UNIVERSITY OF LEEDS

This is a repository copy of *Modelling predicts that soybean is poised to dominate crop production across Africa*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/138279/

Version: Accepted Version

Article:

Foyer, CH orcid.org/0000-0001-5989-6989, Siddique, KHM, Tai, APK et al. (12 more authors) (2018) Modelling predicts that soybean is poised to dominate crop production across Africa. Plant, Cell and Environment, 42 (1). pp. 373-385. ISSN 0140-7791

https://doi.org/10.1111/pce.13466

This article is protected by copyright. All rights reserved. This is the peer reviewed version of the following article: Foyer CH, Siddique KHM, Tai APK, et al. Modelling predicts that soybean is poised to dominate crop production across Africa. Plant Cell Environ. 2018, which will be published in final form at https://doi.org/doi.org/10.1111/pce.13466. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Self-Archiving. Uploaded in accordance with the publisher's self-archiving policy.

Reuse
Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

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

Christine H. Foyer[1,2], Kadambot H. M. Siddique[3.] Amos P. K. Tai[4,5], Sven Anders[6], Nandor Fodor[1,7], Fuk-Ling Wong[5,8], Ndiko Ludidi[9], Mark A. Chapman[10], Brett J. Fergusson[11], Michael J. Considine[1,2,3,12], Florian Zabel[13], P.V. Vara Prasad[14], Rajeev K. Varshney[15], Henry T. Nguyen[16] and Hon-Ming Lam[5,8]

[1]Centre for Plant Sciences, Faculty of Biological Sciences, University of Leeds, Leeds, LS2 9JT, UK; [2]School of Molecular Science, The University of Western Australia, Perth, Western Australia 6009, Australia; [3]The UWA Institute of Agriculture and School of Agriculture and Environment, The University of Western Australia, Perth, Western Australia 6009, Australia; [4]Earth System Science Programme, The Chinese University of Hong Kong, Shatin, Hong Kong Special Administrative Region; [5]Center for Soybean Research of the State Key Laboratory of Agrobiotechnology, The Chinese University of Hong Kong, Shatin, Hong Kong Special Administrative Region; [6]Department of Resource Economics and Environmental Sociology, University of Alberta, Edmonton, AB T6G 2H1, Canada; [7]Agricultural Institute, Centre for Agricultural Research, Hungarian Academy of Sciences, 2462 Martonvásár Brunszvik u. 2. Hungary; [8]School of Life Sciences, The Chinese University of Hong Kong, Shatin, Hong Kong Special Administrative Region; [9]Department of Biotechnology and the DST/NRF Centre of Excellence in Food Security, University of the Western Cape, Private Bag X17, Bellville, 7535, South Africa; [10]Biological Sciences, University of Southampton, Life Sciences Building 85, Highfield Campus, Southampton, SO17 1BJ, UK; [11]Centre for Integrative Legume Research, School of Agriculture & Food Sciences, The University of Queensland, Brisbane, QLD 4072 Australia; [12]The Department of Primary Industries and Regional Development, South Perth, Western Australia 6151, Australia; [13]Ludwig-Maximilians-Universität München, Luisenstrasse 37, 80333 Munich, Germany; [14]Department of Agronomy, College of Agriculture, 108 Waters Hall, 1603 Old Claflin Place, Kansas State University, Manhattan, Kansas 66506, US; [15]Center of Excellence in Genomics & Systems Biology, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Greater Hyderabad, India; [16]Division of Plant Sciences and National Center for Soybean Biotechnology, University of Missouri, Columbia, Missouri 65211, USA.

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., $\partial \ln Y/\partial GDD$ and $\partial \ln Y/\partial KDD$) 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 $\partial \ln Y/\partial GDD$ and $\partial \ln Y/\partial KDD$ 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 CO_2 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 CO_2 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 CO_2 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 ± 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 N_2 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 N_2-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 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.

Acknowledgements

The authors thank the Worldwide University Network (WUN) for financial support.CF and NF thank BBSRC for financial support (BB/N004914/1). The work of CF and NF was undertaken within the auspices of Modelling European Agriculture with Climate Change for Food Security (MACSUR), a FACCE JPI knowledge hub**.** The work of HML was supported by Hong Kong RGC Area of Excellence Scheme (AoE/M-403/16), CUHK VC Discretionary Fund VCF2014004 and the Lo Kwee-Seong Biomedical Research Fund. APKT thanks the General Research Fund (Project ID: 14323116) from Research Grants Council of Hong Kong and the Vice-Chancellor Discretionary Fund (Project ID: VCF2015006) from CUHK given to Institute of Environment, Energy and Sustainability. BF thanks the Hermon Slade Foundation and ARC (DP130103084 and DP130102266) for financial support. MJC acknowledges an ARC project (DP150103211). We thank Miss Cherry Lee (The Chinese University of Hong Kong) for helping to polish the figures and tables. We thank FAO for providing unpublished projection data for making Fig. 3.

References

Akibode S. & Maredia M. (2012) Global and Regional Trends in Production, Trade and Consumption of Food Legume Crops. In: Department of Agricultural, Food, and Resource Economics Staff Paper Series #2012-10, p. 89. Michigan State University.

