethal maximum temperature is exceeded. GDD assigns a heat value to each day, then the values are added together to give an estimate of the amount of seasonal growth that banana plants have to achieved. If the temperature is only slightly above base temperature, few GDD are accumulated. If the temperature is just below the non-lethal maximum temperature, then a higher amount of GDD are accumulated. Depending on the unit of time of the calculations and the temperatures, the number of growing degree days are accumulated for the period. To estimate GDD for banana, monthly temperatures were used. A base temperature of 13 °C was subtracted from the monthly average temperature to give an average GDD. If the average GDD were calculated to be a negative number that number was made equal to zero. If the mean monthly temperature exceeded 35 °C, then the GDD would be 0, due to high temperatures (Thomas *et al.*, 1998; Turner and Lahav, 1983). Monthly GDD were calculated by multiplying daily GDD calculated based on monthly temperatures by the number of days of each month and then summing GDD for each month for the year. The total number of GDD for the year was then converted to the number of leaves by dividing by 108 °C, the number of GDD needed to generate a new leaf. Some effect of photoperiod on GDD accumulation has been shown by Fortescue, Turner and Romero (2011), but that effect was not included in this analysis.

The calculation of number of leaves/year by means of TDU uses GDD reduced by the effects of water limitation. The relationship between TDU and GDD for a time period is:

figure 3

Average monthly temperature and rainfall projections for subtropical banana-growing areas, using average values for 20 GCMs under scenario A2. A: Nelspruit (South Africa), B: Salta (Argentina), C: Brisbane (Australia), D: Uttar Pradesh (India), E: Corupá (Brazil), F: Kaohsiung (Taiwan)

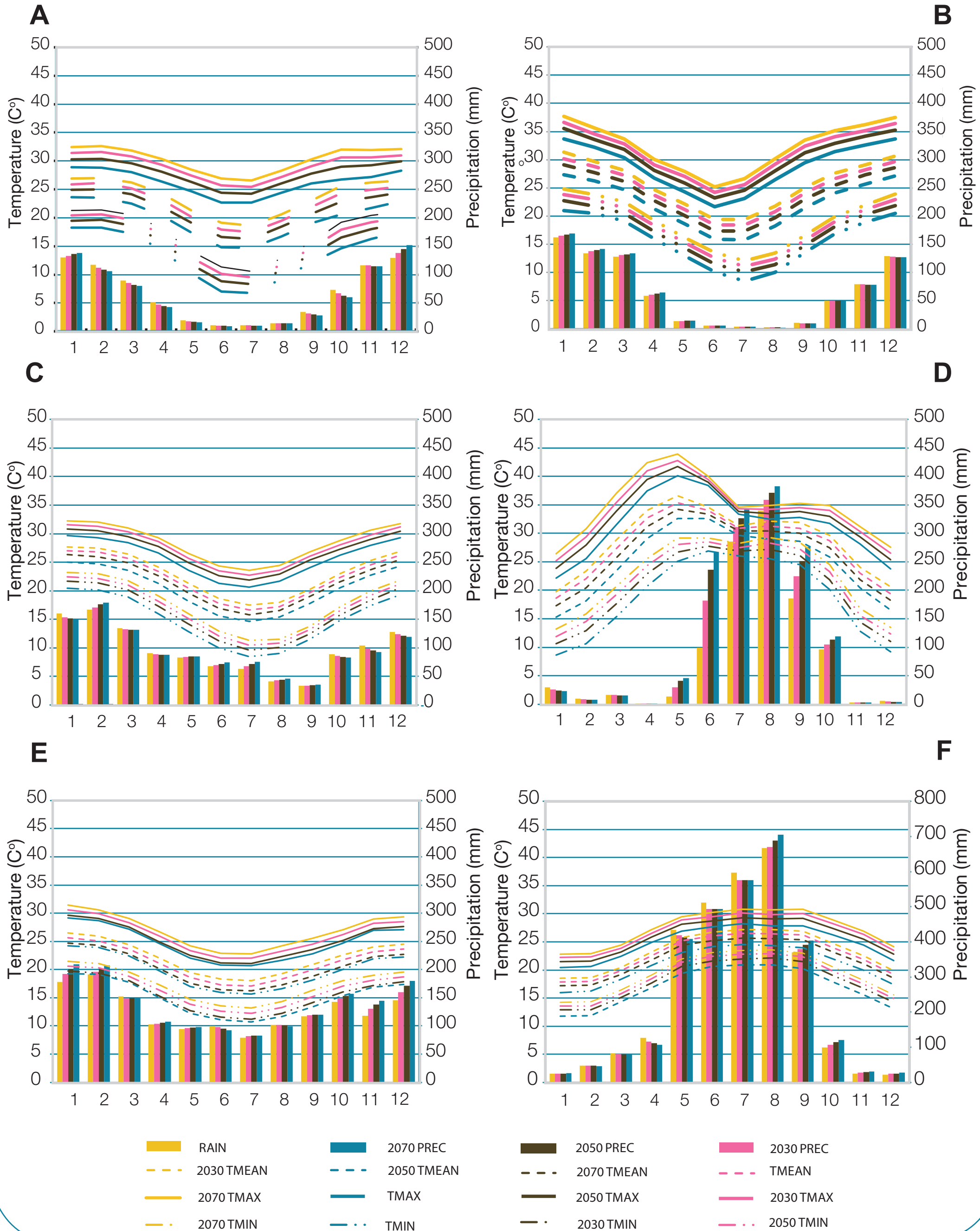


figure 4

Average monthly temperature and precipitation projections for highland tropical banana growing areas, using average values for 20 GCMs under scenario A2. G: Puer (China) subtropical highland, H: Kawanda (Uganda), I: Bujumbura (Burundi), J: North Kivu (DRC), K: Mzuzu (Malawi), L: Armenia (Colombia)

