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Modelling predicts that soybean is poised to dominate crop production across Africa.

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Running title: Soybean production in Africa

Summary statement: Soybean is fast becoming an increasingly attractive cash crop in Africa. We have examined current and future legume production in Sub-Saharan Africa using a modelling approach based on available FAO data to provide projections for 2050. These data predict a large expansion in African soybean production. The resultant great potential for the amelioration of poverty, hunger and malnutrition will be a major driver for farmers and producers to overcome the significant challenges that might otherwise impede soybean production in Africa.

Abstract

The superior agronomic and human nutritional properties of grain legumes (pulses) make them an ideal foundation for future sustainable agriculture. Legume-based farming is particularly important in Africa, where small-scale agricultural systems dominate the food production landscape. Legumes provide an inexpensive source of protein and nutrients to African households as well as natural fertilization for the soil. While the consumption of traditionally grown legumes has started to decline, the production of soybeans (*Glycine max* Merr.) is spreading fast, especially across southern Africa. Predictions of future land-use allocation and production show that the soybean is poised to dominate future production across Africa. Land use models project an expansion of harvest area, while crop models project possible yield increases. Moreover, a seed change in farming strategy is underway. This is being driven largely by the combined cash-crop value of products such as oils and the high nutritional benefits of soybean as an animal feed. Intensification of soybean production has the potential to reduce the dependence of Africa on soybean imports. However, a successful 'soybean bonanza' across Africa necessitates an intensive research, development, extension and policy agenda to ensure that soybean genetic improvements and production technology meet future demands for sustainable production.

Introduction

Assuring sustainable food security for millions of poor producers and consumers across Africa living on \$2 a day or less remains a serious problem, exacerbated by malnutrition (Figure 1). Adding to the pressure exerted by the rural poor are the emerging demands of urban African middle-class consumers, who strive for diets of higher nutritional quality and richer in animal proteins. While these food choices may be influenced by factors such as relative prices, advertising and perception, they are primarily driven by personal preferences in Africa, as in other countries where increased wealth has been accompanied by an increased consumption of meats and dairy products. Satisfying the demands of a rapidly growing population with an increasing appetite for protein rests on the agricultural sector. Smallholder farmers are the bedrock group, who manage 80% of farmland and produce 70% of food in Africa (FAO 2012). Plagued by resource-constrained farming conditions and inadequate technologies, African producers continue to struggle with poor economic returns and trade-offs between subsistence and cash crop production (Timmer 1997, 2004). Much-needed improvements in productivity and choice of crops and farm animals are limited by the availability and access to agricultural inputs and resources. Better training, access to finance and most critically, quality production factors (including seed quality and other inputs) are necessary to eliminate the causes of the much-debated ‘yield gap’, i.e. the difference between maximum achievable crop yields and actual yields (Anderson *et al.* 2016), witnessed by producers across much of Africa (Mauser *et al.* 2015). Many Africa countries have very low agricultural productivity and large yield gaps, which can be attributed in part to environmental constraints including poor soil quality and insufficient water availability. In addition, a lack of technology, inappropriate institutions and/or poor governance, land tenure, declining infrastructure and underdeveloped marketing or poor market infrastructure, make producers adopt risk-minimising cropping choices. It is no surprise therefore that the African yield gap and agricultural poverty cycles continue to persist (Maxwell 1996).

The pivotal role of grain legumes in assuring the current and future sustainability of agriculture across Africa is well documented (Sinclair *et al.* 2014; Foyer *et al.* 2016). The symbiotic nitrogen fixation properties of legumes mean that they are suitable for cultivation on a wide variety of soils (Ferguson *et al.* 2010). Soil fertility management through either crop rotation or intercropping has long been an essential resource for poor farmers unable to access and/or afford more expensive inorganic fertilizer inputs. Further, symbiotic nitrogen fixation also helps protect other vital nutrients such as phosphate (Foyer *et al.* 2016). Grain legumes are

ideally suited to the task of mitigating many of the agronomic and economic constraints faced by producers, while providing positive impacts on soil health (Ferguson *et al.* 2010; Jensen *et al.* 2012; Gresshoff *et al.* 2015). A large number of grain legume species are grown across Africa including many underutilised, orphan or neglected crops. Unfortunately, orphan crops are widely considered to be the ‘poor man’s protein’, particularly by the growing numbers of middle-class consumers across Africa (i.e. Nigeria, South Africa, Uganda), who prefer diets that are rich in animal protein (Chivenge *et al.* 2015). However, these largely undervalued and unappreciated locally-adapted crops have essential stress tolerance traits with high yield stability under suboptimal and often difficult climatic conditions (Cullis & Kunert 2017). Despite these clear benefits, these underutilised and mainstream grain legume species are not viewed as the next generation of ‘super crops’, but rather they face stagnation and declining consumption across the continent and much of the developing world. In contrast, increased demands for soybean production are being driven by increasing incomes and urbanization, and a global dietary transition to diets that are higher in refined sugars, refined fats/oils and meats (Tilman & Clark 2014). It is not surprising that research by the European Commission (Melo *et al.* 2015) confirmed that there is a general decline in consumption within these food groups, which have negative income elasticities, with each additional \$1 in available income. In contrast, the income elasticities for meat, fish, eggs and dairy (sources of protein perceived as more luxurious in the eyes of many Africa consumers), are among the highest positive elasticities reported by this research (Melo *et al.* 2015). Current evidence (Supplementary Table S1) suggests that many grain legumes are destined to face a future as protein of last resort for the rural poor. It is becoming increasingly likely that meat protein consumption will expand across Africa, as grain legume protein and the energy from maize become used more extensively to produce the animal protein. This raises the question of which of the many protein-rich grain legumes grown across Africa is likely to meet demand. We consider that the answer, based on current data and Food and Agricultural Organisation (FAO) predictions, is soybeans, which are discussed in detail below. Moreover, most of the countries in Africa south of the Sahara Desert extending all the way to South Africa are suitable for soybean production. Given these facts, we discuss how the rapidly growing popularity of soybean production across Africa could mark the start of a soybean revolution.

The growing success of soybean

Fifty years ago, soybean was an underutilised niche crop that lacked processing and consumer markets. Global production of soybean has increased 13-fold since 1961 to over 340 million

metric tonnes in 2016 (FAOSTAT). Today, soybean is one of the five most important crops worldwide. The global import and export values of soybean have outstripped all of the other major crops such as wheat, rice and maize, even without the inclusion of soybean oil or other processed forms. Africa has the land, climate and motivation to be a major player in global soybean production in the future. Land dedicated to soybean cultivation in Africa in 2016 exceeded 1.5 million hectares. Development of new rust-resistant varieties and high-yielding lines that are adapted to production in African climates now face a sellers' market, particularly for soybean oil for cooking and high-protein meal cake, which is a much sought-after ingredient in poultry and other animal feeds (Ncube *et al.* 2016). Moreover, in rotation with cereals such as maize and sorghum, soybean production has the potential to provide the bedrock of food and feed supply across Africa. The strong and growing demand for maize and soybeans should provide diverse economic opportunities for smallholders, who are eager to diversify their crop and animal production systems. Hence, we predict sweeping changes in soybean production and use across Africa in the coming decades. We also warn that the current lack of attention to the potential 'soybean bonanza' may result in too little research attention being focused on the genetic improvement of soybean and associated production technologies to support increasing production in Africa, especially in a changing climate.

