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Decision support tools for site-specific fertilizer recommendations and agricultural planning in selected countries in sub-Sahara Africa

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Nutrient Cycling in Agroecosystems

Decision support tools for site-specific fertilizer recommendations and agricultural planning in selected countries in Sub-Sahara Africa

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Response to Reviewers:	The comments of reviewer 1 and Editor Figures have been re-drawn and contents modified to include the equations, the p and r2 values as requested. Also, all figures are now redone in black and white

	Comments of reviewer 2 Original line 409 “Special collaboration” has been taken care of in lines 398 to 401 Also the comment on phosphorous deficiencies, weed management e.t.c. have now been addressed in lines 404 to 406

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Decision support tools for site-specific fertilizer recommendations and agricultural planning in selected countries in Sub-Sahara Africa.

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Abstract

Recommendations and decisions of crop management in sub-Saharan Africa (SSA) are often based on traditional field experimentation. This usually ignores the variability of production factors in space and time, variability that itself invalidates such decisions and recommendations outside of the experimental sites. Yet, the use of alternative or complementary decision support approaches such as crop modelling is limited. In this paper, we reviewed the state of the use of crop modelling in informing site specific fertilizer recommendations in some countries in SSA. Even though nitrogen fertilizer recommendations in most countries across Africa are blanket, the limited employment of models show that optimum nitrogen application should be differentiated according to soil types, management and climate. A number of studies reported on increased fertilizer use efficiency and reduced crop production risks with the use of Decision Support Tools (DST). The review also showed that the gross limitation of the use of models as agricultural decision-making tools in SSA could be attributed to factors such as low capacity due to limited training opportunities, and the general lack of support from national governments for model development and application for policy formulation. Proposals identified to overcome these limitations include (i) introduction of the science of DST in the curricula at the tertiary level, (ii) encouragement and support for the adoption of model use by Governmental and Non-Governmental Organizations as additional tools for decision making and (iii) simplifying DSTs to facilitate their use by non-scientific audience to scale uptake and use for farm management.

Key words: Risk management; Resource use efficiency; Sub Sahara Africa; Soil productivity

Introduction

Agriculture, the mainstay of the economies in sub-Saharan Africa (SSA), is dominated by smallholder farmers, holding often between 0.5-2 ha and relying mainly on rainfall (Adiku et al., 2015). The soils in the region are generally highly weathered (Sanchez, 2002), comprising of Low Activity Clays (LAC) with low inherent fertility (cation exchange capacity *CEC* between 3 and 15 $\mathrm{cmol_c}$/kg soil). In some regions such as the West African Sudano-Sahel, the CEC can be as low as 1 $\mathrm{cmol_c}$/kg soil and hence a great portion of the inherent fertility is derived from the soil organic carbon, which itself is low, often, < 10 g/kg (Bationo and Buekert, 2001). These, in conjunction with poor management practices such as bush burning, residue removal from fields, very low fertilizer application, mono cropping systems and erratic but intense rainfall lead to accelerated soil degradation and fertility decline. Even then, the use of inorganic fertilizer in SSA is low, being only about 10 kg/ha fertilizer a decade ago (Sanchez et al., 2009) although current evidence suggest that several countries have now increased use. For example, current fertilizer use by farmers in Ghana is about 30 kg N/ha (MacCarthy et al., 2017).

It has long been established that increasing the use of inorganic fertilizer on arable land is critical to improving crop productivity and ending hunger in SSA (van Keulen and Breman 1990). But this must go along avoiding the low fertilizer use recoveries under high application rates and high rainfall conditions (Vanlauwe et al. 2011) associated with large losses in runoff or leaching. In other words, efforts towards increasing food production should also include ways to improve efficiency of fertilizer use. In 2003, the heads of states of African countries re-pledged to allocate 10% of their annual budget and to attain 6% growth in agriculture by 2015 (CAADP, 2003), with an enhanced fertilizer use at the core of the strategy. Yet, despite the pockets of increased fertilizer use, the situation has still not changed very much from the observations by Sanchez et al. (2009).