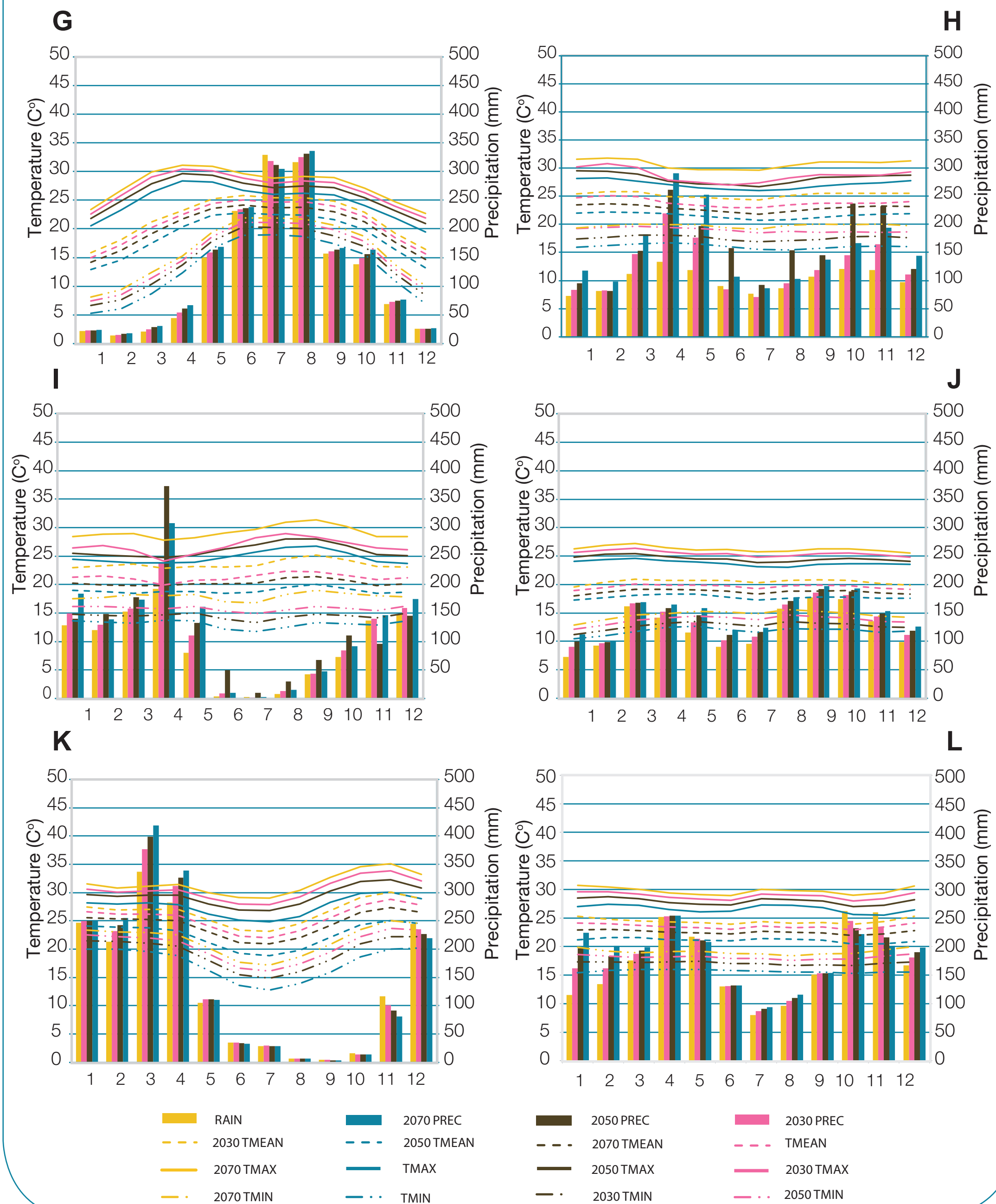


figure 5

Average monthly temperature and precipitation projections for wet/dry tropical banana-growing areas, using average values for 20 GCMs under scenario A2. M: Karnataka (India), N: La Vega (Dominican Republic), O: Kumasi (Ghana), P: Rivas (Nicaragua), Q: Pichilingue (Ecuador), R: Pucallpa (Perú)

