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Global warming: causes and impacts on agroecosystems productivity and food security with emphasis on cassava comparative advantage in the tropics/subtropics

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Abstract

Earth's climate has experienced notable changes during the past 50–70 years when global surface temperature has risen by 0.8ºC during the 20th century. This was a consequence of the rise in the concentration of biogenic gases (carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, and ozone) in the atmosphere that contribute, along with water vapor, to the so-called 'greenhouse effect'. Most of the emissions of greenhouse gases have been, and still are, the product of human activities, namely, the excessive use of fossil energy, deforestations in the humid tropics with associated poor land use-management, and wide-scale degradation of soils under crop cultivation and animal/pasture ecosystems. General Circulation Models predict that atmospheric CO_2 concentration will probably reach 700 µmol(CO_2) mol^{-1}. This can result in rise of Earth's temperature from 1.5 to over 5ºC by the end of this century. This may instigate 0.60–1.0 m rise in sea level, with impacts on coastal lowlands across continents. Crop modeling predicts significant changes in agricultural ecosystems. The mid- and high-latitude regions might reap the benefits of warming and CO_2 fertilization effects *via* increasing total production and yield of C_3 plants coupled with greater water-use efficiencies. The tropical/subtropical regions will probably suffer the worst impacts of global climate changes. These impacts include wide-scale socioeconomic changes, such as degradation and losses of natural resources, low agricultural production, and lower crop yields, increased risks of hunger, and above all waves of human migration and dislocation. Due to inherent cassava tolerance to heat, water stress, and poor soils, this crop is highly adaptable to warming climate. Such a trait should enhance its role in food security in the tropics and subtropics.

Additional key words: agriculture; animal husbandry; carbon dioxide; climate change; crop; forest; greenhouse gas; modeling; photosynthesis; soil; temperature; water stress; wild *Manihot* species; yield.

Introduction

Climate change and global warming phenomenon, whether they are man-made or natural, continue to be a subject of intense scientific, public, and controversial political debate worldwide, particularly in the past two decades (Kerr 1997, Soon and Baliunas 2003, Perrow 2010, Rivera and Khan 2012). However, the important questions often arise: "Is climate change a fallacy or a real event?", and "What does science say in this case?". The Fourth Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change (Metz *et al.* 2007), is the most comprehensive source of climate science and it provides recent empirical evidence in the support of climate change. This report concluded that Earth's climate is currently experiencing consistent changes at a scale that had never been observed during the past 400,000 years (Metz *et al.* 2007). Changes in

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Abreviations: C_i – intercellular CO_2 concentration; [CO_2] – CO_2 concentration; CFCs – chlorofluorocarbons; FACE – Free Air Carbon Dioxide Enrichment; HI – harvest index; g_s – stomatal conductance; IBSNAT– International Benchmark Sites Network for Agrotechnology Transfer; IPCC– Intergovernmental Panel on Climate Change; LAI – leaf area index; PEPC – phospho*enol*pyruvate carboxylase; PNUE – photosynthetic nitrogen use efficiency; P_N – leaf net photosynthetic rate.

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climate are already visually observed and physically felt as the past 70 years were the warmest in the last 1,000 years. They are accompanied with changes in precipitation patterns that have brought about greater incidences and more powerful extremes of climatic events manifested as devastating floods or drought globally. Furthermore, there are notable, though slow rises in sea level due to ice melt from polar reserves as well as from the disappearance of glaciers. In this paper, we briefly reviewed trends in global warming, trends in atmospheric CO_2 concentration ($[CO_2]$), causes of greenhouse gas emissions, impacts of climate changes on agroecosystems, and food security. I emphasized the suitability of the tropical root crop, cassava, under global warming conditions.

Trends in global warming

Air warming increased at the rate of 0.075ºC per decade over the entire 1900–2000 period, *i.e.,* 0.75ºC per a century (Mitchell and Jones 2005, Girvetz *et al*. 2009).

Period	Warming per decade [ºC]
1940–2000	0.11
1950–2000	0.16
1960–2000	0.22
1970–2000	0.30

These trends indicate that there was a clearly observed and accelerating rate of warming during the 20th century. Nevertheless, warming trends vary among regions of the world. Jones and Wigley (1990) analyzed available land and marine meteorological records from 1967 to 1986 and they noted that most regions in both northern and southern hemispheres had experienced marked warming. Few parts in the northern Pacific and Atlantic oceans were the only exception that experienced cooling to some extent. The authors concluded that if climate model predictions are correct, global warming would accelerate in the future. This requires to formulate and implement policy to reduce temperature increases caused by emitted greenhouse gases and to obviate negative consequences on agriculture and food security.

Projected, global atmospheric warming was extensively studied *via* simulation models and reported by Metz *et al.* (2007). Recent analysis across 16 locations throughout both hemispheres and seasons predicted variable increases in seasonal air temperature in 2050 as compared to averages in 2000 (Jaggard *et al.* 2010). All locations are anticipated to become warmer. For example, the mean spring temperature in Manitoba (Canada) should increase from 3.7°C to 6.4°C; similar increases are predicted for Harbin, northern China, and Tambov, Russia. Similarly, mean air temperatures are predicted to rise from 4.8°C to 8.8°C during autumn in Harbin. These warming trends in northern hemisphere are large enough to prolong considerably the growing seasons of crops such as soybean, maize, potato, and beet. This should generate larger crop yields per unit land area, and also should bring more acreages under cultivation, provided that sufficient water supply exists to avoid serious drought.

Metz *et al*. (2007) further predicted the increase in the mean Earth's surface temperature above the pre-industrial temperature, in the range of 1.4 to 5.8ºC by the end of the 21st century. However, other projected estimates suggest that this increase in global mean temperature might be reached by 2050–2080, if the emission levels in trace greenhouse gases keep rising. The rise in air temperature is caused by enhancing atmospheric concentrations of the so-called greenhouse gases. Most important among them are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and ozone (O_3). These gases along with the existing atmospheric water vapor trap the latent heat in the form of infrared radiation, which the Earth's surface emanates, hence, resulting in the rise of air temperature. From the 2nd half of the 19th century and in the 20th century, CO_2 has accounted for more than 50% of all greenhouse gases and is expected to account for 55% or more over the 21st century (Houghton *et al.* 1990). From 1850 (*i.e.*, 100 years after the beginning of the first industrial revolution) to 1980, about 150–200 billion tons of carbon were released from burning of fossil fuels. Changes in land use, by converting huge forests to cultivated areas over the same period, resulted in the release of nearly 100 billion t of carbon (Dale *et al.* 1993). Most of this happened in industrialized countries. Unfortunately, while rich, industrialized countries are better equipped to cope with the negative consequences of climate changes, developing countries are not well prepared to deal with the negative impacts and therefore they are more vulnerable to its consequences.

Trends in changing atmospheric CO_2

Over the past 800,000 years, atmospheric $[CO_2]$ changed between 180 $\mu mol(CO_2)\ mol^{-1}$ (glacial periods) and 280 $\mu mol(CO_2)\ mol^{-1}$ (interglacial periods). From pre-industrial concentration of about 280 $\mu mol(CO_2)\ mol^{-1}$, $[CO_2]$ increased steadily to 400 $\mu mol(CO_2)\ mol^{-1}$ on Thursday, May 9, 2013, according to Mauna Loa Observatory, Hawaii, and Scripps Institution of Oceanography, NOAA, USA. The mean temperature has increased by 0.76ºC over the same time period.

Projections to the end of this century suggest that atmospheric [CO_2] should reach 700 μmol(CO_2) mol^{-1} or more, whereas global temperature should increase by 1.8–5.2ºC, depending on the greenhouse emissions scenario (Metz *et al*. 2007; Da Matta *et al*. 2010). Every year, current estimates are about 10–12 billion t of carbon being released into the atmosphere, thus, contributing to global warming and climate change. In 2010, the top ten emitters, in terms of billions t of CO_2 annually, were listed in a decreasing order: China (8.241), USA (5.492), India (2.070), Russia (1.689), Japan (1.139), Germany (0.763), Iran (0.575), South Korea (0.563), Canada (0.519), Saudi Arabia (0.494) (http://www.huffington-post.ca/2012/02/21/top-10-most-polluting-countries-co2-emissions_n_1291963.html). In terms of carbon, those top polluters contribute collectively 50% (about 5–6 billion t) of world emissions, with USA having the highest per capita rate of over 20 times higher than the global average. Even though the US agricultural and food production systems are prone to climate change impacts, the government has consistently refused to sign the United Nations-sponsored Kyoto Protocol that calls for curbing carbon emissions (McCright and Dunlap 2003). About 50–60% of total carbon emissions originates from consumption of fossil energy sources, such as coal, natural gas, and oil. Worldwide deforestation and associated vegetation burning, particularly in the tropical rainforests, contribute by 15–25%. The rest results from diverse livestock keeping systems, associated with poor manure management and pasture overgrazing, from changes in agricultural land uses that cause partial releasing of the soil-stored organic carbon, from degraded wetland surfaces and erosion of coastal vegetation, and irrigated-fertilized paddy rice (Dale *et al*. 1993, LEISA 2008, Irving *et al*. 2011, Powlson *et al*. 2011). Another potential source exists in frozen lands of organic matter-rich, arctic permafrost, in North Asia/Europe (*e.g.*, Russia and Nordic European countries) and North America (*e.g.*, Canada and Alaska), where greenhouse gases can be released with accelerating warming in the future (Walter *et al*. 2006, Hillel and Rosenzweig 2011). These land deposits may rival fossil fuels in terms of their volume. Vast stores of CH_4 in permafrost contain 25 times more potent greenhouse gas as compared to CO_2 (on a 100 year scale). As Earth warms it could be released from frozen deposits on land and also under the oceans, thus aggravating further global warming (Mascarelli 2009).