Legume production in Africa

Traditional grain legume cultivation (Table 1) is predominant across Africa (Figure 2), however, substantial variations in production and yield outcomes exist, which reflect productivity ceilings due to soil fertility and moisture (Bill & Melinda Gates Foundation 2012; Ortega *et al.* 2016; Tadele 2017). Chickpeas, groundnuts and soybeans have yields above 1.0 metric tons per ha, in comparison to common beans and cowpeas that often have yields below 900 kg per ha (Figure 2). Together, with other African legumes (Table 1), soybeans are a productivity-enhancing crop (Kerr *et al.* 2007) and potentially an economically beneficial choice, especially for small- and medium-scale producers (Kerr *et al.* 2007; Gresshoff *et al.* 2015). Unfortunately, empirical evidence in support of predictions of future grain legume production overall, and for soybeans in particular, is fragmented. Many such predictions have relied on spatially or temporally uncertain results of crop yield model aggregations, which are considered to be significant when underlying production system factors are often uncertain (Mueller *et al.* 2012; Porwollik *et al.* 2017). Despite a paucity of extensive data, the predictions presented here (Figure 3) provide the most realistic scenarios and outcomes. In light of overall limitations in available data across Africa, we chose the consistency of the latest available FAO

data, confirmed by our own analysis of available data, over aggregations of alternative data sources. We reiterate the concerns in previous studies (Tilman *et al.* 2011) regarding the need to overcome major data barriers to predictions of how regional African crop systems might perform under various production conditions, market dynamics, and climate change. Regardless, data from all available sources point to the significant potential of available improved soybean cultivars in sustainable intensification in the coming decades (Tilman *et al.* 2011).

There is a steady increase in soybean production area in Brazil and soybean production is gradually moving west and north (from North America) into Canada as well as northwards from Northeast China into Russia, as varieties that are suitable for these more exacting climates become available. There is also a bright future for soybean production in Africa. Soybean is poised to fill Africa's widening gap in the demand for protein, oil and animal feed legumes that have already uniquely elevated the profile of soybean across southern Africa. However, Africa continues to rely on the investment of largely resource-poor small holders for the majority of crop production. Such producers are inherently limited in their overall ability to adopt the latest soybean technologies and overcome barriers stemming from market access and investment needs (Ray *et al.* 2013; Wilson 2015). Moreover, limited and inconsistent regional producer price data make accurate predictions of the profitability of soybean rotations problematic, i.e. beyond their proven value as substitutes for expensive imports of feedstuffs (Ncube *et al.* 2016). However, it is important to note that soybeans have the lowest producer price in developing countries (Akibode & Maredia 2012). For example, the producer price for soybean in West Africa is significantly lower than the average global producer price for pulse crops (Supplemental Table 2; Akibode & Maredia 2012).

The terms of trade in Africa, soybeans are the most favourable of all the major crops, with export values more than double that of imports (\$US 57M *cf* \$US 25M, 2013) (FAOSTAT). This contrasts starkly with wheat and rice, with trade deficits of \$US 5.4 and \$US 7 billion respectively. While export is constrained by high transport costs and international subsidies, domestic soybean production offers significant value through regional trade and by reducing dependence on imports (Keyser 2007). South Africa and Nigeria currently dominate soybean production in Africa, comprising 70% of the total in 2014 (Akibode & Maredia 2012). Demand for soybean cake for animal feed is increasing rapidly, as a consequence of growth in middle class population in South Africa (Bureau for Food and Agricultural Policy 2017). In South

Africa alone, current production is only 30% of crushing capacity to about *ca* 2 million metric ton (MMT), with total demand at 3.5 MMT. Recent rapid growth in Malawi and Zambia illustrate the geographic expansion and diversification of farming systems since the turn of the century (2003-2014) (Akibode & Maredia 2012). The implementation of soybean-maize crop rotations, supervised by multi-national projects such as Support to Agricultural Research for Development of Strategic Crops in Africa (SARD-SC) has improved on-farm productivity and sustainability. While opportunities still have to be realised in other African countries such as Tanzania (Wilson 2015), activities such as the Tanzania Soybean Development Strategy will lead to exponential increases in soybean production, from *ca* 6,000 tonnes in 2014 to 2 MMT by 2020 (FAOSTAT; Akibode & Maredia 2012).

Models as tools for predicting climate change impacts on agriculture

Crop models are used for an increasingly broad range of applications including climate change impact studies (Challinor et al. 2018; Jones et al. 2017). At present, a range of system models with differing degrees of model complexity have become available. These vary in emphasis with regard to different research questions, crops and regions (Ewert et al., 2015). Observed and projected climate data are key inputs for these models. Land suitability models compare the crop requirements against local climatic conditions/characteristics (e.g. temperature, precipitation, solar radiation), soil (texture, hydraulic properties, pH, organic carbon content, salinity, acidity or alkalinity) and topography (elevation, slope) scoring the area with a value between zero and unity. A value 1.0 is given if the area is perfectly suitable for producing the crop (Zabel et al. 2014). When projected climate data are fed into such models, they are capable of predicting the possible changes in harvest area (Fodor et al. 2017). Crop models are designed to calculate crop yield (and other important parameters of the plant-soil system) as a function of weather and soil conditions, or plant-specific characteristics, as well as the choice of agricultural management practices. Statistical crop models usually express the relationship between yield or yield components and weather parameters in a form of regression equations (e.g. Lobell and Burke 2010), which are calibrated by using corresponding observed yield and weather data varying in time or space or in both domains. Process-based crop models simulate the key processes of the soil-plant system, including crop development (phenology), biomass accumulation, yield, water and nutrient uptake, while taking into account the effects of environmental stresses as well as plant responses to elevated atmospheric carbon-dioxide concentrations (e.g. Müller et al. 2017). Fodor et al. (2017) reported that the vast majority of

soybean-related climate change impact studies using land suitability and/or crop models project positive changes for Sub-Saharan Africa.