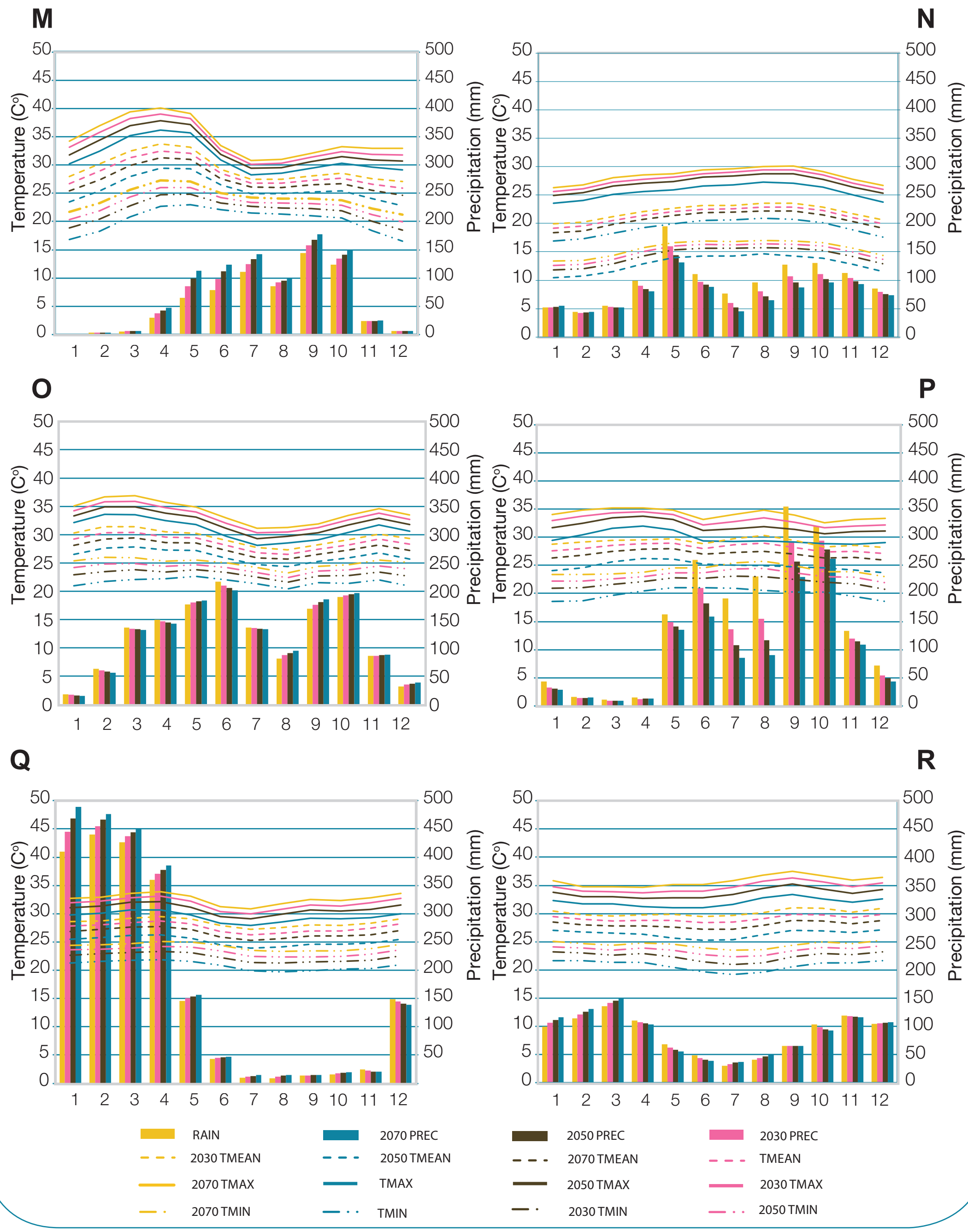
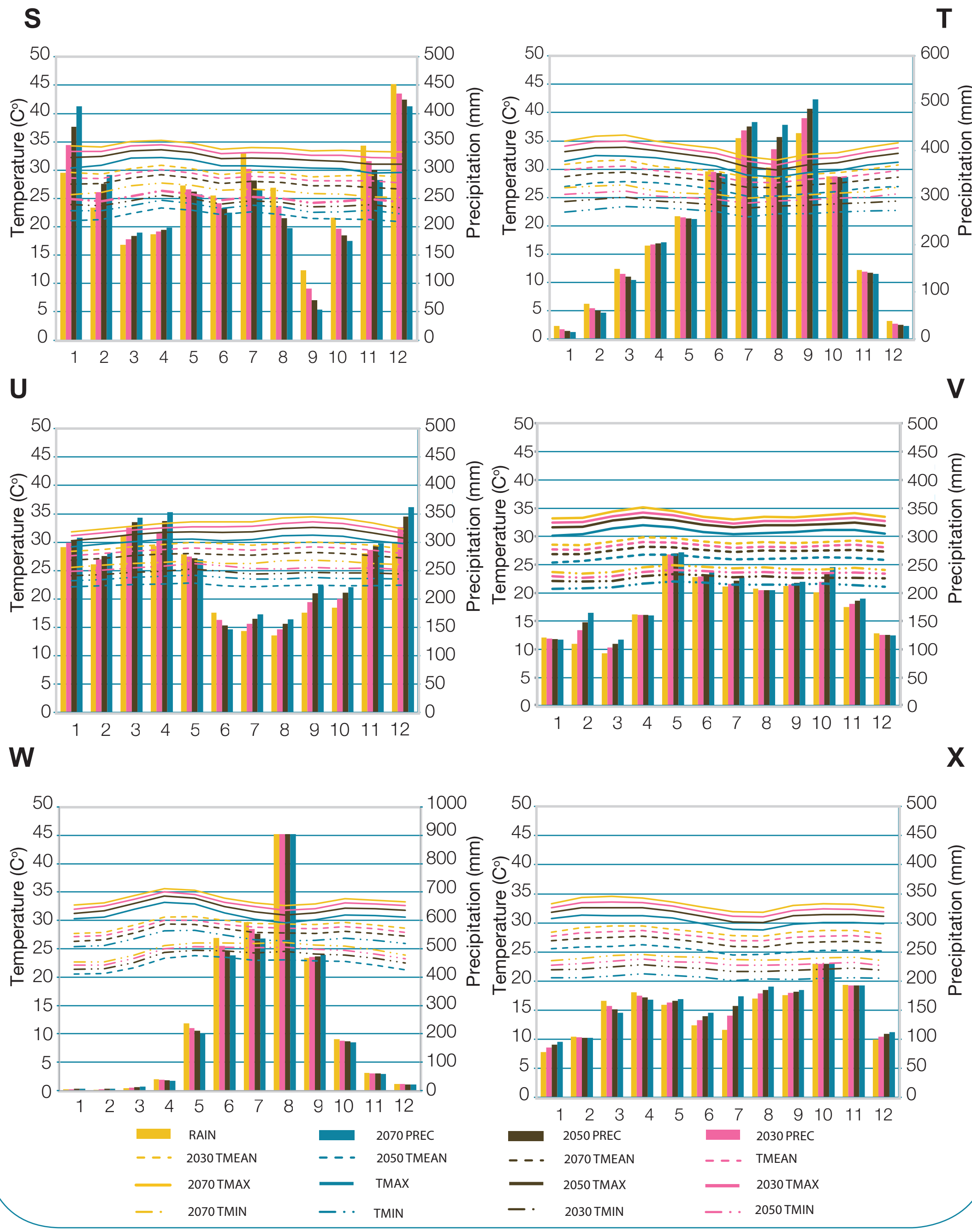


figure 6

Average monthly temperature and precipitation projections for wet tropical banana-growing areas, using average values for 20 GCMs under scenario A2. S: Guapiles (Costa Rica), T: Akwa Ibom (Nigeria), U: Central Kalimantan (Indonesia, V: Davao (Philippines), W: Bani (Philippines), X: Kisangani (DRC)



$$TDU = GDD * Pf * Wf\ (^oC\ d)$$

Where: ***Pf*** is a scalar (0.0 to 1.0) for photoperiod and ***Wf*** is a scalar (0.0 to 1.0) for soil water balance. ***Pf*** was not taken into account in this study. The soil water balance (***Wf***) was estimated monthly, from the ratio of rainfall/potential evaporation (Rain/PET), taking ***Wf*** as 1.0 if the ratio fell between 1.0 and 1.1. If Rain/PET was above 1.1 then ***Wf*** = 1 + 0.2 (1– Rain/PET), allowing for a negative effect for excess of water (Fortescue *et al*., 2011).

5.2 Method to estimate water deficit for bananas

The irrigation water need or water deficit for banana was estimated on a monthly basis and calculated for the year as the difference between the crop water need and that part of the rainfall which can be used by the crop, known as effective rainfall. Actual evapotranspiration (AET) is the quantity of water that is removed from the soil due to evaporation and transpiration processes (Allen *et al*., 1998). AET is dependent on solar radiation and temperature as well as the vegetation characteristics, quantity of water available in the soil and soil hydrological properties (mainly soil water retention curves):

$$AET = Ksoil * Kc * PET\ (mm/month)$$

Where: ***Ksoil*** = reduction factor dependent on volumetric soil moisture content (0-1), ***Kc*** = banana crop coefficient dependent on the development of the crop (0.3-1.3). The crop coefficient (***Kc***) is used to estimate the crop water use for reference PET for different crops or vegetation types. A ***Kc*** value for banana of 1.15 was taken from the literature (Allen *et al*., 1998; Freitas, *et al.*, 2008; Silva and Bezerra, 2009).

