Global Food Security 20 (2019) 180–188

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Understanding the consequences of changes in the production frontiers for roots, tubers and bananas

Athanasios Petsakos[a,*], Steven D. Prager[b], Carlos Eduardo Gonzalez[b], Arthur Chibwana Gama[c], Timothy B. Sulser[d], Sika Gbegbelegbe[e], Enoch M. Kikulwe[f], Guy Hareau[a]

[a] International Potato Center (CIP), Peru
[b] International Center for Tropical Agriculture (CIAT), Colombia
[c] International Potato Center – Sub Saharan Africa (CIP-SSA), Malawi
[d] International Food Policy Research Institute (IFPRI), United States
[e] International Institute for Tropical Agriculture (IITA), Nigeria
[f] Bioversity International, Italy

ABSTRACT

The widely recognized role of roots, tubers and bananas (RT&Bs) in achieving food security and providing income opportunities in the world's poorest regions will be challenged by socioeconomic and climate related drivers. These will affect demand and production patterns and increase pressure on farming systems. Foresight results presented in this paper show that the importance of RT&B crops for food security will likely increase by 2050 despite these challenges. Furthermore, investments targeted at yield growth appear to be more effective than marketing improvements in alleviating production constraints and in strengthening the role of RT&B crops in future food systems.

1. Introduction

The combination of climate change and rising populations are presenting agricultural production systems with challenges that are of increasing concern for food security. These issues are now at the top of the political agenda in many nations; it is therefore important to understand existing and future pressures on agricultural systems and to investigate available options for improving the capacity to supply food and generate income. Modeling future agricultural demand and supply under conditions of climate and socioeconomic changes is one strategy to understand potential system performance, though modeling efforts have typically focused on the cereal crops that currently form a substantial portion of the global diet (e.g., Rosegrant et al., 2014; Wiebe et al., 2015). With recognition that other food commodities also merit systematic analysis, this research examines the dynamics and role of an alternative commodity group.

Roots, tubers, and bananas (including dessert bananas and plantains – or cooking bananas) are important food crops and valuable marketed commodities in many developing countries where their role in food security and income generation has been widely recognized. The importance of these crops (henceforth called RT&Bs) for food security stems from their high yields and their carbohydrate content which translate to a daily energy supply per cultivated hectare that is greater than cereals (RTB, 2016). These two traits make RT&B crops an important source of calories for undernourished populations, particularly in some Sub-Saharan countries where their energy contribution is as high as 50% of the total daily calorie intake (FAO, 2017). RT&B crops are often associated with home consumption and local trade, but because of their ability to grow even in marginal lands (especially cassava, yam and sweetpotato) where other types of crops would not be competitive, they are also considered as subsistence or "famine reserve" crops.

In spite of research investment in developed countries to improve yields and consumer traits of potato, RT&B crops in the developing world have received little benefit from productivity growth as a function of R&D spillover compared to commodities like cereals and livestock that have a more prominent role in western diets (Scott et al., 2000b). In Africa, where their food security role is particularly pronounced, it has even been argued that RT&Bs have been ignored by R&D programs on the premise that they do not respond positively to investments (Nweke, 2015). An indication of this underinvestment is given by the Agricultural Science and Technology Indicators (ASTI) that show that the number of full-time equivalent researchers (FTEs) who worked on RT&B crops in developing countries in Africa, Asia and Latin America during 2010–2014 was almost three times smaller compared to cereals and livestock. The number of FTEs per unit value of gross production of RT&B crops, which can be interpreted as a proxy for research intensity, has also been found in Africa to be lower than cereals

* Corresponding author.
E-mail address: t_petsakos@yahoo.gr (A. Petsakos).

https://doi.org/10.1016/j.gfs.2018.12.005
Received 31 May 2018; Received in revised form 19 October 2018; Accepted 18 December 2018

[authors' calculations based on data from ASTI (2017) and FAO (2017)]. The underinvestment is also mirrored in the small number of existing forward-looking studies on RT&B crops which can inform investment decisions and interventions to address food security issues.

Underinvestment in RT&B research and the corresponding gap in the literature will have important implications for RT&B agriculture. This presents an interesting conundrum when it comes to the development of policy for effective, outcome-oriented investment. While many, if not all, RT&B crops face similar challenges with respect to their propagation mechanisms, breeding, and even marketing (RTB, 2016), the individual context of RT&B crops varies wildly, especially on the demand side. Besides their food security role, some RT&Bs are prominent "high-value" commodities and a cornerstone of many first world agricultural regions with tight links to the processing industry, while others are heavily commodified as exports from the developing to the developed world.

A dichotomy thus arises wherein the agricultural challenges associated with RT&B crops are very similar, but their economic characteristics are nearly orthogonal in many instances. This panoply of issues poses many interesting questions about the contribution of these crops in present and future food systems and about the role of different research agendas in ensuring a stable and appropriate supply of these important commodities. With the research presented here we investigate the evolution of supply, demand and trade of RT&Bs in different world regions as well as their contribution to global food security to the year 2050. We also examine the pressures and constraints associated with RT&B agriculture and characterize the potential impact of different investment options for international agricultural research intended to address these constraints, specifically investments that (i) aim at yield gains versus infrastructure improvements and (ii) have varied local focus.

2. RT&B crops and their role in the global food system to date

Globally, RT&B production has been growing steadily during the last 50 years albeit at a slower rate compared to cereals (FAO, 2017). Growth in RT&B production in Africa has outpaced other regions since all five major RT&B crops are cultivated throughout the continent (Fig. 1a). RT&B agriculture presents an interesting set of contradictions in Africa however, as despite the high dietary contribution and natural resilience to climate change, it is primarily a subsistence activity with limited ties to the processing industry and few examples of value chain development (Sanginga and Mbabu, 2015). RT&B crops are also associated with gender concerns since women are highly involved in their preparation as food and the share of female labor in their production is typically greater than in other crops (Palacios-Lopez et al., 2017).

Of the many RT&B crops, cassava currently dominates production in Africa (Fig. 1b) but demand for the crop varies among different countries. In Nigeria it is often grown as a cash crop and its fresh roots exhibit higher income elasticity of demand than grain cereals (Nweke, 2004). In other countries it is characterized as a famine reserve food, and it has even been argued that it behaves as a Giffen good, with few substitutes during the hunger period (Rusike et al., 2010). Similar uses are reported for yam, especially in West Africa where the crop is also tied to local traditions and cultural rites (Nweke, 2015). Banana cultivation is more equally distributed across the continent, though there is significant variability in the value chains of the different banana types. In West Africa dessert bananas are considered an important export commodity while in East Africa plantain serves as staple food and the region exhibits the highest per capita banana consumption in the world (FAO, 2017). As annual crops, potato and sweetpotato benefit from the double cropping season in some Sub-Saharan countries, facilitating near year-round availability. Although RT&B crops are grown under rainfed conditions everywhere in the continent as a secondary crop, potato in North Africa is irrigated, with early maturing varieties grown as export commodities aimed towards European markets (European Commission, 2007).