Materials and Methods

The aim of the present study was to specifically evaluate the potential impacts of climate change on soybean production in Africa. We applied the methodology of Tai *et al.* (2014) and Tai & Val Martin (2017), which combined process-based modelling for climate and statistical modelling for crop-climate relationships, and compared simulated results with an array of other modelling studies. In a first analysis, we used annual (1961–2010) data from FAO to derive high-resolution (1.9°×2.5° latitude-longitude) time series of annual soybean yield (Y) using a data fusion technique (Monfreda *et al.* 2008), and extract meteorological data from the NCEP/NCAR Reanalysis 1 (Kalnay *et al.* 1996) to derive two important agro-climatic variables: growing degree day (GDD), which is the summation over the growing season of daily mean temperature above a minimum threshold (10°C) but below a maximum optimum (30°C), and represents the beneficial effect of warmth on yield; and killing degree day (KDD), which is the summation over the growing season of daily maximum temperature above the optimum (30°C). KDD represents the adverse effect of temperature extreme and the associated heat and water stress. We applied a constrained linear regression model (Tai *et al.* 2014; Tai & Val Martin 2017), to estimate the local sensitivities of Y to GDD and KDD (i.e., $\partial \ln Y / \partial \text{GDD}$ and $\partial \ln Y / \partial \text{KDD}$) across Africa where data were available. We then obtained climate projections from the Community Earth System Model (CESM) version 1.2, which is a global climate model that computes climate variables by dynamically simulating atmospheric, oceanic and terrestrial processes. Projections were for two future scenarios for year 2050 following two Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCPs): RCP8.5, representing a business-as-usual, pessimistic outlook for the future; and RCP4.5, which assumes an intermediate pathway with aggressive mitigation measures to reduce greenhouse gas emissions. We finally applied the statistical sensitivities $\partial \ln Y / \partial \text{GDD}$ and $\partial \ln Y / \partial \text{KDD}$ to the future changes in GDD and KDD as projected by CESM to estimate the changes in soybean yield from year 2000 to 2050 (Figure 4). In contrast to Tai *et al.* (2014), the projections reported here are not corrected for ozone damage, due the paucity of ozone data (that are required to derive crop-ozone relationships) that are available for Africa .

We also compared our statistical projections with those from other studies (Lobell *et al.* 2008; Deryng *et al.* 2014; Rosenzweig *et al.* 2014; Tai *et al.* 2014; Thomas & Rosegrant 2015), which considered a comprehensive array of different statistical and process-based crop models to account for not only rising temperatures in addition to other biophysical factors that co-vary with climate, such as higher ambient CO₂ levels and soil nitrogen limitations. The comparison is presented in Figure 5 and discussed in the next section.

Results

Climate change is unlikely to have negative impacts on future soybean production in Africa

The uncertainties of climate change, which increase the risks of extreme weather conditions, traditional cropping patterns and disease pressures not only present potential constraints but also opportunities for the successful expansion of soybean production across Africa (Lopez 2012; Siddique *et al.* 2012). The potential agronomic and economic gains from intensification of soybean production by smallholder farmers, therefore hinge on the resilience of new soybean cultivars and their stabilities of yield in the face of biotic and abiotic challenges.

Holistic crop simulation models provide important tools for the assessment of systems-level impacts of climate change on soybean cultivation in Africa. The representative concentration pathways (RCPs) are the four greenhouse gas (GHG) concentration trajectories (IPCC 2013), which are plausible depending on how much GHG is emitted in the future. Such projections suggest only marginal yield losses (-2%) for RCP8.5 with yield gains (11 and 13%) for RCP2.6 and RCP4.5, respectively (Bhattarai *et al.* 2017). In contrast, climate simulations indicate that a 10% decrease in rainfall and a 3°C increase in temperature will result in a median yield reduction of 9% and 35%, respectively, for groundnut in Bulawayo, Zimbabwe (Cooper *et al.* 2009). If climate change mitigation policies can secure a future CO₂ concentration pathway below RCP4.5, then any future potential climatic problems for soybean production in Africa and countries with similar climates will be resolved. Moreover, if appropriate measures are taken, the potential negative effect increased atmospheric CO₂ may have on micronutrients (Myers *et al.* 2014) may also be avoided.

Africa is one of the few continents where substantial arable land is available for crop production; and with mechanisation, the land area under cultivation could grow significantly. Globally,

land that is suitable for soybean production has shown a northward shift in recent years (Lant *et al.* 2016). The projected yield and sowing area gains suggest a large expansion in global soybean production, even though such shifts in production areas will depend largely upon GHG emissions and the success of mitigation strategies (Tai *et al.* 2014; Tai & Martin 2017). Major changes in policy, agricultural practice and diet indicate that there will be major changes in the land areas dedicated to soybean production (Fodor *et al.* 2017). While effective adaptation actions are required to mitigate the harmful impacts of climate change across Europe and other continents, Africa is at the other end of the spectrum. Climate change has the potential to allow a significant increase in soybean production in Africa, irrespective of which production scenario becomes reality in the future (Fodor *et al.* 2017). This finding should come as no surprise because soybean has already been called Africa's Cinderella crop (Kolapo 2011). Moreover, a meta-analysis of projected changes in the production areas depicts a promising future for soybean (Lant *et al.* 2016). Based on this knowledge, we undertook a systematic modelling analysis of future trends based on all the available data for soybean and other major legume crops in Africa. The analysis of all-source data showed similar trends to those predicted by available FAO data. For simplicity and accessibility, we have therefore presented the predictions based only on the FAO data.

The projected changes in soybean yield in Africa in response to 2000–2050 climate change predictions from the statistical model used in the present analysis are shown in Figure 4. Across the two scenarios (RCP4.5 and RCP8.5), the impacts of 2000–2050 climate change alone on soybean yield in Africa are mostly within $\pm 10\%$ in the major producer regions. These relative changes may, when superimposed on the socioeconomic projections (Figure.3), further enhance or partly offset the projected increases in soybean yield. This prediction based on the historical relationships between yield and agro-climatic variables (Figure 4) shows a good agreement with other statistical models (Figure 5), despite the limitations caused by a lack of extensive data. However, future crop–climate relationships may be subject to altered conditions of simultaneous increases in atmospheric CO₂ levels and nitrogen limitations, unless nodule nitrogen fixation can improve to meet the increasing demand (Jensen *et al.* 2012; Aranjuelo *et al.* 2014; Gray *et al.* 2016). Most process-based models that explicitly simulate carbon and nitrogen dynamics on crop growth would generally project a large increase in soybean yield with future elevated CO₂ levels, which offsets any possible negative impacts of climate change (Figure 5).

Discussion

Overall, the expected effects of climate change on agricultural production across Africa depend on the size of the ‘yield gap’ of the underlying production system (Anderson *et al.* 2016). Climate change is likely to have a larger negative effect on intensive farming systems where crops perform near their genetic potential. In such intensive cropping systems, the prevalence of abiotic and/or biotic stress conditions is substantial and accents the positive effects of adopting new and improved cultivars with sustainable yield traits that are able to compensate for any yield-reduction effects of climate change. Expanding the adoption and dissemination of high-yielding soybean cultivars that are adapted to the agro-climatic conditions across Africa, and that address existing crop yield constraints while meeting market demands, should be the focus of intensive research. Ongoing genetic improvements in plant physiology, sustainability of yields and biotic and abiotic stress tolerance are therefore essential to increase the resilience of soybeans to changing environmental conditions (Bishop *et al.* 2015).