Impacts of climate change on natural resource potential and on its viability to feed the world

Of *ca*. 14–16 billion ha of ice-free land on Earth, *ca*. 1.3–1.6 billion ha are used for crop cultivation (about 15–18 % irrigated, and the remaining are rain-fed systems), and about 3.0–4.0 billion ha are used for pastures and animal feed. Forests constitute about 28–30% of ice-free land surface. Cropping systems (Cs), pastures (Ps), and forests (Fr) account collectively for approximately 50–60% of the Earth's land covers (Houghton 1990, FAO 2007, Tubiello *et al*. 2007). Cs, Ps, and Fr constitute the available natural resources for feeding the world population at its present size (*ca*. 7.2 billions) and hopefully can meet the demand of the ever expanding human population (*ca*. 10 billions by the end of this century). Judicious management practices are then required in order to sustain current production level and services, prevent resource degradation and losses, as well as to guarantee the needed supplies of food, feed, energy, timber, and services in the coming decades. The demands for these biological products will increase, in terms of quantity and quality, in coming decades as world population is on the rise associated with longer human age due to improved healthcare systems (Sasson 1990). According to FAO (2007), agroecosystems are progressively exposed to threats from increased seasonal climatic variability and, in the longer run, to climate change, in addition to their degradation by human activities. Abnormal changes in air temperature and rainfall and increasing frequency and intensity of drought and flood events have long-term implications for the viability of these ecosystems. For example, climate changes might translate into major changes in the spatial distribution of agro-ecological zones, in habitat´s suitability for animal and plant species, in biome structures and landraces genetic diversity and their persistence, in distribution patterns and incidence/ infestation of plant diseases and pests, and in fish populations and ocean circulation patterns, all of which can have significant impacts on agriculture and food production. Earth's carrying capacity [*i.e.,* the capacity of resources to supply and sustain human demands; also defined by D. Lallement 1986 (cited in Sasson 1990, p. 218–219) as "the quantity of matter that a biosystem can produce for the use of man or animals within a given period of time without endangering its production capacity"] is reaching its upper limit. Unless unexpected scientific discoveries and more effective technological advances shift the balance, the Malthus prophecy might be realized. The so-called Green Revolution of the 1960's (*i.e.*, the development of innovative agricultural technologies in terms of breeding high-yielding (HY), dwarf, cereal cultivars responding to irrigation and high fertilizer concentrations) saved hundred millions of humans from facing famine. But, unfortunately, after decades of the sufficient food production, significant portion of developing countries is currently facing hunger, while HY cultivars are approaching their maximum biological productivity level in research experimental stations. Moreover, the gap between this experimental productivity and farm yields is still large in most developing countries, particularly in sub-Saharan Africa, some parts in South-East Asia, and the Latin American/Caribbean region. Therefore, we need to close this gap *via* well focused research and new technology development aided by better national, agricultural policy.

There are also concerns about the impacts of climate change on other nonagricultural biological systems possessing immense value to conservation efforts worldwide. These systems are known for their richness in endemic species, and their representation of rare biomes important in understanding the evolutionary phenomena (Olson and Dinerstein 2002, Beaumont *et al.* 2011). The predictions show that average sea levels may rise 0.60–1.00 m by the end of this century because of global warming. This change may occur due to the expansion of the warmer ocean water and the melting of Nordic Greenland and Antarctic ice sheets (Roaf *et al.* 2005). Consequently, many coastal, low-land zones across continents may be submerged. Regions at risk include the lower elevation countries of Europe, eastern England, the Nile delta in Egypt, the Ganges–Brahmaputra, Irrawaddy, and Chao Phraya deltas of south-eastern Asia, eastern Sumatra, and Borneo. In the United States, the mid-Atlantic coastal plain, the Florida Everglades, and the Mississippi delta are particularly vulnerable (Vivian 2005). For example, 1-m rise in the Mediterranean sea level may affect a significant area of the Nile delta in Egypt due to sea water flooding as well as intrusion of saline water into the underground water aquifer (El-Sharkawy *et al.* 2009). More than 6–7 million people may be displaced and about 4,000–5,000 km^2 of cropland would be lost (Dasgupta *et al.* 2009). Moreover, arid and already water-starving Egypt currently faces severe shortages of fresh water and it is wholly dependent on the Nile River water for agricultural, industrial, and domestic uses. Other countries in central and eastern Africa that share the river upstream watersheds and tributaries depend mostly on rainfall for their agriculture and other needs. However, some of the upstream countries are currently constructing large water dams needed for generating hydroelectric power, and perhaps for irrigation projects, that might have serious impacts on Egypt's legitimate share of water flow. Climate change coupled with frequent and prolonged droughts and intensive floods, which often occur in this region, can further aggravate the problem and may result in unwanted conflicts across borders. Simulated flows of the Blue Nile at Diem, Ethiopia, which provides about 50–60% of the inflow to the Nile River, indicate significant reduction due to climate changes in the 21st century (El-Shamy *et al.* 2009). Thus, the Nile River basin issue in a view of climate change consequences should strengthen multinational cooperation.

Experiment-based changes in the yield of major cereals and legumes under elevated CO_2

Early research expected CO_2 elevated up to ≈ 550 µmol (CO_2) mol^{-1} in 2050. The research was conducted under indoor, controlled conditions or in open-top field chambers and it showed enhancement in the yield and biomass ranging from 20 to 50% in most C_3 crops including cereals and grain legumes (Kimball 1983, Kimball *et al.* 2002). In these crops, leaf photosynthetic rates increased with elevated CO_2, but in some cases long-term exposure to higher CO_2 resulted in a down-regulation of photosynthesis (Acock and Allen 1985, Ziska *et al.*1991). C_4 maize and sorghum showed lower enhancement indicating the effect of the so-called 'CO_2 concentrating mechanism' operating in these species (Ziska *et al.* 1999). Drawing a comparison between C_4 crops and weeds indicated that the stimulating effect on leaf photosynthetic rate and biomass production was higher in weeds under elevated CO_2, hence, greater weed competition for resources can be expected under global climate change. This means greater farming costs and perhaps greater yield losses (Ziska and Bunce 1997). However, the enhancement of C_3 crops yields was lesser than 20% , and it was even smaller than 10% in C_4 crops under field conditions using the sophisticated 'Free Air Carbon Dioxide Enrichment (FACE) technique' and in absence of water deficit (Long *et al.* 2006). Assuming uniform CO_2 profile within crop canopy in FACE trials, the discrepancies between the two sets of results might indicate possible differential effects of some critical environmental factors, such as humidity and temperature prevailing in the field, as compared to controlled environments. Thus, data obtained from indoor-grown plants or in open-top field chambers must be calibrated under open-field conditions. This is of paramount importance when such information is used in crop modeling and for predicting possible impacts of global climate change on crop productivity (El-Sharkawy 2005, 2011).

