

Review

Raising Crop Productivity in Africa through Intensification

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Academic Editors: Yantai Gan and Paul C. Struik

Received: 11 September 2016; Accepted: 3 March 2017; Published: date

Abstract: The population of Africa will double in the next 33 years to reach 2.5 billion by 2050. Although roughly 60% of the continent's population is engaged in agriculture, the produce from this sector cannot feed its citizens. Hence, in 2013 alone, Africa imported 56.5 million tons of wheat, maize, and soybean at the cost of 18.8 billion USD. Although crops cultivated in Africa play a vital role in their contribution to *Food Security*, they produce inferior yields compared to those in other parts of the world. For instance, the average cereal yield in Africa is only 1.6 t·ha⁻¹ compared to the global 3.9 t·ha⁻¹. Low productivity in Africa is also related to poor soil fertility and scarce moisture, as well as a variety of insect pests, diseases, and weeds. While moisture scarcity is responsible for up to 60% of yield losses in some African staple cereals, insect pests inflict annually substantial crop losses. In order to devise a strategy towards boosting crop productivity on the continent where food insecurity is most prevalent, these production constraints should be investigated and properly addressed. This review focuses on conventional (also known as genetic) intensification in which crop productivity is raised through breeding for cultivars with high yield-potential and those that thrive well under diverse and extreme environmental conditions. Improved crop varieties alone do not boost crop productivity unless supplemented with optimum soil, water, and plant management practices as well as the promotion of policies pertaining to inputs, credit, extension, and marketing. Studies in Kenya and Uganda have shown that the yield of cassava can be increased by 140% in farmers' fields using improved varieties and management practices. In addition to traditional organic and inorganic fertilizers, biochar and African Dark Earths have been found to improve soil properties and to enhance productivity, although their availability and affordability to African farmers remains to be explored. The concept of Integrated Soil Fertility Management (ISFM) has been successfully implemented in some African countries in the Great Lake Region. Other innovative technologies favorably accepted by farmers are the "Push-pull System" (an elegant method of controlling a devastating insect pest and a parasitic weed) and NERICA (New Rice for Africa, in which rice varieties with desirable nutritional and agronomic properties were developed by crossing Asian and African rice). This review calls for African governments and institutions not only to provide conducive environments but also to abide by the Maputo 2003 Declaration where they agreed to invest 10% of their national budget to agricultural research and development as the outcome has a positive impact on productivity and ultimately improves the livelihood of farmers.

Keywords: agronomy; crop intensification; enabling environment; plant breeding; plant ideotype; yield potential

1. Introduction

Food security is defined as a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life [1]. African population has been growing at a very high rate and is expected to reach 2.48 billion by 2050 from the current 1.25 billion [2]. This almost 100% increase in only 33 years will bring an additional 1.23 billion people to inhabit the continent. The main concern is whether every inhabitant in the continent obtains basic human needs, particularly food. Although at the present time approximately 60% of the African population live in rural areas, the trend is expected to change after 2035, after which more people will live in urban areas, although there is no indication for the provision of enough infrastructures and jobs for newcomers to the cities.

Although large proportions of Africa's populations are engaged in agriculture, the produce from this sector cannot feed its citizens. Hence, many African countries are obliged to import large quantities of grains and oil seeds every year. The top three import items of Africa in 2013 were wheat (40.3 million tons), maize (14.1 million tons), and soybean (2.1 million tons) (Figure 1A) [3]. The continent spent a total of 18.8 billion USD (13.2 billion USD for wheat, 4.3 billion USD for maize, and 1.3 billion USD for soybean) in 2013 to purchase the three items (Figure 1B). This indicates that every year, African governments expend large amounts of their budget to fulfil the demand for food. Although the total amount of imported wheat and maize showed only a gradual increase from 2007 to 2013, the value or cost of these items showed significant increase, especially in the years 2008 and 2011, when the prices of wheat and soybean rose by up to 40% and 70% respectively in a single year. These elevated food prices exposed African countries to extremely high and unplanned expenditures. Increases in food prices were the highest in Africa compared to all other continents.

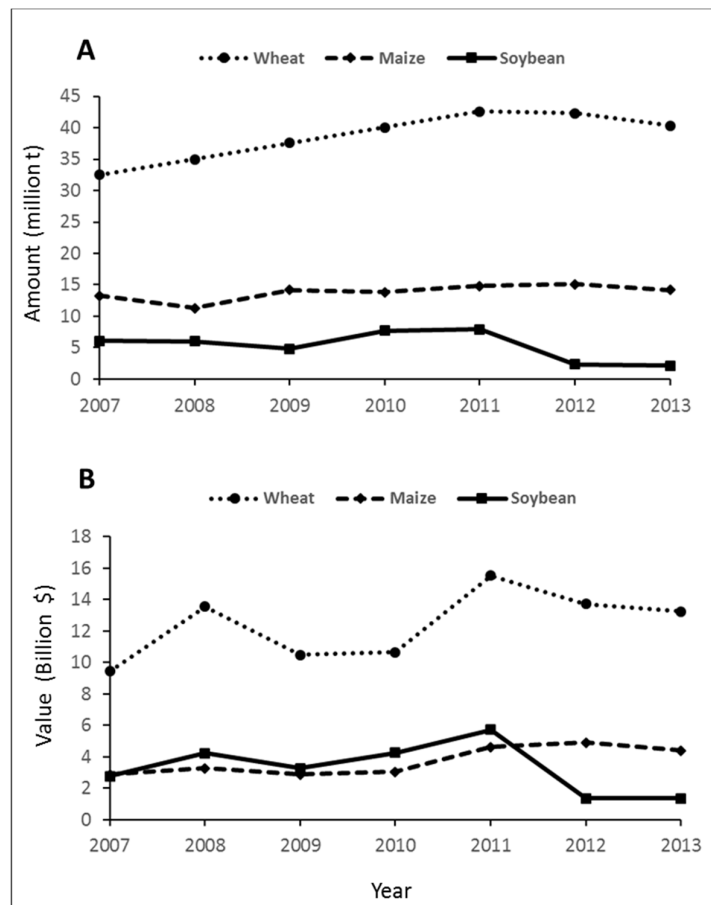


Figure 1. The top three crops imported by Africa from 2007 to 2013. (A) amount of import and (B) total value of three imported crops.

Food security could be improved by focusing on locally important crops commonly known as orphan crops [4], as well as major crops of the world. The need to focus on orphan crops in order to meet the need for food demand has been emphasized by various authors [5,6]. Diverse types of crops that include cereals, legumes, vegetables, root crops, and fruits are cultivated in Africa. Although similar types of crops are cultivated in Africa and the rest of the world, Africa has unique crops that are solely cultivated and consumed on the continent. These include cereals such as fonio [*Digitaria exilis* (Kippist) Stapf. and *D. iburua* Stapf] in the western Africa, and tef [*Eragrostis tef* (Zucc.) Trotter] in the Horn of Africa, a food legume called bambara groundnut [*Vigna subterranea* (L.) Verdc.] in the southern and western Africa, and a root crop called enset [*Ensete ventricosum* (Welw.) Cheeseman] in the densely populated region of Ethiopia. The list of major African crops were presented in earlier reviews [7,8].

Crops cultivated in Africa have a number of advantages in terms of adapting to extreme climatic and soil conditions (Table 1). For instance, cereals such as finger millet (*Eleusine coracana* Gaertn.) and fonio (also known as “acha”) and legumes such as cow pea [*Vigna unguiculata* (L.) Walp.] and bambara groundnut are dominantly cultivated in the semi-arid areas of Africa due to their tolerance to moisture deficit [3,9–11]. Cowpea is also tolerant to heat and performs better than many other crops on sandy soils with low level of organic matter and phosphorus [12]. Tef is also tolerant to abiotic stresses, especially to poorly drained soils that other crops such as maize and wheat cannot withstand [13]. In addition, these crops are rich sources of nutrients (Table 1). The seeds of finger millet contain valuable amino acids, especially methionine [14], which is lacking in the diets of hundreds of millions of the poor who live on starchy staples such as cassava. Some indigenous crops are also considered as life-style crops due to health-related benefits. For instance, finger- and pearl-millet have an anti-proliferative property, and might have potential in the prevention of cancer initiation [15], while the grains of tef do not contain gluten [16,17], the cause for celiac disease. In general, crops cultivated in Africa play key roles in the livelihood of resource-poor farmers and consumers since they perform better than the major world crops under extreme soil and climate conditions prevalent in the continent, provide nutrition to large number of population as well as provide income for smallholder farmers.

Crop intensification or boosting productivity per unit area is the urgent task for those involved in crop improvement due to at least the following three reasons; (i) diminishing size of arable land due to expansion in urbanization and industrialization, (ii) tremendous increases in African population which requires more and more mouths to feed, and (iii) gradual decrease in African population engaged in agriculture. This review shows the significance of crop intensification in raising productivity in Africa. It also provides some agronomic innovations which can be applied to the improvement of crops in Africa.

Table 1. Desirable and undesirable properties of selected crops cultivated in Africa.