Alexandratos N. & Bruinsma J. (2012) World agriculture towards 2030/2050: the 2012 revision. In: ESA Working Paper No. 12-03. FAO, Rome.

Anderson W., Johansen C. & Siddique K.H.M. (2016) Addressing the yield gap in rainfed crops: a review. Agronomy for Sustainable Development 36, 18.

Andrews M. & Andrews M.E. (2017) Specificity in legume-rhizobia symbioses. International Journal of Molecular Sciences 18, 705.

Aranjuelo I., Arrese-Igor C. & Molero G. (2014) Nodule performance within a changing environmental context. Journal of Plant Physiology 171, 1076-1090.

Bendana C. (2017) Uganda removes key hurdle to GM crops. In: Sciencemag. http://www.sciencemag.org/news/2017/10/uganda-removes-key-hurdle-gm-crops

Bhattarai M.D., Secchi S. & Schoof J. (2017) Projecting corn and soybeans yields under climate change in a Corn Belt watershed. Agricultural Systems 152, 90-99.

Bill & Melinda Gates Foundation (2012) Legume Market Analysis: Macro Data & Trends. https://agriknowledge.org/files/3197xm08n.

Bishop K.A., Betzelberger A.M., Long S.P. & Ainsworth E.A. (2015) Is there potential to adapt soybean (Glycine max Merr.) to future [CO_2]? An analysis of the yield response of 18 genotypes in free-air CO_2 enrichment. Plant, Cell & Environment 38, 1765-1774.

Bourion V., Heulin-Gotty K., Aubert V., Tisseyre P., Chabert-Martinello M., Pervent M., …, Lepetit M. (2018) Co-inoculation of a pea core-collection with diverse rhizobial strains shows competitiveness for nodulation and efficiency of nitrogen fixation are distinct traits in the interaction. Frontiers in Plant Science 8, 2249.

Bureau for Food and Agricultural Policy (2017) http://www.bfap.co.za/.

Buruchara R., Chirwa R., Sperling L., Mukankusi C., Rubyogo J.C., Mutonhi R. & Abang M. M. (2011) Development and delivery of bean varieties in Africa: The Pan-Africa bean research alliance (PABRA) model. African Crop Science Journal 18, 227-245.

Challinor, A.J., Müller, C., Asseng, S., Deva, C., Nicklin, K.J., Wallach, D., Vanuytrecht, E., Whitfield, S., Ramirez-Villegas, J., Koehler, A.-K. 2018. Improving the use of crop models for risk assessment and climate change adaptation. Agric Syst. 59: 296–306.

Chivenge P., Mabhaudhi T., Modi A.T. & Mafongoya P. (2015) The potential role of neglected and underutilised crop species as future crops under water scarce conditions in Sub-Saharan Africa. International Journal of Environmental Research and Public Health 12, 5685-5711.

Cooper P., Rao K.P.C., Singh P., Dimes J., Traore P.C.S., Rao K., Dixit P. & Twomlow S.J. (2009) Farming with current and future climate risk: Advancing a 'Hypothesis of Hope' for rainfed agriculture in the semi-arid tropics. Journal of SAT Agricultural Research 7, 1-19.

Cullis C. & Kunert K.J. (2017) Unlocking the potential of orphan legumes. Journal of Experimental Botany 68, 1895-1903.

Curtin S.J., Zhang F., Sander J.D., Haun W.J., Starker C., Baltes N.J., …, Stupar R.M. (2011) Targeted mutagenesis of duplicated genes in soybean with zinc-finger nucleases. Plant Physiology 156, 466-473.

de Jager I., Abizari A.-R., Douma J.C., Giller K.E. & Brouwer I.D. (2017) Grain legume cultivation and children’s dietary diversity in smallholder farming households in rural Ghana and Kenya. Food Security 9, 1053-1071.

Deryng D., Conway D., Ramankutty N., Price J. & Warren R. (2014) Global crop yield response to extreme heat stress under multiple climate change futures. Environmental Research Letters 9, 034011.

Ewert, F., Rötter, R.P., Bindi, M., Webber, H., Trnka, M., Kersebaum, K.C., et al. (2015) Crop modelling for integrated assessment of risk to food production from climate change. Environ. Model. Software. 72: 287–303.

FAO (2012) Smallholders and Family Formers. In: Sustainability Pathways. http://www.fao.org/nr/sustainability/fact-sheets/en/

FAOSTAT (Accessed 20.11.2017) http://www.fao.org/faostat.

Ferguson B.J., Indrasumunar A., Hayashi S., Lin M.H., Lin Y.H., Reid D.E. & Gresshoff P.M. (2010) Molecular analysis of legume nodule development and autoregulation. Journal of Integrative Plant Biology 52, 61-76.

Fodor N., Challinor A., Droutsas I., Ramirez-Villegas J., Zabel F., Koehler A.K. & Foyer C.H. (2017) Integrating plant science and crop modeling: assessment of the impact of climate change on soybean and maize production. Plant and Cell Physiology 58, 1833-1847.