The effective rainfall in this study was estimated using an empirical formula from FAO/Water Resources, Development and Management Service (AGLW) based on analysis carried out for various climatic data (Clarke *et al*., 2001; Smith, 1992).

Both TDU and AET depend on an estimation of potential evaporation (PET). The Hargreaves model was chosen (Hargreaves and Allen, 2003), as it performed almost as well as the FAO Penman-Monteith model, but required less parameterization (Hargreaves and Allen, 2003; Trajkovic, 2007). To calculate PET, the Hargreaves model uses mean monthly temperature and global solar radiation at the surface, measured in units of water evaporation.

5.3 Method to estimate water deficit for bananas

The calculations for annual leaf emission based on GDD (Table 8) show the effects of the linear increase in temperature alone on total leaf emission for a 12-month period. From the present to 2070, GDD will increase by 30 percent, i.e. about 1000-1200 across all sites. This increase results from the increase in monthly average temperatures. This represents an increase in leaf emission of about 10 leaves, although a few sites show slightly lower increases. This increase represents more potential bunches/hectare per year. The site in Uttar Pradesh, India, is notable, since by 2070, the site is no longer viable for banana based on an extended period of over three months with average temperatures of about 35 °C.

The calculation of leaf emission based on TDU takes into account not only the effects of temperature, but also the water limitations for rainfed production (Figure 7, Table 8). In those sites where total leaf emission continues to be limited by water, rather than temperature, leaf emission rates are stable or increase only slightly. In other sites with more uniform rainfall throughout the year, such as Kisangani, Corupá and Armenia, leaf emission increases by up to ten leaves over the 12-month period by 2070.

The differences between increases in leaf emission based on GDD and TDU highlight the importance of water availability in banana productivity. This is projected using a calculation of water deficit (Table 9). From the present through 2070, the increase in average temperature will result not only in an increased leaf emission potential and the accompanying increase in number of bunches, but also an increase in crop water demand to meet PET. The amount of water to be applied as irrigation to meet plant needs will increase by 12-15 percent over the period. The demands are higher for the drier sites than for sites with rainfall >2500 mm/year.

6. Changes in leaf diseases for six key banana-growing sites in Latin America, Africa and Asia for 2030, 2050, and 2070

In addition to effects on leaf emission and water demand, average climate change may also affect the conditions for disease incidence and severity. The most important leaf disease, Mycosphaerella fijiensis or black leaf streak (BLS), was used as an indicator of the projected effect of climate change on banana pest management.

Six of the 24 sites were chosen for more detailed analysis based on the rainfall categories – three subtropical sites: Salta (121); Brisbane (222); and Puer (321), one tropical upland site: Kawanda (222) and two tropical sites: Pichilingue (331); and Davao (332).

To project the effect of changes in average climate on BLS, daily weather data are needed. The simulator program MarkSim works at a scale of 30 arc-seconds to simulate daily rainfall patterns from the database WorldClim (Hijmans *et al*., 2005). For each of the years 2030, 2050 and 2070, MarkSim was run ten times to generate daily rainfall patterns. These were then averaged to obtain a single daily rainfall pattern for the location. These daily patterns were then used in two calculations for BLS – velocity of evolution and state of evolution.

The velocity of evolution of BLS is linked to temperature. The minimum temperature for the germination of BLS is 12 °C, the optimal is 27 °C and the maximum is 36 °C (Porras and Perez, 1997). In general, the germination of conidia is optimal between 25 °C and 30 °C following a quadratic function type-response with an estimation of 26.5 °C as an optimal temperature for germination. Additionally, almost 100 percent germination is presented after 24 hours (Jacome *et al*., 1991; Jacome and Schuh, 1992). For ascospore germination, the estimated optimal temperature is 25 °C (Jacome *et al*., 1991; Jacome and Schuh, 1992). Ascospores and conidia have different responses to relative humidity. Ascospores germinate only when relative humidity is higher than 98 percent, while conidia germinate in a wider range of humidity (88 to 100 percent) (Jacome *et al*., 1991). The daily sum of development rates of evolution of BLS was calculated based on maximum and minimum daily temperature with a simple regression developed by Porras and Perez (1997).

The projected increase in temperatures at all six sites could be expected to result in increased growth rates for the germination tube of spores of BLS and more rapid disease development. As shown in Figure 8, response is variable by site, but in general by 2050 and 2070 the velocity of evolution is projected to increase.

A second approach to projecting the effect of average climate change on BLS is based on the state of evolution or advance of the disease. In general, leaf infection by BLS ascospores is not observed in the absence of leaf wetness. Infection by BLS conidia occurs at leaf wetness of between 0 to 18 hours. Leaf lesions appear 14 days after inoculation of plants subjected to 18 hours of leaf wetness (cited by Jacome and Schuh, 1992). In general, the development of BLS in the field can be monitored by the evolution of BLS in leaf four (EE4H) or leaf five (EE5H). Taking into account the 14-day delay before appearance of the disease, Perez *et al*. (2006) developed a model to predict the evolution state of EE4H based on the accumulated rainfall for 14 days five weeks before

table 8

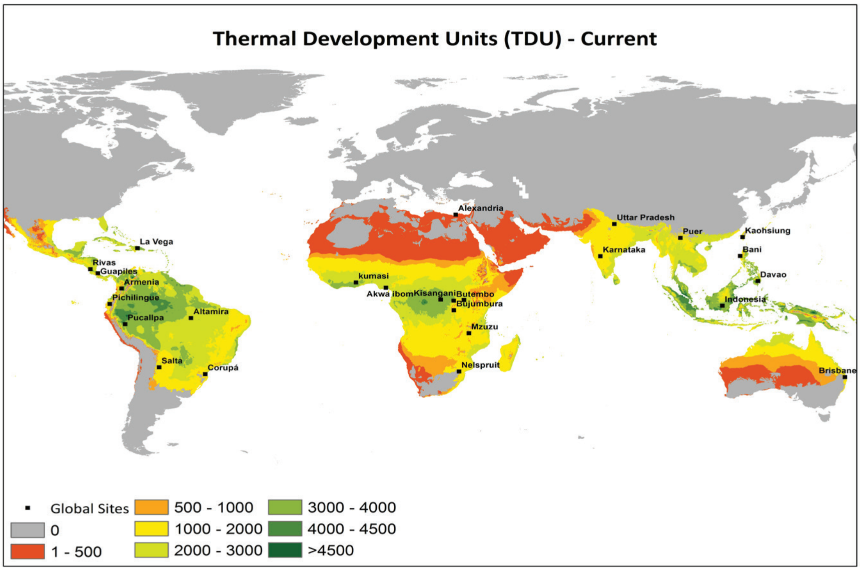
Total annual leaf emission based on temperature (GDD) and temperature and water (TDU)