Crop (Scientific Name)	Desirable Properties *								Undesirable Properties **								Reference
	1	2	3	4	5	6	7	8	A	B	C	D	E	F	G	H	
Cereals																	
Barely (<i>Hordeum vulgare</i>)							x					x	x				[18]
Finger millet (<i>Eleusine coracana</i>)		x		x	x		x		x		x						[19]
Fonio (<i>Digitaria exilis</i>)			x		x		x		x								[14,20]
Maize (<i>Zea mays</i>)	x		x		x						x	x			x	x	[21]
Pearl millet (<i>Pennisetum glaucum</i>)		x	x		x				x					x			[22]
Rice (<i>Oryza sativa</i>)					x						x	x				x	[21]
Sorghum (<i>Sorghum bicolor</i>)		x	x						x						x	x	[21]
Tef (<i>Eragrostis tef</i>)			x		x	x		x	x								[13,16]
Wheat (<i>Triticum aestivum</i>)	x					x						x	x				[23]
Food legumes																	
Bambara groundnut (<i>Vigna subterranea</i>)		x			x							x			x		[24]

Chick pea (<i>Cicer arietinum</i>)			x			x	x		[25]	
Common bean (<i>Phaseolus vulgaris</i>)						x	x		[26]	
Cowpea (<i>Vigna unguiculata</i>)	x	x	x		x	x			[12,26]	
Grass pea (<i>Lathyrus sativus</i>)	x		x			x		x	[27]	
Groundnut (<i>Arachis hypogaea</i>)							x		[26]	
Pigeon pea (<i>Cajanus cajan</i>)	x	x	x						[28]	
Roots and tubers										
Cassava (<i>Manihot esculentum</i>)	x				x	x	x	x	x	[29]
Enset (<i>Ensete ventricosum</i>)	x					x	x	x		[30]
Potato (<i>Solanum tuberosum</i>)					x	x		x		[31]
Sweet potato (<i>Ipomoea batatas</i>)	x				x	x	x	x		[32,33]
Taro (<i>Colocasia esculenta</i>)			x		x	x		x		[34]
Yam (<i>Dioscorea spp</i>)	x				x	x	x	x		[35]
Oil seeds										
Castor seed (<i>Ricinus communis</i>)	x		x	x	x	x		x		[36]
Mustard (<i>Brassica carinata</i>)	x		x							[37]
Noug (<i>Guizotia abyssinica</i>)				x	x					[38]
Sesame (<i>Sesamum indicum</i>)	x	x		x	x			x		[32]
Fruits										
Banana/plantain (<i>Musa spp.</i>)			x	x		x		x		[39,40]
Mango (<i>Mangifera indica</i>)				x		x		x		[41]
Papaya (<i>Carica papaya</i>)			x	x		x		x		[42]

* 1: High productivity; 2: Drought tolerance; 3: heat tolerance; 4: disease/pest tolerance; 5: rich in nutrients; 6: quality oil; 7: healthy food; 8: fast maturing. ** A: low yield; B: poor in nutrients; C: disease/pest susceptibility; D: susceptibility to moisture scarcity E: post-harvest loss; F: toxic substances; G: late maturing; H: sensitivity to parasitic weed.

2. Constraints to Productivity of Crops Cultivated in Africa

Although crops grown in Africa possess many desirable agronomic and nutritional properties, they are not blessed with everything. Undesirable properties or traits of selected crops are shown in Table 1. Due to little genetic improvement, most of these crops produce inferior yield in terms of both quality and quantity. Although global areas of 67% cassava, 43% sweet potato, and 30% banana are in Africa, the contribution of these crops to the global production are only 52% for cassava, 17% for sweet potato and 15% for banana [3]. These extremely low productivities in Africa are due to the prevalence of a huge number of biotic and abiotic stresses, the use of inefficient agricultural inputs, and policy-related problems.

Waddington et al. [43] studied yield constraints for six major food crops in Africa and Asia based on surveys made of 13 farming systems. The authors identified four major categories of constraints, namely abiotic, biotic, management, and socio-economic. These limitations varied from crop to crop and region to region. For instance, the main bottlenecks for sorghum were weed competition, soil degradation, poor soil fertility, and drought, while for cassava they were marketing and lack of finance. Similarly, Reynolds et al. [44] identified moisture scarcity, nutrient limitation, and biotic stresses in cereal crops such as maize, sorghum, and rice, and biotic stresses and post-harvest losses in root and tubers such as cassava, yam, and sweet potato as major environmental constraints in Sub-Saharan Africa.

2.1. Environmental Stresses

Environmental stresses are broadly grouped into biotic and abiotic stresses based on the source of the cause.

2.1.1. Biotic Stresses

Constraints related to biotic factors cause tremendous losses to crops cultivated in Africa due to the presence of conducive environmental conditions (especially temperature and humidity) for these crop nuisances, and due to less application of control measures. Goldman [45] indicated that the

production of many crops in Kenya, Nigeria, and other regions in Africa declined sharply as a result of pest and disease outbreaks.

Insect pests: Dipterous and lepidopterous stem borers are the major insect pests. Crop yield losses due to insects are estimated between 30% and 60% in Africa [46]. The study on three important insect pests that inflict tremendous crop losses in Africa showed that habitat suitability for these poikilothermic pests is increasing across the continent due to the expected changes in climate [47].

Diseases: A variety of fungal, bacterial, and viral diseases cause considerable damage to crops cultivated on the continent. Among these, a devastating wheat stem rust called Ug99 is not only the major threat in Africa but also globally, since 90% of the wheat varieties grown worldwide are susceptible to this pathogen [23].

Weeds: In addition to major broadleaf and grassy weeds, parasitic weeds, particularly witchweed (*Striga hermonthica*), are not only widespread in Africa, but also annually cause tremendous yield losses to cereal crops such as sorghum, maize, millet, and rice [21].

2.1.2. Abiotic Stresses

A number of soil- and climate-related constraints cause substantial yield losses to crop plants. The effects of several abiotic stresses are briefly shown below.

Soil fertility: Most African soils are inherently low in fertility due to high weathering and leaching; hence they are deficient in major nutrients such as nitrogen and phosphorus [48]. Poor soil management and removal of crop residues from the field also contribute for the substantial reduction in soil fertility.

Drought: Moisture scarcity is the most wide-spread challenge to crop production in Africa. It affects both the quantity and quality of the produce. Yield losses due to drought are estimated to be 40% in tef [49], 51% in pearl millet, and 57% in bambara groundnut [50]. Drought became more intense and widespread in Southern Africa due to the long-term variability and changes in rainfall [51].

Waterlogging: The waterlogging problem is prevalent on poorly drained soils commonly known as Vertisols, black clay soil with high water-holding capacity. About 43 million ha of land in 28 African countries are covered with this problematic soil [52]. Since soil pores during waterlogging are filled with water, the diffusion of gases is hampered, resulting in anaerobic conditions. As a result, the normal functioning of stomata, photosynthesis, and roots are severely affected [53].

Soil acidity: Toxic levels of aluminum affect root growth and resulted in stunted growth, small grain size, and poor yield of the plant [54]. From the total global arable area, 40% is currently affected by soil acidity [55]. According to Goussard and Labrousse [56], large areas of soil in Africa are less productive due to acidity related to parent material and low retention capacity of chemical fertilizers. Reclaiming acid soils is mostly done using large amount of lime or calcium carbonate. The application of lime is not only unaffordable by small-scale farmers in Africa due to large quantity requirement, but is also less accessible in the market.

Soil salinity: Soil salinity, which is characterized by a high concentration of soluble salts, affects crop productivity. From the total global arable area, a third is affected by salinity [55]. About five percent of the land in Africa is affected by salinity [57]. The accumulation of salts depends on the quality of irrigation water, irrigation management, and the drainage of the soil. Reclaiming saline soil is not affordable by small-scale farmers as it requires large amount of water to leach and remove salts away from the root zone. The study in tef showed that saline soil causes up to 93% yield loss [58].

High air temperature: Studies on maize, cotton, and soybean indicated that with heat, yields increase until a crop-dependent threshold temperature, but temperatures above these thresholds become detrimental to the productivity of each crop [59]. Global warming is also expected to negatively affect crop production. According to Bitu and Gerats [60], an increase of 3 to 4 °C in air temperature reduces crop productivity by 15–35% in Africa and Asia. Lynas [61] predicted drastic negative consequences on the ecosystem due to the expected increase in air temperature between 1 to 6 °C.

2.2. Inefficient Use of Agricultural Resources and Inputs

Improved technologies or inputs that enhance productivity are poorly implemented in Africa. Access and timely availability to inputs such as improved seeds, fertilizers, pesticides, irrigation, and machinery have substantial effect in promoting productivity.

Land productivity and tenure system: Land is the major resource on which agriculture is based. The fertility of the land and the land tenure system have a huge impact on crop productivity. According to the FAO [3], only a portion of the total land area is suitable for crop cultivation in Africa. Even this suitable land is not efficiently utilized. The area under arable and permanent crops is higher in Asia than in Africa, indicating more land use in Asia. While the percentage of these crops reached up to 74% in Southern Asia, a maximum of 33% land is under these crops in Africa. The type of land tenure or ownership also affects crop productivity.

Improved seeds: Information on the number of improved crop varieties and their dissemination in the Sub-Saharan Africa is presented by DIIVA (Diffusion and Impact of Improved Varieties in Africa) [62]. At the present time, information is available for 21 crops in 29 countries that represent 70% of the total value of agricultural production. The number of crop varieties released in a country is not correlated to the number of inhabitants the country. For instance, Benin is home to only 11 million people and has released 36 maize, 24 cowpea, and 15 yam varieties, while Nigeria, the most populous country in the continent (with a population several folds higher than Benin), released less varieties, although this might be due to the lack of updating the latest figures. Although the number of crop varieties released shows the size of investment in research, it does not reveal the level of dissemination and adoption of released varieties by the farming community.

