

CHAPTER 12

Climatic Resilient Agriculture for Root, Tuber, and Banana Crops using Plant Growth-Promoting Microbes

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12.1 INTRODUCTION

Sub-Saharan Africa (SSA) is amongst the poorest regions of the world, where around 386 million people earn less than US\$1.25 per day

(Ravallion, 2012). Agriculture is a major source of income here, employing 65% of the labor force and contributing up to 32% to the national gross domestic product (Chauvin et al., 2012). Root, tuber, and banana (RTB) crops are major crops and they represent the backbone of food security and nutrition across the tropics of SSA. They are the most important source of nutrition and income for an average of 300 million poor people in different developing countries. RTB crops constitute the major staple foods of SSA, with banana, cassava, yam, cocoyam, Irish and sweet potatoes as the major ones. Besides the low production costs, RTB crops (such as yam, cassava, potato, and sweet potato) are also rich in nutrients. They contribute to the energy and an important source of income in various areas of SSA mostly populated by smallholder farmers. Along with food security, they are regular food crops, cash crops, livestock feed and serve as raw material for many industrial products. However, the production of RTB crops is greatly influenced by nutrient exchange, energy, soil environment, and atmosphere (Lehmann and Kleber, 2015). Also, the indiscriminate use of chemical fertilizers has led to a reduction in soil pH and exchangeable ions causing an unavailability of nutrients for crops, thus, leading to a decrease of productivity. RTB crops also suffer from biotic stress (insects, disease) and abiotic stress (light, temperature, etc.) that the environment imposes (Gabriela et al., 2015). In SSA agricultural productions are mostly rainfed, and thus, their success is totally dependent on climate variability. The global temperature has been rising since the late 19th century. The impacts of climate change will lead to a decrease in the crop productivity of RTB crops in various regions of SSA where 95% of agriculture is still rainfed. This is because high temperatures can lead to reduced yields due to elevated development rates and enhanced respiration. Although, climate change could also result in increased incidence of diseases, leading to economic losses and vulnerability of various crops. Plant–microbe interactions are vital to responding to these intense biotic and abiotic situations, resulting in better economic viability and environmental intensification (Compant et al., 2016; Khan et al., 2016). There are different approaches to achieving this, which include biofertilization, phytoremediation, and plant stress control (Goswami et al., 2016). Microbial populations colonize, interact, and associate with their hosts in various activities through different means. These include absorption of water, nutrient uptake from a limited soil nutrient pool, and stabilizing plant stress. However, environmental conditions are drastically altered due to climate change, which impacts on beneficial plant–microbe

associations. For instance, elevated CO₂ concentrations diminished the growth of mycorrhizal hyphae and thus, alter the whole structural network of mycorrhizal systems. Higher CO₂ concentrations increase C allocation to plant roots, which impacts on the normal physiological and growth promoting attributes of rhizospheric microbes. Drought is expected to be responsible for severe impediments to the growth of crops on more than 50% of the Earth's arable land by 2050 (Vinocur and Altman, 2005). In drylands, drought stress is a major consequence of climate change and is responsible for significantly decreasing the microbial colonization process (Kaushal and Wani, 2016). Drought usually affects root activity, general morphology, and the functioning of host plants and their interactions, which are parallelly related to impacts on potential crops as well modifications of pest and pathogen activities. In addition, drought causes losses in photosynthates acquired in plants during photosynthesis as well as decreasing the formation of extra mycorrhizal mycelium in plant roots. Sometimes late-maturing cultivars can face drought, however, crops with shorter life spans can escape harm due to early maturity before the drought arrives. In regards to the climate change issue, exploration of beneficial microbes in integrated nutrient management systems is necessary to combat the agriculture against drought and disease stress situations.

There is sufficient data published on the enhancement of plant growth through plant growth-promoting microbes but only a paucity of information is available on the potential of these microbes under drought stress conditions in crops. Very little effort has also been made to introduce beneficial rhizospheric microbes as a mitigative tool in climate resilient agriculture. This chapter highlights the impacts of climate change on RTB crops and describes approaches involving plant growth-promoting microbes used to mitigate climate change impacts and enhance their productivity under drought stress in SSA. The chapter also identifies some of the challenges that climate change might pose to crop improvement and describes the efficacy of rhizobacteria to overcome these challenges for dryland agriculture. The potential impacts of climate change on the performance of plant growth-promoting microbes are also reviewed. Special focus is given to countries designated by the United States Agency for International Development (USAID) for the Feed the Future (FTF) program. These countries are specified because of their high poverty and hunger rates, greater opportunities for agricultural-led growth, host country leadership and governance, and resources availability (Ho and Hanrahan, 2011).