In contrast, RT&B growth in Asia since the mid 70's has resulted in Asia becoming the largest RT&B producing region in the world. Much of this growth is attributed to potato and sweetpotato production concentrated in China. While potato is often considered a high value vegetable (Scott and Suarez, 2012a), sweetpotato is used primarily as pig feed and as a secondary vegetable. However, total sweetpotato demand has been decreasing because of the lower prices of competing feed grains, and as a function of "Bennet's law", the propensity of individuals to spend less on starchy food staples as income increases (Fuglie, 2004). Cassava production is concentrated in South East Asia and is particularly prevalent in Thailand and Indonesia (FAO, 2017) where it is grown for food, feedstock for starch and ethanol manufacture, and feed. Cassava also figures prominently in international markets with dried cassava having competed in the past against feed grains in Europe when protectionist policies led to cereal price spikes (Bruinsma, 2003). Similarly, the profile of banana production varies by region, with India responsible for more than a forth of global production. In India, banana is considered both as an important staple as well as a cash crop to be sold in local markets. In contrast, dessert banana is an important agricultural export commodity in the Philippines, which is currently one of the major players in the global banana trade.

RT&Bs have, likewise, long played a key role as both staple and cash crops throughout Latin America and the Caribbean (LAC), often contributing significantly to economic growth. Sweetpotato, for example, has served as an import element in different intercropping systems, but production and area harvested has been declining due to changing dietary habits and urbanization (Mukhopadhyay et al., 2011). Cassava

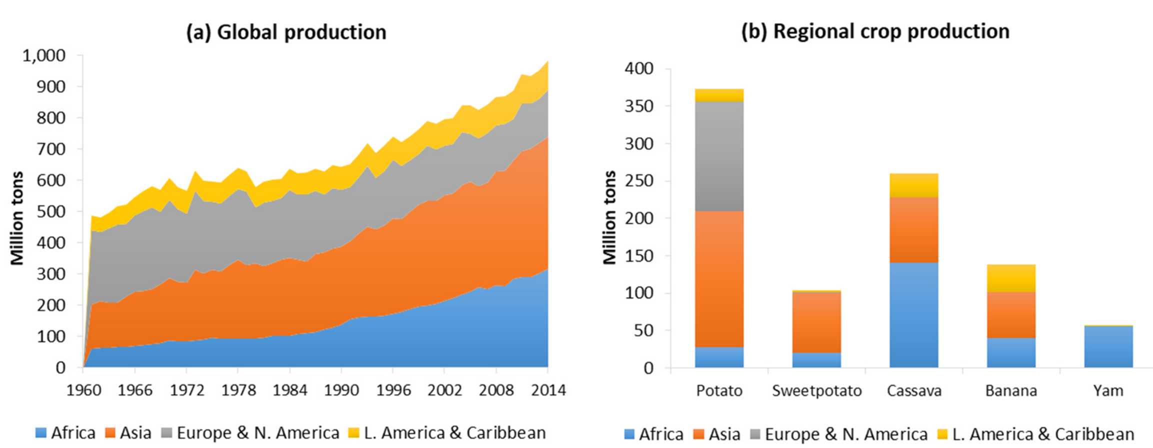

Fig. 1. Global RT&B production statistics of fresh produce: (a) Regional aggregate production trends; (b) average regional production distribution of major RT&B crops 2011–2014 (Source: FAO, 2017).

production, on the other hand, remains abundant and the crop is found throughout its viable range for consumption as fresh root, as well as in value chains for various processed products including starches and flours (Henry and Hershey, 2002). Banana exports to the United States and the European Union have been a key motor of economic growth in LAC, though often with high environmental and social costs (Murray and Raynolds, 2000). As the potato center of origin, the Andean region has been one of the key areas for advancing of both smallholder potato production and the development of more sophisticated potato value chains (Devaux et al., 2009). With harvested areas increasing in Peru and Bolivia (FAO, 2017), potato remains the trademark staple in the Andean region as well as an important crop for multiple uses.

The dynamics of RT&B agriculture in the developed world are comparatively simpler than in the developing world. Banana consumption (i.e., dessert banana rather plantain) is enabled principally through imports from the tropics, cassava consumption is typically in the form of imported feed or starch, and potatoes tend to dominate both the North American and European RT&B sectors. Despite the competitiveness of the European potato processing industry, production in the continent has decreased significantly over the last decades because of lower demand for fresh potatoes due to the shift of diets towards low-calorie food, and because of lower utilization of potato as animal feed (European Commission, 2007).

3. RT&B Foresight: Interpreting the past to understand the future

As crops grown and consumed throughout both the developing and developed world, RT&Bs are commodities with global importance yet serve multiple and differentiated roles. In order to understand how focused investments have the potential to bolster RT&B crops in the agriculture economy it is necessary to examine long-term trends in RT&B supply and demand using modeling and quantitative foresight approaches. Until now, most forward-looking studies on RT&B crops tend toward limited geographical coverage, disciplinary specificity, and only examine a subset of potential range of crops. The result is several short and medium-term crop-specific projections for yields and/or supply and demand in various countries or regions based on economic models or statistical extrapolation of historical trends (Jaggard et al., 2010; Scott and Suarez, 2012b). Other studies have examined the productivity changes brought about by climate (e.g. Raymundo et al., 2018), although focusing on climate alone is insufficient to assess future developments in food systems since price effects and technology will largely determine farmers' response to climate change (Islam et al., 2016; Reidsma et al., 2015). More comprehensive analyses wherein the impact of socioeconomic drivers of change on the production and demand of RT&B crops has only been considered in a handful of studies. Except for the projections for world agriculture by the Food and Agriculture Organization (FAO) (Alexandratos and Bruinsma, 2012; Bruinsma, 2003), only Scott et al. (2000a, 2000b) have attempted similar global projections for root and tuber crops, but not banana. While useful in their own right, these projections did not consider the impact of climate and are now outdated, with a time horizon of 2020.

A key objective of this work is to update previous projections and to characterize future trends for RT&B crops within a framework that accounts for possible changes in both the agroecological and socio-economic environments in which farmers operate. We leverage the findings from the foresight study of Rosegrant et al. (2017) examining large scale investment in agriculture, and build on this to explore RT&B crop dynamics. This study provided a baseline projection for 2050 across major crop production systems, as well as a quantitative assessment of the impacts of alternative investment options for agricultural research, resource management and infrastructure. Due to the breadth of the exercise, however, it did not include an analytical discussion for every commodity modeled. In this paper we examine in detail results related to RT&B crops and compare them, when possible, with findings in the relevant literature in order to understand potential future changes to RT&B farming systems from a global food security perspective, vis-à-vis other commodities.

The projections by Rosegrant et al. (2017) were produced with an integrated modeling framework developed around the global partial equilibrium model IMPACT, linked to a set of crop, livestock and hydrological models, in what is commonly characterized as a "structural modeling approach" (Islam et al., 2016). This model ensemble captures the effect of multiple drivers of change, namely climate, water availability, technology, population growth and market effects. Detailed information about the different components of the IMPACT modeling framework can be found in Robinson et al. (2015).

Baseline projections serve as the counterfactual against which to evaluate shocks and perturbations to the agriculture system, in this case the impact of different types of investments. The assumptions incorporated in the baseline scenario in Rosegrant et al. (2017) derive from a combination of socioeconomic and climate change pathways, namely the Shared Socioeconomic Pathway 2 (SSP2) and the Representative Concentration Pathway 8.5 (RCP8.5), both developed by the Intergovernmental Panel for Climate Change (IPCC). The combination of the two pathways produces a simulation scenario which posits a "middle of the road" scenario for trends related to population and economic growth, and a climate scenario that characterizes fairly rapid change with limited implicit consideration of adaptation or mitigation policies. The socioeconomic assumptions associated with SSP2 are illustrated in Fig. 2.