Fertilizer use: Fertilizer is the most important input in crop production. The use of the three most important nutrients (nitrogen, phosphorous, and potassium) is the lowest in Africa both in terms of the amount of nutrient per capita (Figure 2A) and the amount of nutrient per agricultural land (Figure 2B). Micronutrients such as iron, zinc, and manganese are also useful, although they are required by plants in small quantities. The efficiency of nutrient uptake and use varies among crop types and among varieties of the same crop type. According to the study made in West Africa, the amounts of nitrogen, zinc, and manganese removed by the upland and lowland rice varieties were similar, although the amounts of phosphorus, potassium, calcium, and magnesium removed were higher for the lowland than for the upland rice [63]. Nevertheless, the major constraint to smallholder farmers in Africa is the access to fertilizers (i.e., the availability at the required time and affordability in terms of cash or credit).

Irrigation use: Irrigation is considered as a key factor to boost crop productivity. Irrigation is widely implemented in Asian countries, especially in the southern part of the continent where it is applied to about 35% of the agricultural land (Figure 2C). On the contrary, below one percent of the agricultural land in the Sub-Saharan Africa is under irrigation.

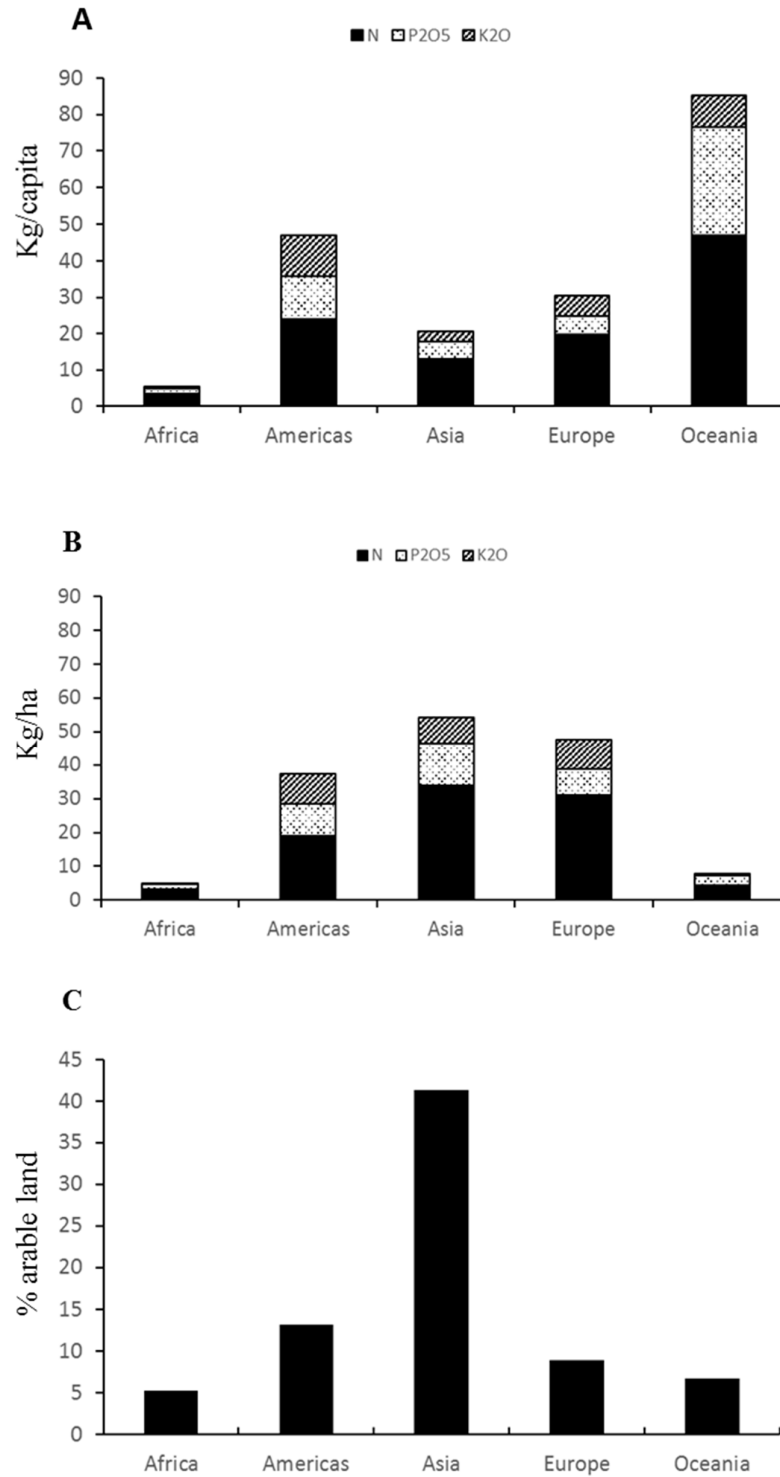


Figure 2. Agricultural input use is the lowest in Africa. (A) Fertilizer use (kg nutrient per capita of the population); (B) fertilizer use (kg nutrient per ha of agricultural land); and (C) irrigation use (% of arable land). Americas refers to both North and South America as well as the Caribbean. Adapted from: FAOSTAT.

2.3. Inadequate Investment in Agricultural Research and Development

In a meeting in Maputo, Mozambique, in 2003, member countries of an African Union agreed to allocate at least 10% of their national budgetary resources to agriculture and rural development [64]. The recent report showed that although the 10 percent target was not achieved in the majority of the countries, productivity on existing farmlands increased by 5.9% to 6.7% per year in some countries [65]. African governments also need to implement conducive land, marketing, and credit policies that support agricultural development and favor productivity. In general, poor crop productivity in Africa is due to the use of inefficient agricultural practices that begin from land preparation, weeding, harvesting, and finally threshing. In addition, sub-optimal use of inputs such as fertilizers, herbicides, and pesticides are also responsible for the low productivity of crops in the continent [66,67].

3. Boosting Crop Productivity through Intensification

Intensification refers to improved productivity or output using proper agricultural inputs in optimum amount and time. Inputs that play a key role in agricultural intensification refer to direct inputs that can directly alter the outputs from the farm (e.g., fertilizer, labor, and water) and indirect inputs that facilitate or modify the direct inputs (e.g., finance, market, and knowledge) [68]. Based on a legume-maize farming systems in four east African countries, Kassie and colleagues concluded that the adoption of sustainable intensification practices by farmers is influenced by several factors including quality of extension services, access to market, and tenure security. The inputs include improved crop varieties and proper crop management practices, as well as credit and marketing facilities [69].

Three categories of outputs reported for agricultural intensification are (i) production, which refers to the total amount of food per unit input, (ii) income, which refers to the amount of net income generated per unit input, and (iii) nutrition, which refers to the human consumption of nutrients per unit input [68].

3.1. Sustainable Intensification

Sustainable intensification (SI) is defined as a process or system where agricultural yields are increased without adverse environmental impact and without the conversion of additional non-agricultural land [70].

Three approaches of sustainable intensification are identified [68]. These are (i) Genetic intensification, which refers to the use of conventional and modern improvement techniques in order to boost crop yield, improve nutrition, and enhance resilience to environmental challenges; (ii) Ecological (also known as Agro-ecological) intensification, which refers to simultaneously improving the productivity and environmental management of agricultural land [71]; and (iii) Socio-economic intensification, which creates conducive markets and develops human capacity [68]. While the first two are technological approaches, the third provides an enabling environment in order to support technology adoption. Although some distinct differences exist between the two technological approaches, they share some common elements in agricultural practices which enhance soil fertility (e.g., cropping systems) and integrated pest management. However, the major difference between the two are on the amount and type of agricultural inputs used. Genetic intensification is the “high input” system due to the intensive use of chemicals such as fertilizers, herbicides and fungicides; while ecological intensification is the “low input” option.

The type of ecological intensification that has been extensively tested in 50 countries and proved to substantially increased rice productivity is known as System Rice Intensification (SRI) [72]. SRI applies improved planting and growing techniques such that more yield can be obtained using fewer seeds and less water through management of the relationship between the plant and soil. The recent meta-analysis based on 25 field studies in China between the SRI and improved practices showed that the former had over 10% yield advantage over the latter [73]. Although SRI claimed to boost rice productivity [74], it has been contested by several researchers in the last decade [75–77]. The main argument against SRI is the lack of replicating extremely high yields reported for SRI compared to

the conventional system. Studies at four sites in China [75] and at over 30 locations in Bangladesh, China, Laos, Nepal, and Thailand [76] revealed no significant benefit of SRI over the conventional system. The controversy between proponents and critics of SRI received heated debates as early as 2004 [78–80] and continued until recently [81–83].

In order to transfer the knowledge and experience developed by SRI to other crops, a network of System of Crop Intensification (SCI) was formed. Several years of SCI studies on major crops such as rice and wheat, as well as indigenous crops such as finger millet, tef, and mustard resulted in significantly higher yields compared to the conventional methods [84]. However, SCI could not be easily adopted by farmers cultivating small cereals such as tef. The main reason for low acceptance of the system in tef is the need to transplant tef seedlings during the rainy season when the soil is extremely wet and sticky due to the high clay content of the dominant soil type where tef is extensively cultivated. This makes tef transplanting difficult, if not impossible. In addition, transplanting during this time of the year competes with scarce labor force as it coincides with other farm practices (e.g., hand weeding of other crops). However, the development of small-scale tef transplanters that improve the transplanting process might enhance the adoption by farmers, since significantly higher tef yield from SCI over conventional method has already been witnessed [85].