Inadequate early season rainfall and day length requirements for flowering may limit expansion of existing soybean varieties in Africa. However, varieties with increased tolerance for early-season water deficits provide opportunities to increase yield sustainability in marginal regions by >10% (Maxwell 1996). Genetic variation in flowering time, as for example exists in the germplasm resources of the USA, offers opportunities to extend the latitude range. Moreover, a vast amount of precise information on soybean responses to high CO₂ in the absence or presence of other stresses has been gained from Free Air Carbon Dioxide Enrichment (FACE) studies in the USA. Compelling evidence shows that drought stress will constrain CO₂ fertilisation effects in forecast climate scenarios (Bishop *et al.* 2015). However once again, considerable genetic variation exists in drought tolerance, providing opportunities to sustain or improve yields under conditions of limited water availability (Valliyodan *et al.* 2016). Extensive germplasm stocks and genetic tools are now available for soybean, with climate resilience featuring highly (Sinclair *et al.* 2014; Valliyodan *et al.* 2016; Li *et al.* 2017). More recent developments, such as the passing of Uganda’s National Biosafety Act provide further pathways to exploit genetic variation (Bendana 2017). Such technological advances and political decisions will drive further growth in the soybean revolution (Alexandratos & Bruinsma 2012; Vadez *et al.* 2012).

Recent advances in genome editing technologies offer the potential to accelerate the breeding of current legume crops for diverse African environments. Genome editing-based breeding is faster than conventional or transgenic breeding and is not limited by available natural variation

(Alexandratos & Bruinsma 2012; Vadez *et al.* 2012; Jacobs *et al.* 2015; Li *et al.* 2015; Schaeffer & Nakata 2015; Valliyodan *et al.* 2016; Bendana 2017; Li *et al.* 2017; Scheben & Edwards 2017). Zinc-finger nuclease-based editing has been successfully applied in legumes (Curtin *et al.* 2011). The CRISPR/Cas9 system is tending to dominate current thinking regarding future genetic engineering approaches to crop improvement, and benefits from relatively low costs and high specificity (Jacobs *et al.* 2015; Li *et al.* 2015; Schaeffer & Nakata 2015; Scheben & Edwards 2017). Finally, strains of rhizobia that fix N₂ at high rates are not always competitive for colonisation and nodulation (Remigi *et al.* 2016). They can be out-competed for nodule occupation by resident strains that have poor rates of N₂-fixation. It therefore will be crucial to isolate and characterise highly effective strains that are also competitive for nodulation (Munoz *et al.* 2016). For example, *Sinorhizobium* is widespread in Chinese soil, but has low N-fixing efficiency with US soybeans, which are typically inoculated with more effective *Bradyrhizobium* strains (Thoenes 2016). However, these bacteria can have equal N-fixation ability when partnered with certain Chinese soybean varieties and some soybean genotypes are able to differentially restrict nodulation by specific serogroups of *Bradyrhizobium* or *Sinorhizobium* strains. Identification of genes that either exclude or substantially reduce nodulation by ineffective indigenous strains will be invaluable in improving the efficiency of symbiotic nitrogen fixation in African soils (Andrews & Andrews 2017; Bourion *et al.* 2018).

The role of soybean in poverty alleviation

Soybean production is primed to expand rapidly to meet the rising demand for protein to feed animals and supply the increased meat demand across Africa. Local production could meet this demand either alone or in harmony with the production of other legumes such as cowpea and peanut that also produce protein that could supply the demand for animal feed. Much of Africa currently lacks the capital and equipment to mechanize the planting, weed control and harvesting of soybean. Such limitations could be adequately addressed through the mobilization of governmental programs with Non-Governmental Organizations (NGO) support. South Africa is spearheading the intensification of soybean production in Africa, built on government and industry advocacy in support of soybean–maize rotations.

A major economic driver of the intensive expansion of soybean production, however, is the increasing level of household incomes and middle-class consumer preferences for meat and dairy products. This growing demand for meat protein has led to rising imports of soybean

meal mainly from Argentina that over time, have accounted for up to 90% of domestic feed demand (Ncube. *et al.* 2016). While today roughly 90% of Africa's soybean production is based in South Africa, Nigeria, Zambia, Malawi, Benin and Zimbabwe, countries across Africa have experienced relatively high economic growth and urbanisation resulting in growing populations of middle-class consumers (Melo *et al.* 2015). The associated shifts in consumption preferences combined with the emergence of a biofuel sector in South Africa are poised to incentivise growth in soybean cropping areas and the adoption of soybean-maize rotations where possible (Thoenes 2016). Nonetheless, local farmer perceptions of soybean, as well as guidance in home garden vs. cash crop farming and the availability of mechanisation still need to be addressed in some regions to ensure more widespread adoption through relaying the benefits to local farmers (de Jager *et al.* 2017). In addition, whilst crop yield increases through the soil fertilisation benefits of incorporating soybean into rotations or intercrops may be substantial (Ojiem *et al.* 2014) this effect may not be seen until three to four seasons of intervention have passed (Naab *et al.* 2017).

Strong demand in domestic (e.g. South Africa, Nigeria) and international (e.g. China) markets have made soybean an increasingly attractive cash crop. However, much of Africa is still import-dependent, which under current favourable world market prices puts immense pressures on the soybean-feed, animal protein and processed foods prices. Soybean production and market policies pursued by leading producers and exporters (i.e. USA, Argentina, Brazil and the EU) weigh heavily on the growth opportunities of a domestic African soybean industry. Market price and sector-specific support policies incentivise increased production, thus lowering international soybean price. In addition, greater funding opportunities for research and breeding programs, and non-specific income support programs give soybean producers in major producer countries a significant competitive advantage over their current and future African competitors (Thoenes 2016).

The development of economically sustainable soybean supply chains, especially outside of South Africa, will be no small feat (Monfreda *et al.* 2008). Nevertheless, producing enough soybean-based feed and food in the region can create significant value-added products that will potentially save billions in foreign currency spent on feed imports. In 2013, Africa's imports of soybean, -oil, and -cake equalled US\$ 5.55 billion (FAOSTAT). For soybeans to generate the economic returns necessary to allow small- and medium-scale producers to benefit economically, possibly from future exports of soybean to Europe or Japan (Ncube *et al.* 2016),

large-scale investments ranging from infrastructure to processing and marketing and sound regulatory systems are needed, especially outside South Africa. Favourable governance and government policies are typically a scarce resource in Africa, and therefore productivity research and advanced genetics alone are likely not sufficient to drive African soybean industry's growth moving forward.

Without market-oriented policy changes across Africa that focus on generating private investment in marketing and transportation infrastructure, the privatisation of state-owned grain elevators, port facilities and railroads and the elimination of damaging agricultural policies (e.g. export taxes, import restrictions) are needed to allow investment to take place for a African soybean industry to emerge. Last but not least, the economic success of soybean across Africa relies heavily on establishing regional trade relationships between a large number of producers and regional hubs of food and feed processing that may only build around major consumer and livestock markets. Such alliances are still rare across Africa, where the aforementioned lack of market liberalisation has hindered the development of regional agricultural trade and supply chains (Ncube *et al.* 2016). This may especially have a negative impact on South African soybean production, which is closest to becoming a new hub for soybean production and processing in the African continent.

Sustainable agriculture and food security are largely inseparable from key social science issues concerning inequalities, organisation of knowledge systems, and scientific collaboration. Changes in food production systems must be driven or designed in collaboration with farmers, local agricultural policymakers, and organizations that distribute the crops in question (Tadele 2017). In the case of African soybean production, the driver is essentially economic, based on the certain knowledge that soybean markets and futures are secure but also science-based because soybean is well suited to Africa and a vast amount of germplasm is available for breeding and selection of improved cultivars. For example, Brazil has appropriate maturity classes that could be used in the different African environments.