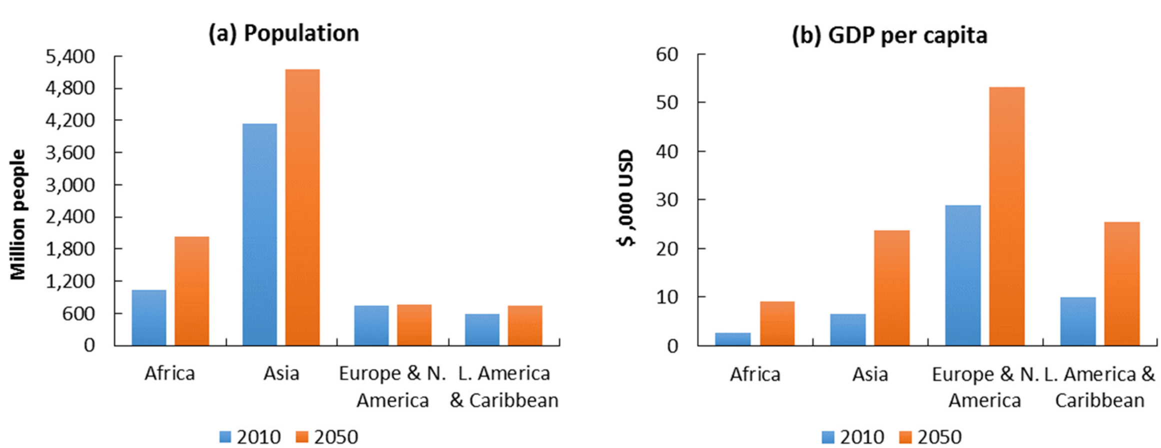

Fig. 2. Baseline scenario socioeconomic assumptions: (a) Population projections per region; (b) GDP per capita projections per region in 2010 constant prices (Source: Rosegrant et al., 2017).

4. Understanding the baseline: RT&B agriculture through 2050

Under baseline conditions for 2050, Rosegrant et al. (2017) suggest that production of RT&B crops will reach 1400 million tons (fresh produce), a global increase of almost 50% over 2010. Increase in supply is expected to exhibit higher concentration in developing countries, with Africa emerging as the world's biggest RT&B producing and consuming region. This result is consistent with the projections for population growth in the continent which is expected to double by 2050 (Fig. 2a) and increases in income, both of which will stimulate increased demand for food. The composition of demand will exhibit minor changes, with the percentage of RT&B crops used as food remaining stable. However, the feed share is expected to decline since the already observed trend in Europe and China of substituting grain cereals for RT&B crops as animal feed will persist.

The impact of population growth on the supply and demand equilibrium is confounded by climate change and water availability which will be key factors for crop productivity. Whereas some of the crops in the group like potato and banana are sensitive to water stress, others like cassava, yam and sweetpotato are intrinsically drought tolerant and can grow in regions with limited rainfall (Acevedo Mercado et al., 2015; Jarvis et al., 2012; Mukhopadhyay et al., 2011). Banana will exhibit the highest growth in supply and demand among all RT&B crops and across all regions (Fig. 3). In line with the previously mentioned agronomic traits, the projected supply increase for banana is expected to be land-driven. Given future pressures in land availability that will arise due to population growth and changes in income, rapid urbanization and competition with other crops, the increase in banana harvested area requires the intensification of existing croplands and adoption of management practices like intercropping with coffee, which can provide significant agronomic benefits for both crops and higher profits to the adopting farmers (Van Asten et al., 2011).

Results from Rosegrant et al. (2017) further suggest that per capita consumption of RT&Bs will increase in developing countries, particularly in Africa, which is consistent with the argument that agroecological conditions combined with poverty may drive a transition towards RT&B crops (Alexandratos and Bruinsma, 2012). A similar increase is projected in the energy contribution of RT&Bs to human diets in Africa, although the relative change is smaller compared to other commodities (Table 1). Elsewhere, the percentage calorie intake from RT&Bs will decrease slightly, following the expected shift from traditional staples towards other foods, primarily meat. Despite these regional dietary differences, the RT&B energy contribution to diets is expected to increase by 2050 globally.

The projected increase in food availability of RT&B crops in Africa is in line with earlier estimates of Alexandratos and Bruinsma (2012) who argued that the potential for productivity growth in cassava and yam by 2050 in the Sub-Saharan region could be an important driver for increasing RT&B consumption. Indeed, Rosegrant et al. (2017) project a significant supply increase for yam and cassava in Africa that will be achieved through yield improvements. The yield growth for yam can also be attributed to the localized nature of its production and consumption; assuming that yam processing would not change much between 2010 and 2050, with minimal exports restricted between neighboring countries (Nweke, 2015), yam would still be consumed where it is grown, and the projected yield growth is necessary for matching the increase in consumption.

Sweetpotato production in Africa is also expected to more than double, driven mainly by improvements in yield which is currently far below the world average. Since increased market demand is an effective driver of agricultural technology adoption, and hence of productivity improvements (RTB, 2016), an additional potential driver of