The outputs from sustainable intensification are two-fold: multiplicative (boosting yield per unit area) and additive (diversification through introducing new crops or other food items) [86]. The evaluation of the performance of 40 projects in the sustainable intensification in 20 African countries indicated that food outputs are both multiplicative and additive [86]. While the increase in productivity from the combined use of improved varieties and agronomic management is multiplicative, the diversification which resulted in the emergence of a range of new crops and livestock is additive.

The present review focuses on the genetic intensification which deals with enhancing productivity of crops through improved seeds and agronomic practices. Genetic intensification is also known as conventional intensification [87].

3.2. Green Revolution: A Missed Opportunity for Africa

Agricultural revolution especially the famous Green Revolution contributed for significant boost in crop production and productivity in Asia. The major breakthrough of the Green Revolution was the development and extensive dissemination of semi-dwarf and disease resistant wheat and rice varieties along with optimum level of inputs such as fertilizers, herbicides, and fungicides. In addition, several Asian countries introduced new structural changes in their agricultural policies that facilitated the promotion of agricultural intensification [88,89]. According to the International Food Policy Research Institute [90], the Green Revolution represented the successful adaptation and transfer of scientific revolution in agriculture.

While the success of Green Revolution in Asia was due to the creation and dissemination of modern crop cultivars that are responsive to fertilizer application, in Africa, traditional varieties are widely used that are less responsive to fertilizer application [91]. Although substantial efforts and investments have been made by nations and institutions in the developed world to support the advancement of African agriculture, some of their initiatives were not successful mainly due to their focus on exotic crops with poor adaptation to local environment and less acquaintance to the diet of local people. In addition, most of these projects did not involve potential stakeholders at different phases of projects (e.g., planning, execution, reporting). Among the potential partners who were not consulted by some of these projects are researchers at the national institutes, farmers, extension agents, NGOs, and policy makers.

Apart from the famously known Green Revolution, other types of agricultural revolutions are suggested for Africa. These include Doubly Green Revolution which focuses on both conservation and productivity [92], Evergreen Revolution which focuses on economic viability [93], and Rainbow Evolution which includes diverse techniques and participate farmers [94]. African Green Revolution Alliance (AGRA) [95] and other international and regional institutions are currently implementing different strategies to promote crop productivity in the continent.

3.3. Genetic Improvement to Enhance Productivity

3.3.1. Key Terms Related to Crop Productivity and Yield Potential

Crop intensification can be explained in terms of productivity level or yield potential of each crop type or cultivar. Various names and definitions have been given to describe diverse types of yield potentials. The sketch in Figure 3 indicates factors which affect crop productivity under farmers' and research centers' conditions for rainfed and irrigated systems. Lobell et al. [96] estimated the yield potential for several cereal crops in irrigated and rainfed systems. Although up to 80% of the yield potential was achieved for irrigated wheat, rice, and maize, a maximum of only 50% of the yield potential was obtained for rainfed condition, indicating that large increases in crop production is expected from the latter system [96]. Terms related to yield potential which were defined by Global Yield Atlas [97] and others are briefly described below.

- Potential yield (Y_p) refers to the yield of a cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting and with pests, diseases, weeds, lodging, and other stresses effectively controlled [98]. Hence, it refers to the maximum yield under given area for a given cultivar. Potential yield is influenced by yield defining factors such as solar radiation, temperature, CO_2 concentration, and genetic characteristics.
- Water-limited yield (Y_w) is similar to Y_p , but crop growth is also limited by water supply, and hence influenced by soil type and field topography.
- Farmers' attainable yield is affected by yield limiting factors such as nutrient deficiencies and water stress.
- Average actual yield (Y_a ; also known as farmers' average yield) is defined as the average yield achieved by farmers in a given region under the existing management practices (sowing date, cultivar maturity, and plant density) and soil properties. It takes into account yield reducing factors such as weeds and pests.
- Yield gap (Y_g) is the difference between Y_p (irrigated crops), or Y_w (rainfed crops) and actual yield (Y_a).

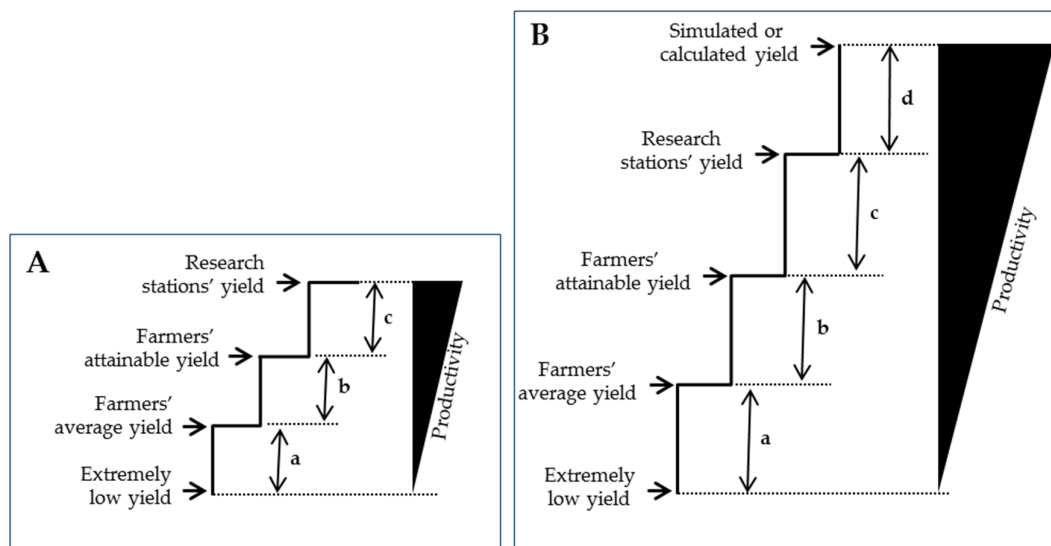


Figure 3. Sketch showing the contribution of different yield potentials to productivity of crops under rain-fed or moisture-limited (A), and irrigated or moisture-unlimited (B) conditions. Lower case letters show the yield gap between the two consecutive yield levels.

3.3.2. Yield Potential of Crops Cultivated in Africa

Only few studies were made to investigate the yield potential of crops grown in Africa, some of which were recently reviewed [99]. Studies on the yield potential and gap for several of these crops

including cassava and tef showed that crop productivity could be increased several-folds by using improved genotypes and/or management (for review, [8]). Since some studies showed that agricultural production can be improved in Africa through optimum use of inputs such as fertilizers, herbicides and pesticides [66,67], this sector needs to be given priority. For instance, experiments in Uganda and Kenya showed that the yield of cassava could be raised by about 140% from the farmer average yield of only 8.6 t ha⁻¹ using improved management, cultivars, and fertilizer [100]. Anderson [101] stressed the significance of crop management in reducing the yield gap especially under rainfed conditions. Investigations carried out at over 100 on-farm and on-station trials showed that constraints for cassava production varied strongly between sites and years although the most important constraints are poor soil fertility, early water stress and sub-optimal weed management.

Based on the 50-year data of the United Nations Food and Agriculture Organization [3], quantifications were made to determine the contribution of intensification on the total production of four widely cultivated crops in Africa, namely maize, sorghum, cassava, and cowpea. Although maize and sorghum are the most extensively cultivated crops on the continent (Figure 4A), in terms of total production, cassava and maize are the leaders (Figure 4B). Significant increases in the production over years for the two latter crops were due to both area expansion (Figure 4C) and intensification (Figure 4D). During the past five decades, while the total area allocated to both cassava and maize has doubled, the productivity was raised by 90% for cassava and by 80% for maize. This also shows that intensification has played an insignificant role for sorghum and cowpea in Africa. In general, poor productivity of crops in Africa is related to little scientific research and the prevalence of diverse environmental stresses that substantially affect the yield.

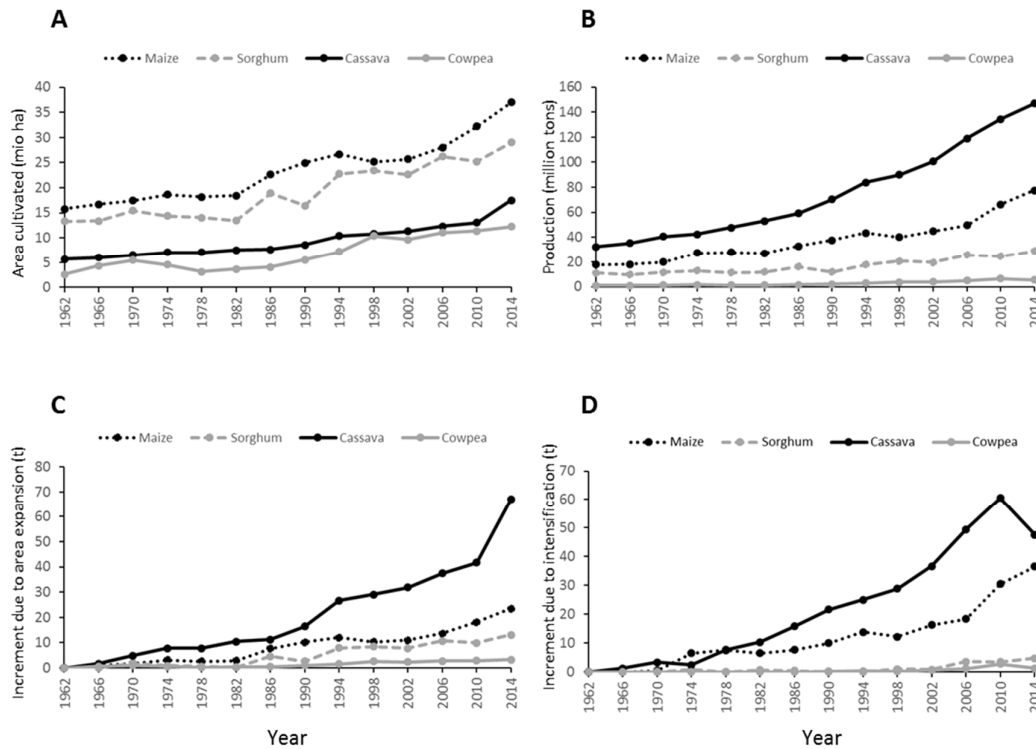


Figure 4. The contribution of crop intensification in four crops predominantly cultivated in Africa. (A) area of cultivation; (B) total production; (C) increment due to area expansion; and (D) increment due to intensification which includes improved varieties and management practices. Calculations for (C,D) are based on the yields of 1962 where they were 1.11 t/ha for maize, 0.83 t/ha for sorghum, 0.66 t/ha for cassava, and 0.33 t/ha for cowpea. Source for (A,B): FAOSAT.