Simulated crop yield taking into account the direct effect of CO_2 fertilization

Rosenzweig *et al.* (1993) reported on the simulated effects of climate change on crop yields across 112 sites selected from 18 developed and developing countries using 3 different general circulation models (GCMs) and known crop growth models. The GCMs used are those from the Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and United Kingdom Meteorological Office (UKMO). The crop models used were CERES-Wheat (Ritchie and Otter 1985, Godwin *et al.* 1989), CERES-Maize (Jones and Kiniry 1986, Ritchie *et al.* 1989), CERES-Rice (paddy and upland) (Godwin *et al.* 1993), and SOYGRO (Jones *et al.* 1989). Calculated percentage change of world-averaged crop yields is shown in Fig. 1 in three cereal

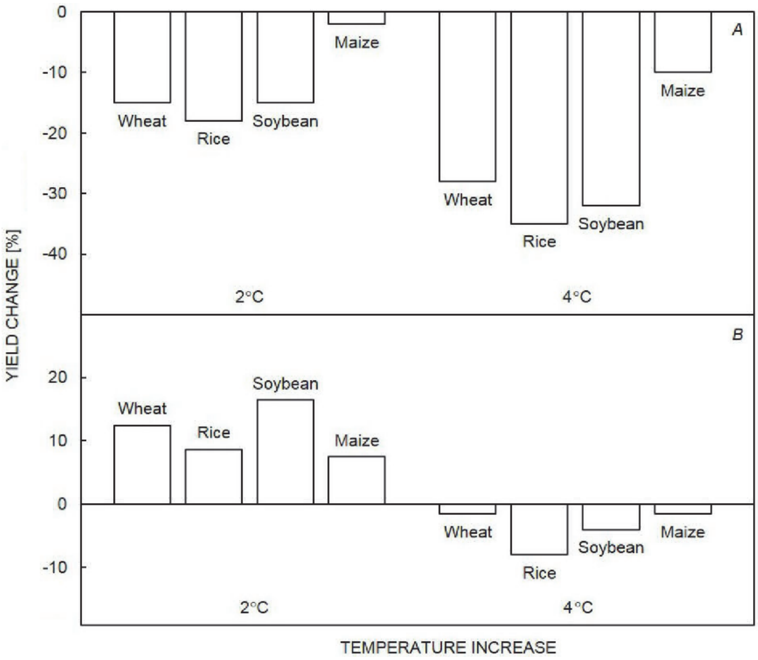

Fig. 1. Aggregated IBSNAT crop model yield changes for + 2ºC and +4ºC temperature increase without (*A*) and with (*B*) direct CO_2 effects. Direct effects of CO_2 on crop growth and water use are taken into account. Source: Rosenzweig *et al*. 1993, Rosenzweig and Hillel 1995.

Table 1. Predicted changes in Earth's surface temperature and in rainfall in 2050, performed by the three GCMs. Source: Rosenzweig *et al*. 1993.

GCM	Year	Temperature [ºC]	Rainfall [%]
GISS	1982	+ 4.2	+ 11
GFDL	1988	+ 4.0	+ 8
UKMO	1986	+ 5.2	+ 15

grain crops and soybean as a result of 2 and 4°C increase in the average global surface temperature, with and without direct effects of [CO_2]. On one hand, without considering CO_2 direct effects, reductions were found in projected yields of all crops at both temperature increases, with the largest reductions at 4ºC. On the other hand, considering the direct effects of elevated CO_2 [(≈ 550 μmol(CO_2) mol^{-1}], average crop yields weighted by national production showed a positive response to +2ºC warming and a negative response to +4ºC in absence of changes in rainfall patterns (Fig. 1). Wheat and soybean yields increased by 10–15%, and maize and rice yields should be about 8% higher under the +2ºC rise. Yields of all 4 crops turned negative at +4ºC. It indicated the threshold of the compensation of direct CO_2 effects for temperature rise between 2 and 4ºC, as simulated in the IBSNAT crop models. Rice and soybean

Table 2. Predicted percent change in wheat yield under elevated CO_2 [≈ 550 μmol(CO_2) mol^{-1}] in 2050 as performed by the three GCMs with and without CO_2 fertilization effects. Source: Rosenzweig *et al.*1993.

Country	Change [%]					
	With CO_2 effects			Without CO_2 effects		
	GISS	GFDL	UKMO	GISS	GFDL	UKMO
Australia	+ 8	+ 11	+ 9	– 18	– 16	– 14
Brazil	– 33	– 17	– 34	– 51	– 38	– 53
Canada	+ 27	+ 27	– 7	– 12	– 10	– 38
China	+ 16	+ 8	0	– 5	– 12	– 17
Egypt	– 31	– 26	– 51	– 36	– 28	– 54
France	+ 4	– 15	– 9	– 12	– 28	– 23
India	+ 3	– 9	– 33	– 32	– 38	– 56
Japan	– 1	– 5	– 27	– 18	– 21	– 40
Pakistan	– 19	+ 31	– 55	– 57	– 29	– 73
Uruguay	– 23	– 31	– 35	– 41	– 48	– 50
USSR (former)						
Winter	+ 29	+ 9	0	– 3	– 17	– 22
Spring	+ 21	+ 3	– 25	– 12	– 25	– 48
USA	– 2	– 2	– 14	– 21	– 23	– 33
World	+ 11	+ 4	– 13	– 16	– 22	– 33

were most negatively affected at +4ºC. Moreover, if global warming raises Earth's surface temperature for more than 4ºC, as some GCMs predict (Table 1), dramatic reductions (or even failure) in agricultural productivity in all crops may occur. Particularly, tropical regions are the most vulnerable because current temperatures are at the higher limit of thermal adaptation for most crop species. Consequently, the less heat tolerant cereal and legume crops can suffer greatly in the tropics, which could result in severe shortages in food supply, aggravated by the recent trends of using foodstocks in biofuel production.

Nevertheless, these aggregated and averaged results mask apparent differences among individual countries (Table 2). Thus, in Canada, a +2ºC temperature increase with no precipitation change could result in the increasing wheat yield (with direct effects of CO_2 taken into account), while the same changes in Pakistan would result in declining wheat yield average by about 12%. Moreover, in semiarid and subtropical regions, the 2ºC temperature increase will surely cause yield reduction in all crops. In general, 20% higher precipitation improved the simulated yields of the crops tested and 20% lower precipitation reduced the yields of all crops. Rosenzweig *et al.* (1993) concluded that climate change induced by increasing greenhouse gases is likely to affect crop yields differently from region to region across the globe. Under the climate change scenarios adopted in the study, the effects on crop yields in mid- and high-latitude regions appear to be less adverse than those in low-latitude regions. The conclusions were further substantiated by subsequent analyses using higher resolution climate models for different time periods with greater accuracy in the projections of climate change resulting from greenhouse gas-forcing (Parry *et al.* 2004, Parry 2007). For example, cereal yields projected for 2080 without, and with CO_2 fertilization effects, showed strong reductions in tropical areas, especially Africa, the Middle East, and the south Asia. Across Africa, the predicted mean yields were lowered by 17% (wheat), 5% (maize), 15% (sorghum), and 10% (millet) in 2050 and beyond. Across South Asia, the estimated mean yields were reduced during the same period by 16% (maize) and 11% (sorghum) (Knox *et al.* 2012). Using several global climate change scenarios, Blanc (2011, 2012) estimated that expected yield changes in 2100 (relative to no climate change) were *ca.* zero (cassava), –19% to +6% (maize), –38% to –13% (millet), and –47% to –7% (sorghum) in sub-Saharan Africa. These predictions point out cassava apparent tolerance to climate change.

Another simulation predictions of yield changes in 2050 without accounting for possible CO_2 fertilization effect, and averaged across developing and developed countries, showed significant reductions in the yield, as compared to the current yields, of the three major cereals (wheat, rice, and maize), irrespective of their CO_2 fixation pathways (Nelson *et al.* 2009, Table 3). The projection did not take into account whether the crops were irrigated or rain-fed. The yield reductions were more serious in developing countries. Predicting future agricultural productivity and food security under the projected climate changes remains uncertain, because simulators are far from being perfect tools and they rely on unrealistic assumptions in many cases (White *et al.* 2011a, van Wart *et al.* 2013). Rate-determining, input parameters are limited, derived weather data in absence of local-specific weather databases are used, and hypothetical, untested, control factors and genetic-dependent constants/coefficients must be used (IBSNAT 1993, El-Sharkawy 2005, van Keulen *et al.* 2008, Affholder *et al.* 2012, van Wart *et al.* 2013). To alleviate partly this concern, policy makers, donors, research managers, and involved scientists must take account of useful research under near natural conditions (including testing and selecting cultivars tolerant to heat and water stress). Developing improved technology is a highly needed objective to increase agricultural productivity in order to meet rising demands for food, fiber, and energy for the expected world population that might reach around 9–10 billions before the end of this century (Sasson 1990, Rosenzweig *et al.* 1993, Rosenzweig and Iglesias 1994). Most of the world population increase occurs in developing countries that are already plagued with severe shortages of food supply. Consequently, shortages in food supply might become more acute in the near future in developing countries considering the recent tendency to convert cereal grains, starchy roots, oil crops, and sugarcane to bioethanol and biofuels.

Table 3. Mean percentage yield changes by 2050, in the absence of a CO_2 fertilization effect, estimated using climate changes simulated from two simulators and yields simulated with the DSSAT crop-growth models. Source: Adapted from Nelson *et al.*, 2009.