Region	Country	Town	GDD				TDU			
			Current	2030	2050	2070	Current	2030	2050	2070
Africa	Uganda	Kawanda	25	30	32	36	21	24	24	25
Africa	DRC	Butembo	15	20	22	26	13	12	14	18
Africa	Burundi	Bujumbura	34	38	39	44	24	21	19	23
Africa	Ghana	Kumasi	39	44	46	50	29	32	35	35
Africa	Nigeria	Akwa Ibom	41	46	47	50	27	28	29	33
Africa	Malawi	Mzuzu	26	31	32	36	16	17	18	20
Africa	DRC	Kisangani	37	42	44	48	35	40	41	44
Africa	South Africa	Nelspruit	19	26	29	33	16	16	17	18
America	Brazil	Corupá	20	25	27	31	18	21	24	27
America	Argentina	Salta	27	31	34	37	16	18	19	19
America	Colombia	Armenia	21	27	28	31	19	26	27	29
America	Costa Rica	Guapiles	40	44	46	49	35	39	40	43
America	Dominican Rep.	La Vega	14	18	19	21	21	24	24	26
America	Nicaragua	Rivas	40	47	51	55	24	27	27	27
America	Peru	Pucallpa	40	45	48	52	36	38	40	41
America	Ecuador	Pichilingue	36	41	42	45	19	23	25	28
Asia	Taiwan	Kaohsiung	24	26	27	29	13	15	17	16
Asia	India	Karnataka	38	43	44	48	16	16	16	17
Asia	India	Uttar Pradesh	35	41	42	0	17	19	19	0
Asia	Philippines	Davao	39	43	44	47	35	37	38	41
Asia	Philippines	Bani	42	47	48	49	17	17	19	18
Asia	Indonesia	Kalimantan	40	44	46	49	35	37	40	42
Asia	China	Puer	16	22	23	28	14	18	18	21
Australia & Oceania	Australia	Brisbane	22	26	28	32	20	23	25	26

figure 7

Thermal Development Units (TDU) for current climate and projection for 2050, using average values for 20 GCMs under scenario A2. A: Current, B: 2050

A: Current



B: 2050

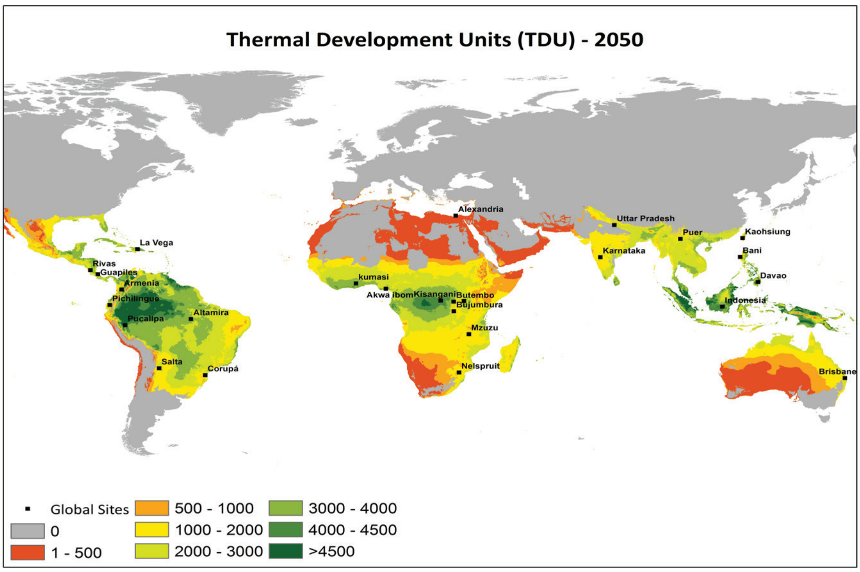


table 9

Banana water demand (AET) and deficit (mm/year) for 24 banana-growing zones for current climate and projections

Region	Country	Town	Crop Water Demand (AET)				Water Deficit (AET-effective rainfall)			
			Current	2030	2050	2070	Current	2030	2050	2070
Africa	Uganda	Kawanda	1743	1829	1899	1988	1077	1203	1312	1405
Africa	DRC	Butembo	1525	1556	1614	1695	651	802	855	873
Africa	Burundi	Bujumbura	1733	1806	1854	1942	996	1339	1432	1446
Africa	Ghana	Kumasi	2026	2084	2095	2241	1154	1106	1104	1320
Africa	Nigeria	Akwa Ibom	1678	1759	1806	1879	613	729	763	777
Africa	Malawi	Mzuzu	1497	1546	1582	1664	642	699	710	734
Africa	DRC	Kisangani	1852	2010	2078	2177	794	943	1046	1150
Africa	South Africa	Nelspruit	1420	1550	1605	1686	992	1165	1215	1312
America	Brazil	Corupá	1316	1347	1336	1399	358	350	397	391
America	Argentina	Salta	1820	1858	1879	1985	1383	1360	1366	1458
America	Colombia	Armenia	1586	1711	1702	1761	370	338	332	565
America	Costa Rica	Guapiles	1879	1924	1940	2000	105	221	230	260
America	Dominican Rep.	La Vega	1712	1808	1835	1893	1016	1113	1149	1231
America	Nicaragua	Rivas	2062	2138	2206	2306	1043	1271	1418	1600
America	Peru	Pucallpa	1995	2061	2090	2202	977	1104	1124	1241
America	Ecuador	Pichilingue	1808	1859	1911	2048	844	837	866	954
Asia	Taiwan	Kaohsiung	1352	1441	1462	1511	410	481	449	526
Asia	India	Karnataka	2058	2097	2133	2169	1682	1757	1790	1786
Asia	India	Uttar Pradesh	1887	2055	2078	2043	1300	1434	1428	1439
Asia	Philippines	Davao	1892	2018	2046	2120	527	669	692	652
Asia	Philippines	Bani	1849	1928	1946	1971	976	1033	1030	1087
Asia	Indonesia	Kalimantan	1658	1741	1768	1883	196	281	324	434
Asia	China	Puer	1716	1700	1753	1973	884	938	957	1119
Australia & Oceania	Australia	Brisbane	1355	1410	1464	1545	691	706	789	866

the date of prediction and the average potential evapotranspiration two weeks before the date of prediction (Perez *et al*., 2006).