12.2 AGRICULTURE IN SUB-SAHARAN AFRICA

Agriculture is a major contributor to the economies of various countries in the world. In SSA, agriculture is dominated by smallholder farmers who contribute up to 90% of the agricultural production (Wiggins and Keats, 2013). Major crops of RTB are used as food as well as cash crops and include cassava, yam, potato, maize, sweet potato, and banana. Despite the major contribution of RTB crops to the economies of the countries of SSA, yields remain beneath the global average. In general, availability of water is considered as the primary limiting factor with only 3.5% of the total cultivated area under irrigation (Foster and Briceno-Garmendia, 2010). Temperature in SSA is projected to rise more rapidly than in the rest of the world, which may outpace a 4°C increase by the end of 21st century. However, in areas with enough water and heat (due to climate change) it has been predetermined that pathogen and insect prevalence will further damage agricultural crops (Ziska et al., 2011). Also, if the temperature in a particular region goes higher than normal, climate change and precipitation variability could become the limiting factors for RTB crops. Precipitation variability also adds to the magnitude and recurrence of drought, decreases water availability of crops, and reduces the productivity of rainfed agriculture in SSA. Among the various physiological changes brought about because of climate change, drought stress is the most important and widely studied. Drought stress leads to an overall decrease in the yields of RTB throughout SSA by reducing the length of the growing season, amplifying water stress, and increasing the incidences of disease and pest outbreaks. During developmental phases drought alters carbon-assimilation processes, including transpiration, photosynthesis, and respiration, resulting in low plant growth and productivity (Bitá and Gerats, 2013). Even short duration heat shock when coinciding with the reproductive stage substantially lowers the crop yield (Teixeira et al., 2013), with a reduction in leaf area and the closing of stomata to minimize water loss. Drought stress is also projected to reduce the length of the growing season while spatially shrinking the suitable areas for crop production (Kaushal and Wani, 2015).

12.3 IMPACTS ON MAJOR CROPS OF SUB-SAHARAN AFRICA

12.3.1 Cassava

Cassava is one of the most vital crops in SSA in relation to caloric intake (Rosenthal and Ort, 2012). In terms of its total production and as an

important staple food, cassava is traditionally cultivated mainly in the Great Lake regions of Africa (Kenya and Tanzania) and in some parts of northern Zambia and Mozambique (Fig. 12.1).

Cassava is more resilient to drought due to its tolerance to high temperatures as compared to other RTB crops. However, a prolonged drought period during the root thickening initiation stage leads to root yield declines of up to 60% (Jarvis et al., 2012). It is also well-studied that cassava has superior yield gains than that of other crops at high CO₂ concentrations and can even recover from severe drought conditions (Rosenthal and Ort, 2012). Studies on cassava reported positive or minimum impacts and better performance of cassava crop in the near future under the raised CO₂, elevated temperature, and uncertain rainfall patterns that have been projected. Using 16 models under the A1B storyline, 8% yield reduction is projected for cassava compared to the 17%–22% reductions for other crops, such as maize, sorghum, millet, and groundnut, by the mid-21st century in SSA (Schlenker and Lobell, 2010). Also, a slight enhancement of cassava production is projected in east Africa by 2030 compared to 2000 (Lobell et al., 2008). Another study, utilizing the Improved Global Agro-Ecological Zones method under the A1B storyline, projected a 10% enhancement in cassava yields in Africa by the 2090s compared to the 1990s (Tatsumi et al., 2011). However, studies conducted by the International Food Policy Research Institute (IFPRI) using the IMPACT model, showed an elevation in cassava production of between 40% and 100%

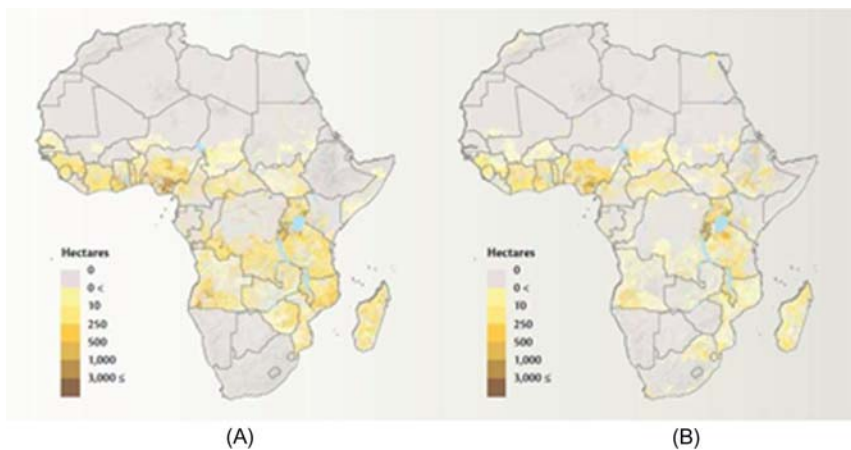


Figure 12.1 Production of (A) cassava and (B) sweet potato in SSA. FAO

in Malawi, Rwanda, and Uganda with no significant change in Mozambique and Tanzania by 2050 (Maure et al., 2012). Employing the same model, a raise in cassava productivity by 0.42% and 0.75% in eastern Africa and southern Africa respectively is projected for 2050 (Ringler et al., 2010). Overall, cassava yield will be the least impacted under different climate change scenarios compared to maize, beans, potato, and banana, thus, making it a potential candidate to ensure future food security in SSA.