3.3.3. Narrowing the Yield Gap: Lessons from Other Regions

Yield gap analysis was performed for various crops and geographical regions as well as diverse crop management systems [102–105]. According to Neumann et al. [102], the actual grain yield in some regions of the world has already approached its maximum achievable level while in some other regions substantial yield gaps were observed. The study made at a global scale using the 18 most dominant crops indicated that the small yield gaps are concentrated in developed countries or in regions with relatively high-input agriculture [103]. On the other hand, in the wheat-maize cropping systems in China where 362 farms were surveyed, wheat yields ranging from 3.4 t·ha⁻¹ to 9.0 t·ha⁻¹ and maize yields ranging from 3.4 t·ha⁻¹ to 11.3 t·ha⁻¹ were recorded between the actual and simulated yield [104]. The yield gap study for rice during wet and dry seasons in the Southeast Asia showed that the yield gaps reached up to 5.0 t·ha⁻¹ between the average and maximum yield potential and up to 2.6 t·ha⁻¹ between the average and the best farmers' yields [105]. According to same authors, the yield gaps between the average and best farmers' yields were higher in rice-importing countries such as Indonesia and Philippines compared with rice-exporting countries such as Thailand and Vietnam.

The study in Western Australia on rainfed wheat showed that the environment was responsible for up to 80% in grain yield, while management practices and cultivars played minimum role [101]. The yield gap between the potential and the attainable are reduced through the implementation of diverse strategies, for example, using proper soil management practices [101] and optimum amount of nitrogenous fertilizer [106]. According to Jeon et al. [107], the yield potential of rice could be raised by modification of plant architecture, and enhancement of photosynthesis. In general, the global yield variability is significantly influenced by fertilizer, irrigation and climate [108].

3.3.4. Plant Ideotypes with Desirable Agronomic Properties

The term ideotype was first used five decades ago by Donald [109] to describe the biological model that is expected to perform in a predictable manner with a defined environment. Several studies were made by researchers of major crops to determine best plant type or ideotype that can efficiently utilize resources and convert them into maximum obtainable yield. The ideotype approach has been used in global rice breeding programs where “super” hybrid cultivars with high yield potential were developed [110]. These rice plants possess large panicle size, reduced tillering capacity and improved lodging resistance. The best wheat ideotypes are those with shorter plant height, wider root plate, and appropriate stem strength especially at the bottom internode [111].

Several studies were made by researchers of major crops to determine best plant types that can efficiently utilize resources and convert them to maximum obtainable yield. Morphological and physiological properties of ideotypes of selected crops are shown in Table 2. Progresses made on ideotype breeding for rice and wheat are briefly presented below.

- Rice: The “super” hybrid varieties developed in China produced superior yield due to improvement in both source and sink [112]. For instance, a rice line with submergence tolerance and best cooking quality (also called ideotype 1, ID1) exhibited a low-amylose content, a fragrance and a high alkali spreading value [113]. The best preferred rice plant also has the following properties: low tillering capacity (3–4 productive tillers), 200–250 grains per panicle, very sturdy stems, erect leaves, and high harvest index [114].
- Wheat: Berry et al. [111] indicated that the best ideotype of wheat plant is the one with the yield potential of 8 t·ha⁻¹. Key parameters required to develop this type of wheat are shorter plant height, wider root plate, and appropriate stem strength especially at the bottom internode [111]. According to Tendon and Jain [114], the model plant designed for wheat has thick stems, fewer tillers, large heads, higher number of grains, and high harvest index.

Traits with potential application to the improvement of crops cultivated in Africa are briefly discussed below.

Plant architecture and anatomy: Architectural changes in plant include alteration in branching pattern and reduction in plant height (Table 2). Semi-dwarf wheat and rice varieties developed during the Green Revolution tremendously increased the productivity of these crops. Plants with

erect leaf phenotype or narrow leaf angle are efficient in capturing the light and hence boosting productivity. According to Rasmusson [115] barley plants with large stems, leaves, and heads produce superior yield.

Root anchorage and nutrient utilization: According to Mi et al. [116], in order to effectively utilize nitrogen, the maize plant need to have the following: (i) deeper roots with high activity that are able to uptake nitrate before it moves downward into deep soil, (ii) vigorous lateral root growth under high nitrogen input conditions so as to increase spatial nitrogen availability in the soil, and (iii) strong response of lateral root growth to localized nitrogen supply so as to utilize unevenly distributed nitrate especially under limited nitrogen conditions.

Photosynthetic efficiency: In wheat, improving photosynthesis by exploiting natural variation in Rubisco's catalytic rate or adopting C₄ metabolism raised the yield potential by at least 50% through genetic improvement of radiation use efficiency (RUE) [117]. Hence, attempts have been made by the Wheat Yield Consortium (WYC) to improve the performance and regulation of Rubisco, introduction of C₄-like traits such as CO₂-concentrating mechanisms, improvement of light interception, and improvement of photosynthesis at the spike and whole canopy levels [118]. According to Parry et al. [119], although past increases in yield potential of wheat have largely resulted from improvements in harvest index, further large increases in harvest index are unlikely, but an opportunity exists for increasing productive biomass and harvestable grain through improving photosynthetic capacity of wheat. Foulkes et al. [120] proposed six approaches that can improve photosynthetic capacity of wheat. These include spike growth, spike fertility, grain size, and lodging resistance of the plant.

Yield components: Since yield is affected by multiple traits, breeding programs have focused mainly on improving individual traits known as yield components or yield-related traits such as panicle yield, number of tillers, seed weight, and others. Qi et al. [121] investigated several plant growth models to design ideotypes of maize with desirable traits, particularly those with high-yield and optimum source-sink. According to Peng et al. [110] China's "super" rice breeding project has developed many F₁ hybrid varieties using a combination of the ideotype approach and inter-sub-specific heterosis. These hybrid varieties produced grain yield of 12 t·ha⁻¹ in on-farm demonstration fields, 8%–15% higher than the hybrid check varieties.

Stress tolerance and water-use efficiency: Due to the presence of extreme climatic and soil conditions that adversely affect crop productivity, many breeding programs are geared towards developing crops that are resilient to some of these environmental calamities. Breeding for effective use of water is considered the best strategy towards mitigating the effects of moisture scarcity and to develop drought tolerant crops [122]. In moisture scare areas, breeding for higher water-use efficiency (WUE) is the best strategy. According to Araus et al. [123], WUE may be modified not only through a decrease in stomatal conductance, but also through an increase in photosynthetic capacity. Thus, phenological traits which increase the relative amount of water use during grain filling period or which adjust the crop cycle to the seasonal pattern of rainfall may be useful. Indigenous crops with an increased tolerance to drought have high potential in moisture-scare areas in Africa, provided productivity of these crops is improved through research [124].

Table 2. Key features of ideotypes of selected crops.

Crop Type	Ideal or Preferred Phenotypes	Reference
Cereals (general)	<ul style="list-style-type: none"> • High harvest index • High water-use efficiency (WUE) • High nitrogen-use efficiency (NUE) 	[125]
Maize	<ul style="list-style-type: none"> • Low numbers of tillers • Angled leaves for good light interception 	[126]
Sorghum	<ul style="list-style-type: none"> • High grain yield • Harvest index greater than 30 • high ear head exertion • Panicle DM of total DM: >50% 	[127]

	<ul style="list-style-type: none"> • Higher relative water content 	
Rice	<ul style="list-style-type: none"> • Heavy & drooping panicles at maturity • Plant height: ≥ 100 cm • panicle length: ≥ 60 cm • Harvest index: 0.55 	[110]
Wheat	<ul style="list-style-type: none"> • Plant height: 0.7 m • Root plate spread: 57 mm • Width of bottom internode: 0.65 mm • Length of flag leaf: 50 cm • Angle of the flag leaf: 58° • Narrow and V-shape leaves • Leaf area index (LAI) of top three leaves: 6.0 • High grain yield • High harvest index • lodging tolerant 	[111]
Food legumes (general)	<ul style="list-style-type: none"> • Determinate plant type • Erect and upright plant • Average plant height • Early vigour • Early flowering and synchronous maturity • Pod bearing from well above the soil surface • more pods/plant and more number of seeds/pod • high harvest index • yield stability 	[128]

3.4. Agronomic Improvement to Enhance Crop Productivity

In conjugation with improved varieties, optimum agronomy practices significantly boost productivity of crops. Diverse types of yield potentials shown in Figure 3, therefore, reflect the level of adoption of improved technologies that include crop varieties and agronomic practices. Major agronomic practices that enhance productivity and/or mitigate environmental constraints are briefly discussed below.