Crop and water regime	Developing countries	Developed countries
Maize irrigated	− 2.4	− 5.0
Maize rain-fed	− 0.3	− 2.6
Rice irrigated	− 16.5	− 4.5
Rice rain-fed	− 0.9	+ 14.4
Wheat irrigated	− 31.3	− 5.3
Wheat rain-fed	− 1.3	+ 2.8

Impacts of [CO_2] and temperature interactions on plant photosynthesis and growth

The growth-enhancing effects of elevated CO_2 usually increase with rising temperature to levels approaching the maximum thermal limits (*e.g.*, Acock and Allen 1985, Acock *et al.* 1990). This important physiological phenomenon was illustrated by Jurik *et al.* (1984). Big tooth aspen (*Populus grandidentata*) leaves were exposed to atmospheric CO_2 concentrations of 325 and 1,935 µmol (CO_2) mol^{-1} and their photosynthetic rates were measured at different temperatures. Results shown in Fig. 2 illustrate two relationships defined to both warmer and cooler conditions (Idso and Idso 1994). At 10°C, elevated CO_2 did not essentially affect net photosynthesis in this particular species. However, Idso and Idso (1994) have indicated that such a phenomenon characterizes plant species in general. On one hand, at 25°C and the maximal net photosynthetic rate of the leaves exposed to 325 µmol (CO_2) mol^{-1}, the extra CO_2 boosted the net photosynthetic rate (P_N) of the foliage by nearly 100%. On the other hand, at 36°C and the maximal P_N of the leaves exposed to 1,935 µmol(CO_2) mol^{-1}, the extra CO_2 boosted the P_N of the foliage by 450%. In addition, we can readily see that the extra CO_2 increases the optimum temperature for P_N in this species by about 11°C: from 25°C under 325 µmol (CO_2) mol^{-1} to 36°C under 1,935 µmol (CO_2) mol^{-1}. The data argue for the positive effects of CO_2 fertilization in global warming climate. It was found that P_N increased under elevated [CO_2] by more than 200%, whereas dark respiration decreased linearly to only 20% of its initial value during a long-term CO_2-enrichment [up to about 1,000 µmol(CO_2) mol^{-1})] experiments with sour orange grown in open-top chambers under the hot, sunny environment of Arizona, USA. Doubling of the ambient air CO_2 concentration enhanced the growth of the trees by about 380% (both tops and roots) in the first 3–5 years (Idso and Kimball 1992, 2001). After 13 years with continuous CO_2 enrichment, the increase in biomass nearly leveled off at about 230%. Similar increases in P_N, growth, and biomass due to elevated [CO_2] were reported for field-grown *Pinus taeda* (Tissue *et al.* 1997). These trends in tree responses contrast with much lesser responses observed in annual, herbaceous grain and legume crops (Long *et al.* 2006), probably due to sink limitations for photoassimilates in these species. Nevertheless, such effects might vary in its magnitude by the presence of soil-borne pests that infest/feed on plant roots (Johnson and Riegler 2013) and by nutrients and water availability for plants (Lynch and St.Clair 2004, Reddy and Zhao 2005, Kirkham 2011, Hertel and Lobell 2012, Singh *et al.* 2013). It might vary under water-deficit situations when stomatal conductance to gas diffusion is reduced under both high CO_2 and water stress (Kimball 1983, Kimball *et al.* 2002). These biotic and abiotic factors should be considered in cropping system models used for predicting responses under elevated CO_2 (IBSNAT 1993, El-Sharkawy 2005, 2011; White *et al.* 2011a).

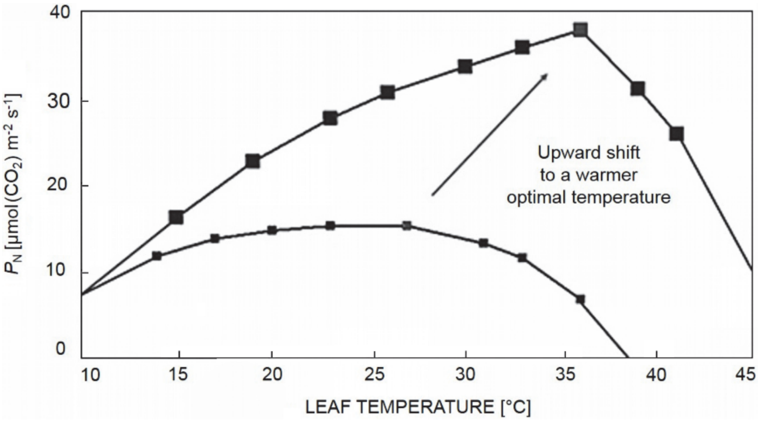

Fig. 2. Effects of high CO_2 concentrations on leaf photosynthetic rate (P_N), of bigtooth aspen (*Populus grandidentata*) grown in the field. *Upper curve* represents plants grown at 1,935 µmol(CO_2)mol^{-1}; *Lower curve* represents plants grown at 325 µmol(CO_2) mol^{-1}. Source: Jurik *et al.* 1984, Idso and Idso 1994.

In viewing the warm-temperature projections, the transition from positive to negative P_N, which denotes a change from life-sustaining to life-depleting conditions, occurs likely in the vicinity of 39°C in air of 325 µmol (CO_2) mol^{-1} but being close to 50°C under 1,935 µmol (CO_2) mol^{-1}. (Fig. 2). Hence, the optimum temperature for the growth of big tooth aspen was not only greatly increased by the extra CO_2 in this experiment, but also the temperature range above, which life can be sustained increased, and by about the same amount, *i.e.* 11°C.

Interactions of elevated [CO_2] with soil nutrients and its implication for forage quality

The combinations of elevated CO_2 with changes in rainfall and temperature are likely to impact significantly on grasslands and rangelands *via* increased biomass production, especially in the humid, temperate ecosystems (Easterling *et al.* 2007). However, the positive effects of elevated CO_2 on forage quantity are likely to be

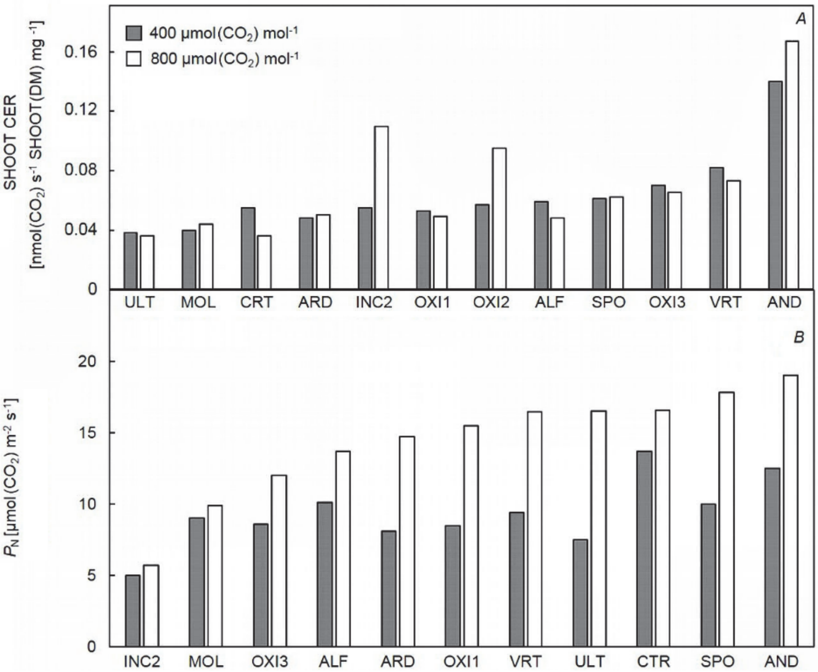

Fig. 3. Shoot carbon exchange rate (CER) and unit area leaf photosynthesis (P_N) (*A* and *B*, respectively) of *Festuca arundinacea* grown in 12 and 11 soils, respectively, plus a high-fertility control (CTR) under elevated [800 µmol (CO$_2$) mol^{-1}, *open bars*] and ambient [400 µmol(CO$_2$) mol^{-1}, *shaded bars*] atmospheric CO$_2$. Soil identification: ALF (Alfisol), AND (Andisol), ARD (Ardisol), INC2 (Inceptisol), MOL (Mollisol), OXI1, OXI2, OXI3 (Oxisol), SPO (Spodosol), ULT (Ultisol), VRT (Vertisol). Source: Jaramillo *et al.* (unpublished).