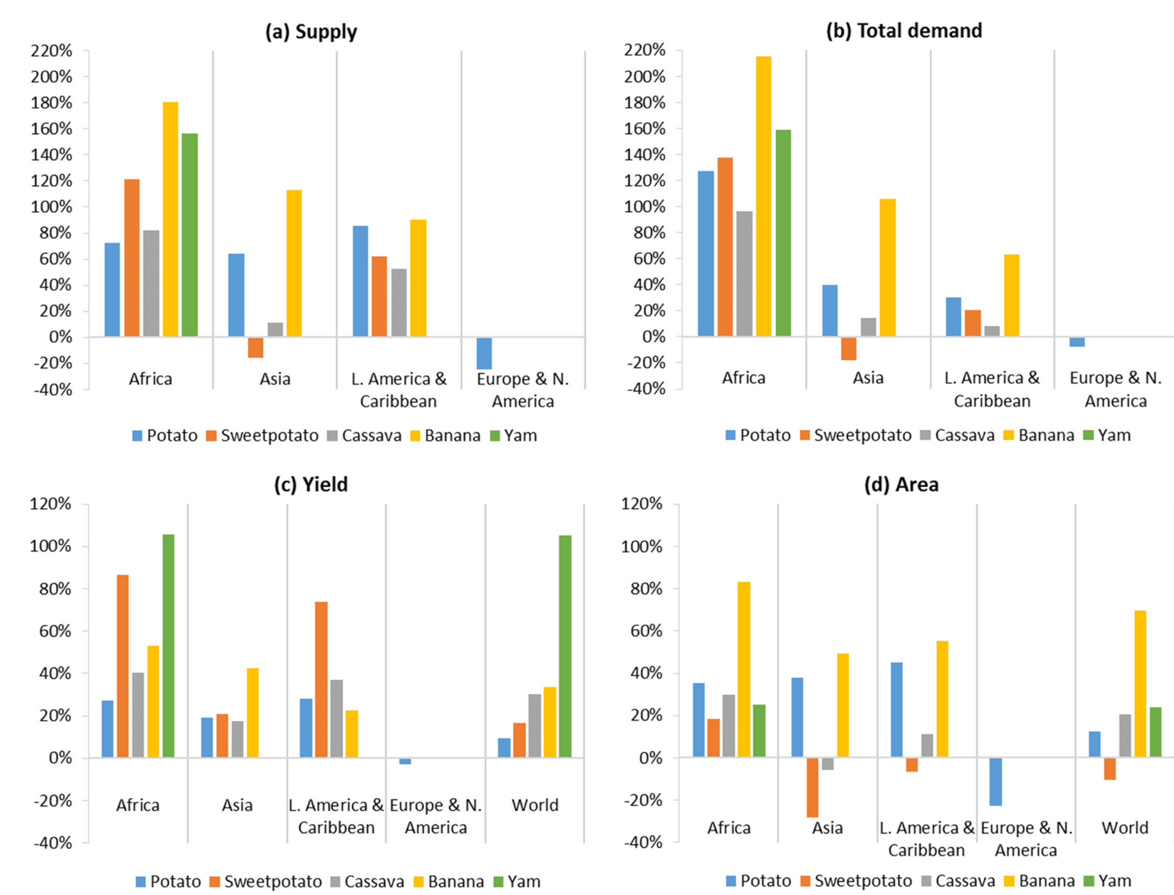

Fig. 3. Changes in RT&B agriculture for 2010–2050 under a baseline foresight scenario. (Source: Authors' calculations, based on Rosegrant et al., 2017).

Table 1
Change in food availability and dietary energy contribution of RT&B crops by 2050 under the baseline scenario. Source: Authors' calculations, based on Rosegrant et al. (2017).

	2010–2050 change in food availability (% of kg of fresh produce/person)			2010–2050 change in diet contribution (% of total Kcal)		
	RT&B	Cereals	Meat	RT&B	Cereals	Meat
Africa	15.4%	− 2.7%	88.5%	1.1%	− 6.6%	2.5%
Asia	6.8%	− 1.6%	40.0%	− 0.5%	− 9.0%	0.6%
L. America & Caribbean	3.4%	− 3.9%	23.2%	− 0.4%	− 4.4%	1.4%
Europe & N. America	− 6.9%	− 1.8%	5.2%	− 0.4%	− 0.9%	0.5%
Developed countries	− 6.2%	− 0.5%	10.1%	− 0.4%	− 1.0%	0.9%
Developing countries	19.2%	− 2.8%	35.0%	0.8%	− 8.0%	0.6%
World	16.4%	− 2.1%	23.7%	0.7%	− 6.3%	0.5%

sweetpotato yield growth is the high nutrition value of orange-fleshed sweetpotato varieties that are ideal for combatting vitamin A deficiency (Low et al., 2017); behavioral change, in the form of consumers seeking more nutritious food, could boost sweetpotato consumption in the region. This also implies value chain improvements and the strengthening of sweetpotato markets which are currently very small (Low et al., 2009). In Asia, evidence suggests that Bennet's Law and the "westernization" of diets that has reduced sweetpotato demand for food (Pingali, 2006) will persist, while demand for feed is also expected to decrease.

The high-income elasticity of demand for potato may also prove an important driver for production growth in some developing countries (Alexandratos and Bruinsma, 2012). Rosegrant et al. (2017) report similar findings for LAC and Asia, particularly in India, where land expansion is projected to increase potato supply by 180% compared to 2010; this growth surpasses the expected increases in food demand due to population growth alone. Elsewhere, instead of land expansion, the sustainable intensification of existing cereal systems, especially rice, with early maturing potato varieties can increase overall productivity and agricultural income (Biswas et al., 2006). We note that the projected growth in potato yields in India is lower than those estimated through statistical extrapolation (Jaggard et al., 2010). However, given that potato consumption in the country is currently lower than in other parts of Asia, and that India is predominantly a vegetarian culture, the projections by Rosegrant et al. (2017) may prove conservative. Economic growth by 2050 is likely to result in higher consumption levels for potato and may lead to further productivity growth and investment from the processing industry (Scott and Suarez, 2011).

Even with aggregate increases in potato supply and demand in Asia, consumption will likely decrease in China as a function of the lower population growth rates posited by SSP2, and diets moving more towards meat and cereal products. The demand projections for potato contradict previous empirical short-term estimates that were based on historical trends (Scott and Suarez, 2012b). Nevertheless, the high growth trends of potato demand reported for China until recently are unlikely to persist given the population assumptions incorporated in SSP2. One uncertainty surrounds unanticipated demand, especially as related to value chain improvements and stronger links to the industry that can increase supply of processed products (Scott and Suarez, 2012b).

5. Investment as a driver of alternative futures for RT&B crops

The baseline results in Rosegrant et al. (2017) suggest that, as a function of their food security role, RT&Bs will increase in terms of presence and importance in the world's most populous regions. With a baseline scenario reflecting a "business-as-usual" pathway that typifies ongoing underinvestment in RT&B crops, the question of investment remains. Could new R&D investments in RT&Bs alleviate existing challenges in their production and marketing, generate new demand and strengthen the long-term economic viability of these key crops?

5.1. Overcoming production challenges

Although climate is an important factor affecting crop yields, currently in many developing countries the full yielding capacity of RT&B crops is also restrained by poor water, crop and soil management practices. Adoption of better agronomic management is a key strategy for yield improvements (RTB, 2016), especially when combined with favorable market conditions, as is shown by Howeler (2014) for cassava in Asia. However, climate change will not only affect future crop yield through abiotic stresses but will also have an indirect effect in facilitating change in the ecological niches associated with the frontiers of related pests and diseases. With increasing globalization, the economic repercussions of pest and disease shocks have the potential to ripple through many different regions if not quickly and effectively mitigated through improved management (Wyckhuys et al., 2018).

As vegetatively propagated crops, biotic constraints present greater challenges for RT&Bs than for cereals because planting material must be free of pathogens; pathogens in RT&B systems are easily spread through affected planting material and result in yield and quality losses (Thomas-Sharma et al., 2016). The lack of formal seed systems, i.e. the regulated production and distribution of certified quality planting material, is often seen as a major productivity constraint for RT&B crops in many developing countries (RTB, 2016). Strengthening the policy environment surrounding certification and use of RT&B seeds by smallholder farmers via action with National Agricultural Research Systems (NARS) and the private sector is seen as a key solution to overcoming the seed system challenges in RT&B crops (Minot et al., 2007).

Vegetative propagation also has implications for breeding since the use of botanical seed translates to slow recombination rates and has historically led to slower and proportionally smaller yield improvements compared to grain crops (Brown et al., 2014). In addition, the genetic complexity of most RT&B crops and the genetic incompatibility issues that arise due to polyploidy (more than two paired chromosome sets), further complicate the genomic and genetic analysis of trait segregation patterns for breeders (RTB, 2016). Breeding difficulties also beget the proportionally lower interest from the private sector and are a key reason why national breeding programs for RT&Bs are generally weaker than cereals (Scott et al., 2000a).

Underinvestment in R&D has further marketing implications for RT&B crops because they are harvested fresh with a water content that ranges between 60–80% (USDA, 2018) and are therefore more perishable than grains (Affognon et al., 2015). Various storage methods are used for reducing post-harvest losses in yield and quality, but their applicability and adoption depends on the usage of the harvested product, with more advanced storage methods reserved for products often found in export markets. Investments in improving existing storage and marketing infrastructure are therefore necessary to extend the shelf life of RT&Bs. Such improvements can increase RT&B food availability and food stability, facilitate the development of higher-value supply chains, strengthen links with the processing industries, and ultimately enhance the income generation function of RT&B crops. In turn, higher

Table 2
Investment scenarios for RT&B crops. Source: Rosegrant et al. (2017).