Foyer C.H., Lam H.M., Nguyen H.T., Siddique K.H.M., Varshney R.K., Colmer T.D., …, Considine M.J. (2016) Neglecting legumes has compromised human health and sustainable food production. Nature Plants 2,16112.

Gray S.B., Dermody O., Klein S.P., Locke A.M., McGrath J.M., Paul R.E., …, Leakey A.D.B. (2016) Intensifying drought eliminates the expected benefits of elevated carbon dioxide for soybean. Nature Plants 2, 16132.

Gresshoff P.M., Hayashi S., Biswas B., Mirzaei S., Indrasumunar A., Reid D., …, Ferguson B.J. (2015) The value of biodiversity in legume symbiotic nitrogen fixation and nodulation for biofuel and food production. Journal of Plant Physiology 172, 128-136.

IPCC (2013) Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds. by Stocker TF, Qin D, Plattner G-K, et al), pp. 1–30. Cambridge University Press, Cambridge, United Kingdom.

Jacobs T.B., LaFayette P.R., Schmitz R.J. & Parrott W.A. (2015) Targeted genome modifications in soybean with CRISPR/Cas9. BMC Biotechnology 15, 16.

Jensen E.S., Peoples M.B., Boddey R.M., Gresshoff P.M., Hauggaard-Nielsen H., Alves B.J.R. & Morrison M.J. (2012) Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. Agronomy for Sustainable Development 32, 329-364.

Jones, J. W., Antle, J. M., Basso, B., Boote, K. J., Conant, R. T., Foster, I., Godfray, H.C.J., Herrario, M., Howitt, R.E, Janssen, S., Keating, B.A., Munoz-Carpena, R., Porter, C.H.. Rosenzweigm C. & Wheeler, T. R. (2017). Brief history of agricultural systems modeling. Agr. Syst., 155, 240–254.

Kalnay E., Kanamitsu M., Kistler R., Collins W., Deaven D., Gandin L., …, Joseph D. (1996) The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society 77, 437-471.

Kerr R.B., Snapp S., Chirwa M., Shumba L. & Msachi R. (2007) Participatory research on legume diversification with Malawian smallholder farms for improved nutrition and soil fertility. Experimental Agriculture 43, 437-453.

Keyser J.C. (2007) Zambia Competitiveness Report. In: Competitive Commercial Agriculture in Africa (CCAA). The World Bank.

Kolapo A.L. (2011) Soybean: Africa's Potential Cinderella Food Crop. In: Soybean (ed. by Ng TB). IntechOpen.

Lobell, D.B. and Burke, M.B. (2010) On the use of statistical models to predict crop yield responses to climate change. Agri. Forest Meteorol. 150: 1443–1452.

Lant C., Stoebner T.J., Schoof J.T. & Crabb B. (2016) The effect of climate change on rural land cover patterns in the Central United States. Climatic Change 138, 585-602.

Li M.W., Xin D.W., Gao Y.S., Li K.P., Fan K.J., Munoz N.B., Yung W.S. & Lam H.M. (2017) Using genomic information to improve soybean adaptability to climate change. Journal of Experimental Botany 68, 1823-1834.

Li Z.S., Liu Z.B., Xing A.Q., Moon B.P., Koellhoffer J.P., Huang L.X., …, Cigan A.M. (2015) Cas9-Guide RNA Directed Genome Editing in Soybean. Plant Physiology 169, 960-970.

Lobell D.B., Burke M.B., Tebaldi C., Mastrandrea M.D., Falcon W.P. & Naylor R.L. (2008) Prioritizing climate change adaptation needs for food security in 2030. Science 319, 607-610.

Lopez K. (ed) (2012) A success tale on improving two legume crops in Africa. In: International Institute of Tropical Agriculture. http://r4dreview.iita.org/index.php/tag/soybean/.

Mauser W., Klepper G., Zabel F., Delzeit R., Hank T., Putzenlechner B. & Calzadilla A. (2015) Global biomass production potentials exceed expected future demand without the need for cropland expansion. Nature Communications 6, 8946.

Maxwell S. (1996) Food security: A post-modern perspective. Food Policy 21, 155-170.

Melo P.C., Abdul-Salam Y., Roberts D., Gibert A., Matthews R., Colen L., Mary S. & Paloma S.G.Y. (2015) Income Elasticities of Food Demand in Africa: A Meta-Analysis. https://ec.europa.eu/jrc/en/publication/income-elasticities-food-demand-africa-meta-analysis

Monfreda C., Ramankutty N. & Foley J.A. (2008) Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochemical Cycles 22, GB1022.

Müller, C., Elliott, J., Chryssanthacopoulos, J., Arneth, A., Balkovic, J., Ciais, P., et al. (2017) Global gridded crop model evaluation: benchmarking, skills, deficiencies and implications. Geosci. Model Dev. 10: 1403–1422.

Mueller N.D., Gerber J.S., Johnston M., Ray D.K., Ramankutty N. & Foley J.A. (2012) Closing yield gaps through nutrient and water management. Nature 490, 254-257.