This latter approach to projecting the response of BLS to average climate change (Figure 9) indicates that there will probably be little change in the dynamic of BLS seasonally. The lines of different colours in the Figure largely overlap for each of the locations. Given that the rainfall distribution is not projected to change and that this calculation is based on wetness parameters, the disease will continue to be highly problematic in the rainy season and much less aggressive during drier periods of the year.

Bringing together the two calculations for BLS epidemiology and management, the following implications can be tentatively proposed. The period of the year when BLS is the most difficult to manage will remain the same – primarily the rainy season. The disease may become more aggressive, as the velocity of growth of the germination tube of the spores is projected to increase in response to temperature. However, this will only occur in the presence of leaf wetness.

7. Changes at the margins – potential areas lost and gained for banana production in 2030, 2050 and 2070

The shift among the different climatic zones for banana production globally provides a final view of the implications of climate change for the world's capacity to produce bananas. Based primarily on changes in average temperature, the world will continue to have large land areas which are suitable for banana production. We examine first the areas lost to production due to excessively high temperatures, then look at the trends for shifts from unsuitably cold temperatures to 13-18 °C and from 13-18 °C to >24°C for each of the major continents (Table 10).

By 2070, projections indicate that certain areas in Africa and Asia will have at least three months with average monthly temperatures above 35 °C, conditions not suitable for banana production (Table 10). These areas are found in the interior of the Sahara and of India. No areas are projected to be lost in Latin America and the Caribbean.

On the other end of the scale – areas that are unsuitable due to extended cold periods below 13 °C – there is a decline in all continents from the current status through 2070 (Table 10). Over five million square kilometres will shift out of the unsuitably cold category globally, with over 87 percent in Asia, 12 percent in Latin America and only very small areas in Africa.

The category of lands in the range of temperature from 13-18 °C will show an increase in potential banana-growing area based on lands shifting away from unsuitably cold, but will also lose lands due to a shift into the category 18-24 °C. On balance, the lands in this latter category will decline by nearly four million square kilometres. Given the global nature of increasing temperatures, it can be assumed that all shifts are into the next higher temperature category. Shifts due to declining temperatures are unlikely, as are shifts of lands by two categories. The shifts into the 13-18 °C range are quite equally distributed among the three continents. Combining gains and losses over the period of the projections, over nine million square kilometres total may be shifting into this category.

The category of lands in the range of temperature from 18-24 °C will show an increase based on lands shifting from 13-18 °C, but will also lose lands due to a shift of lands into the temperature range >24°C. Over the period of climate change projections done in this study, lands in the range of 18-24 °C will decline by nearly ten million square kilometres – over 60 percent in Africa, followed by 25 percent in Latin America and the Caribbean, with the remainder in Asia. More detailed studies would be useful, but

figure 8

Sums of velocity of BLS evolution based on temperature.
A: Salta, (Argentina), B: Brisbane (Australia), C: Puer (China), D: Kawanda (Uganda),
E: Pichilingue (Ecuador), F: Davao, (Philippines).