Type of investment	Scenario	Description	Rationale
Productivity Enhancement (Improving food availability)	HIGH R&D (HIGH)	High increase in CGIAR investments globally	It can alleviate existing breeding challenges for RT&B crops and expedite yield gains
	HIGH R&D + NARS (HIGH + NARS)	High increase in CGIAR investments globally and increased investments from National Agricultural Research Systems (NARS)	Derived from the HIGH scenario by assuming additional yield gains attributed to the empowerment of NARS. It is an extreme investment scenario under which both CGIAR and NARS increase their research funding. It targets challenges related to seed systems and decentralized breeding, but can also cover personnel gaps for NARS in key disciplines (Beintema and Stads, 2017)
	REGIONAL FOCUS (REGION)	High increase in CGIAR investments for Sub-Saharan Africa (SSA) and South Asia (SAS). Medium increase in CGIAR investments elsewhere	A scenario that focuses on SSA and SAS which will be the world's most populous regions by 2050, where RT&B crops are considered food security crops
Infrastructure and Agricultural Marketing (improving access to food)	Improved market access (RMM)	Improvements in energy, transportation and storage infrastructure to increase market efficiency	It can induce productivity growth and improve access to food through improvements in every segment of the value chain. Improvement of storage facilities to reduce post-harvest losses and marketing innovations also fall under this investment scenario

agricultural incomes can provide additional incentives for the adoption of improved RT&B technologies among smallholder farmers who are now often unwilling or unable to innovate (Fermont et al., 2010; Gildemacher et al., 2009).

5.2. Alternative futures with strategic investments

We examine three productivity growth-related investment scenarios and one marketing improvement scenario presented in Rosegrant et al. (2017). The investments simulated in these scenarios, summarized in Table 2, simulate improvements in two different pillars of food security, namely food availability and access to food (FAO et al., 2013). The scenarios do not focus exclusively on RT&B crops, rather they constitute different examples of investment strategies that can help improve the international agricultural research portfolio. Nevertheless, the assumptions incorporated in the selected scenarios makes them particularly relevant for RT&B agriculture and can also reveal the response of the RT&B sector to non-crop specific investments to research, also vis-à-vis other commodities.

As shown in Fig. 4, all investment scenarios that intend to improve productivity have the potential to increase global supply and per capita consumption of RT&B crops compared to the baseline 2050 scenario. This would lead to a new market equilibrium for each crop that corresponds to lower prices and higher demand levels. The HIGH + NARS scenario exhibits the highest growth among all scenarios in both demand and supply, as it assumes additional investments designed to strengthen NARS as compared to the HIGH scenario. Although it is evident that empowered NARS working in close collaboration with CGIAR centers can bring about higher benefits for RT&B crops, HIGH + NARS does not necessarily correspond to a realistic funding scenario because increased investments in the CGIAR could potentially result in a crowding-out effect, discouraging local governments to allocate public funding going towards agricultural research and extension. In this sense, HIGH + NARS should rather be viewed as a sensitivity test to examine what would happen if public funding for empowering NARS could be designed in such a way so as to complement CGIAR investments.

In contrast to production-oriented scenarios, the RMM scenario does not directly affect crop yield. It instead represents improvements to market efficiency by reducing the cost for food while allowing

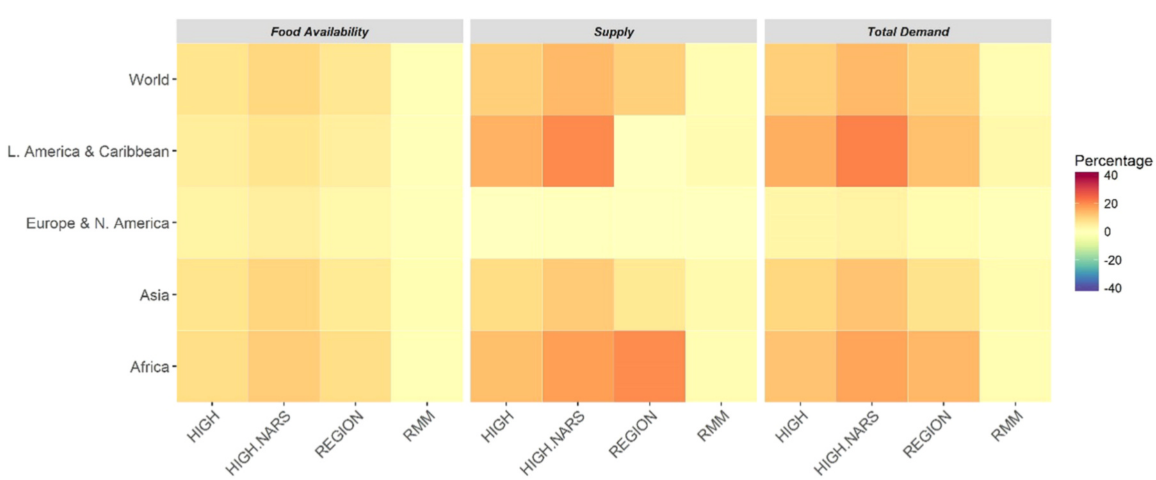

Fig. 4. Regional changes in demand and supply of RT&B crops by 2050 under different investment scenarios (percentage changes of 2050 projections with investments over the 2050 baseline projections without investments). Total demand for RT&B crops is measured in metric tons and is calculated as the aggregate of all demand types (food, feed, seed, industry, other). Food availability is measured in kilograms per capita and represents the per capita consumption of food, that is, the "food" part of total demand. The simulated market equilibrium by IMPACT sets total demand equal to supply (also measured in metric tons) and hence the depicted changes for demand in line "World" are equal to the changes in supply. (Source: Rosegrant et al., 2017).