3.4.1. Cropping Systems

Diverse types of cropping systems are practiced by smallholder farmers in Africa, although the dominant ones are rotation and intercropping.

Crop rotation: A crop rotation of 3–4 cycle is commonly used by famers. The main benefits of rotation are to improve the fertility of the soil and tackle major biotic stresses, which include pests, diseases, and weeds.

Intercropping: Intercropping refers to growing two or more crops in a piece of land at the same growing season. Intercropping has the following advantages: (i) it reduces soil erosion due to maximum land coverage with vegetation, (ii) it increases the amount of harvest from the intercropped crops, (iii) it diversifies the diet and provides cheaper source of protein using legumes in the intercrop, and (iv) it improves soil fertility since legumes add nitrogen to the soil. In addition to these benefits, Agroforestry, the type of intercropping where bushes and shrubs are used, provides feeds to livestock.

Slash-and-burn: Slash-and-burn is a system in which the forest is cleared and burnt to grow crops for few years before abandoning and moving to the new site to implement similar practice. This system of land utilization is discouraged due to its unsustainability and the resulting environmental degradation and deforestation. The recent study at four sites in Western Ethiopia indicated that due to the conversion of natural forests and grasslands to plantations, several adverse effects occurred in the soil [129]. Among these, reduced soil carbon and micronutrient and increased soil compaction are the major ones.

3.4.2. Soil Management

Prior to devising a particular management practice, the inventory of the physical and chemical properties of the soil (also known as 'soil sensing'), is useful as it provides basic information on the potential of a particular soil to crop production, climate adaptation and environmental sustainability [130].

Conservation Agriculture (CA): CA has been suggested as an alternative to traditional or conventional tillage which exposes the soil to erosion. CA is a broad term which is based on three principles, (i) minimal soil disturbance by employing zero- or minimum tillage; (ii) continuous soil cover with crops or mulches; and (iii) crop rotation [131]. Among the benefits of CA, reduced water run-off, increased water infiltration and reduced soil erosion are the major ones [132]. The types of CA practiced in the world including those in Africa were recently described [131]. Corbeels and colleagues analyzed 42 tillage experiments conducted on major and staple crops in 13 Sub-Saharan African countries [133]. The main conclusion of the analysis was that positive effect of no-tillage/reduced tillage was obtained only when it was accompanied by mulching and/rotation. The study in Malawi showed that the benefits of mulching in CA was pronounced in areas with high evapotranspiration [134]. Although CA showed positive results in countries such as Zimbabwe [135], its acceptance was low in most African countries mainly due to poor crop germination, increased weed population and disease incidence, as well as insufficient partnership and investment [132,136]. Hence, measures should be obtained to overcome these constraints so that CA tillage obtains a momentum for adoption by African farmers.

Soil fertility management: Improved soil fertility plays key role in yield increments illustrated in Figure 3 under both rainfed and irrigated systems. Diverse sources and practices enhance soil fertility among which few are briefly discussed below.

Organic fertilizers: The use of organic fertilizers is low in Africa. A recent study on 324 smallholder farmers in Malawi showed that only 20%–40% of farmers apply organic manure or compost to their maize field [137]. Since most farmers in Africa use their crop residues and manure as a source of fuel and/or as a livestock feed, the use of organic sources to replenish soil nutrition is very low.

Inorganic fertilizers: The use of inorganic fertilizers is also low in Africa (Figure 2). This suboptimal use of fertilizers contributes to lower productivity of both the staple and exotic crops in the continent. Among major soil nutrients, phosphorus (P) is limited in most agricultural soils in Africa. The comprehensive study in West Africa on sorghum and pearl millet indicates the need to determine P-uptake and P-utilization in developing P-efficient varieties [138]. On the other hand, using phosphate rocks in Ghana, the yield of rice was increased not only for a single year but also for subsequent 2–3 years due to the residual effect [139].

Biochar: Biochar is a fine-grained charcoal produced from biomass which is exposed to high temperatures in the absence of oxygen. Biochar improves soil properties and increases crop yield [140]. The International Biochar Initiative (IBI) was established to support developing countries with biochar research and development through information exchange and basic technical advice [141]. Similarly, the Biochar for Sustainable Soils (B4SS) Project was recently formed to promote the adoption of sustainable land management practices involving biochar [142]. The project has been implemented in several countries in Asia, Latin America, and Africa, where Kenya and Ethiopia represented Africa. On the other hand, the amount of biochar recommended for use might not be affordable by smallholder African farmers due to extremely high application rate. Although the optimum rate depends on the fertility status of the soil and the type materials used to make the biochar, up to 20 t ha⁻¹ biochar has been suggested for use [140]. Hence, the system which provides biochar in affordable and economical way should be investigated. The recent report from South Africa which investigates the technical and economic feasibility of biochar suggested detailed studies at a local level [143].

African Dark Earths: African Dark Earth, which is made traditionally in West Africa from waste deposits, is not only source of soil fertility, but also improves soil properties including carbon sequestration. Using these earths, organic carbon has increased up to three-fold and cation exchange capacity up to four-fold over the soil without dark earths [144].

ISFM (The Integrated Soil Fertility Management): ISFM refers to the application of diverse soil fertility management practices and improved germplasm to adapt to local conditions in order to increase agronomic efficiency and boost productivity. In order to achieve these conditions, ISFM applies proper agronomic and economic principles which includes the following concepts: (i) focusing on agronomic use efficiency of crops, (ii) application of fertilizer to improved germplasm on responsive soils, (iii) combined application of organic and mineral fertilizers, (iv) adaptation of the system to local conditions, and (v) implementation of what is called “complete ISFM,” which refers to the combined use of improved germplasm and fertility management at local conditions [145]. ISFM emphasizes the optimization of agronomic efficiency through maximizing the efficiency of fertilizer and organic inputs since these resources are the most limiting in areas where crop intensification is implemented [146]. The concept of ISFM has been successfully implemented in maize- and cassava-based cropping systems under the name CIALCA (Consortium for Improving Agriculture-based Livelihoods in Central Africa) in three countries in the African Great Lakes Region namely, Burundi, Democratic Republic of the Congo and Rwanda [147]. The progress from this initiative shows that using diverse soil fertility practices which are based on local conditions, do not only improve the productivity of crops but also enhance the livelihood of small-scale farmers. According to the recent adoption study on 420 farms in the Democratic Republic of Congo, only few farmers reached full ISFM indicating sequential technology adoption rather than simultaneous [148].

Mitigation of Problematic Soils: The reclamations of problematic soils (e.g., those affected by erosion, drainage, acidity and salinity) are major challenges to African smallholder farmers. Soil acidity occurs mostly in high rainfall areas due to the accumulation of aluminum ions in the root zones. On the contrary, saline soils are prevalent in warmer areas where evapotranspiration is high leading to the accumulation of salts on the surface of the soil. Mitigation of saline soils requires collaborative efforts with several stakeholders including donors since this practice is not only expensive for resource-limited African farmers but also requires special knowledge to ameliorate the constraints before soil becomes productive. The need for supporting farmers’ investments in sustainable land management through provisions of incentives was emphasized [149]. On the other hand, Vertisols, soils with extreme poor drainage, affect the workability during the rainy season as well as crop establishment. The broad-bed maker (BBM), a low-cost modification of the traditional Ethiopian plow, has been efficiently utilized to drain excess moisture from fields containing Vertisols through the creation of broad-beds and furrows (BBF). Due to the improved drainage using BBM, a grain yield increase of 78% and straw yield increase of 56% were obtained for wheat in the central highlands of Ethiopia [150]. Since about 43 million ha of Vertisols exist in 28 countries in Africa [52], the use of improved drainage system on these poorly drained soils has a potential to boost productivity of crops.

3.4.3. Water Management

Rain-fed agriculture: Appropriate water harvesting technique improves crop productivity in semi-arid areas where moisture is the major constraint. Experiments conducted in Kenya where moisture scarcity substantially affects productivity of maize and wheat showed that the use of ridge-furrow mulching significantly increased water storage, grain yield and water use-efficiency compared to the ridge-furrow without mulching [151,152]. Among three types of mulches investigated (grass, transparent polyethylene, and black polyethylene), grass mulches gave the lowest benefits. Although polyethylene films possess several desirable properties, the availability and affordability of these materials by smallholder farmers need to be investigated.

Irrigated agriculture: Salinization or excess amounts of sodium, potassium or magnesium salts on the soil surface negatively affects germination and development of crops. The main causes of salinization are (i) high salt content of parent material and ground water and (ii) inappropriate irrigation practices. The latter is related to the insufficient and improper drainage after irrigation especially in warmer and drier areas where evapotranspiration is higher than precipitation. Hence, optimum application of water in terms of both the amount and frequency is suggested.

3.4.4. Crop Management

Crop management refers to cultural practices which begin from land preparation to harvesting and post-harvesting. Only few of these practices are briefly mentioned below.

Sowing time: In semi-arid areas sowing time based on soil moisture is more advantages than calendar-based sowing as the onset of rainfall is less predictable in these regions. Based on over 40 years of climatic study in the Sahel region where moisture scarcity is the most limiting factor for crop growth, sowing sorghum at the onset of rain is the best although this cannot be attained due to slow and long soil preparation procedures by farmers [153]. Similarly, sowing time based on onset of rainfall was also considered the best in Ghana in achieving high maize yield [154].