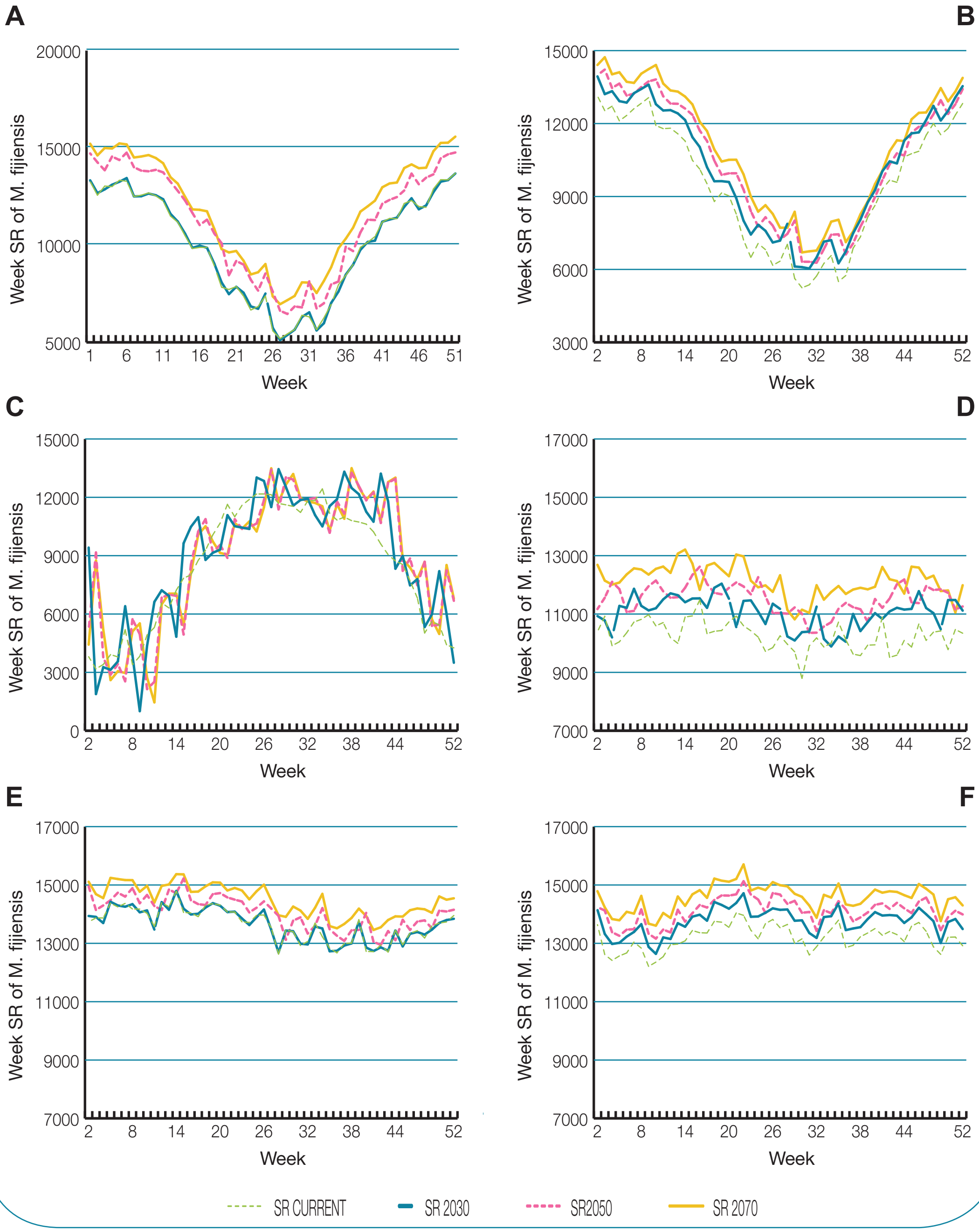
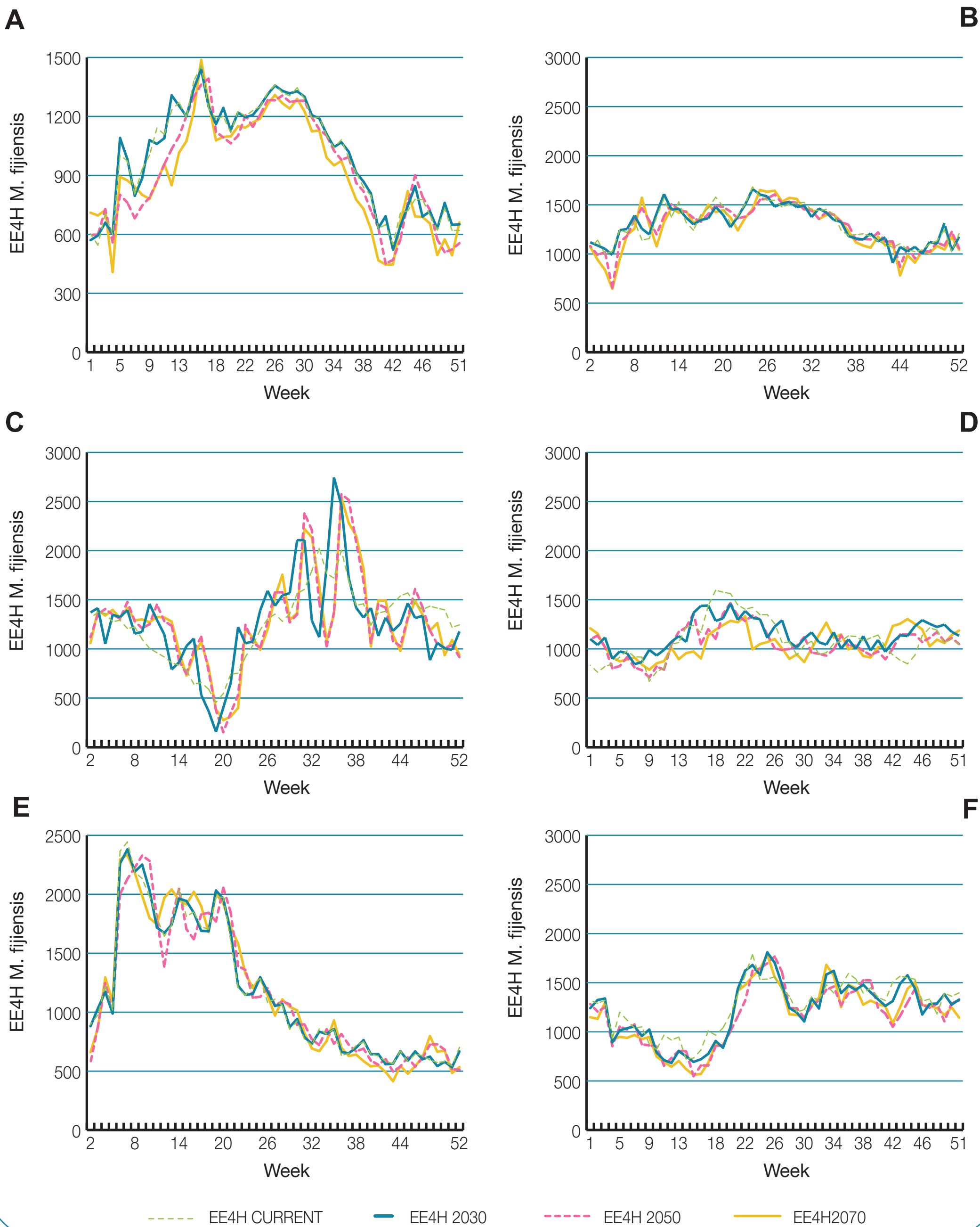


figure 9

State of BLS evolution based on precipitation and EVT. A: Salta (Argentina), B: Brisbane, (Australia), C: Yunnan (China), D: Kawanda (Uganda), E: Pichilingue (Ecuador), F: Davao (Phillipines)



increasing temperatures in tropical highlands and in the subtropics are likely to be responsible for these projected changes. Several of the 24 sites reviewed earlier are projected to shift out of the 18-24 °C range into more tropical zones.

The only category that will increase in area through 2070 is in the temperature range of >24 °C. There will be an increase of nearly 50 percent globally for lands in this category, from 40 to 60 million square kilometers. This increase is primarily divided between Africa and Asia, with seven million square kilometres in each continent and the remainder in Latin America.

By 2070, the 60 million square kilometres of land area in the temperature category >24 °C will provide abundant land for banana production. In terms of available rainfall, 44 percent of this consists of dry lands with <900mm of annual rainfall (agroclimatic zones 131 and 132) (Table 11). Banana production under such conditions requires supplemental irrigation. Land surface in zones 231/232 and 331/332 comprises another 45 percent of the area in this category, divided roughly equally between the two zones. While these four zones represent the most favourable natural conditions for banana production globally, the climatic zone 331 stands out as the best of the four. With 1500-2500 mm annual rainfall and <3 months of dry season, banana plants will grow well throughout the year without additional irrigation. The area of land in this category is largely stable from current conditions to 2070, although for zones 231 and 332, land area will increase by 50 percent due to climate change (Table 11).