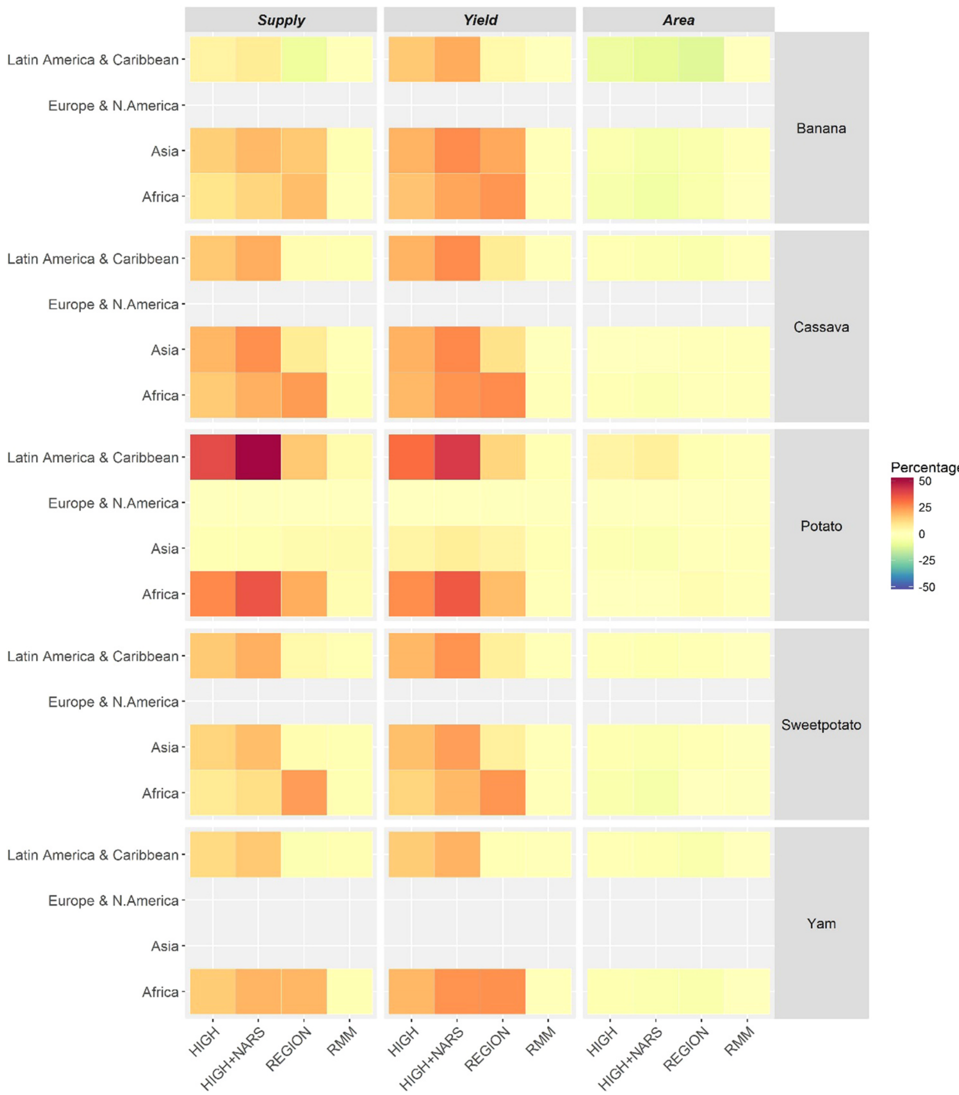

Fig. 5. Regional changes in production statistics of RT&B crops by 2050 under different investment scenarios (percentage changes of 2050 projections with investments over the 2050 baseline projections without investments). Grey boxes indicate low importance or no cultivation. (Source: Rosegrant et al., 2017).

producers to capture a greater share of the final consumer price. The goal is to enhance certain dimensions of food security (economic and physical access to food) through improved pricing instead of improved quantities; this results in the lowest aggregate growth in supply and demand and thus to smaller reductions in prices compared to the three productivity improvement scenarios. Since commodity prices are indicators of economic access to food (FAO et al., 2013), these results indicate that the RMM scenario, as specified and simulated by Rosegrant et al. (2017), can provide only marginal contributions to the role of RT&B agriculture in enhancing global food security. Moreover, the RMM scenario does not explicitly consider how localized consumption, production and trade, and the lack of appropriate institutions might actually impede the development of high value RT&B chains in many developing countries. These factors ultimately relate to physical access to food and likely require quantitative tools operating at finer geographical scales; there is no clear consensus regarding the appropriate level of the analysis or the appropriate indicators (Van der Ploeg et al., 2015).

The HIGH and REGION scenarios lead to an almost similar increase in global supply growth of RT&Bs over the 2050 baseline but differ significantly on the spatial distribution of supply growth because of the different assumptions they incorporate (Fig. 5). The different spatial patterns are clearly evident in the decrease in banana production in LAC, since investments under the REGION scenario target higher productivity growth in South Asia and Sub-Saharan Africa (as explained in Table 2), shifting the concentration of banana production towards these regions. The decrease of banana production in LAC under the REGION scenario is manifested mainly through a decline in cultivated area. Similar declines in harvested areas, compared to the 2050 baseline, are projected under all investment scenarios for most RT&B crops. Potato appears as an exception to this trend since its cultivation will expand in LAC under the REGION scenario and in Africa under the HIGH and HIGH + NARS scenarios. Potato land expansion is mainly associated with irrigated areas (e.g., coastal Peru, and North Africa) where the crop is grown primarily for commercial purposes and is accompanied by high productivity improvements. This result reveals that the commercial orientation of crop production and irrigation may have a multiplier effect to the investment-induced productivity growth.

Whereas supply growth compared to the 2050 baseline differs among the various scenarios, the simulated increase in demand is spatially more homogeneous as it depends on the changes in prices. However, price reductions brought about by increased food supply will modify the relative prices of agricultural commodities and trigger substitution effects in consumption. Under these changes, all investment scenarios can increase RT&B demand in all regions compared to the 2050 baseline projections (Fig. 4). The percentage caloric intake

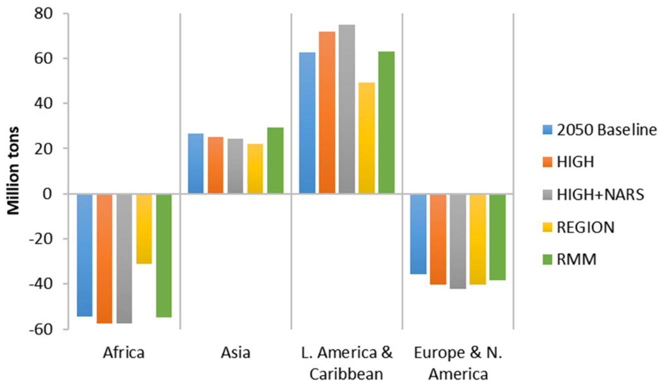

Fig. 6. Net trade of RT&B crops by 2050 under the baseline and different investment scenarios. (Source: Rosegrant et al., 2017).

from RT&B crops is also expected to increase slightly in both developed and developing countries.

The different spatial patterns of supply and demand growth ultimately lead to differences in comparative advantage and net trade of RT&B crops among the various scenarios; under REGION, the trade balance for African countries improves compared to HIGH and HIGH +NARS, since the greater supply growth minimizes the need for imports, which in turn leads to a decrease in exports from Asia and LAC (Fig. 6). This result reveals that spatially-targeted investments can have further positive impacts on food security over and above what is incurred by productivity growth, as they can improve the self-sufficiency of food production, reduce dependency from imports, and finally decrease the risk from volatile world prices and productions shocks in exporting countries. Despite these changes, however, traded RT&B volumes remain relatively small compared to total production in all investment scenarios.

6. Discussion and conclusions

RT&B crops are grown in different contexts and for different purposes, serving as food, feed and cash crops, or as primary input for derivative products. However, their key role in supplying calories and nutrition to the food systems in many developing countries makes it important to look at future production and demand trends and to better understand how R&D investments might be best targeted. The structural modeling approach shows that under a baseline simulation scenario, production of RT&B crops by 2050 can increase in developing countries, driven mainly by yield improvements. Food availability and energy contribution to diets will also increase, which indicates the growing importance RT&Bs for food security in regions where they are used as staples, particularly in Africa. Potato is the crop that stands out because of its role in food systems for both developed and developing countries. As such, the crop is more affected by changing preferences than are other RT&B crops, especially in countries like China where the baseline scenario posits rapid economic development but low population growth.