Munoz N., Qi X., Li M.W., Xie M., Gao Y., Cheung M.Y., Wong F.L. & Lam H.M. (2016) Improvement in nitrogen fixation capacity could be part of the domestication process in soybean. Heredity 117, 84-93.

Myers S.S., Zanobetti A., Kloog I., Huybers P., Leakey A.D.B., Bloom A.J., …, Usui Y. (2014) Increasing CO_2 threatens human nutrition. Nature 510, 139-142.

Naab J.B., Mahama G.Y., Yahaya I. & Prasad P.V.V. (2017) Conservation agriculture improves soil quality, crop yield, and incomes of smallholder farmers in North Western Ghana. Frontiers in Plant Science 8, 996.

Ncube, P.S., Roberts, S. & Zengeni, T. (2016) Development of the animal feed to poultry value chain across Botswana, South Africa, and Zimbabwe. In: WIDER Working Paper. World Institute for Development Economic Research Helsinki: UNU-WIDER.

Ojiem J.O., Franke A.C., Vanlauwe B., de Ridder N. & Giller K.E. (2014) Benefits of legume–maize rotations: Assessing the impact of diversity on the productivity of smallholders in Western Kenya. Field Crops Research 168, 75-85.

Ortega D.L., Waldman K.B., Richardson R.B., Clay D.C. & Snapp S. (2016) Sustainable intensification and farmer preferences for crop system attributes: evidence from Malawi’s Central and Southern regions. World Development 87, 139 - 151.

Pan-Africa Bean Research Alliance. (2017) www.pabra-Africa.org.

Porwollik V., Muller C., Elliott J., Chryssanthacopoulos J., Iizumi T., Raye D.K., …, Wu X.C. (2017) Spatial and temporal uncertainty of crop yield aggregations. European Journal of Agronomy 88, 10-21.

Ray D.K., Mueller N.D., West P.C. & Foley J.A. (2013) Yield trends are insufficient to double global crop production by 2050. Plos One 8, e^{66}428.

Remigi P., Zhu J., Young J.P.W. & Masson-Boivin C. (2016) Symbiosis within symbiosis: evolving nitrogen-fixing legume symbionts. Trends in Microbiology 24, 63-75.

Rosenzweig C., Elliott J., Deryng D., Ruane A.C., Muller C., Arneth A., …, Jones J.W. (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proceedings of the National Academy of Sciences of the United States of America 111, 3268-3273.

Schaeffer S.M. & Nakata P.A. (2015) CRISPR/Cas9-mediated genome editing and gene replacement in plants: Transitioning from lab to field. Plant Science 240, 130-142.

Scheben A. & Edwards D. (2017) Genome editors take on crops. Science 355, 1122-1123.

Siddique K.H.M., Johansen C., Turner N.C., Jeuffroy M.H., Hashem A., Sakar D., Gan Y.T. & Alghamdi S.S. (2012) Innovations in agronomy for food legumes. A review. Agronomy for Sustainable Development 32, 45-64.

Sinclair T.R., Marrou H., Soltani A., Vadez V. & Chandolu K.C. (2014) Soybean production potential in Africa. Global Food Security-Agriculture Policy Economics and Environment 3, 31-40.

Tadele Z. (2017) Raising crop productivity in Africa through intensification. Agronomy 7, 22.

Tai A.P.K. & Val Martin M. (2017) Impacts of ozone air pollution and temperature extremes on crop yields: Spatial variability, adaptation and implications for future food security. Atmospheric Environment 169, 11-21.

Tai A.P.K., Val Martin M. & Heald C.L. (2014) Threat to future global food security from climate change and ozone air pollution. Nature Climate Change 4, 817-821.

Thoenes P. (2016) Soybean - International Commodity Profile. In: Background paper for the Competitive Commercial Agriculture in Sub–Saharan Africa (CCAA) Study. Food and Agriculture Organization of the United Nations.

Thomas T.S. & Rosegrant M.W. (2015) Climate change impact on key crops in Africa: Using crop models and general equilibrium models to bound the predictions. In: Climate change impact on key crops in Africa: Using crop models and general equilibrium models to bound the predictions (ed. by Aziz E), pp. 146-75. Food and Agricultural Organization of the United Nations (FAO), Rome, Italy.

Tilman D., Balzer C., Hill J. & Befort B.L. (2011) Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America 108, 20260-20264.

Tilman D. & Clark M. (2014) Global diets link environmental sustainability and human health. Nature 515, 518-522.

Timmer C.P. (1997) Farmers and markets: The political economy of new paradigms. American Journal of Agricultural Economics 79, 621-627.

Timmer C.P. (2004) Food security and economic growth: an Asian perspective. In: Heinz W. Arndt Memorial Lecture, Canberra, Australia.

UNICEF-WHO-The World Bank Group (2017) Joint Child Malnutrition Estimates-2017 edition (Accessed 26.10.2017) https://data.unicef.org/resources/joint-child-malnutrition-estimates-2017-edition/.

Vadez V., Berger J.D., Warkentin T., Asseng S., Ratnakumar P., Rao K.P.C., …, Zaman M.A. (2012) Adaptation of grain legumes to climate change: a review. Agronomy for Sustainable Development 32, 31-44.