Conclusions and Perspectives

The accelerated incorporation of soybean as a major cash crop and animal-feed protein in African production systems will be cost-effective and address the dual challenges of malnutrition and climate change resilience. Africa has the potential to be a world leader in the

production of soybean as well as other key grain legumes. The genetic yield potential of soybean in Africa has, yet, hardly been considered or exploited. There is a pressing need to develop superior soybean cultivars for Africa. Realising the full potential of soybean production in Sub-Saharan Africa will require a concerted global effort of researchers, farmers, policy makers and traders. Nevertheless, it is clear that soybean production is set to increase in Africa. Only the future will tell whether this occurs at the expense of other legumes. Moreover, the extent of success in terms of income generation depends on major adjustments in the market for example in terms of trade barriers and tariffs for imports such as soybean cake. However, limited and inconsistent regional production and producer price data currently complicate the reliability of predictions of the profitability of soybean supply-chain development. While countries such as Zambia, Zimbabwe and South Africa have the capital and mechanization to capitalise on these opportunities, we are optimistic that advances in soybean improvement, food chains and pipelines will percolate outwards to encompass the small-scale producers in Central and West Africa.

Soybean production is expected to dominate in the future in Africa due to its cash-crop value from oil extraction and as animal feed. Governmental and agro-industries can help provide the required economic opportunities through improved soybean-based supply chains involving consumers and producers. With intensive support from non-governmental agencies and research organisations, the typical African farmer's production efficiency can also be improved to address the current situation of lower than average yields and higher than average production costs. This problem of the current 'yield gap' attributable to the production inefficiency in farming is not insurmountable, particularly if basic and social scientists can come together to jointly better identify and eliminate current bottlenecks to the potential for production improvements, especially from an African smallholder farmer's perspective.

We do not underestimate the challenges faced by resource-poor soybean producers, who are inclined to adopt risk-minimizing technologies due to the inherent high variability of returns from new cropping varieties. The risks of adoption of new varieties will be minimised if intensive efforts are made to select improved soybean varieties, together with the best rhizobial strains, that are suited to African climates and soils. Equally, the characteristically low adoption of technologies by farmers in Sub-Saharan Africa can be influenced by the demonstration of successful soybean production across the continent.

Poverty, hunger and malnutrition are chronic problems in Africa, where agriculture employs most of the workforce and accounts for much of the Gross Domestic Product. Grain legumes already play a key role in the improvement of livelihoods of the rural poor and urban consumers in Africa. While a wide variety of different grain legumes will continue to be grown in Africa over the coming decades, the trend for enhanced soybean production as an economically viable and environmentally sustainable option for income generation can no longer be ignored. Soybean is already one of the five major crops that ensure global food security. In addition to the high value of soybeans as a cash crop, the beans are rich in high-quality protein, as well as fibre, minerals and metabolites that are ideal for human and animal health. These attributes alone are providing a significant driver for African producers to overcome challenges that might impede or limit soybean production in Africa. Such challenges should therefore be addressed by effective application of science, engineering and crop management, policy and social interventions, together with the development of a high value food chain from production to consumption.

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Legends to Figures

Figure 1. Wasting and stunting prevalence in children under age 5 in Sub-Saharan regions (UNICEF/WHO/World Bank Group 2017). The data were obtained from the FAO database (FAOSTAT). The definition of different regions is according to FAO; Eastern Africa: Burundi, Comoros, Djibouti, Eritrea, Ethiopia, (Ethiopia PDR), Kenya, (Madagascar), Malawi, Mauritius, (Mayotte), Mozambique, (Réunion), Rwanda, Seychelles, Somalia, South Sudan, Uganda, United Republic of Tanzania, Zambia, Zimbabwe; Middle Africa: Angola, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Sao Tome and Principe; Southern Africa: Botswana, Lesotho, Namibia, South Africa, Swaziland; Western Africa: Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, (Saint Helena Ascension and Tristan da Cunha), Senegal, Sierra Leone, Togo. Countries with missing or incomplete data were bracketed. Details are shown in Supplementary Table S1.

Figure 2. Area harvested, production and yield of five major legumes in Sub-Saharan regions. The area harvested and production (2005–2014) of dry bean, chickpea, cowpea, pigeon pea and soybean are shown for Sub-Saharan regions, using FAO data (FAOSTAT). The definition of different regions is according to FAO (see legends in Figure 1). Details are shown in Supplementary Table S2.

Figure 3. FAO soybean data on crop production by country, harvested area by country and crop yield in 2000 and projections for 2050 for Sub-Saharan Africa. (a) Present-day (year 2000) and (b) projected (year 2050) soybean production, harvested area and yield for Africa. Present-day production and harvested area data are from FAO data (FAOSTAT), and the yield data in 0.1×0.1 resolution were obtained using a data fusion technique (Monfreda *et al.* 2008) scaled to be consistent with country-by-country FAO yield data (FAOSTAT). Year 2050 projections were derived by FAO (Alexandratos & Bruinsma 2012), and are driven by population and socioeconomic trends constrained by land availability, yield growth potential and ceiling, and water availability and irrigation potential under present-day prevailing climatic conditions. Column (c) shows the growth factors, which are the values in column (b), divided by those in column (a). Blank colour denotes a lack of data or projections for soybean. Note that the direct

biophysical effects of climate change are unaccounted for in these projections (Detailed data are shown in Supplementary Table S3).

Figure 4. Projected impacts of 2000–2050 climate change on soybean yields for Sub-Saharan Africa. The projections are based on the statistical model of Tai *et al.* (2014) and Tai & Val Martin (2017), driven by climate projections from a global climate model for two future scenarios following the Representative Concentration Pathways (RCP4.5 and RCP8.5).

Figure 5.

Climate-change impacts on grain legume yield for Sub-Saharan Africa under various scenarios from different studies. Except for L08 Sahel (red rectangle = cowpea), L08 Eastern Africa (red circle = cowpea) and L08 Eastern Africa (red triangle = common bean), all other marks denote soybean yield changes. Values are either mean or median projections. Green and yellow marks denote projections from process-based (mechanistic) models with and without consideration of the CO₂ fertilization effect, respectively; and red marks denote projections from empirical (statistical) models, none of which considers CO₂ fertilization. The differences even for the same colors can be attributed to different climate scenarios, different model treatments of nitrogen fertilization and irrigation, as well as geographical variations in baseline production, climate and soil quality. R14 stands for Rosenzweig *et al.* (2014), D14 stands for Deryng *et al.* (2014), T15 stands for Thomas & Rosegrant (2015), L08 stands for Lobell *et al.* (2008), and T14 stands for Tai *et al.* (2014), which presented statistical projections consistent with this study.

Table 1. Traditionally grown legumes in Africa:

Common bean (dry bean: *Phaseolus vulgaris* L.)