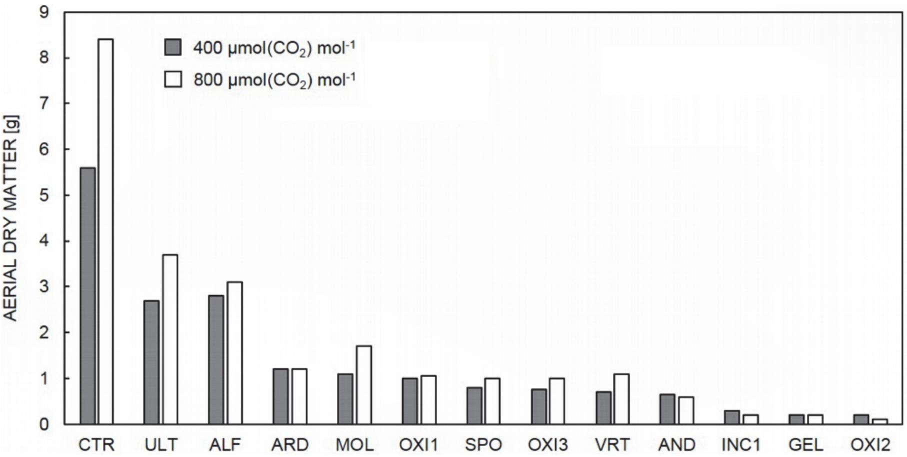

Fig. 4. Production of shoot biomass (DM) of *Festuca arundinacea* grown in 12 different soils and a high-fertility control (CTR) under elevated [800 µmol(CO$_2$) mol^{-1}, *open bars*] and ambient [400 µmol(CO$_2$) mol^{-1}, *shaded bars*] atmospheric CO$_2$. Soil identification as in Fig. 3. GEL (Gelisol). Source: Jaramillo *et al.* (unpublished).

lesser than the negative effects on forage quality. The negative effects of elevated CO$_2$ on forage N and crude protein concentrations are usually greater than on fiber (*e.g.*, celluloses, lignin) fractions, which can result in lower digestibility. Recent research has indicated the significant effects of soil nutrient contents, particularly nitrogen, phosphorus, and potassium, on plant response to elevated CO$_2$ (Lynch and St.Clair 2004, Reddy and Zhao 2005, Tubiello *et al.* 2007, DaMatta *et al.* 2010, Lobell and Burke 2010, Lobell *et al.* 2011, Singh *et al.* 2013). Generally, in the absence of adequate contents of nutrients, lesser responses to elevated CO$_2$ were commonly observed in most of field crops tested. However, in the case of nitrogen nonfixing, rangeland plants, such as grasses, the application of nitrogen fertilizer should enhance response to elevated CO$_2$, whereas phosphorus is essential for nitrogen-fixing forage legumes. Adopting a mixture of legumes and grasses might lead to a better response to elevated CO$_2$ in pasture systems. To enhance protein content in carbon-rich biomass is mandatory to reach balanced C/N ratios for adequate forage quality.

Most agroecosystems are limited by at least one mineral nutrient. Our current understanding of how climate change interacts with mineral toxicity and deficiency is quite limited. Until now, FACE trials with elevated CO$_2$ have not dealt seriously with soil nutrient contents and plant nutrient acquisition capacity in interaction with soil water status. These important, edaphic factors can determine plant adaptability to climate change. Moreover, recent research showed that climate change probably alters plant phenology, which in turn alter acquisition and use of water and nutrients (Nord and Lynch 2009, St.Clair and Lynch 2010). Soil fertility is likely to be degraded by more intense rains (erosion) and greater temperatures (oxidation of soil organic matter), particularly in warmer, lower latitude, tropical regions, where resource-limited farmers rarely apply fertilizers to pasture or crop ecosystems. Fig. 3 illustrates shoot and leaf photosynthetic responses to elevated CO_2 when plants were grown in different soils. Fig. 4 illustrates shoot biomass responses to elevated CO_2 when plants were grown in different soils. Data show interactions of soil type *vs.* CO_2 concentration. These findings suggest that native soil characteristics are important in conditioning ecosystem reaction to climate change (personal communication, R. Jaramillo, E.A. Nord and J.P. Lynch). Future research on global climate change and its impacts on agroecosystems must account for the interactive effects of soil nutrient contents and water status and try to develop submodels for edaphic stresses. It should improve the accuracy and validity of current cropping system models. Methods were recently developed to study the combined effects of elevated CO_2, temperature (*via* installing infrared heaters), and water deficits under field conditions and to investigate the many aspects of crop biological responses (Wall *et al.* 2011, White *et al.* 2011b, Erbs *et al.* 2012, Kimball *et al.* 2012). To meet this objective, multidisciplinary approach must be adopted with teams of researchers and model specialists collaborating in the research required. Such a research is especially important in the tropics/subtropics, where inadequate agricultural research, training, and service limit the capacity of farmers to adapt to climate change. Furthermore, developing novel technologies leading to breeding and selection of cultivars tolerant to combined biotic and abiotic stresses under climate changes are of paramount importance in this case (Sasson 1990).

Elevated CO_2 and crop water-use efficiency

We expected that plant water-use efficiency (CO_2 uptake/H_2O loss) should improve under CO_2 enrichment (Eamus 1991, Shimono *et al.* 2010, Hillel and Rosenzweig 2011, Kirkham 2011, Fleisher *et al.* 2011) since elevated CO_2 enhances leaf photosynthetic rates of most field crops regardless of their photosynthetic pathway (*i.e.*, C_3, C_4, and CAM), while reducing stomatal conductance (Kimball 1983, Kimball *et al.* 2002). However, at the canopy level, the crop water-use efficiency (biomass/evapotranspiration) should be modulated not only by CO_2 atmospheric concentration but also by air temperature, atmospheric humidity, soil water content, and plant nutrients status. Most available data show that elevated CO_2 enhances the water-use efficiency at the canopy level, particularly under soil water shortages (*e.g.*, Fleisher *et al.* 2011, 2013). Due to the apparent increase of atmospheric CO_2 [about 55 $\mu mol(CO_2)\ mol^{-1}$] over the period between 1984 to 2008, Kirkham (2011) calculated that the water requirement to produce a unit of wheat and sorghum grains were reduced by 6% and 4%, respectively, in Kansas State, USA. Thus, improved technologies must be developed *via* breeding/selection of new cultivars with higher photosynthetic capacities, tolerant to water- and heat stresses to mitigate the adverse effects of climate change.

Agronomical and physiological comparative advantage of cassava in warming climate

Very few staple crops are tolerant to high temperatures coupled with prolonged droughts. The root crop, cassava, might play a greater role as a source for human food and animal feed in tropical and subtropical regions negatively affected by climate change (El-Sharkawy *et al.* 1992a,b, 1993; Kamukondiwa 1996, Blanc 2011, 2012, Hershey *et al.* 2012, Jarvis *et al.* 2012, Knox *et al.* 2012, Gabriel *et al.* 2014). Fig. 5 illustrates the responses of leaf P_N to measuring temperature under 335 $\mu mol(CO_2)\ mol^{-1}$ and near-saturation, PAR in cassava leaves that developed under cool climate (mean daily temperatures were < 20ºC), in cool-climate leaves that were acclimated for 7 d at the warmer climate (mean daily temperature around 25ºC), and in leaves that were developed on the same plants in the warmer climate. Leaf P_N (Fig. 5 *A,B*) was the lowest in the cool climate leaves. P_N increased partially with an apparent upward shift in optimum temperature after 1 week of acclimation in the warmer climate. The shift in the optimum temperature was more pronounced in cv. M Col 2059 of cool-humid habitat. P_N of the leaves developed in the warm climate was the highest, showing also an apparent upward shift in the optimum temperature in both cultivars. P_N in all sets of leaves was greater in the hot-humid cultivar, M Bra 12, from Brazil. These findings attest the cassava adaptability to expected warmer climate in the tropics and subtropics. Fig. 5*C* illustrates responses of these sets of leaves to measuring PAR in one cultivar, M Col 2059. The lack of light saturation in the warm-climate leaves, as compared to cool and warm-acclimated leaves, illustrates the adaptation of cassava photosynthetic capacity to the warmer temperature and to high irradiances. In these trials, 8 cultivars representing cassava ecosystems, *i.e.*, hot humid low-land, hot-dry low-land, humid high altitude, and subtropic cool ecozones, were tested and all had shown the same responses to temperature and irradiance, indicating cassava resilient response to varying climatic conditions. Cassava leaves also remained reasonably active during extended water shortages in the field (Fig. 6, El-Sharkawy *et al.* 1992b, El-Sharkawy 1993, 2010). Stressed leaves were capable of maintaining P_N at *ca.* 40–60% of that in nonstressed leaves during the entire, 3-month stress period (El-Sharkawy *et al.* 1992b, El-Sharkawy 1993). Because stomatal conductance (g_s) was greatly reduced by stress, and, hence, reduction in transpiration water losses, leaf intrinsic water-use efficiency (P_N/g_s) was about 40% greater (El-Sharkawy 2010). There were differences among cultivars; cv. M Col 1684, CM 489-1, and CM 1335-4 showed the least reduction in P_N. Cassava is identified as C_3-C_4 intermediate (El-Sharkawy and Cock 1987, El-Sharkawy 2004, 2006; El-Sharkawy *et al.* 2008, 2012a,b,c). Therefore, the elevated activity of the C_4 phospo*enol*-pyruvate carboxylase (PEPC) (10–25% of activity typical in C_4 species, such as maize and sorghum) is responsible for cassava tolerance of water deficits (El-Sharkawy 2004, 2006; El-Sharkawy *et al.* 2008, 2012a,b,c; Table 4). Recent genomic analysis indicated that cassava possesses C_4 genome with several genes responsible for C_4 photosynthesis, including the genes encoding PEPC, with activities observed at transcriptional level (Saithong *et al.* 2013).