While simulated investments for improving yields suggest significant productivity gains and induce demand growth due to lower prices, focusing on yield alone is shortsighted. Yield-increasing investments are shown to increase food availability and the energy contribution of RT&B crops to human diets compared to the baseline scenario for 2050. This does not consider, however, the highly local nature of much of the RT&B economy. The analysis also reveals that more spatially targeted investments can further strengthen the role of RT&Bs as food security crops. Specifically, investments that aim at increasing productivity in regions which are expected to face high population pressures, like Sub-Saharan Africa and South Asia, can serve to efficiently target increasing supply and reducing dependency from imports, thus improving stability of food access (FAO et al., 2013). On the contrary, the foresight results analyzed herein do not provide enough evidence to support the supposition that economic incentives to strengthen supply and demand through reducing market inefficiencies have the potential to affect the food security role of RT&B crops.

One of the challenges for agriculture in the future is arguably the competition between food, feed and fuel. Although the modeling framework employed by Rosegrant et al. (2017) addresses the food vs feed question endogenously (Robinson et al., 2015), it does not examine how the increasing demand for biofuels can affect the food security role of RT&B crops. Production of ethanol from cassava and sweetpotato is a practice that is being pursued in several countries like China and Indonesia (Qiu et al., 2010) and may put additional pressure to RT&B production systems. Nevertheless, achieving food and fuel objectives can present synergies like the absorption of market shocks by the biofuel sector, resulting in more stable access to food (Drabik et al., 2016). Furthermore, this analysis does not consider the fundamental shift toward cassava production for starch in South-East Asia, and trends for cassava and competing starches may not adequately reflect this regional dynamic. Finally, both the baseline and the investment scenarios assume a continuation of existing agricultural and trade policies toward RT&B crops. Although policy changes can possibly lead to significant deviations from the projections presented herein, they are beyond the scope of foresight analysis because the main objective is to capture and explain future trends in the evolution of RT&B farming systems.

Despite these caveats, our analysis clearly shows the potential of RT&B crops to continue being the mainstay of human diets in many of the world's poorest regions. Given the climate resilience of most RT&B crops, and the nutritional benefits that come from biofortification and their high energy content, RT&Bs can form a strong basis for development programs that aim at reducing malnutrition and poverty in developing countries. The scenarios examined provide evidence that appropriate investments can offer significant productivity gains to RT&B agriculture and can, in turn, become an important part of the success of different development programs. It has also been shown, in the case of potato, that links to markets can amplify the impact of these investments on crop productivity. Improving the commercial prospects of RT&B crops requires the appropriate institutional and policy interventions to facilitate innovation in production and marketing that will finally allow their transformation from subsistence commodities to high value products. This transformation will enhance the income generation role of RT&B crops and increase the employment opportunities for both men and women throughout the world's many and diverse RT&B producing areas.

Acknowledgements

This work was undertaken as part of the Global Futures and Strategic Foresight project (GFSF) of the CGIAR Research Program on Policies, Institutions, and Markets (PIM). Funding support was provided by the CGIAR Research Program on Policies, Institutions and Markets (PIM), and the CGIAR Research Program on Roots, Tubers and Bananas (RTB). The authors would like to thank Graham Thiele, Michael Friedman and the participants of the GFSF project for their comments and suggestions that have greatly improved this manuscript. The opinions expressed here belong to the authors, and do not necessarily reflect those of PIM, RTB or CGIAR.

Declarations of interest

None.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gfs.2018.12.005.

References

Acevedo Mercado, A.N., Sandoval Assia, I.S., Salcedo Mendoza, J.G., 2015. Development and productivity in yam (Dioscorea trifida and Dioscorea esculenta) under different water conditions. Acta Agron. 64, 31–36.

Affognon, H., Mutungi, C., Sanginga, P., Borgeimeister, C., 2015. Unpacking postharvest losses in Sub-Saharan Africa: a meta-analysis. World Dev. 66, 49–68.

Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision (ESA Working Paper No. No. 12-03). Food and Agriculture Organization of the United Nations (FAO), Agricultural Development Economics Division.

ASTI, 2017. Agricultural Science and Technology Indicators (ASTI). 〈https://www.asti.cgiar.org〉 (accessed 21 November 2017).

Beintema, N., Stads, G.-.J., 2017. A Comprehensive Overview of Investments and Human Resource Capacity in African Agricultural Research. ASTI Synthesis Report. 〈https://www.asti.cgiar.org/sites/default/files/pdf/SSA-Synthesis-Report-2017.pdf〉 (accessed 21 November 2017).

Biswas, B., Ghosh, D.C., Dasgupta, M.K., Trivedi, N., Timsina, J., Dobermann, A., 2006. Integrated assessment of cropping systems in the Eastern Indo-Gangetic plain. Field Crops Res. 99, 35–47.

Brown, J., Caligari, P., Campos, H., 2014. Plant Breeding, 2nd ed. Wiley, Chichester, UK.

Bruinsma, J., 2003. World Agriculture: Towards 2015/2030. An FAO Perspective. Earthscan Publications, London, UK.

Devaux, A., Horton, D., Velasco, C., Thiele, G., López, G., Bernet, T., Reinoso, I., Ordinola, M., 2009. Collective action for market chain innovation in the Andes. Food Policy 34, 31–38.

Drabik, D., Ciaian, P., Pokrivčák, J., 2016. The effect of ethanol policies on the vertical price transmission in corn and food markets. Energy Econ. 55, 89–99.

European Commission, 2007. The potato sector in the European Union. Commission Staff Working Document No. 533. Brussels.

FAO, 2017. FAOSTAT Database. 〈http://www.fao.org/faostat/en/〉 (accessed 1 May 2017).

FAO, IFAD, WFP, 2013. The State of Food Insecurity in the World 2013. The multiple dimensions of food security. Rome, FAO.

Fermont, A.M., Babirye, A., Obiero, H.M., Abele, S., Giller, K.E., 2010. False beliefs on the socio-economic drivers of cassava cropping. Agron. Sustain. Dev. 30, 433–444.

Fuglie, K.O., 2004. Challenging Bennet's law: the new economics of starchy staples in Asia. Food Policy 29, 187–202.

Gildemacher, P.R., Kaguongo, W., Ortiz, O., Tesfaye, A., Woldegiorgis, G., Wagoire, W.W., Kakuhenzire, R., Kinyae, P.M., Nyongesa, M., Struik, P.C., Leeuwis, C., 2009. Improving potato production in Kenya, Uganda and Ethiopia: a system diagnosis. Potato Res. 52, 173–205.

Henry, G., Hershey, C., 2002. Cassava in South America and the Caribbean. In: Hillocks, R.J., Thresh, J.M., Bellotti, A.C. (Eds.), Cassava: Biology, Production and Utilization, pp. 17–40.

Howeler, R., 2014. Sustainable soil and crop management of cassava in Asia – A reference manual. CIAT Publication No. 389. Centro Internacional de Agricultura Tropical (CIAT). Cali, Colombia. Retrieved from: 〈http://ciat-library.ciat.cgiar.org/articulos_ciat/Sustainable_soil_crop_management_cassava_asia_2014.pdf〉.

Islam, S., Cenacchi, N., Sulser, T.B., Gbegbelegbe, S., Hareau, G., Kleinwechter, U., Mason-D′Croz, D., Nedumaran, S., Robertson, R., Robinson, S., Wiebe, K., 2016. Structural approaches to modeling the impact of climate change and adaptation technologies on crop yields and food security. Glob. Food Secur. 10, 63–70.

Jaggard, K.W., Qi, A., Ober, E.S., 2010. Possible changes to arable crop yields by 2050. Philos. Trans. R. Soc. B 365, 2835–2851.