- Provides dietary protein for >200 million people in Africa (Buruchara *et al.* 2011).
- It is the most widely produced grain legume in Sub-Saharan Africa (6 million metric tonnes, 2014; Supplementary Table S2).
- Production is steadily transforming from a traditional subsistence to market-oriented grain legume crop, with major impacts on household incomes, food and nutritional security, and national economies.
- The Pan-Africa Bean Research Alliance (PABRA), which is a consortium of 30 bean-producing countries in Africa involving more than 350 partner public and private organisations that are coordinated by the International Centre for Tropical Agriculture (CIAT), has accelerated the transition of bean from a subsistence crop to a modern commodity in Africa (Buruchara *et al.* 2011; Pan-Africa Bean Research Alliance 2017).
- The PABRA model led to the release of more than 200 bean varieties from 2003–2010 (Buruchara *et al.* 2011).

Pigeon pea (*Cajanus cajan* L.)

- Mainly produced in Kenya, Malawi, Mozambique, Tanzania and Uganda (Supplementary Table S2), the current area and production is 1.14 million ha and 1.47 MMT (million metric tonnes) respectively.
- Since 2001, area and production have increased by 96% and 175%, respectively, contributing to 21% of global production (FAOSTAT).
- About 6 million smallholder subsistence farmers in Eastern and Southern African (ESA) countries cultivate pigeon pea, exporting 0.29 MMT of grain/year, worth US\$203 million (FAOSTAT).
- ESA is a secondary centre of genetic diversity with about 1500 unique germplasm accessions.
- To date, 34 improved varieties of pigeon pea were released for cultivation in ESA due to an active collaboration between ICRISAT and ESA countries.

Cowpea (*Vigna unguiculata* (L.) Walp.)

- Widely produced across Africa, contributing *ca* 94% of global production (2014)

(FAOSTAT).

- About 70% cowpea production is concentrated in Nigeria and Niger (FAOSTAT).
- Cowpea production in Africa more than doubled between 1993 and 2014 to 5.2 MMT.

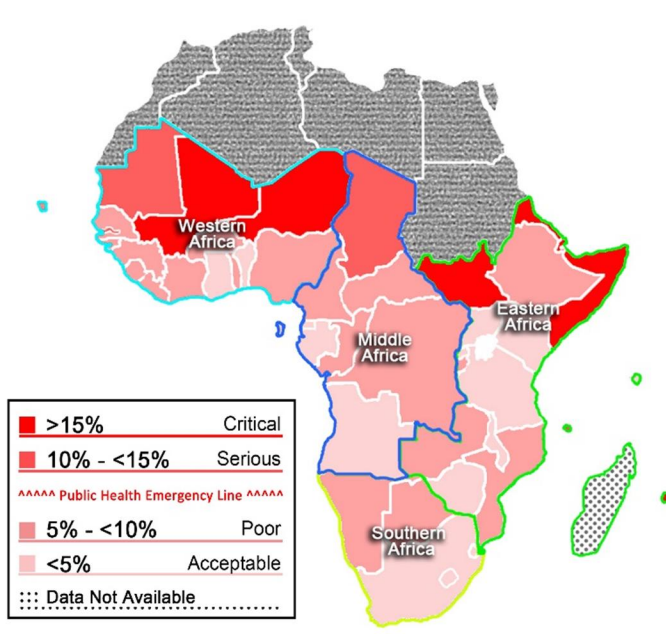
Supplementary Tables (not included at this stage)

Supplementary Table S1. Wasting and stunting prevalence in children under age 5 in Sub-Saharan regions.

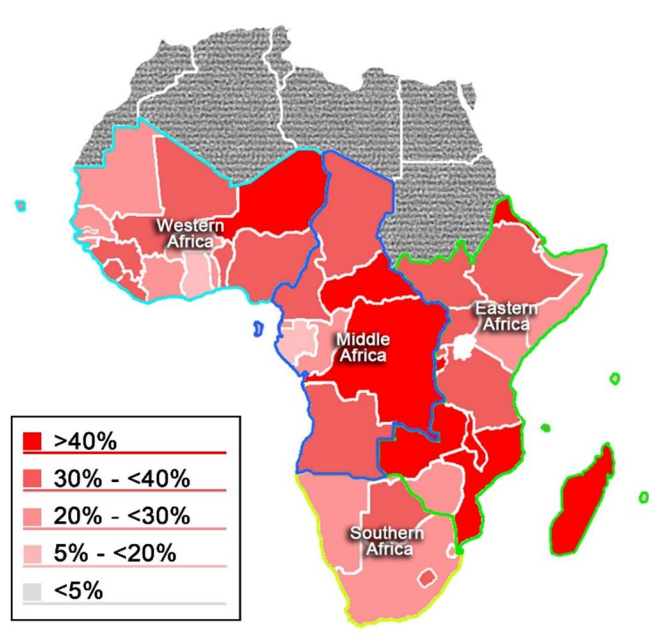
Supplementary Table S2. Market price of the five top legumes in countries of Sub-Saharan Africa.

Supplementary Table S3: FAO data of area harvested and production of five major legumes in Sub-Saharan regions (2005-2014).

Wasting prevalence in children under age of 5 in Sub-Saharan Africa



Stunting prevalence in children under age of 5 in Sub-Saharan Africa

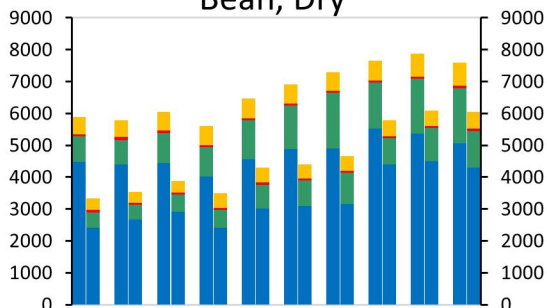


	Eastern Africa	Southern Africa	Western Africa	Middle Africa
Average wasting prevalence in children under age of 5 (%)	9.18	4.76	8.95	6.37
Average stunting prevalence in children under age of 5 (%)	34.69	27.42	29.71	30.51
Population under 5 ('000s)	61,878	6,369	58,272	26,156
Survey Years	1995-2016	1994-2014	2006-2016	2010-2016

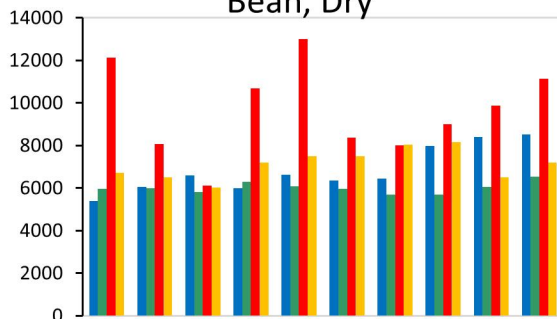
* Wasting prevalence, stunting prevalence and population data were not available in Ethiopia PDR, Mayotte, Réunion and Saint Helena Ascension and Tristan da Cunha. Wasting prevalence data was not available in Madagascar.