Valliyodan B., Qiu D., Patil G., Zeng P., Huang J.Y., Dai L., …, Nguyen H.T. (2016) Landscape of genomic diversity and trait discovery in soybean. Scientific Reports 6, 23598.

Wilson R.T. (2015) The Soybean Value Chain in Tanzania: A report from the Southern Highlands Food Systems Programme. In: Sustainable Food Value Chains Knowledge

Platform. Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/sustainable-food-value-chains/library/details/en/c/285412/

Zabel, F., Putzenlechner, B. and Mauser, W. (2014) Global agricultural land resources—a high resolution suitability evaluation and its perspectives until

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 CO_2 fertilization effect, respectively; and red marks denote projections from empirical (statistical) models, none of which considers CO_2 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.

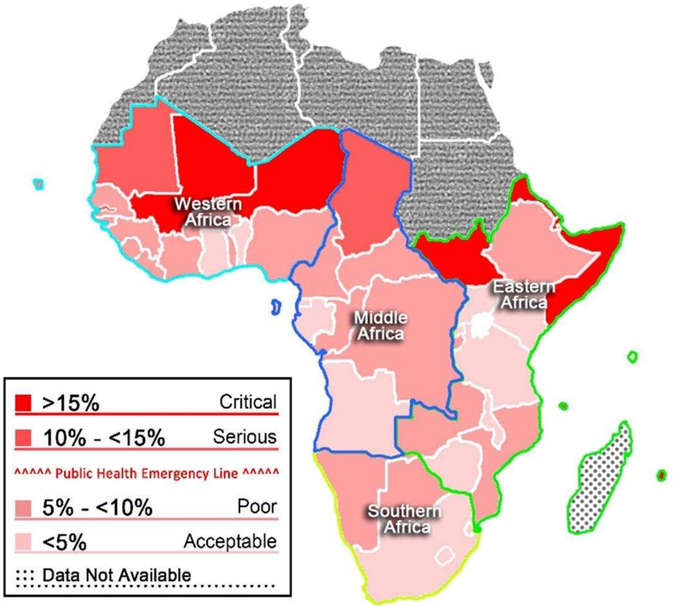
Supplementary Tables (not included at this stage)

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

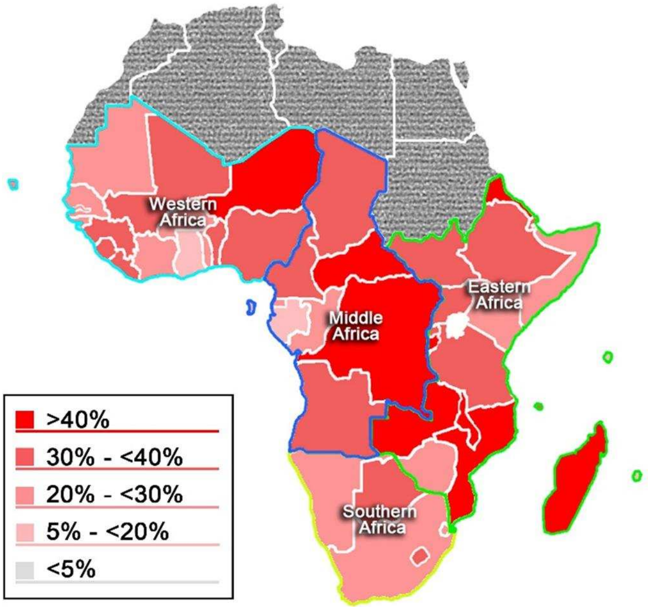
Supplementary Table S2. Market price of the five top legumes in countries of Sub-Saharan Africa.