The low application of fertilizers in agriculture in SSA can be attributed to several challenges. First, there is the socio-economic aspects of low incomes of most farmers, and hence their inability to afford fertilizers. This aspect will not be discussed here. From the biophysical point of view, blanket fertilizer recommendations which have been the general approach in many SSA countries have little scientific rigour. For example in Ghana, the fertilizer recommendations for both sorghum and maize are similar and in Zimbabwe recommendations have been done for most crops grown by both commercial and smallholder farmers across the five agro-ecological zones (FAO, 2006). The failure to formulate fertilizer recommendations that are soil- and crop-type specific and that also considers the effect of climate variability results in either wastage or deficiencies in fertilizer use. In sum, current fertilizer recommendation practices in the SSA do not properly address the specific local biophysical agricultural production systems, hence making them unprofitable in several instances (Kihara et al., 2015), and a disincentive for smallholder farmers.

Improving the formulation of fertilizer recommendations in the SSA is hampered by the expensive and time-consuming field experimentation and soil analysis approaches that are logistically too expensive to conduct at every location of interest. . The results are low adoption rates as the field- and soil analysis-based methods alone do not capture the possible range of yield variabilities that can be associated with a given fertilizer application rate and, in many cases , variable weather. The need for the use of complementary procedures that can more effectively assess the many possible interactive effects of biophysical attributes and management practices including soil and crop types, varieties, fertilizer types, application rates and timing on crop productivity under varying weather, cannot be overemphasized. Typically, these are known as Decision Support Tools (DST) or crop modelling. The purpose of this paper is to provide a historical review of the use of models as DSTs in SSA, and to understand reasons limiting the wide-scale use of these models for agricultural research and development planning and especially for formulating site-specific fertilizer requirements.

Globally Available Decision Support Tools (DSTs)

Decision support tools range from empirical static models that enable the assessment of soil nutrient concentrations and identify limiting productivity, to dynamic software support that combine soils, crop-specific growth parameters and weather. Empirical and static models date back to 1930s (Akponikpe et al, 2014) when a number of nutrient response functions were derived often for single factors (e.g. rainfall, fertilizer, among others) to predict crop response to nutrient application. Indeed, as early as 1913, Mitscherlich derived simple, easy to follow equations to predict crop response to nitrogen application (Mitscherlich, 1913), the foundations of which continue to play roles in agronomic research and advice. A suite of such empirical response functions led to development of a set of improved response models that consider multiple soil nutrients such as QUEFTS (Jansen et al., 1990), the effects of soil acidity on crop productivity e.g. NuMAS (Maran and Leatherman, 1992) and the effects of soil organic matter management on soil productivity and crop performance, e.g. NUTMON (Stoorvogel and Smaling, 1990). The major limitation of these types of models is the lack of dynamic response to changing management and climate. Their use for future predictions is thus limited.