Moreover, wild species, such as *Manihot rubricaulis,* has greater PEPC activity and its P_N responded positively to CO_2 enrichment under field conditions (Table 4, Fig. 7). It is noteworthy to indicate that wild manihot possesses amphistomatous leaves with a 2nd, short palisade layer at the abaxial surface, anatomical characteristics that should enhance further leaf P_N (El-Sharkawy 2004). The wild species are useful genetic sources for breeding cassava cultivars with higher P_N.

Enzyme activity significantly correlated with upper canopy leaf P_N, photosynthetic leaf nitrogen-use efficiency (PNUE) [(μmol(CO_2) g^{-1}(total leaf nitrogen)], and with final harvested storage root yield determined in the field during dry period (El-Sharkawy *et al.* 2008, 2012a, b,c, El-Sharkawy 2009, 2010, 2012). Since genetic diversity in PEPC activity and Rubisco exists (Paul and Yeoh 1987, 1988, El-Sharkawy 2004, 2006; El-Sharkawy *et al.* 2008, 2012a,b,c), selection for high PEPC and Rubisco activities should be considered in cassava breeding programs. Such genetic diversity in terms of leaf photosynthetic capacity is beneficial for breeding and selecting improved cultivars adapted to climate change with prolonged water deficits coupled with high temperature.

Table 4. Activity of phospho*enol*pyruvate carboxylase expressed per fresh mass (FM) [μmol(NADH) kg^{-1}(FM) s^{-1}] or chlorophyll (Chl) [mmol(NADH) kg^{-1}(Chl) s^{-1}] content in leaf extracts of various plant species and cultivars. Means of four leaves ± SD (El-Sharkawy 2006).

Species	per FM	per Chl
Maize cv. CIMMYT 346	250 ± 27	116 ± 60
Common beans cv. Calima G4494	3 ± 1	5 ± 2
Cassava cv. M Mex 59	53 ± 10	37 ± 16
Cassava cv. M Nga 2	22 ± 2	7 ± 15
Manihot grahami	67 ± 14	47 ± 20
Manihot rubricaulis	97 ± 9	57 ± 22

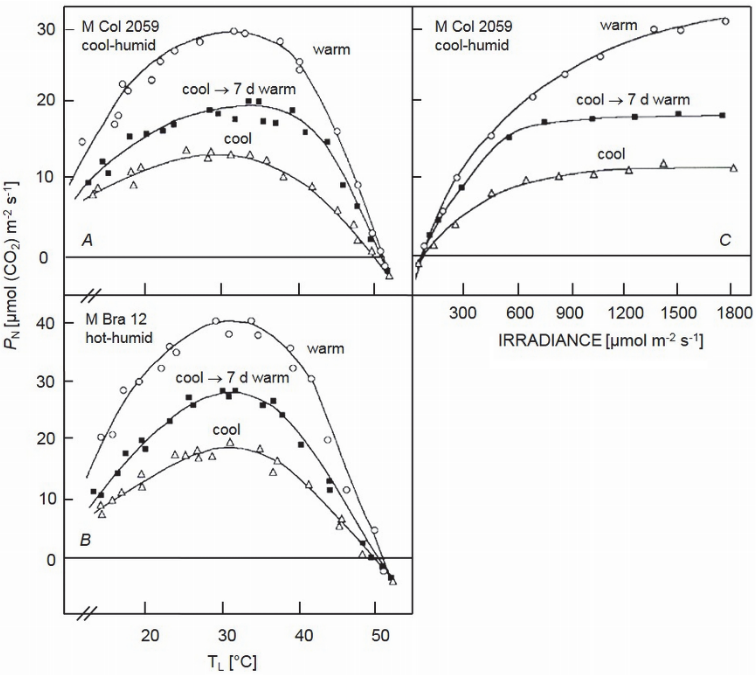

Fig. 5. Responses of net photosynthetic rate (P_N) to leaf temperature (T_L) in cv. M Col 2059 and M Br12 show the apparent upward shift in optimum temperature from cool to warm-acclimated and warm climate leaves (*A* and *B*), and the lack of photon saturation in warm climate leaves (data shown for M Col 2059), as compared to cool and warm-acclimated leaves (*C*). Higher maximum P_N was found in all sets of leaves of cv. M Bra 12 from hot-humid habitat (*B*) compared to the cool-climate cv. M Col 2059 (*A*, *C*) (CIAT 1992, El-Sharkawy *et al.* 1992a, 1993; El-Sharkawy 2006).

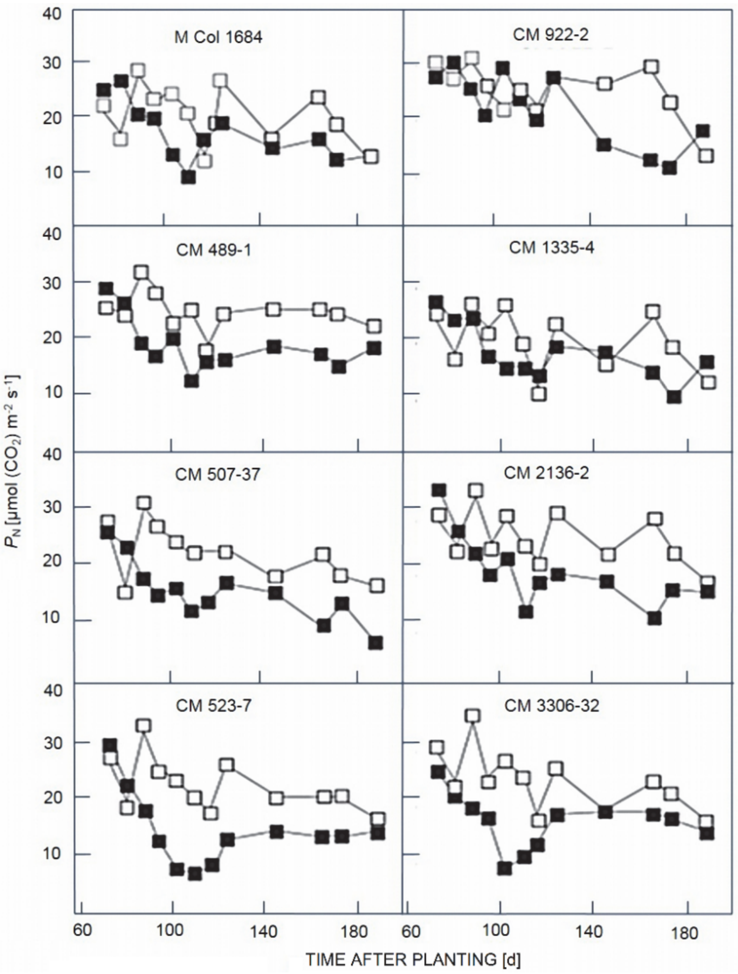

Fig. 6. Response of cassava leaf P_N to prolonged water stress (120 d), imposed at 60 d after planting (control, *open symbols*; stress, *solid symbols*), (CIAT 1987–1989 Report; El-Sharkawy 2010). In these cultivars leaf intrinsic water-use efficiency (P_N/g_s) was 40% greater in water-stressed plants due to reduction in stomatal conductance and, hence, reduction in transpiration water losses.

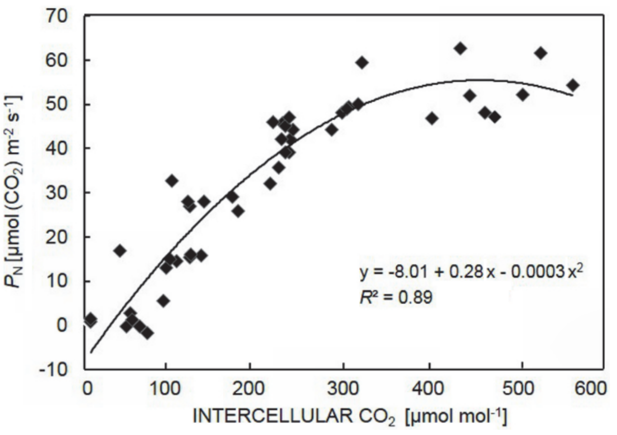

Fig. 7. Response in leaf P_N of field-grown *Manihot rubricaulis* to intercellular [CO$_2$] (de Tafur and El-Sharkawy 1995, unpublished; El-Sharkawy *et al*. 2012). Note the low CO$_2$ compensation concentration [around 30 µmol(CO$_2$) mol^{-1}] and P_N saturation at 400–500 µmol(CO$_2$) mol^{-1}, which correspond to 800–1,000 µmol(CO$_2$) mol^{-1} in measurement [CO$_2$].