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

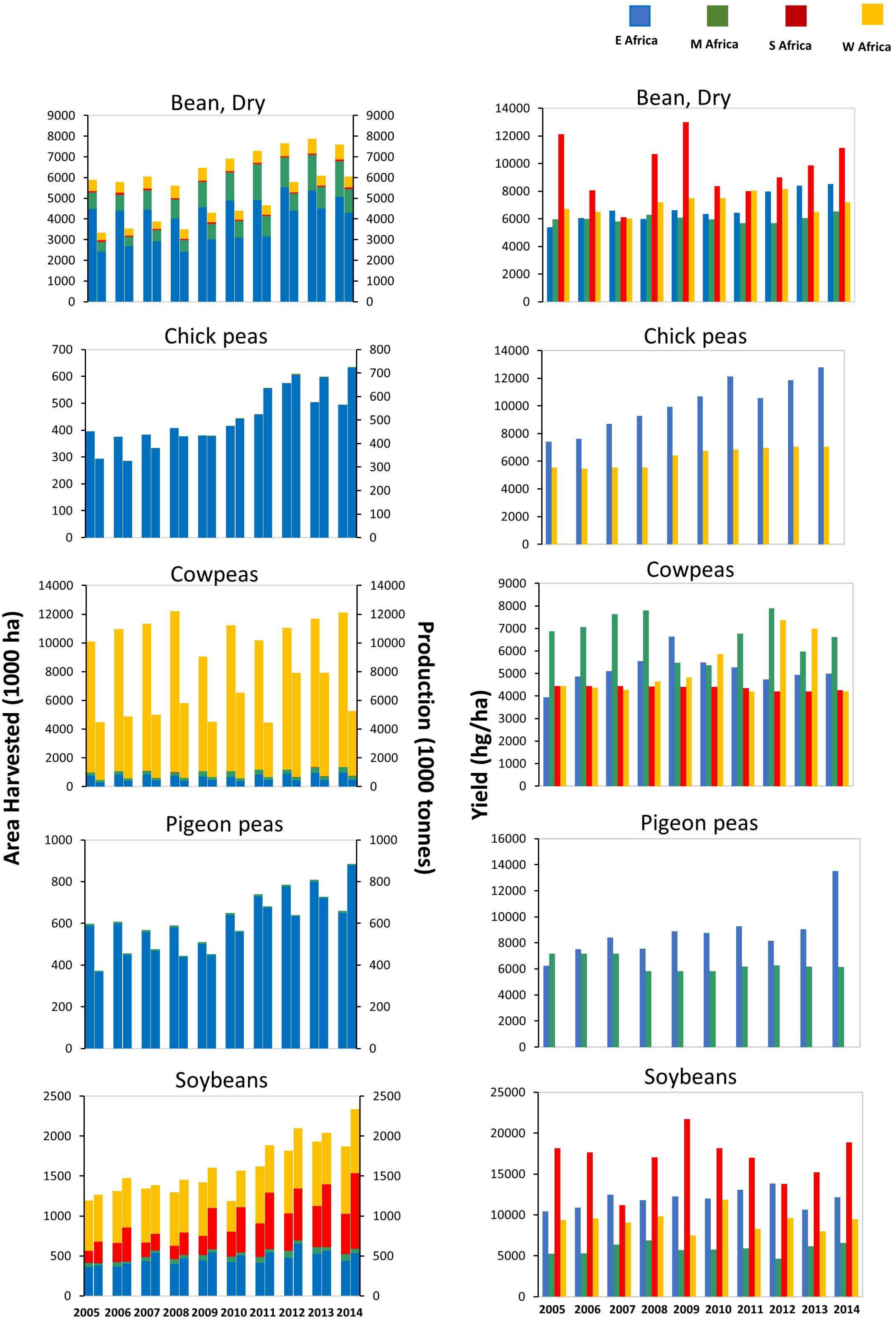


Stunting prevalence in children under age of 5 in Sub-Saharan Africa

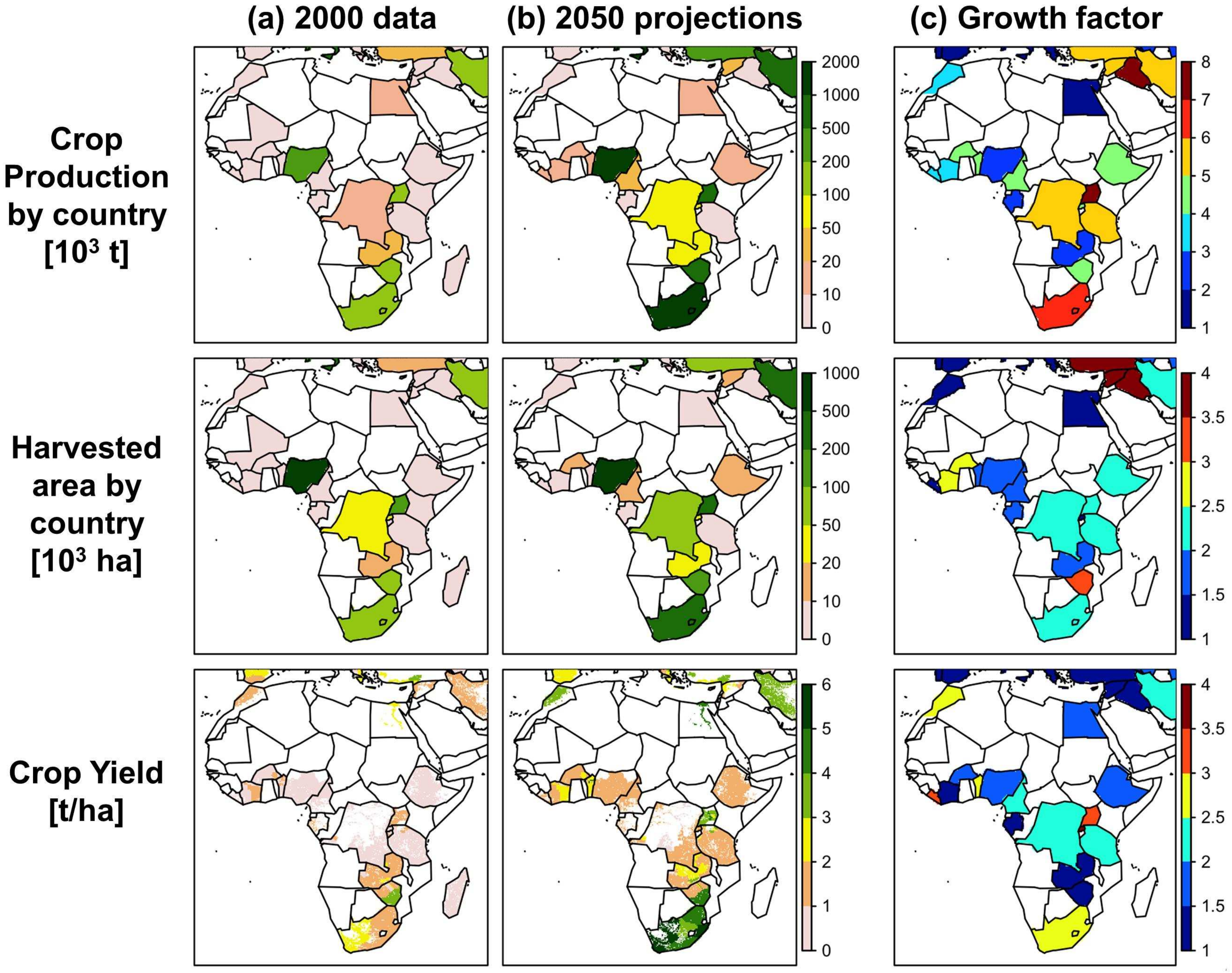


	Eastern Africa	Southern Africa	Western Africa	Middle Africa
Average wasting prevalence in children under age of 5 (%)	9.18	4.76	8.95	6.37
Average stunting prevalence in children under age of 5 (%)	**34.69**	**27.42**	**29.71**	**30.51**
Population under 5 (‘000s)	61,878	6,369	58,272	26,156
Survey Years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

* Wasting prevalence, stunting prevalence and population data were not available in Ethioppia 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
Chick peas
Cowpeas
Pigeon peas
Soybeans
Area Harvested (1000 ha)
Production (1000 tonnes)
Yield (hg/ha)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
100
200
300
400
500
600
700
800
10000
12000
14000
16000
20000
25000
15000
2500
1500
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014