12.3.2 Sweet Potato

Sweet potato is the most widely grown crop in SSA, mostly in Uganda, Rwanda, and parts of Tanzania, Kenya, and Ethiopia. Mainly cultivated by smallholder farmers, sweet potato is a major staple food in SSA and is also the most important source of carbohydrates. Sweet potato is mostly grown at altitudes of 800–1900 m a.s.l with temperatures between 20°C and 25°C, sometimes ranging from 15°C to 33°C. For tuber formation, low night temperatures are required, but higher temperatures during the day support vegetative growth. The susceptibility of sweet potato to drought stress and the low temperatures needed during the night for tuber formation make the crop vulnerable to climate change (Agili, 2012). The impacts of climate change on the production of sweet potato are sparsely known, but in comparison to other SSA crops it was the second most impacted after wheat. Hikes of 1.06% in eastern Africa and 1.14% in southern Africa are projected in sweet potato yield by 2050 through the utilization of the IMPACT model (Ringler et al., 2010). Also, a 15% decline in production is projected in eastern Africa by the 2090s compared to the 1990s if five general circulation models (GCM) are employed under the A1B storyline and the Improved Global Agro-Ecological Zones model (Tatsumi et al., 2011).

12.3.3 Potato

Mostly grown by smallholders, potato is grown in all the FTF nations, mainly focused in the highland areas. Malawi and Kenya are the biggest potato producers in SSA (Fig. 12.2).

Studies have also indicated that Kenya has exceeded Malawi with over 5 million tons of potato production in 2012 (FAO, 2013). In Kenya and Rwanda, potato is the second most important crop following maize and banana, respectively, mostly grown in the highlands of the

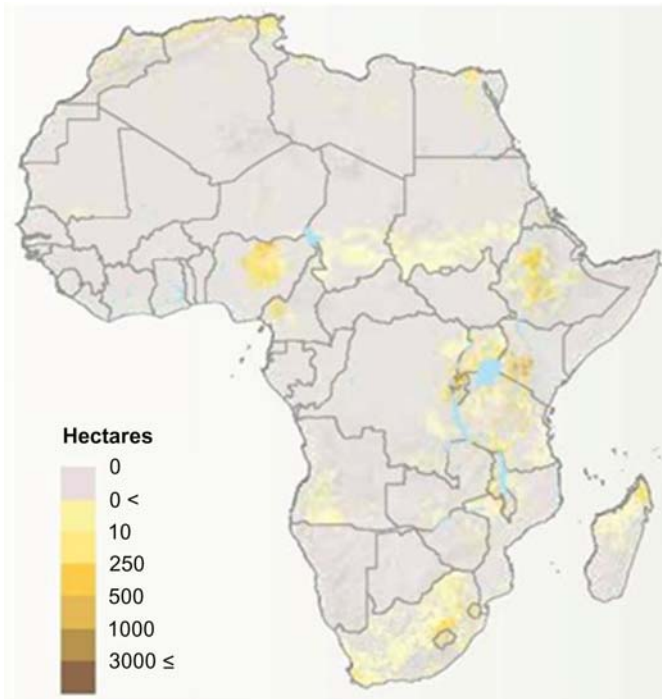


Figure 12.2 Production of potato in SSA. FAO

southwest and northern regions (Muhinyuza et al., 2012). Potato is cultivated by about 500,000 smallholder farmers, making it one of the most important sources of income and employment in rural areas. Also, Rwanda (2.3 million tons) and Tanzania (1.8 million tons) rank third and fourth among the FTF nations, respectively, while Zambia is the lowest producer with only 30,000 tons in total annual production (FAO, 2013). Optimally grown at 17°C, potato production has been observed to decrease above this temperature due to the reduced development and productivity of the plant caused by stress or decreased assimilative partitioning to the tubers. Stress due to moisture also reduces crop yields by contracting the growing and dormancy periods and by lowering the number and size of potato tubers. Like the C3 crop sweet potato, elevated atmospheric CO₂ concentrations enhance potato yields by multiplying the number of tubers, but actual yield profits may be insignificant under limited fertilization and water stressed conditions (Ainsworth and McGrath, 2010). Also, like sweet potato, the impacts of climate change on potato production in SSA has been scarcely studied.

The impacts of increased CO₂ concentrations on water use efficiency and yield were observed using six coupled GCMs under the A2 storyline in four potato-growing agroecosystems (Haverkort et al., 2013). Employing the IMPACT model, the IFPRI predicted an up to 100% enhancement in potato yields and a 50% increase in cultivation area in Rwanda in 2050 compared to 2010 (Tenge et al., 2012), leading to the prediction of double or triple the potato production by 2050. However, using 20 GCMs under the A1B storyline, a 15% reduction in potato yield is projected in Africa by 2030 (Jarvis et al., 2012). Similarly, utilizing five GCM models under the A1B storyline, a 17% decline in potato yield is projected in Africa in the 2090s compared to the 1990s (Tatsumi et al., 2011).