The foundation for the dynamic crop models was laid in the 1950s by de Wit (1958) and van Bavel (1953) (see Jones et al., 2016). These types of models, popularly referred to as "Models of Agricultural Systems" combine physical and biological principles to model agricultural systems. Such models, including APSIM, DSSAT and more recently SEAMLESS, harnessed the strengths of non-system models such as EPIC (Willams, 1983), CENTURY (Parton et al., 1987), NTRM (Shaffer et al., 1983), PARCH model (Hess et al., 1997), STICS (Brisson et al., 1998) and PERFECT (Littleboy et al., 1989) in dealing with soil resources under long-term farming activities, but also recognized their weakness in addressing important systems aspect of cropping such as residue management, crop rotation and dynamic management decisions that are responsive to weather, soil and genotype and hence, affect crop yield (Keating et al., 2003). These model development efforts and applications have occurred in other places such as Australia, America and Europe. Even though model uptake worldwide for agricultural planning beyond the research community has been generally low (Rose et al., 2016), there are indeed efforts and success stories where models have been used in the broader agricultural planning context by farmers, communities and monitors. The FARMSCAPE model (Carberry et al., 2002) provides a proof of one such case in northern Australia. It provides a workable interface between researchers, farmers, communities, among others, enabling model application beyond researchers use. Another DST that is used by farmers and consultants in Australia is the "Yield Prophet" which provides growers with integrated production risk advice and monitoring decision support relevant to farm management. The Monsanto Seed Company employs models to assess the greenhouse gas emission reduction potentials of crops such as maize and soybean under varying soil conditions. Thus, in several respects, some efforts have and continue to be made in modest to popularize the use of models in many ways. In SSA, however, model use is mainly limited to largely donor-funded calibration and validation studies within the research domain. The more crucial aspect of model development to address the peculiar challenges such as soil acidity, phosphorus fixation, soil salinity, among others, on crop production and the adoption of the models by National Governments to assist policy formulation is almost completely under-funded.

Though crop modelling in the world spans more than 60 years or more, it was not until the mid-1980s that both empirical and functional dynamic models were introduced to SSA. Perhaps the earliest model use in the SSA was in South Africa in the early 1970s (Schultze, 1975), followed by a rather slow spread to the other regions. Empirical and the semi-empirical models such as AQUACROP (Raes et al., 2009), CROPSYST (Stockle et al., 2003), STICS, WOFOST (Van Diepen et al.,, 1989), QUEFT and NUTMON took precedence over the more dynamic ones that simulated the dynamics of the crop growth, development and soil processes. By the mid-1980s, the first application of functional dynamic crop-soil systems model in a developing SSA country was probably in Kenya, within the Australia Dry-land Farming Systems Project (McCown et al., 1992; Keating et al., 1991) that spanned 1985 to 1992. This formed the foundation of modeling low input systems with the use of the CERES Maize model and then evolved into the use of the Agricultural Production Systems Simulator (APSIM) (McCown et al., 1992). Other decision support tools in use in SSA include WOFOST (Kassie et al.,. 2015) used to assess the impact of the variability of weather parameter on the yield of maize in Ethiopia and SARA-H, a water balance/stress index based model used mainly in the Sahelian regions of West Africa and that has been used extensively for agrometeorological and food security assessments (Sultana et al., 2005; Akponikpe et al., 2014).

Despite efforts by Consortium of International Agriculture Research Centres (CGIAR) (e.g. ICRISAT, CIAT and IITA) and IFDC among others to promote DST using software such as Decision Support System for Technology Transfer (DSSAT; Hoogenboom et al., 2010) and APSIM, most of the users from SSA are from the research domain and not from the policy makers' domain. In effect, the needs for the types of interface suitable for the non-research community have not been expressed to the model developers. Also, SSA can hardly showcase any model development works except the South African sugar cane model and some limited work to extend some models such as APSIM to include intercropping systems (Adiku, 1995; Adiku et al., 1998).

Challenges to fertilizer recommendation formulation in the SSA

Soil and crop-specific nutrient management recommendations are required to increase farm productivity. The challenge of providing these recommendations to farmers in Africa is huge because soils and climate are highly heterogeneous even over short distances. Local soil variability also results in variability in yields even among replicates of the same treatment (Akponikpe et al., 2014). Crop productivity and profitability of fertilizer use vary widely in space and time even on the same soil, particularly under rain-fed agriculture (MacCathy et al., 2015; Naab et al., 2015). Some other studies in the Savannah region of West Africa also point to differences in the use efficiencies of applied N fertilizer as a result of differences in the land use history of the fields (MacCarthy et al., 2010).