In summary, the effects of climate warming are clearly evident in this last analysis. The climatic zones with lower average annual temperatures are projected to lose land area on all three continents, while the land area in the zones with temperatures of >24 °C will increase. This change will favour potential banana productivity due to the increase in bunch number per hectare per year. The average temperature for potential banana lands in this zone is also likely to increase over the period of projections. Among the 24 sites analysed earlier, the lowland tropical areas showed an increase from 25 °C to 28 °C, over the period of the projections. While banana productivity is favoured by this increase, the appearance of zones with excessive heat during certain periods of the year (three months >35 °C) in both Asia and Africa indicates that climate warming must be addressed.

It is worth noting that bananas are often grown in mixed crops with perennials and annuals. Even if increasing temperatures are not unfavourable for banana, they may be unfavourable for the associated crops. We have also used the temperature parameters in this study based on the Cavendish variety. Other banana cultivars may have other critical parameters not yet established. In particular, the group of East African Highland cultivars is known to perform well at higher elevations. Farmers depending on this cultivar group may expand the upper limit in altitude for these cultivars as temperatures increase, but may need to switch cultivars at lower elevations where they are currently grown.

8. Implications of climate change for global banana production

The present study provides the basis for the following implications of climate warming on banana production and suitability globally:

- Growing conditions are suitable for banana in wide areas of the subtropics, the tropical highlands and the lowland tropics. A climatic zoning approach based on monthly temperatures, monthly rainfall and length of dry season provides the basis for quantifying the suitability of global land area for banana production. Although much of the global land surface is not suitable for banana-growing, the land area in two categories of annual temperature – 18-24 °C and >24 °C – with favourable rainfall, makes up about 37 million square kilometres. This stands in contrast to the 126 000 square kilometres of land area currently occupied by banana and plantain.

- According to global projections of climate change based on climatic zoning and the 24 selected sites representing important banana-growing zones, the area not suitable for growing banana will decrease over the period 2030, 2050 and 2070. Land area with lower productivity potential due to lower temperatures will decline, and land area characterized by temperatures >24°C will increase. Calculations using leaf emission rate as an indicator of banana productivity indicate that, based on temperature alone, the leaf emission rate will increase by 10 leaves per year across most sites.
- The productivity of banana based on temperature and available water in the different agroclimatic zones and the 24 sites as measured by leaf emission rate will increase by 10 leaves per year only in the sites with abundant water year-round. In many other sites with a longer dry season only 4-6 additional leaves per year are likely in response to climate warming. The increased temperature that is associated with faster leaf emission rate will also be associated with an increased water demand of 10-15 percent across the sites as a result of increasing temperatures for the period through 2070.
- Black leaf streak, one of the most important leaf diseases of banana, may become more aggressive with increased temperatures, since the growth of the germination tube of spores accelerates with higher temperature. However, spore germination is primarily based on leaf wetness. The climate projections indicate that rainfall distribution on average will not change over the projection period for any of the 24 sites studied and therefore black leaf streak will continue to be a challenge during the rainy periods, just as it is currently.
- An overview of the shifts among different climatic zones showed that the climatic zones with lower average annual temperatures are projected to lose land area in all three continents, while the land area in the zones with temperatures >24 °C will increase. This change will favour potential banana productivity. The average temperature for potential banana lands in this zone is also likely to increase over the period of projections. Among the 24 sites analysed, the lowland tropical lands showed an increase in temperature from 25 °C to 28 °C, over the period of the projections. While banana productivity is favoured by this increase, the appearance of zones with excessive heat during certain periods of the year (three months >35 °C) in both Asia and Africa indicate that climate warming must be addressed.
- Even though increasing temperatures are not unfavourable for banana, they may be unfavourable for perennial and annual crops with which bananas are often grown. Farm households growing crops such as coffee, with banana as a secondary crop, may abandon banana when they abandon coffee because of climate change.
- The temperature parameters used in this study were based on Cavendish export banana. Other banana cultivar groups – in particular, the group of East African Highland cultivars – is known to perform well at higher elevations. This cultivar group may expand into higher altitudes as temperatures increase, but farmers may need to switch cultivars at the lower elevation range.

The implications summarized here are based on projections of average temperature and rainfall. Climate warming is also linked to increasing volatility of weather. Additional analyses are needed to quantify the type and frequency of weather events of moderate and extreme variability and the implications for banana productivity and management.

table 10

Changes in suitability areas (km_2) for banana production by major temperature categories due to projected climate change through 2070 for three continents

		Current	2030		2050		2070	
Unsuitable	LAC	3 226 450	2 802 200	-	2 568 425	-	2 306 525	-
	Africa	109 175	47 075	-	28 850	-	19 100	-
	Asia	22 491 675	20 256 675	-	18 891 200	-	17 809 400	-
	Total	25 827 300	23 105 950	-	21 488 475	-	20 135 025	-
13-18 °C	LAC	3 312 150	2 502 875	-	2 091 125	-	1 885 300	-
	Africa	1 630 625	860 000	-	477 000	-	235 950	-
	Asia	7 589 450	7 210 925	-	6 838 750	-	6 485 150	-
	Total	12 532 225	10 573 800	-	9 406 875	-	8 606 400	-
18-24 °C	LAC	6 675 800	5 313 650	-	4 783 075	-	4 318 275	-
	Africa	9 639 025	7 213 200	-	5 519 750	-	3 616 250	-
	Asia	11 119 175	10 331 425	-	9 989 500	-	9 580 650	-
	Total	27 434 000	22 858 275	-	20 292 325	-	17 515 175	-
24-35 °C	LAC	12 406 025	14 892 450	+	16 068 550	+	17 001 075	+
	Africa	14 843 075	18 070 025	+	20 164 475	+	22 291 875	+
	Asia	14 059 675	17 297 875	+	19 375 850	+	21 184 925	+
	Total	41 308 775	50 260 350	+	55 608 875	+	60 477 875	+
Unsuitable due to high temperatures	LAC	0	0		0		0	
	Africa	0	0		225	+	27 125	+
	Asia	0	0		0		21 650	+
	Total	0	0		225	+	48 775	+

table 11

Global land area (km^2) for category of lands >24°C under different rainfall regimes

Climate category	Current	2030	2050	2070
131	16 354 225	20 460 100	23 591 850	26 378 825
132	3 325	5 250	4 725	4 950
231	8 055 150	10 132 325	11 109 325	12 206 500
232	583 850	948 275	1 019 725	1 183 700
331	3 270 050	4 555 150	5 441 425	6 103 275
332	7 975 475	8 492 200	8 354 475	8 141 575
431	462 200	604 350	706 675	803 475
432	4 604 500	5 062 700	5 380 675	5 655 575

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