When grown in low-fertility soils, cassava tends to reduce its aboveground growth. Smaller leaf canopy is observed due to slower rate of leaf formation, smaller leaf size, and shedding of older canopy leaves (CIAT 1987–1989, Cock and El-Sharkawy 1988b, Pellet and El-Sharkawy 1993a, 1997; El-Sharkawy 2012). By reducing leaf canopy, cassava optimizes the use of limited nutrients and stabilizes nutrient concentrations in attached, upper canopy leaves. It leads to higher rates of leaf P_N as compared to other species lacking such mechanism (Table 5; CIAT 1987–1989; Cock and El-Sharkawy 1988b; Pellet and El-Sharkawy 1993a; El-Sharkawy 2012). Furthermore, high N application increased specific leaf area of cassava (leaf area/unit dry mass), that is thinner leaf, which led to about 12% increase in PNUE [µmol(CO$_2$) g^{-1}(leaf N)], indicating relatively better N-use efficiency in cassava, whereas high N reduced PNUE by 15% in beans and 30% in maize (Porto *et al.* 1987).

In most plant species, leaf P_N, as well as whole canopy CO$_2$ exchange, responds positively to leaf N concentration, particularly in upper canopy layers, where irradiance and leaf shading is not limiting (Hirose and Werger 1987, Morgan 1988, Evans 1989). Moreover, in large field trials with 33 cassava cultivars grown in acidic soils low in phosphorus (P), upper canopy leaf P_N was significantly higher [31 µmol(CO$_2$) m^{-2} s^{-1}] in plants without P application than values in plants grown with 75 kg ha^{-1} P [27 µmol(CO$_2$) m^{-2} s^{-1})] (CIAT 1987–1989, 1992; El-Sharkawy 2012). This response coincided with increases in g_s and in mesophyll conductance to CO_2 coupled with lower intercellular CO_2 concentration (C_i) in low-P leaves. It suggests that the difference may be attributed to both stomatal behavior as well as to mesophyll biochemical and anatomical characteristics. Since canopy leaf area index (LAI) was significantly lower at low P (LAI = 2 in low-P plants as compared with 3.1 in high-P plants), the higher P_N could be partly attributed to lesser water stress resulting from lower transpiration losses by smaller crop canopy. Alternatively, the difference in P_N may be also attributed to feedback inhibition by leaf-accumulated photoassimilates at high P because of larger crop LAI, which represents greater crop photosynthetic surface capacity. Moreover, specific leaf area was similar in plants of both P regimes, though slightly greater in low-P leaves (21.3 and 21.1 $m^2\ kg^{-1}$ of dry mass under low P and high P, respectively) (CIAT 1992, Pellet and El-Sharkawy 1993a). Therefore, source-sink relationship for photosynthetic products was implicated in this sort of phenomenon (Wardlaw 1980, Pellet and El-Sharkawy 1994). In view of this, it is predicted that by maintaining stable, leaf, nutrient contents, especially nitrogen, cassava leaf P_N could be further enhanced by the future increase in atmospheric CO_2 with high air temperature.

It is a response contrasting to that observed in grain cereals that show photosynthetic downregulation at high CO_2 and high temperatures, particularly during reproductive stages (Lin *et al*. 1997). In the tropics, Fernandez *et al*. (2002) reported the lacking downregulation of leaf P_N in field-grown cassava when exposed to elevated CO_2 throughout the growth period using open-top chamber method. Furthermore, the reduction in leaf canopy results in more efficient distribution of dry matter toward the storage roots, as compared to shoots, thus increasing the harvest index (HI, storage roots/total biomass) of the cassava. These remarkable physiological and growth characteristics should strengthen cassava adaptability to climate change, especially when resource-limited farmers

Table 5. Net photosynthetic rate (P_N) of cassava, common beans, and maize; leaf nitrogen concentration on dry mass basis; and leaf nitrogen content on area basis. Plants were grown in 40-L pots in acidic soils provided with high (H) and none (L) nitrogen fertilizer application and left outdoors. Source: M.C.M. Porto, M.A. El-Sharkawy, J.H. Cock 1982, unpublished; Porto *et al.* 1987, Cock and El-Sharkawy 1988b.

Species	N application level	N concentration [%]	N content [g(N) m^{-2}]	P_N [μmol(CO_2) $m^{-2}\ s^{-1}$]
Cassava	L	4.6	2.15	29.4
	H	4.6	1.92	29.4
Common beans	L	3.4	1.17	18.2
	H	5.0	2.12	28.0
Maize	L	1.9	0.79	30.1
	H	3.4	1.49	39.9

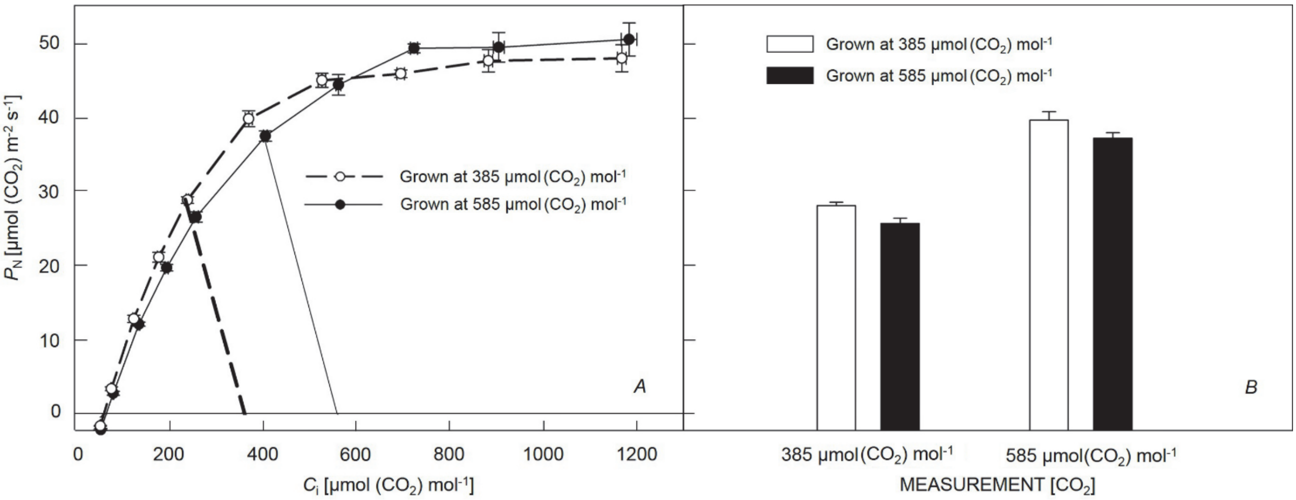

Fig. 8. The response of cassava photosynthesis to CO_2 concentration [CO_2] when grown for 30 d at ambient [385 μmol(CO_2) mol^{-1}] and elevated [585 μmol(CO_2) mol^{-1}] [CO_2] in the field using FACE method. (*A*) The response of photosynthesis to internal [CO_2] (C_i). The dashed and solid straight lines intersect the x-axis at the growth [CO_2] of the plants used to measure these curves. (*B*) Instantaneous photosynthesis for ambient- and elevated-grown plants measured at their respective growth [CO_2]. (Source: Rosenthal and Ort 2012).

do not apply agrochemicals or plant residues to their cassava cropping systems in marginal lands. Thus, breeding and selection for better PNUE is warranted since strong association among root yield, P_N, and PNUE exists in the large group of cassava cultivars grown in seasonally dry environment in the Patia Valley, Colombia, which is characterized by high temperature and high solar radiation (El-Sharkawy *et al.* 1990, 2008; El-Sharkawy 2004).

Field-grown cassava under ambient and elevated [CO_2] of 585 μmol(CO_2) mol^{-1}, for 30 days using the FACE method, had greater P_N when measured at 585 μmol(CO_2) mol^{-1}, compared to rates measured at ambient [CO_2] of 385 μmol(CO_2) mol^{-1} , with the former showing greater response (Rosenthal and Ort 2012, Fig. 8). However, when leaf photosynthesis was measured at [CO_2] greater than 600 μmol(CO_2) mol^{-1}, plants grown at elevated CO_2 showed consistent and slightly higher rates than the plants grown at ambient CO_2. Such data indicate that acclimation of photosynthesis (*i.e.*, the lower maximum carboxylation capacity of Rubisco) may not result in reduction in cassava growth and productivity if it occurs due to long exposure to higher CO_2. Moreover, cassava is resilient due to its plasticity in its growth habits. In most cultivars, plants form on main stems several branches associated with reproductive organs (*i.e.*, flowers and seeds), thus, providing alternative sinks (in addition to its starchy storage roots) for extra photoassimilates (Cock *et al.* 1979, Connor and Cock 1981, Veltkamp 1986, Cock and El-Sharkawy 1988a, Pellet and El-Sharkawy 1993a,b, 1994, 1997; El-Sharkawy 2004). This type of growth and phenology behavior with multiple and larger sink demands for photoassimilates should enhance leaf photosynthesis under elevated [CO_2] and, hence, it could lead to greater total biomass and yield (El-Sharkawy 2005, 2009). In recent field research using the FACE method, elevated [CO_2] resulted in substantial increases in aboveground biomass (30%) and in dry storage root yield (over 100%) as compared to ambient [CO_2] (Rosenthal *et al.* 2012). Thus, elevated [CO_2] increased the cassava crop harvest index, which in turn improves the efficiency of water and nutrient used in storage root production. Fernandez *et al.* (2002) reported similar enhancements in leaf P_N, biomass, and yield in field-grown cassava subjected to elevated [CO_2] in the tropics. Indoor-grown cassava showed significantly greater leaf P_N, biomass, and root yield, when grown under enriched CO_2, compared with cassava grown under ambient CO_2 (Ziska *et al.* 1991).