It was noted earlier that several fertilizer recommendations in SSA do not consider variations in local settings but are rather uniform in space and in time. Furthermore, research sites on which the recommendations are based are sometimes higher in fertility due to better management and residual nutrients from previous trials thus, making them unsuitable as basis for the larger recommendations. Wopereis et al. (2006) observed in the West African Savannah that maize response to fertilizer application was affected by the mineral fertilizer management of maize on farmers' fields as well as inherent soil organic matter. The crop response to fertilizer is also strongly affected by weather variability. With little or no ability to forecast the weather, investment in fertilizer can lead to farmer indebtedness, a phenomenon that serves as a disincentive for the adoption of innovative practices that enhances intensification (Hansen, 2005). Several other studies have reported the weather dependence of crop response to fertilizer use and the subsequent inter-seasonal yield variations (MacCarthy et al., 2009; MacCarthy et al., 2015; Naab et al., 2015; Akponikpe et al., 2010).

The response to mineral fertilization is also dependent on the crop and on the variety of crop being used (Haefele et al., 2010). Improved crop varieties which are often used in these fertilizer trials are more responsive than the traditional varieties that most farmers use with the former being less resilient to local weather and disease conditions. Soil physical properties such as texture also influence the response of crops to fertilizer application (Zingore et al., 2007). A large spatial variability in yields can occur on a seemingly uniformly-textured soil over short distances (Voortman et al. 2004), posing a challenge to interpretation and potentially point to other interacting factors. The variation of soil physical, chemical and other properties in space, particularly in smallholder systems, due to previous variations in soil fertility management imply that the responses to mineral fertilization would also vary largely in space. The practice of precision agriculture to address such challenges is yet to get a foothold in the SSA.

Thus, to adequately consider the above-mentioned factors in determining fertilizer recommendations for farmers will require some form of decision support tools that take these factors into account in determining crop yield. Decision support tools provide the opportunity to assess the impact of fluctuations in weather parameters on the inter-annual variability on fertilizer use efficiency of crops. It also allows for the assessment of the impact of different management practices on soil properties and processes as well yield. If the SSA is to meet its aim of increasing its fertilizer use by 2050 (CAADP), then the reliance of field experimental procedures alone cannot provide the necessary policy foundation.

Role of decision support in SSA

The use of DSTs specifically for fertilizer recommendation formulation in SSA is limited. Several studies, however applied the tools in various ways. Smaling and Fresco (1993) used the NUTMON as a decision support tool to monitor the effects of changing land use, and suggest interventions that improve the nutrient balance in Kisii district of Kenya. They concluded that DST has the potential to inform decision makers in determining the effects of current and alternate land use types on crop productivity and long-term sustainability of cropping systems. De Jager et al. (1998) also used the same model in Kenya and concluded that cash crops such as tea and coffee yielded higher economic benefits to farmers and considerably mined less soil nutrient than food crops such as maize and maize-beans systems. Haefele et al. (2003) applied QUEFTS as a DST to study the internal nutrient efficiencies, fertilizer recovery rates and indigenous nutrient supply of irrigated lowland rice in Sahelian West Africa. Similarly, Wopereis et al. (2003) utilized RIDEV-phenology model in the Sahel to develop a DST for determining appropriate time for cultivating rice to avoid yield lose due to increased temperature. Other studies also calibrated and evaluated DSSAT and APSIM for sorghum, millet and maize-based cropping systems on which fertilizer recommendations could be made (MacCarthy et al., 2010; Akponikpe et al., 2010; Fosu et al., 2012; MacCarthy et al., 2012; Fosu-Mensah et al., 2012).