12.3.4 Banana

In Uganda and Rwanda banana has an annual per capita consumption of >135 kg (FAO, 2013), but also being largely produced and consumed in other regions of SSA. The crop is mostly grown in East Africa, including southwestern and central Uganda, some parts of Rwanda, the northern, southern, and eastern highlands in Tanzania, and the central and Kisii regions in Kenya (Fig. 12.3).

Studies have revealed that drought stress is the most critical constraint to banana production in the region (Van Asten et al., 2011). Another study demonstrated that banana plants can survive water stress for long periods of time as well as minimal soil moisture, but extended exposure to intense temperatures (above 35°C) can lower banana production (Thornton and Cramer, 2012). In parts of SSA that receive annual rainfall of below 1100 mm, droughts reduce yields by up to 65% (Van Asten et al., 2011). By 2020, in parts of Eastern and Southern Africa, banana production is projected to experience an increase in suitable areas ranging from 1% to 11% (Ramirez et al., 2011). On the other hand, highland bananas are projected to observe a significant loss in overall yield due to the inflation of pests and diseases if the temperature were to rise by 2°C (Thornton and Cramer, 2012). Similar to other RTB crops, quantitative measures under climate change impacts for banana yield are limited. In general, slight increase in environmental temperature would bring positive impacts for banana yield in highland areas, however, it could bring negative impacts for banana yield in lowland areas in the near future.

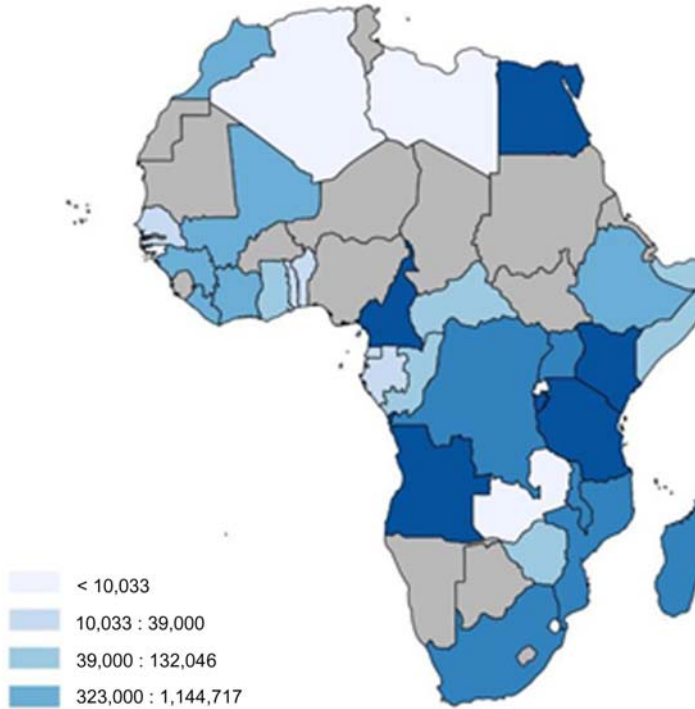


Figure 12.3 Production of banana in SSA. *FAO*

12.3.5 Maize

Maize, primarily grown by smallholders, is the most widely cultivated (on about 25 million hectares) staple crop in SSA, 77% of which is consumed as food (Fig. 12.4).

In addition to being a source of dietary protein, maize is also the second most significant source of calories in eastern and southern Africa (Broughton et al., 2003). Compared to other crops of SSA, the impacts of climate change on maize are well studied. An increased maize yield was observed with an elevation in temperature up to 29°C followed by a sharp decline with further increases (Schlenker and Roberts, 2009). The optimum temperature for growing maize is 25°C, however, each degree increase above 30°C has been found to lower the final maize yield by 1% (Lobell et al., 2011). Some studies suggest that a 1°C increase above the norm lowers maize yield by 10%. Temperatures between 32.2°C and 37.8°C are good for corn yield if available with adequate moisture. A 9% decrease in maize yield with every 1-inch cutback in rainfall was observed with high