Jarvis, A., Ramirez, J., Herrera, B.V., Navarro, C., 2012. Is cassava the answer to African Climate Change Adaptation? Trop. Plant Biol. 5, 9–29.

Low, J., Lyna, J., lemaga, B., Crissman, C., Barker, I., Thiele, G., Namanda, S., Wheatley, C., Andrade, M., 2009. Sweetpotato in Sub-Saharan Africa. In: Loebenstein, B., Thottappilly, G. (Eds.), The Sweetpotato. Springer, The Netherlands, pp. 359–390.

Low, J.W., Mwanga, R.O.M., Andrade, M., Carey, D., Ball, A.-M., 2017. Tackling vitamin A deficiency with biofortified sweetpotato in sub-Saharan Africa. Glob. Food Secur. 14, 23–30.

Minot, N., Smale, M., Eicher, C., Jayne, T., Kling, J., Horna, D., Myers, R., 2007. Seed Development Programs in Sub-Saharan Africa: A Review of Experiences. Report prepared for the Rockefeller Foundation. International Food Policy Research Institute (IFPRI), Washington D.C.

Mukhopadhyay, S.K., Chattopadhyay, A., Chakraborty, I., Bhattacharya, I., 2011. Crops that feed the world 5. Sweetpotato. Sweetpotatoes for income and food security. Food Secur. 3, 283–305.

Murray, D.L., Raynolds, L.T., 2000. Alternative trade in bananas: obstacles and opportunities for progressive social change in the global economy. Agric. Hum. Values 17, 65–74.

Nweke, F.I., 2015. Yam in West Africa: food, Money, and More. Michigan State University Press, Lansing, Michigan.

Nweke, F.I., 2004. New challenges in the cassava transformation in Nigeria and Ghana. Discussion Paper No. 118. International Food Policy Research Institute (IFPRI), Washington D.C.

Palacios-Lopez, A., Christiaensen, L., Kilic, T., 2017. How much of the labor in african agriculture is provided by women? Food Policy 67, 52–63.

Pingali, P., 2006. Westernization of Asian diets and the transformation of food systems: implications for research and policy. Food Policy 32, 271–298.

Qiu, H., Huang, J., Yang, J., Rozelle, S., Zhang, Y., Zhang, Y., Zhang, Y., 2010. Bioethanol development in China and the potential impacts on its agricultural economy. Appl. Energy 87, 76–83.

Raymundo, R., Asseng, S., Robertson, R., Petsakos, A., Hoogenboom, G., Quiroz, R., Hareau, G., Wolf, J., 2018. Climate change impact on global potato production. Eur. J. Agron. 100, 87–98.

Reidsma, P., Wolf, J., Kanellopoulos, A., Schaap, B.F., Mandryk, M., Verhagen, J., Van Ittersum, M.K., 2015. Climate change impact and adaptation research requires integrated assessment and farming systems analysis: a case study in the Netherlands. Environ. Res. Lett. 10, 045004.

Robinson, S., Mason-D′Croz, D., Islam, S., Sulser, T.B., Robertson, R., Zhu, T., Gueneau, A., Pitois, G., Rosegrant, M., 2015. The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). Model Description for Version 3. IFPRI Discussion Paper No. 01483. International Food Policy Research Institute (IFPRI), Washington D.C.

Rosegrant, M.W., Koo, J., Cenacchi, N., Ringler, C., Robertson, R., Fisher, M., Cox, C., Garrett, K., Perez, N.D., Sabbagh, P., 2014. Food Security in a World of Natural Resource Scarcity: the Role of Agricultural technologies. International Food Policy Research Institute (IFPRI), Washington D.C.

Rosegrant, M.W., Sulser, T.B., Mason-D′Croz, D., Cenacchi, N., Nin-Pratt, A., Dunston, S., Zhu, T., Ringler, C., Wiebe, K., Robinson, S., Willenbockel, D., Xie, H., Kwon, H.-.Y., Thomas, T.S., Wimmer, F., Schaldach, R., Nelson, G.C., Willaarts, B., 2017. Quantitative Foresight Modeling to Inform the CGIAR Research Portfolio. Project Report for USAID. International Food Policy Research Institute (IFPRI), Washington D.C.

RTB, 2016. RTB CRP Full Proposal 2017–2022, Volume I. CGIAR Research Program (CRP) on Roots, Tubers & Bananas (RTB). Retrieved from 〈http://www.rtb.cgiar.org/blog/publication/rtb-proposal-2017–2022-volume-i/〉.

Rusike, J., Mahungu, N.M., Jumbo, S., Sandifolo, V.S., Malindi, G., 2010. Estimating impact of cassava research for development approach on productivity, uptake and food security in Malawi. Food Policy 35, 98–111.

Sanginga, N. Mbabu, A., 2015. Root and Tuber Crops (Cassava, Yam, Potato and Sweet Potato). Background paper for the Conference Feeding Africa 21-23 October, Dakar, Senegal. Retrieved from 〈https://www.afdb.org/en/documents/〉.

Scott, G.J., Suarez, V., 2011. The rise of Asia as the center of global potato production and some implications for industry. Potato J. 39, 1–22.

Scott, G.J., Rosegrant, M.W., Ringler, C., 2000a. Global projections for root and tuber crops to the year 2020. Food Policy 25, 561–597.

Scott, G.J., Rosegrant, M.W., Ringler, C., 2000b. Roots and Tubers for the 21st Century. Trends, Projections, and Policy Options. Vision 2020 Food, Agriculture, and the Environment Discussion Paper No. 31. International Food Policy Research Institute (IFPRI) and the International Potato Center (CIP), Washington D.C.

Scott, G.J., Suarez, V., 2012a. The rise of Asia as the center of global potato production and some implications for industry. Potato J. 39, 1–22.

Scott, G.J., Suarez, V., 2012b. From Mao to McDonald's: emerging markets for potatoes and potato products in China 1961–2007. Am. J. Potato Res. 89, 216–231.

Thomas-Sharma, S., Abdurahman, A., Ali, S., Andrade-Piedra, J.L., Bao, S., Charkowski, A.O., Crook, D., Kadian, M., Kromann, P., Struik, P.C., Torrance, L., Garrett, K., Forbes, G.A., 2016. Seed degeneration in potato: the need for an integrated seed health strategy to mitigate the problem in developing countries. Plant Pathol. 65, 3–16.

Van Asten, P.J.A., Wairegi, L.W.I., Mukasa, D., Uringi, N.O., 2011. Agronomic and economic benefits of coffee–banana intercropping in Uganda's smallholder farming systems. Agric. Syst. 104, 326–334.

Van der Ploeg, M., Dutko, P., Brenerman, V., 2015. Measuring food access and food deserts for policy purposes. Appl. Econ. Perspect. P. 37, 205–225.

USDA (2018). Food Composition Databases. https://ndb.nal.usda.gov/ndb/search/list (accessed 19 December 2018).

Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., van der Mensbrugghe, D., Biewald, A., Bodirsky, B., Islam, S., Kavallari, A., Mason-D′Croz, D., Müller, C., Popp, A., Robertson, R., Robinson, S., van Meijl, H., Willenbockel, D., 2015. Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. Environ. Res. Lett. 10 (085010–085010).

Wyckhuys, K.A.G., Zhang, W., Prager, S.D., Kramer, D.B., Delaquis, E., Gonzalez, C.E., van der Werf, W., 2018. Biological control of an invasive pest eases pressures on global commodity markets. Environ. Res. Lett. 13, 094005.