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



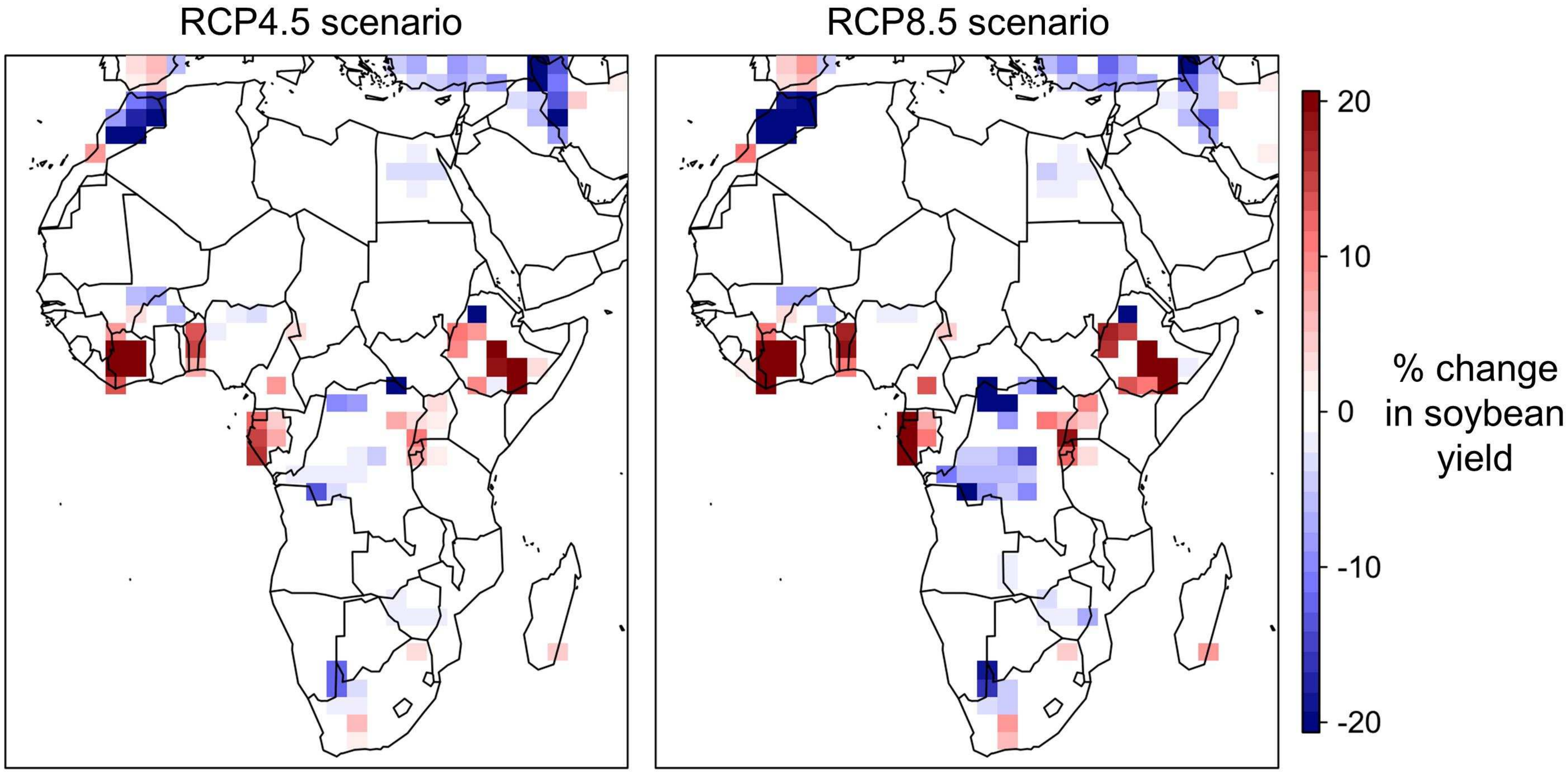
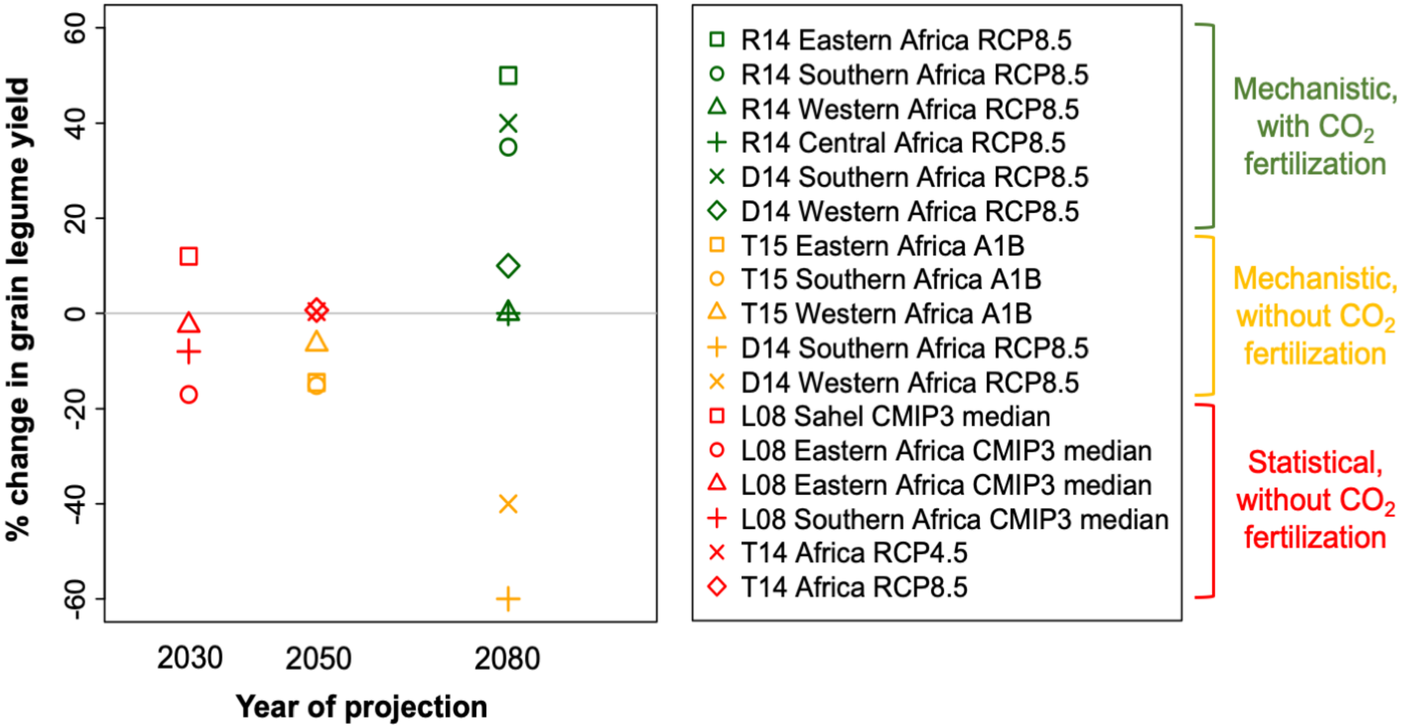

RCP4.5 scenario
RCP8.5 scenario
20
10
0
-10
-20
% change in soybean yield

Figure 5.



% change in grain legume yield
60
40
20
0
-20
-40
-60
2030
2050
2080
Year of projection
R14 Eastern Africa RCP8.5
R14 Southern Africa RCP8.5
R14 Western Africa RCP8.5
R14 Central Africa RCP8.5
D14 Southern Africa RCP8.5
D14 Western Africa RCP8.5
T15 Eastern Africa A1B
T15 Southern Africa A1B
T15 Western Africa A1B
D14 Southern Africa RCP8.5
D14 Western Africa RCP8.5
L08 Sahel CMIP3 median
L08 Eastern Africa CMIP3 median
L08 Eastern Africa CMIP3 median
L08 Southern Africa CMIP3 median
T14 Africa RCP4.5
T14 Africa RCP8.5
Mechanistic, with CO_2 fertilization
Mechanistic, without CO_2 fertilization
Statistical, without CO_2 fertilization