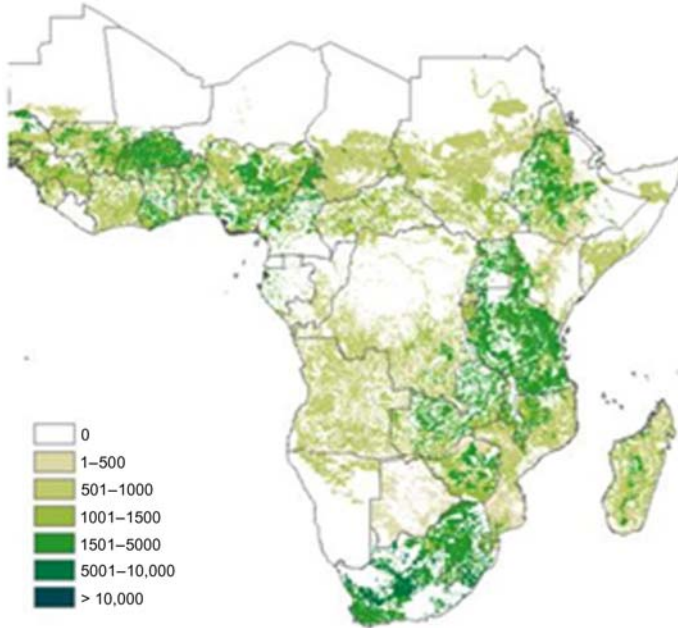


Figure 12.4 Production of maize in SSA. FAO

temperatures, which suggests that maize is susceptible to heat as well as to moisture stress. Also, between 3% and 19% decrements in maize yields are projected in the FTF countries by 2055 compared to 2000 utilizing the CERES-Maize model with Mozambique, the most affected country (Jones and Thornton, 2003). Yield profits in Kenya and Rwanda of 5% and 11% by 2030 and 18% and 15% by 2050, respectively, are attributed to elevated temperatures (Thornton et al., 2010) that may bring growing season temperatures close to optimum. A 7%–10% attrition in maize yields were observed by 2050 in SSA under the A2 storyline (Nielson, 2009). A 1°C rise in temperature is projected to lower maize yield by 65% even under good rainfed conditions (Lobell et al., 2011). Despite the large variations in projections observed, it has been widely accepted that climate change will adversely disturb maize yield in SSA and could increase losses by up to 40% of its production by the end of the 21st century.

12.4 PLANT GROWTH PROMOTING MICROBES IN SUB-SAHARAN AFRICA AGRICULTURE

Rhizosphere is the ecological niche surrounding plant roots with high microbial populations that are greatly influenced by root exudates.

In general, the ratio of microbial population in non-rhizospheric to rhizospheric soil is 1:10. The higher microbial population in the rhizosphere region is because of root exudates secreted by plant roots which microbes utilize efficiently. Plant roots also secrete photosynthetic products (about 5%–30%) in the form of different sugars, which in turn are used by microbial populations (Glick, 2014). The group of bacteria that reside in rhizospheric soil regions and that improve plant growth and yield are known as plant growth-promoting rhizobacteria (PGPR). The majority of PGPR belong to genera *Acinetobacter*, *Agrobacterium*, *Azotobacter*, *Azospirillum*, *Bacillus*, *Burkholderia*, *Rhizobium*, *Frankia*, *Serratia*, *Pseudomonads*, and *Bacillus* (Vessey, 2003). PGPR boost plant growth and yield through various direct and indirect mechanisms. PGPR also help plants cope and increase yield during stress conditions through various mechanisms called RIDER (rhizobacteria induced drought endurance and resistance), a term coined by Kaushal and Wani (2015).

12.5 MECHANISMS OF PLANT GROWTH-PROMOTING RHIZOBACTERIA

In order to maximize growth and yield, complete knowledge of PGPR mechanisms is required to manipulate microbial flora in the rhizosphere region. In general, PGPR aids the direct and indirect mechanisms of plants. Direct mechanisms activate plant metabolisms toward enhancing their adaptive capacity (Govindasamy et al., 2011), whereas indirect mechanisms involve plant defensive processes (induced systemic resistance and systemic acquired resistance).

12.5.1 Direct Mechanisms

Rhizosphere bacteria have high potential to produce various classes of well-known phytohormones, including auxins, gibberellins, cytokinins, ethylene, and abscisic acid. Plants respond well to these phytohormones in the rhizosphere which can mediate various processes, including plant cell enlargement, division, and extension in roots (Glick, 2014).

Indole-3-acetic acid (IAA), also known as auxin, produced by various PGPR are primarily involved in plant growth and development processes, such as cell elongation, cell division, and tissue differentiation. Continuous treatment of IAA in plants with highly developed roots, allows plants to uptake more nutrients ultimately improving overall plant growth (Aeron et al., 2011). IAA produced by rhizobacteria also elevate the size and surface area of root systems in contact with soil, which leads to an increased

ability for nutrient and water uptake ultimately improving plant growth and yield (Kaushal et al., 2017).

Cytokinins is another class of phytohormones produced by PGPR. Cytokinin application in plants results in enhanced cell division and shoot initiation (Jha and Saraf, 2015) by influencing their physiological and developmental mechanisms. Some other processes in plants, like nutritional signaling, expansion of leaf, promotion of seed germination, and delay of senescence are also greatly influenced by cytokinins (Wong et al., 2015).

Gibberellins (GAs), another group of phytohormones, influence many developmental processes in higher plants and can travel from roots to the aerial parts of plants. GAs are responsible for seed germination, flowering, and fruit setting (Hedden and Phillips, 2000). The enhancement of plant growth and yield by GA producing PGPR has been widely reported (Gutierrez-Manero et al., 2001). Impacts on the aerial parts of plants are increased when PGPR also secrete auxins that stimulate their root system architecture (RSA) through elevated nutrient supply, which supports growth of the aerial parts (Wong et al., 2015).