In the case of functional dynamic crop models, their use has largely remained on the calibration and validation for specific locations in the SSA. For many years in the past, most publications on crop modelling from SSA focused on model calibration (Mabhaudhi et al., 2014; Fatondji et al., 2012; Fosu et al., 2012; MacCarthy et al., 2012; Dzotsi et al., 2010) (Table 1). Zinyengere et al. (2015) tested the usefulness of crop models (DSSAT) under data limited dryland conditions of southern Africa using both experimental trial data and district-wide crop yield estimates. Also, Mabhaudhi et al. (2014) calibrated and evaluated AQUACROP for the taro plant in South Africa. Not all calibration attempts were successful; For example, Fosu et al. (2012) explained the failure to predict appropriately yields at high N level (unlike the good predictions at low N) to water stress in the gravelly and shallow soils at the experimental site. Gungula et al. (2003) reported on the inability of the CERES Maize model to predict maize phenology under nitrogen stress condition. Wafula (1995) applied CERES-Maize model to support farmers' decision making with respect to farm management options and the inherent economic implications. The Agricultural Production System sIMulator was applied by Masikati et al. (2014) to show the positive effect of maize mucuna rotation on water productivity in smallholder systems in Zimbabwe. A few studies have recently used crop models for yield gap analysis (van Ittersum et al., 2013; Kassie et al., 2014). A study by Diarisso et al. (2015) in Burkina Faso indicated substantial yield gaps in the smallholder systems which they attributed to low soil fertility, sub-optimal fertilizer input and erratic rainfall condition. Kassie et al. (2014) also applied the DSSAT and the WOFOST DSTs to assess climate-induced yield variability and yield gap of maize in the Central Rift Valley of Ethiopia. Dzotsi et al. 2003 also used the DSSAT model to provide a DST that enabled optimum cultivar-sowing date combination of maize in southern Togo.

Link between DST and site specific fertilizer recommendation

Decision support tools integrate a multiple of parameters known to affect response of crops to inorganic N such as rainfall distribution, type of soil, crop type and crop variety in simulating crop yield. As such, DST is an appropriate tool to enhance farmer decision making especially with regards to site specific fertilizer recommendation. With the use of DST, it can be shown that a wide range of yields can occur even at a given N application rate across soil types, under variable management, or even at same location but under different weather conditions. In Ghana for example, a farmer investing in 120 kg N/ha application rate can obtain yields varying from 1900 kg/ha to more than 4000 kg/ha (Fig. 1). This variation can be attributed to rainfall variability. Without the use of DSTs, such yield/fertilizer response information would require many years of field experimentation to obtain. DSTs can be used together with weather forecast for instance to select appropriate sowing time (MacCarthy et al., 2017) or advise on range of fertilizer to use based on the forecast in order to maximize fertilizer use.

Recently, Nureeden (2014) used the DSSAT – CSM to refine fertilizer recommendations in Sudan Savannah agro-ecological zone in Ghana. Atakora et al. (2014) also used the DSSAT – CSM to determine fertilizer recommendations for a site in the Guinea Savannah Zone of Ghana. A comparison of these two studies which were both located in the northern part of Ghana show differences in recommended N rates that should be applied to maize to optimize yield. These were all applied on point scale just like most other model applications in SSA. Using the N response data (Fig. 1) for Tamale, Ghana, a strategic analysis of the monetary returns of the various N inputs showed 60 kg N ha^{-1} as most appropriate to be recommended to farmers since the returns from that were similar to those obtained from N application levels beyond 60 kg N ha^{-1} (Fig. 2). The economic optimum rate was determined using Gini coefficient (Adnan et al., 2017) which determines the best economic strategy. Environmental limitations combined with management and socio-economic conditions also need to be considered when assessing cost benefit for fertilizer recommendations. For example, at optimal simulated fertilizer application of 60 kg/ha in soil with average % SOC 0.6, 0.8 and 0.5 and annual rainfall of 850, 1200 and 650 mm median maize yield was 5200, 3216 and 2780 kg/ha for Malawi, Mozambique and Zimbabwe, respectively (Fig. 3 a-c). Risk is higher in Zimbabwe at the recommended application rate as shown by high variability of both maize grain and stover yields. While 60 kg N/ha is recommended for Zimbabwe, production at that fertilizer rate gives yields that are 20% less than area potential, i.e., due to soil quality, optimal benefits of applying recommended rates can be compromised. In Senegal for instance, yield increases of between 1000 – 2300 kg/ha and profitability of USD 216 – 640 per ha were reported as benefit from using Nutrient Manager for Rice (NMR) decision support systems for irrigated rice (Saito et al., 2015). A simple Microsoft excel decision support tool has been developed in Uganda to help optimize fertilizer use by farmers and about 400 extension workers and farmers trained on their use. This was part of the Optimizing Fertilizer Recommendation in Africa (OFRA) which is a project being done in 7 countries in SSA and is expected to optimize fertilizer use efficiency. The FERRIZ model was also calibrated and evaluated by Segda et al. (2005) and used to improve fertilizer recommendations for irrigated rice in Burkina Faso. These alternative fertilizer recommendations increased the gross returns compared to farmers' practices and existing recommendations.