Weed management: Since weeds compete with crop plants for light, water, and nutrients, controlling these unwanted plants using a variety of measures is crucial for boosting crop productivity. Innovative techniques such as AFROweeds, the electronic tool with both the online and offline function for identification of rice weeds in Africa assists researchers and development agents in fast identification and management of weeds [155].

Pest and disease management: Farmers are encouraged to implement Integrated Pest Management (IPM) due to its several benefits. However, similar to CA and organic fertilizer, IPM has low success, especially on African staple crops [156]. A group of researchers and development agents in several West African countries have launched in 2010 a network called Divecosys (Diversity of cropping systems and ecologically-based pest management in West Africa) in order to devise sustainable pest management [157].

3.5. Enabling Environment

Enabling environment refers to policy and institutional settings that facilitate the success of a particular intervention or technology. Key elements to be considered are briefly discussed below.

Investment: Investment in agricultural research and development need to be increased to promote food production in Africa. It is expected from large number of African countries to meet the Maputo declaration where they agreed to invest at least 10% of their national budgetary resources to agriculture and rural development [64].

Land policy: Land tenure system affects productivity. Studies in Uganda indicated that secure land tenure is important since it provides incentives to small-scale farmers for the long-term investment that in turn promotes crop productivity [158]. Hence, governments in Africa need to implement landholding system that guarantee long-term investment by farmers.

Inputs: The access to agricultural inputs such as improved seeds and fertilizers in terms of timely availability and affordability by smallholder farmers is important. Since farmers face shortage of cash during the growing season, the availability of inputs could be facilitated through the provision of credits.

Insurance: Agricultural insurance is not common in Africa, especially against environmental calamities such as drought and flooding. The Kilimo Salama Insurance Program was established in 2009 in East Africa by Syngenta Foundation for Sustainable Agriculture to reach smallholder farmers using mobile technologies. In 2014, Kilimo Salama was replaced by a private commercial company called ACRE (Agriculture and Climate Risk Enterprise). ACRE has expanded its activities in Kenya, Rwanda, and Tanzania to insure 800,000 farmers against drought, excess rain, and storms [159].

Extension system: A vibrant extension system is key not only in knowledge transfer between research and farming community, but also in facilitating the provision of improved technologies to farmers. The acceptability of new technologies by farmers depends mainly on the commitment of extension personnel who not only introduce new technologies but also track their adoption by farmers.

Capacity: Qualified and dedicated professions, as well as functional facilities, are key to the success of intervention in both research and development.

Farmer participation: Involving farmers at different levels of technology development starting from research to validation is important as their participation affects the level of acceptance and adoption of a new technology or intervention.

According to Schut and colleagues [160], institutional innovations which include access to credit, inputs and markets, are required to address about 70% of constraints in the sustainable intensification in the Central Highlands of Africa. The study in West Africa also indicated the need for strengthening innovative systems in enabling institutions in order to boost productivity of smallholder farmers [161]. In general, a policy which promotes sustainable use of resources such as land and water and at the same time boost productivity is suggested.

4. Successful Agricultural Innovations in Africa

Juma et al. [162] listed key agricultural innovations in Africa along with their yield and other benefits. These innovations include those that have either direct effect on productivity (e.g., *Striga* resistant maize and conservation agriculture) and those that have indirect benefit on productivity (e.g., Farmer Field Schools and Ethiopia Commodity Exchange). Below, several other cases are presented where the productivity of crops increased in some parts of Africa using proper soil and water management and/or pest control practices.

4.1. Push-Pull Technology for Multitude of Benefits

The Push-Pull system was developed by the International Centre of Insect Physiology and Ecology (ICIPE) in Kenya and is effective in protecting maize from dangerous stem borers and a parasitic weed called *Striga* [163]. In this system, maize is intercropped with a forage legume called Desmodium (*Desmodium uncinatum*) whereas Napier grass (*Pennisetum purpureum*) is planted around the field. While Desmodium produces a smell that drives away stem borer adults (“push”) and also produces a chemical that suppresses *Striga* from attaching to maize roots, the Napier grass attracts stem borer adults towards it (“pull”). The adult insects lay their eggs on the Napier grass and when the eggs hatch, the grass produces a sticky substance that kills the larvae or young stem borers. The system is also useful in reducing the amount of pesticide application [163]. In addition to improving the productivity of maize through controlling insect pests and parasitic weed, the Push-Pull technology provides forage for the livestock, releases essential plant nutrients to the soil and reduces soil erosion [164]. The effectiveness of the Push-Pull system was recently investigated on 395 farmers in drier regions of Kenya, Uganda and Tanzania who adopted the technology [165]. According to authors, compared to the monocropping maize, the Push-Pull system reduced the *Striga* level by 18-times and stem borer by 6-times while it increased maize yield by 2.5-times. The Push-Pull technology has high acceptance by farmers. A recent study on 898 farmers showed that 92% respondents in Tanzania, 89% in Ethiopia and 84% in Kenya are willing to adopt the Push-Pull system [166]. This high acceptance rate is due to its effectiveness in insect pest and parasitic weed control, soil fertility maintenance, provision of feed for livestock and boosting maize productivity. According to the recent report, the livelihood of about 100,000 smallholder and subsistence farmers in Eastern and Central Africa have improved due to the adoption of push-pull system [167].

4.2. NERICA (New Rice for Africa): High Yielding and Climate-Smart Crop

Improved cultivars of NERICA were developed by the Africa Rice Center through crossing the high yielding Asian rice (*Oryza sativa* L.) to the locally adapted African rice (*O. glaberrima* Steud.). Both Asian rice types (i.e., *O. sativa* L. ssp. indica and *O. sativa* L. ssp. japonica) were introgressed to the African rice. While the progenies of *O. glaberrima* and *O. sativa* ssp. indica were better adapted to rainfed and irrigated wetlands, those of *O. glaberrima* and *O. sativa* ssp. japonica performed better under rainfed drylands [168]. The major desirable traits of the African rice are its weed competitiveness, drought tolerance and ability to grow under low input conditions [169]. While those of NERICA rice are high grain yield, high protein content, early-maturity, resistance to diseases and insects, and good taste. Some varieties of NERICA have additional desirable traits. For example, NERICA 1 is not only resistant to *Striga hermonthica*, an obligate root hemi-parasite which causes tremendous yield losses [170] but also is highly productive in Kenya and Tanzania [170,171]; whereas NERICA-L-44 is tolerant to an elevated air temperature both at the vegetative and reproductive

stages and able to produce high grain yield with superior quality [172]. The wide-spread dissemination of NERICA in Uganda significantly decreased the poverty level [173] mainly due to increased production and income to farmers [174]. NERICA genotypes alone do not boost productivity unless supplemented with the proper amount and time of soil nutrient application [175] and crop management practices [176]. Studies in West Africa showed that the yield of NERICA has doubled by applying 120 kg N, 26 kg P and 25 kg K per ha (equivalent to the amount recommended for high input farmers) compared to no NPK fertilizer [175] indicating that improved NERICA varieties are responsive to fertilizer application; and hence are considered efficient in fertilizer use.

4.3. DTMA and WEMA: Drought Tolerant Maize for Moisture-Scarce Environment

DTMA (Drought Tolerant Maize for Africa) was formed by two International Agricultural Research Centers (namely CIMMYT and IITA) in close collaboration with private and public sectors. The network developed over 200 maize varieties in 13 African countries, namely Angola, Benin, Ethiopia, Ghana, Kenya, Malawi, Mali, Mozambique, Nigeria, Tanzania, Uganda, Zambia, and Zimbabwe. In these regions, where maize significantly suffers from moisture scarcity, about 54,000 metric tons of certified drought-tolerant seed was produced through the program in a single year [177,178]. Countries which benefited a lot from the program by releasing the highest number of varieties for diverse agro-ecologies and growing conditions are Nigeria (21 varieties), Zambia (18), and Malawi (17). WEMA (Water-Efficient Maize for Africa) is a project which is coordinated by AATF (African Agricultural Technology Foundation) and focuses on five countries, namely Kenya, Mozambique, South Africa, Tanzania and Uganda [179]. While WEMA develops drought-tolerant maize varieties using conventional breeding, marker-assisted breeding, and transgenic approaches, DTMA varieties are non-GMO; hence the improved varieties from DTMA receive fast acceptance and adoption as they do not require a lengthy and expensive regulatory procedures imposed on transgenic crops.

4.4. Re-Greening the Sahel

Re-greening refers to a process in which farmers protect and manage trees that naturally regenerate on their land rather than cut them down. The system not only restores degraded lands but also increases crop productivity, recharges groundwater, and provides feed for livestock. The African Re-greening Initiative (ARI), which began in Niger in 2007, became operational in several African countries in the Sahel including Burkina Faso, Mali, Niger, and Ethiopia [180]. Re-greening projects in several African countries proved to have the following benefits: (i) economic or highly cost-effective, (ii) improved household food security as it is more resilient to drought, (iii) higher crop yields when nitrogen-fixing trees are used, (iv) savings on the costs for inputs/fertilizers, and (v) diversification since trees produce fruit and leaves with high vitamin content for human consumption as well as fodder, which allows farmers to keep more livestock and thus have more manure to fertilize the fields [181,182].

5. The Way Forward

Summary of the current review is presented in Figure 5, where major crop production constraints, interventions to tackle the constraints, and expectations at the post-intervention are indicated. While interventions refer to a variety of breeding and agronomy techniques as well as enabling environment, post-intervention refers to the three items (namely output, outcome, and impact) used to monitor the effect of a particular intervention.