Nitrogen and phosphorous are the most limiting nutrients to plants. Despite the abundance of phosphorous present in soil, it is not in an available form that is suitable for plant uptake. Plants can only absorb mono- and dibasic phosphate in soluble form (Jha and Saraf, 2015). PGPR that behave as phosphate-solubilizing bacteria (PSB) are responsible for the solubilization of complex structured phosphates, such as tricalcium phosphate and rock phosphate. Phosphate solubilizing microbes (PSB) converts organic phosphorus into inorganic form through the secretion of acids because of sugar metabolism and ultimately available to the plants. Microbes inhabiting the rhizosphere utilize sugars from root exudates and metabolize them to produce organic acids (Goswami et al., 2014). These organic acids further act as good chelators of divalent Ca^{2+} cations and release phosphates from insoluble phosphate compounds. PSB also lowers the pH of the medium through the secretion of organic acids, such as acetic, malic, oxalic, and citric acids. PSB isolated from the rhizosphere regions are metabolically more active than those isolated from non-rhizosphere/bulk soil. Among the soil bacterial communities, *Pseudomonas* and *Bacillus* spp., have been identified as excellent phosphate solubilizers (Goswami et al., 2014). The most common organic acids produced by PSB are oxalic acid, citric acid malonic acid, succinic acid, and glycolic acid (Jha and Saraf, 2015).

Nitrogen fixation by PGPR is an important mechanism that has been widely studied. Traits of nitrogen fixation by PGPR are either of root/legume-associated symbiotic bacteria (*Rhizobium* spp.) or free living bacteria (*Azotobacter* spp.). Symbiotic bacteria possess the specificity and infect the roots to produce nodule or free-living nitrogen fixers (Oberson et al., 2013). Free-living nitrogen fixers include *Azospirillum*, *Azotobacter*, *Bacillus*, *Burkholderia*, and *Herbaspirillum*. In general, these nitrogen fixers fix between 20 and 30 kg of nitrogen per hectare per year. *Azotobacter chroococcum* and *Azospirillum brasilense* have gained importance especially in cereals as they possess the *nif* gene cluster which codes nitrogenase, a key enzyme required for nitrogen fixation.

12.5.2 Indirect Mechanisms

Iron, an essential nutrient for plants, also acts as a cofactor for many enzymes required for physiological processes such as nitrogen fixation. Despite the fact that iron is quite abundant in soils, like phosphorus, iron is frequently unavailable for plants and soil microbes. Plants either release certain organic compounds that can chelate iron and convert it into soluble form that can then be absorbed by the enzymatic system, or they directly absorb the complex formed by the organic compound and Fe^{3+} and the iron is then reduced inside the plant and thus readily absorbed. Some PGPR release low molecular weight iron-chelating compounds (siderophores) in the rhizosphere, which serves to attract iron toward the rhizosphere and thus be readily absorbed by plants. Mostly the genus *Pseudomonas* produce siderophores to increase their competitiveness, and thus, improve plant health. Siderophores also improve iron nutrition, inhibit the growth of other microbes by releasing antibiotics, and suppress the growth of pathogens by limiting the iron availability to them.

Another indirect mechanism of PGPR is to control soil borne pathogens through the secretion of cell wall breaking enzymes, such as β -1,3-glucanase, chitinase, and cellulase, which exert a direct inhibitory effect on the cell wall of phytopathogens. These cell wall-degrading enzymes secreted by rhizobacteria negatively impact on the structural integrity of the walls of the targeted phytopathogen. For instance, chitinase degrades chitin, the major component of fungal cell walls. Various strains of *Paenibacillus* sp. and *Streptomyces* spp. can synthesize β -1,3-glucanase, which degrades the cell walls of *Fusarium oxysporum*. Similarly, *Bacillus cepacia*

synthesizes β -1,3-glucanase, which inhibits the cell walls of *Rhizoctonia solani*, *Phythium ultimum*, and *Sclerotium rolfsii* (Compant et al., 2005).

The most common PGPR belong to *Bacillus* and *Pseudomonas* species and also play an important role in the suppression of pathogens through the production of antibiotics. These antagonists suppress phytopathogens by secreting extracellular metabolites, which are inhibitory even at very low concentration. These include a wide variety of antibacterial and antifungal antibiotics, such as subtilin, subtilosin A, mycobacillin, rhizocticins, surfactin, iturin, and fengycin.

An effective strategy of PGPR for plant protection is the induced systemic resistance. In this PGPR elicits host defense responses and thus reduce the incidence of diseases caused by phytopathogens that are spatially differentiated from the inducing agent. In this process the inducing rhizobacteria in plant roots produce a signal which disseminates systemically in different parts of the plants and enhances the defensive capacity of far-flung tissues against subsequent infection by phytopathogens (Thakker et al., 2012).