Sangpenchan (2009) used the Erosion-Productivity Impact Calculator/Environmental Policy Integrated Climate (EPIC) crop model to assess the impact of climate change on cassava adaptability and productivity in marginal lands of Northeastern Thailand. He reported that cassava grown in water-limited areas could benefit from the so-called "CO_2 fertilization" when combined with improved production technologies. Moreover, this crop would likely respond to rising [CO_2] by decreasing its evapotranspiration rate because of its tight stomatal control mechanism, *i.e.*, lower g_s. Thus, it shows increasing efficiency of using limited water supply, which is predicted with climate changes (El-Sharkawy *et al.* 1992b, El-Sharkawy 1993, 2004, 2006, 2010; Rosenthal *et al.* 2012). The lack of climate change research in the tropics/subtropics warrants field-based trials using FACE methodology coupled with simulation exercises in order to assess cassava potential in warming climate. The selection of adapted cultivars to soil fertility, water, and heat stresses would be of paramount importance.

Simulated cassava crop adaptability to climate change

Cassava as the important food, feed, and biofuel crop can surely expand further because of its tolerance to low-fertility soils, heat, and drought stresses (Cock and El-Sharkawy 1988b, Pellet and El-Sharkawy 1993a,b, 1997, El-Sharkawy 1993, 2004, 2006, 2010, 2012, Fermont 2009, Hershey *et al.* 2012, Howeler *et al.* 2013, Gabriel *et al.* 2014). In the tropics and sub-tropics, it is contrary to the production of most food crops, such as cereals and grain legumes (Fig. 9; Blanc 2011, 2012; Jarvis *et al.* 2012; Knox *et al.* 2012) in the face of climate change/ global warming trends that are predicted (Fig. 10). The predicted remarkable suitability of cassava to possible increases in average surface Earth's temperatures caused by expected rises in atmospheric CO_2 (and perhaps other greenhouse gases) in the year 2030 and beyond (of at least 1.5ºC, although some projections are higher, depending on the Global Circulation Models used). This simulated performance is substantiated by the experimental data on the photosynthetic responses in cassava to temperature, water stress, and CO_2 (Figs. 5–8). Research on cassava physiology at CIAT showed that maximum P_N, maximum growth, and productivity in absence of soil nutrient stress require high temperature (>25ºC), high solar radiation, high air humidity, and sufficient rainfall during most of the growth period (CIAT 1987 – 1989; El-Sharkawy *et al.* 1990,1992a,b, El-Sharkawy 1993, 2004, 2006, 2010, 2012). Moreover, cassava ecophysiological research, reviewed here and elsewhere (*e.g.*, El-Sharkawy 1993, 2004, 2006, 2010, 2012, El-Sharkawy *et al.* 2012a,b,c, Hershey *et al.* 2012, Howeler *et al.* 2013, Gabriel *et al.* 2014), has been providing needed information for breeding, as well as, for crop management and modeling (IBSNAT 1993, Mathews and Hunt 1994, Hoogenboom *et al.* 2012, CIAT 2013). Yet, more research is needed to fill many gaps in current knowledge about this traditionally neglected, but important crop (C. Hershey, CIAT's cassava program leader, personal communications; Gabriel *et al.* 2014).

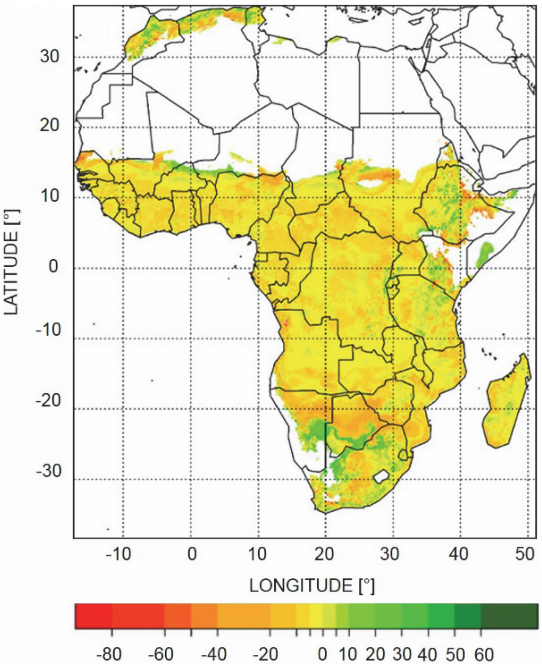

Fig. 9. Predicted suitability changes in the year 2030 for maize, sorghum, millet, common beans, potato, and banana, as average of 24 Global Circulation Models in North Africa, and sub-Saharan region (Jarvis *et al*. 2012). *Green shades* indicate a degree of suitability. NOTE: The contrasting suitability changes for these 6 food crops with that of cassava in Fig. 10.

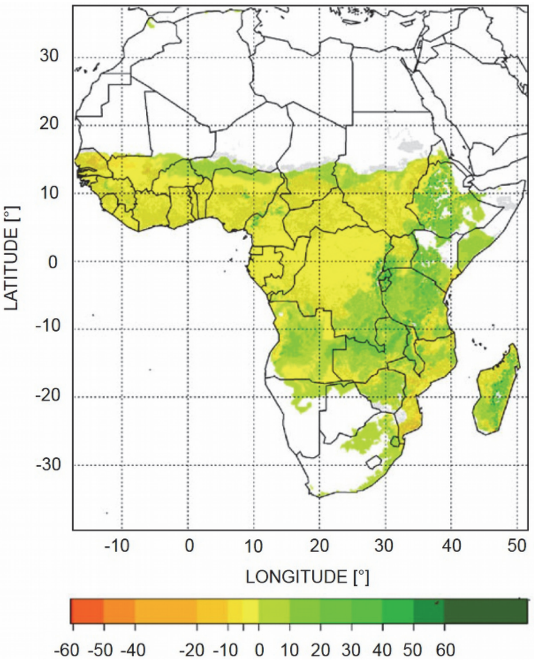

Fig. 10. Predicted changes in cassava suitability in the year 2030 as average of 24 Global Circulation Models in sub-Saharan countries where cassava is a common crop (Jarvis *et al.* 2012). *Green shades* indicate a degree of suitability.

Conclusion: As shown in this review, there is a strong evidence that changes in greenhouse-gas concentrations due to human activity are the dominant cause of the global warming that has taken place over the last century. Excessive use of fossil energy in industrialized countries, deforestation in humid tropics/subtropics at large scales, and inappropriately managed pastures and agroecosystems accounts for a major share of greenhouse-gas emissions that had led to warming the Earth's atmosphere by a global average of 0.8ºC. This warming trend is expected to continue, probably at an accelerating rate. Changes in rainfall are also expected in the long term in many regions. Increases in sea level are likely consequences that have profound implications for coastal communities and ecosystems. Positive changes in agricultural production, crop yield, and expansion toward new lands are more likely to occur in temperate zones. In most of the tropics and subtropics, the reverse trend might occur with much lower agricultural productivity due to unfavorable higher temperature coupled with predicted extended periods of droughts. Most staple food crops would be adversely affected resulting in food shortages. The root crop, cassava, is among the very few crops adapted to climate change and benefits under elevated [CO_2]. It is highly tolerant to poor soils, heat, and drought stresses. Its role as a food security might increase in the tropics and subtropics.

Hertel and Lobell (2012) concluded that the effects of climate change on farming will be most severe in low-income, agriculture-dependent, tropical countries, with minimal adaptive capacity, the very countries worst equipped to cope with these changes. Since current climate change models are based mostly on assumptions appropriate for rich industrialized countries, their outcome can likely underestimate impacts on the poorest and most vulnerable regions, particularly in sub-Saharan Africa.

Socioeconomic factors and food security are perhaps key triggers of conflicts in poor nations (Schmidhuber and Tubiello 2007). Future climate change is expected to substantially increase conflicts in resource-limited developing countries with uncontrolled population growth. In a recent in-depth and quantitative analysis, Hsiang *et al.* (2013) found strong causal evidence linking climatic events to human conflicts across a range of spatial and temporal scales and across all major regions of the world. Moreover, in its latest report of 2014, IPCC concluded that 'climate change can indirectly increase risks of violent conflicts in the form of civil wars and inter-group violence by amplifying well-documented drivers of these conflicts such as poverty and economic shocks' (Metz *et al.* 2014).

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