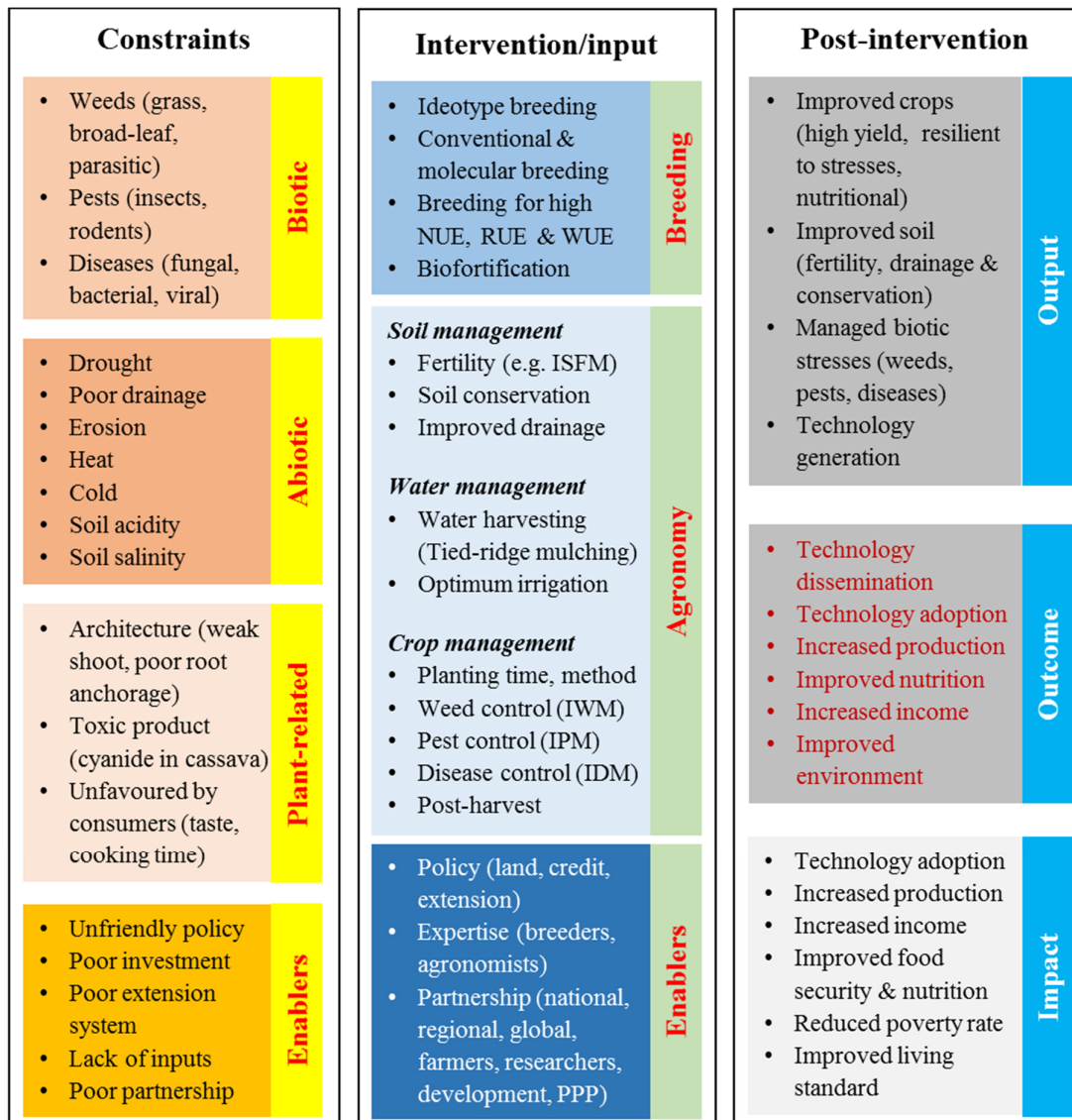


Figure 5. Diverse types of constraints facing African farmers and possible ways of interventions as well as expectations (outputs, outcomes and impact) from interventions. IDM: integrated disease management; IPM: integrated pest management; ISFM: integrated soil fertility management; IWM: integrated weed management; NUE: nutrient-use efficiency; PPP: public-private partnership; RUE: radiation-use efficiency; WUE: water-use efficiency.

Various suggestions have been given to the future directions of sustainable agricultural intensification in Africa. Among these, the one by the Montpellier Panel, which consists of 15 international experts in the area of agriculture, sustainable development, trade, policy, and global development and focuses on food security priorities in Sub-Saharan Africa [183], is worth mentioning. The six-point recommendations provided by the Panel are (i) the adoption of policies that combine intensification with sustainable solutions, (ii) increased financial support for research and innovation, (iii) scaling up and out of appropriate technologies and processes, (iv) increased investment in market systems and linkages, (v) access to inputs and credit as well as rights to land and water by smallholder farmers, and (vi) building and sharing the expertise of smallholder farmers [68].

Several of the above suggestions are policy-related, which need the attention of either individual or groups of nations in Africa. African governments also need to promote farmer- and consumer-friendly policies in the area of land-use and/or tenure; access to agricultural inputs such as water,

improved seeds, and chemicals; access to credit and insurance facilities; and the availability of markets since they have direct or indirect effect on crop productivity.

The following five key points might serve as a guideline for those interested in crop intensification in Africa although the list is by no means complete. These points which might also have some overlap in their application can be represented in a single word PASTE which stands for Partnership, Aim, Sustainability, Technology, and Enabler.

- Partnership (stakeholders, networking);
- Aim (goal and strategy);
- Sustainability;
- Technology (improved seed and agronomy);
- Enabler (policy, capacity, inputs and extension).

These five points are briefly discussed below.

5.1. Partnership

- Stakeholders: (i) Public-private partnership (PPP) with grant, research and developmental institutions and/or individuals; (ii) collaborations among national, regional, and global institutions.
- Networking: Establish and/or strengthen the networks of African professionals for efficient utilization of resources including human expertise. For example, the Association of African Agricultural Professionals in the Diaspora (AAAPD) [184].

5.2. Aim

- Goal: (i) Demand-driven or problem-oriented research to address major constraints in the region, country, or specific locality; (ii) focus on innovative research.
- Strategy: Value-chain approach from research to development, marketing and to distribution.

5.3. Sustainability

- Sustainable in production and environment protection.

5.4. Technology

- Improved seeds: (i) Locally-adapted and consumer-preferred crops; (ii) improved crops responsive to input application (e.g., fertilizers); (iii) climate-smart or resilient crops to environmental stresses.
- Agronomy: (i) Optimum crop, soil and water management practices for each locality; (ii) promote technologies with high chance of acceptance by farmers.

5.5. Enablers

- Policy: Conducive policies that enhance productivity and facilitate marketing and distribution.
- Capacity: Skilled personnel and infrastructure in both research and development.
- Inputs: Timely availability and affordability of agricultural inputs.
- Extension: (i) Dissemination of improved technology through favorable extension system; (ii) encourage farmer-to-farmer extension system.

6. Conclusions

Today, large numbers of African population are affected by shortage of food and malnutrition. This situation will be aggravated in the future due to the high rate of population growth and lack of infrastructures and job opportunities unless proper policy measures are taken. Locally adapted crops are vital in contributing to food security in Africa, particularly under the present scenario of increasing population and changing climate, as these crops have the advantage of fitting into the socio-economic and ecological context. Despite their huge importance, crops cultivated in Africa have

generally received little attention by the global scientific community. Major constraints affecting the productivity of these crops are a variety of biotic and abiotic stresses, global warming, and the competition with biofuel crops that are grown on the same agricultural land. Among abiotic stresses, desertification, soil erosion, acidification, and salinization, as well as several other constraints cause significant losses to crop production in Africa. In order to devise a strategy towards boosting crop productivity in the continent, these production constraints need to be thoroughly investigated and properly addressed. Increase in production can be achieved by either expanding the arable area or through intensification using improved seeds, fertilizer, fungicides, herbicides, irrigation, and the like.

Among the major breakthroughs known to boost crop productivity in agriculture, the Green Revolution is mentioned first and foremost. The next Green Revolution for Africa needs to include not only the major crops of the world but also locally important crops that are mostly known as orphan crops. Although orphan crops are largely unimproved, the implementation of modern improvement techniques on these crops has many advantages. Studies on the yield potential and gap for several understudied crops showed that crop productivity could be increased several folds using improved genotype and/or management. In order to tackle food insecurity in Africa and promote sustainable crop intensification, the commitment of diverse stakeholders including researchers, development agents, and policy makers at the national, regional, and global level is required. It is worthwhile to mention that all 15 international agricultural research centers under the CGIAR (Consultative Group on International Agricultural Research) and some academic and developmental institutions in Europe and the USA are contributing toward the improvement of African agriculture. While several CGIAR centers focus on major crops of the world (e.g., wheat, maize and rice), others include regionally important crops (e.g., millets, root and tubers, and beans) in their mandate. In addition to national agricultural research systems, Africa based institutions such as AGRA (Alliance for a Green Revolution in Africa), CAADP (Comprehensive Africa Agriculture Development Programme), and FARA (Forum for Agricultural Research in Africa) play key roles in achieving the next agricultural revolution in the continent.

Acknowledgments: I would like to thank Syngenta Foundation for Sustainable Agriculture, the University of Bern, and SystemsX for financial support.

Conflicts of Interest: The author declare no conflict of interest.

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