12.6 PLANT GROWTH-PROMOTING RHIZOBACTERIA AS BIOFERTILIZERS AND BIOCONTROL AGENTS

Several PGPR strains are used as biofertilizers and biocontrol agents and are commercially obtained as formulated products (Jha and Saraf, 2015). In general, alginate gel is used to prepare bacterial and fungal formulations (Desai et al., 2002). Bacterial biofertilizers are formulated in many ways depending upon the nature of isolated strains. Sporulating Gram-positive bacteria that possess heat-resistant spores are exploited to formulate stable and dry powder products. The suspension of microbes in oil is an alternative to solid-powdered formulation, where oxygen is excluded to prevent respiration (Kamilova et al., 2015). Sometimes silica gel is added to oil formulations in order to enhance shelf life. Currently, commercialization of microbial based products are receiving huge attentions especially in SSA and thousands of companies are commercializing this as biofertilizers/biocontrol agents, of which the most exploited genera are *Pseudomonas*, *Bacillus*, *F. oxysporum*, *Pythium aphanidermatum*, *Streptomyces griseoviridis* strain K61, *Bacillus licheniformis* strain SB3086, *Coniothyrium minitans*, and many others. Many Gram-negative bacterial strains are also highly efficient as biocontrol agents, but they are difficult to formulate due to nonproduction of spores, short shelf life, and being easily destroyed

when the formulations are desiccated. The main challenge faced by commercial developers is varying agroclimatic and environmental conditions, such as temperature, rainfall, soil type, cultivar, which change from one field/location to another, which cause variations in the potentiality of bio-fertilizer strains (Kamilova et al., 2015). However, researchers are still trying to develop better biofertilizers/biocontrol agents with improved shelf life that possess better adaptability in various agroclimatic zones and compatibility with different hosts. These improved bio-fertilizers could bring huge scope for enhancing agricultural productivity.

12.7 ROLE OF MICROBES IN RESILIENCE OF ROOT, TUBER, AND BANANA CROPS IMPACTED BY CLIMATE CHANGE

Statistical shifts in the circulation of weather patterns over a period of time is known as climate change (Compant et al., 2010). Plant–microbe interactions are greatly affected as climate change alters environmental conditions drastically because all microbial processes are dependent environment (Classen et al., 2015). Rising CO₂ concentrations increase carbon allocation to plant roots and thus, impact on the normal physiological and growth promoting exercises of root linked microbes. The impact of elevated temperatures on plant–microbe interactions are variable and may affect the performance of plant-beneficial bacteria (Egamberdiyeva and Hoflich, 2003) with varying soil types. However, there are certain PGPR that perform better at high temperatures and are, thus, of greater interest for application in climate smart agriculture. Global temperatures are continuously rising due to climate change and are predicted to elevate between 1.8°C and 3.6°C by the year 2100. Another major consequence of climate change is drought stress which effects many RTB crops in SSA and also leads to microbial community shifts under low soil water availability. Drought is also known to bring about many physiological, biochemical, and molecular changes in plants leading to reductions in crop productivity. In such stress conditions, rhizobacterial inoculants can, thus, be used either as a biofertilizer or phytostimulator depending on their mode of action and efficacy (Sharma et al., 2014). The ability of plants to sustain growth and survive during long periods of drought stress is known as drought resistance (Chaves et al., 2003). Plants have developed mechanisms to fight drought stress, including morphological adaptations, osmotic adjustment, antioxidant systems, reactive oxygen species, and a variety of stress-responsive genes and proteins (Kaushal and Wani, 2016).

Drought stress also affects rhizospheric microbial populations through osmotic stress and resource competition (Chodak et al., 2015), which can result in the damage of nucleic acid via alkylation or oxidation, crosslinking, or base removal. It also results in the accumulation of free radicals because of conformational protein changes, restricted enzyme efficiency, and changes in electron transport chains (Berard et al., 2015) leading to the denaturation of proteins, lipid peroxidation, and ultimately cell lysis. Rhizobacteria employ a variety of physiological mechanisms to protect cell structures and other organelles from drought stress. These include the accumulation of compatible solutes and heat shock proteins and the production of exopolysaccharide and spores. Compatible solutes, such as proline, glycine betaine, and trehalose, enhance thermotolerance of enzymes, suppress protein denaturation, and preserve membrane integrity (Kaushal and Wani, 2016). Exopolysaccharides (EPS) protects the cell membrane integrity of plants. Some bacteria store large quantities of ribosomes and respond with rapid protein synthesis during stress conditions (Placella et al., 2012). Many drought-tolerant varieties developed through conventional plant breeding techniques have been used to diminish the negative impacts of drought stress on crop growth and yields (Eisenstein, 2013). Currently, plant–microbe interactions have received a lot of attention for increasing crop productivity by providing resistance against various types of stress (Yang et al., 2009). Some well-studied examples of plant–microbe interactions include mycorrhizal fungi (Azcon et al., 2013), nitrogen-fixing bacteria (Lugtenberg and Kamilova, 2009), and plant growth-promoting rhizobacteria (Glick, 2012). PGPR have the ability to colonize roots and produce various enzymes and metabolites that benefit plants in biotic and abiotic stress tolerance (Chauhan et al., 2015). Studies have been conducted on harnessing beneficial soil microbes to boost crop production under changing climatic conditions (Nadeem et al., 2014). PGPR assist all RTB crops with their efficacy to confer drought tolerance. In SSA, plants possess adaptive traits to endure drought stress and improved RSA with PGPR. RSA integrates root system topology, primary and lateral roots spatial distribution, and the number and length of various diameters of roots (Vacheron et al., 2013). A correlation between prolific root systems and drought resistance has been observed in several crops, such as soybean (Sadok and Sinclair, 2011), maize (Hund et al., 2011), and wheat (Wasson et al., 2012). Plants inoculated with PGPR under drought stress are able to maintain normal shoot growth, leading to an enhancement in crop productivity. Relative water content