E Africa M Africa S Africa W Africa

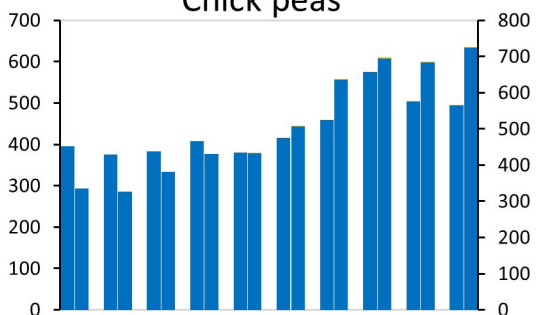
Bean, Dry



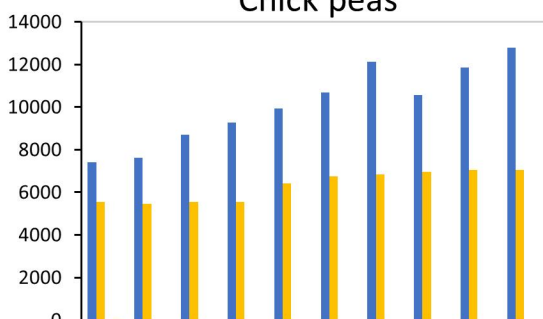
Bean, Dry



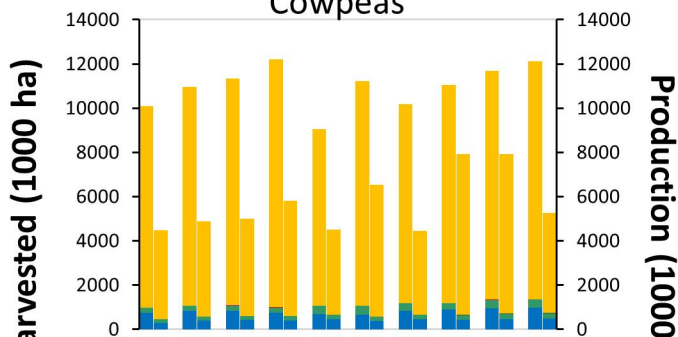
Chick peas



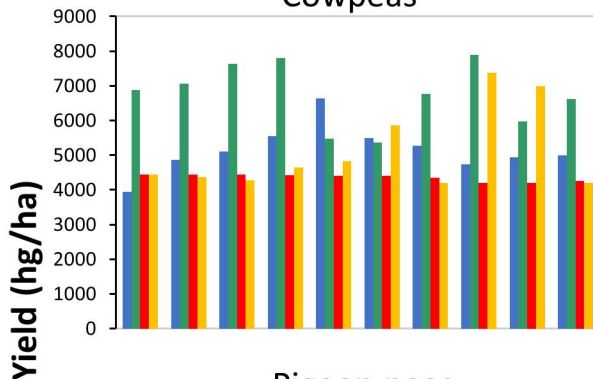
Chick peas



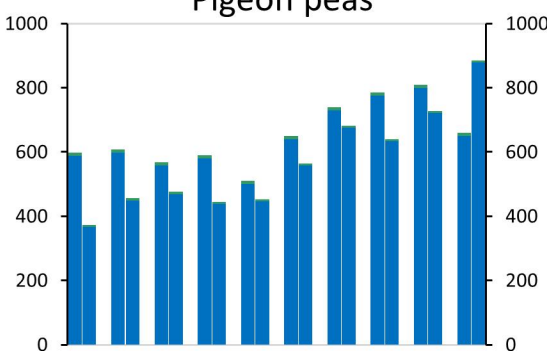
Cowpeas



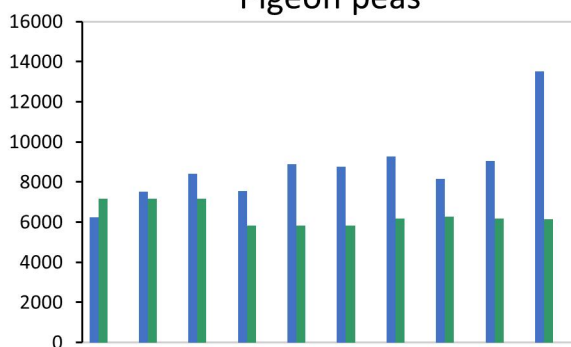
Cowpeas



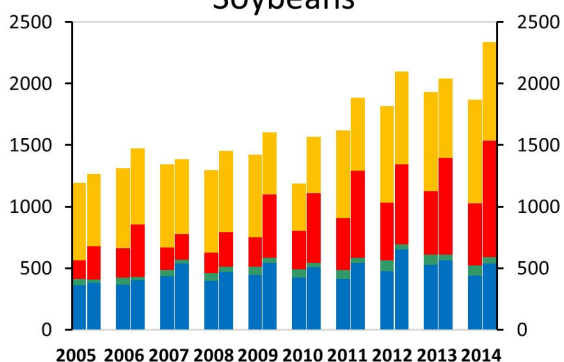