(RWC) in plants measures water status and maintains metabolic activity in tissues. A decline in RWC results in loss of turgor pressure which limits cell expansion and reduces growth in plants (Castillo et al., 2013). Maize plants, when treated with PGPR strains under drought stress, displayed elevated RWCs compared to nontreated plants (Naveed et al., 2014). Osmotic adjustment protects enzymes, proteins, cellular organelles, and membranes from oxidative damage (Huang et al., 2014). Proline is another important osmolyte that accumulates in plants due to drought stress and contributes to stabilizing cellular structures and redox potential. Increased proline levels have been demonstrated in maize (Naseem and Bano, 2014) which confers drought tolerance by protecting plants from dehydration. Antioxidant enzymes (such as catalase, superoxide dismutase, glutathione reductase, ascorbate peroxidase) represent another approach used to assess and cope with drought stress, which serves to minimize oxidative injury. PGPR also promote plant growth during drought stress by modifying the phytohormone content (Bresson et al., 2014), such as decreasing ethylene production and balancing Abscisic acid (ABA) and Indole acetic acid (IAA) signaling. It is also evident, that plant-associated bacteria elicit a plant response by inducing systemic tolerance. Climate change/stress may impact on all types of beneficial plant–microbe interactions. In general, drought stress decreases the colonization of plant-beneficial microbes, but inoculation with PGPR diminishes drought stress and enhances plant performance. Also, the compositions of microbial communities directly relate to plant physiology and are driven by root exudates. Sometimes plant growth-promoting rhizobacteria support plants to adapt to drought stress/new environmental conditions.

12.8 MICROBIAL ADAPTATION IN SUB-SAHARAN AFRICA

Microbial adaptation aimed at improving the growth and yield of RTB crops in SSA involves several other critical components, such as soil health, water conservation, and capacity building. It is evident from this chapter that RTB crops will be primarily affected by drought stress in the future in whole of SSA being most severe in the eastern regions. For example, with maize being more affected by drought stress, it would be useful to switch drought-sensitive with drought-tolerant crops, such as cassava, which may mitigate temperature stress-related crop failure. As an adaptive precaution to climate change, growers in SSA have already begun mixed cropping selections, such as cassava with coffee crops, based

on the prevailing climate. Climate impacts in future could bring more water runoff in northern parts of SSA than that of southern regions (Adhikari et al., 2015). Also, wide resource and social constraints may impact on the capacity of smallholder farmers to adopt irrigation as an adaptation in SSA. Thus, currently, farmers are also more aware and enthusiastic for the use of commercialized technologies of PGPR/endophytes available on the market to mitigate various types of stress. The development and commercialization of drought-tolerant microbial strains also helps to reduce climate change impacts on RTB crops in drought-prone areas. Growth and yield of microbially inoculated plants raised up to 40% advising the potentiality of PGPR in drought stressed agriculture. Thus, the role of plant-associated microbiomes against drought in plant adaptation is highly emerging. Microbiome configuration may differ significantly in fluctuating environmental circumstances depending on the taxonomic vulnerability of the linked plant species.

12.9 CONCLUSION

Climate change negatively influences the growth and yield of RTB crops in SSA due to changes in plant physiology and root exudation. It is projected that the yields of different RTB crops will decrease by up to 65% by 2030. Drought stress induced by climate change also has a significant impact on beneficial microbial populations in soil and thus on plant–microbe interactions. In general, drought decreases the colonization of plant-microbes, but it is also true that plant performance is improved by reducing the impacts of drought when inoculated with PGPR. Growing drought-tolerant varieties is one way to cope with the climate change scenario. Sometimes drought-tolerant cultivars are not fully adapted to new environmental conditions, which could also be supported by inoculating with potential plant growth-promoting microbes. Microbial strains collected from local drought-affected locations performed better in enhancing tolerance of plants to drought stress than those that were isolated and brought from other regions that do not experience drought. However, integrating the testing of microbial strains from drylands into plant breeding techniques for drought resistant may help SSA agriculture to adapt to the continually changing climate. Future research is required to quantify the impacts of climate change on regionally imperative staple food crops as well as cash crops in order to better formulate potential coping techniques against drought.

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