Pigeon peas



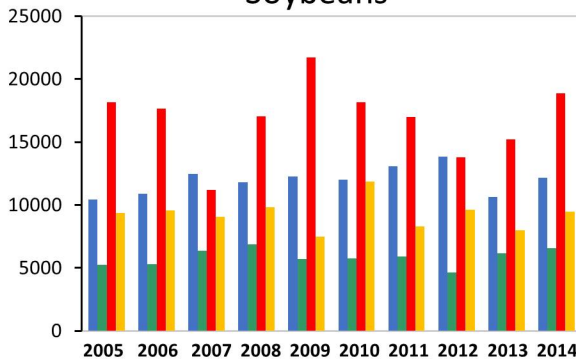
Pigeon peas



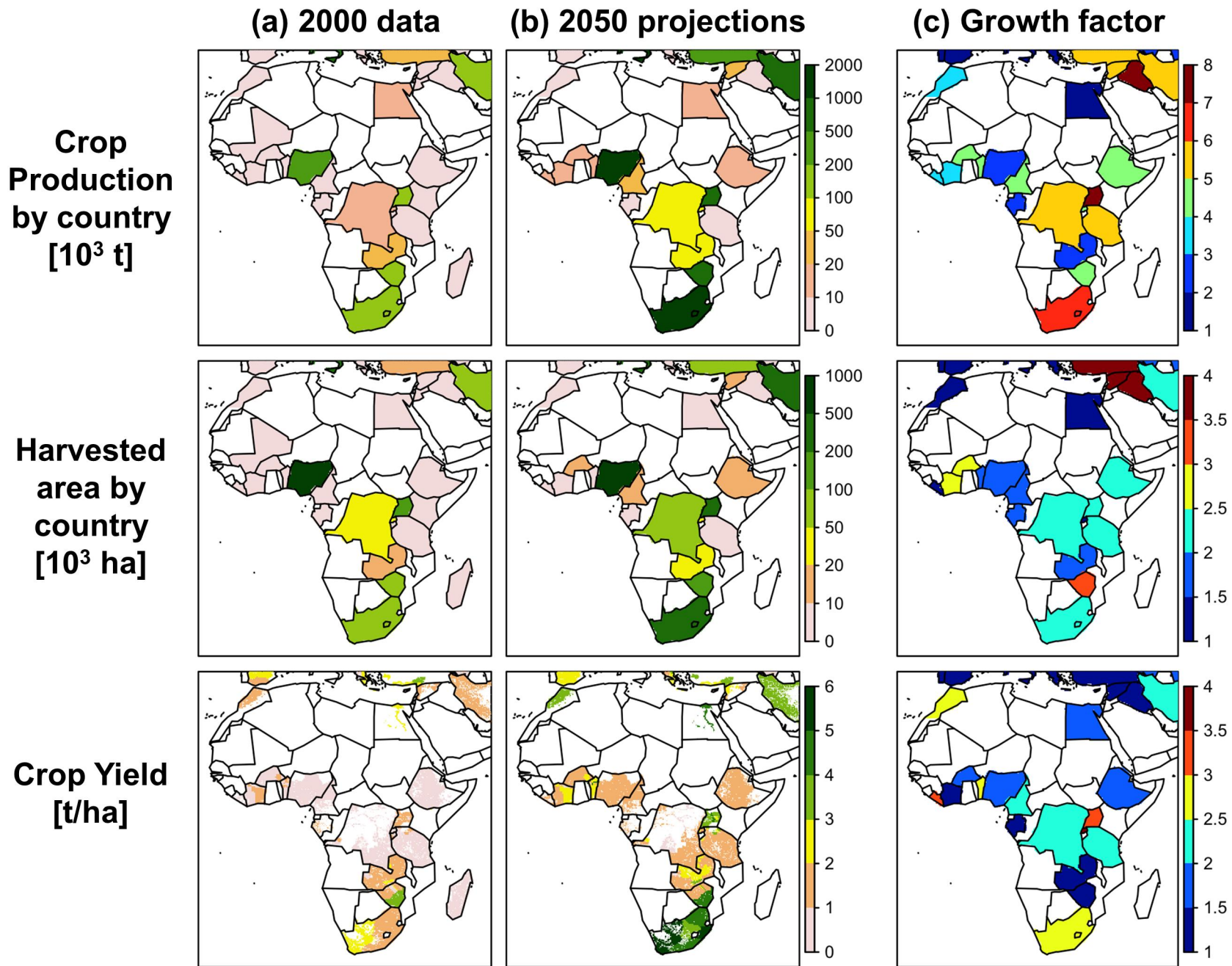
Soybeans



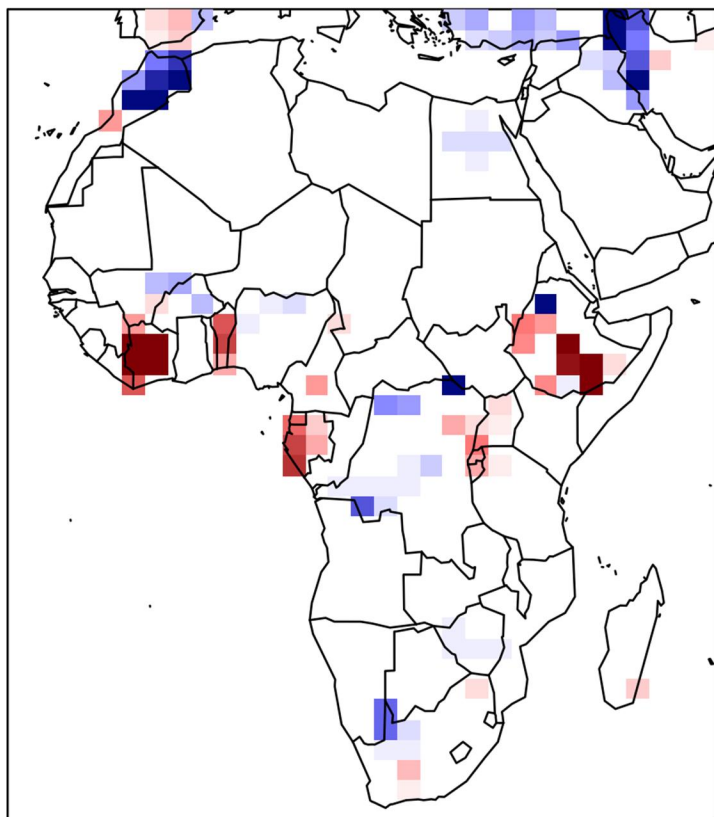
Soybeans



FAO soybean data (2000) and projections (2050) for Sub-Saharan Africa



RCP4.5 scenario



RCP8.5 scenario

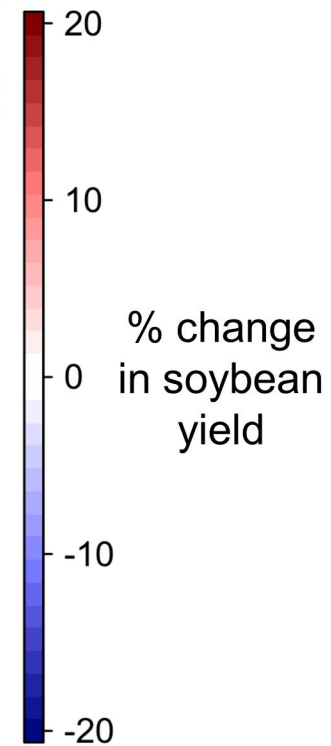
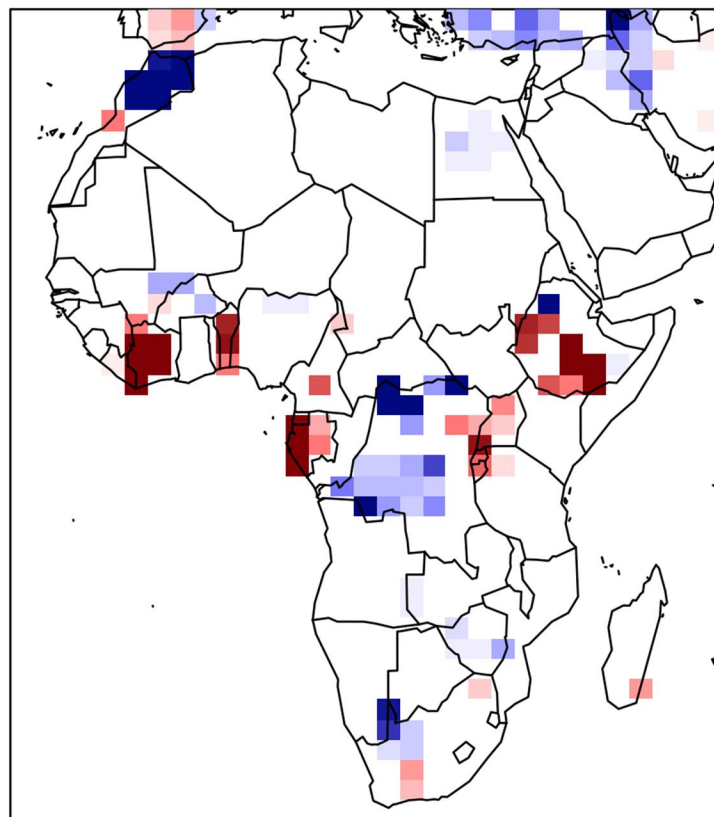


Figure 5.