The shape of simulated response of maize to different levels of N fertilizer vary with soil's water holding capacity as observed in Koutiala, Mali (Fig. 4). While grain yield seemed to have peaked at 120 kg N ha^{-1} on soil water holding capacity (WHC) of 50 mm, the response curve for soil with a higher WHC (55 mm) suggested further grain yield increase beyond 120 kg N ha^{-1}. Similarly, the response of crops to N fertilization is also influenced by time of planting (Fig. 5). While the use of 120 kg N/ha can result in median yield of about 4000kg/ha with early planting, using same amount of fertilizer in the late planting window produced a median yield of less than 3000 kg N/ha. Decision support tools can also be used to explore what management options to use to minimize yield losses to enhance farmer confidence in fertilizer adoption. Thus, the need to promote site specific fertilizer recommendation to optimize returns on input cannot be over- emphasized.

Models as DST for future climate

Climate change is a major threat to agricultural productivity in the SSA, especially because of (i) high dependence of people and their livelihoods on natural resources, (ii) the rapid degradation of these resources and resilience loss, (iii) extreme poverty and (i) lack of interventions such as crop insurance. The lingering question is how SSA agriculture will be impacted by future climate. This question cannot be addressed without the use of models. Several projections have been put forward based on different models. IFPRI, for example, simulated changes in crop productivity relative to current yield over several countries in Africa. Others reporting impacts of climate change on agriculture productivity include Jones and Thornton (2003) and Thornton et al. (2009). The work of Thornton et al. (2009) in East Africa highlighted the spatial variability of crop response to climate change and, hence, discouraged the use of spatially contiguous developmental domains in the identification and implementation of adaption options. Areas where yield decline is predicted at current practices are also shown to have yield increases when technological changes, including increased use of fertilizer and varietal improvement, are considered.

Traditionally, DST for future predictions were applied in a variety of ways. In some studies, point based scenarios with single General Circulation Models (GCM) were used, whereas others used point simulation but with multiple GCM (Tachie-Obeng et al., 2013). The trend is now towards the use of multi-locations as well as multi-GCMs (Adiku et al., 2015; Masikati et al., 2015; Rao et al., 2015; Beleste et al., 2015). Within the Agriculture Model Improvement and Inter-comparison Project (AgMIP) framework (Rosensweig et al., 2013), a combination of biophysical and socio-economic models is being used as DST to assess the impact of climate change on agriculture in various zones of the world. For the West African region, the work is summarized in “Climate Change Impact on West Africa Agriculture: A Regional Assessment” (Adiku et al., 2015). The results showed that net farm income would reduce under climate change. In East Africa, the project focuses on the “Impacts of climate variability and change on Agricultural Systems in East Africa”. The results (Rao et al., 2015; 2012, Kaissie et al., 2015) indicated that the impact of climate change is not uniform across locations, and that some areas will actually benefit from climate change impacts. Hence the impact on the livelihoods of farmers will also vary based on their location. In other studies, it was projected that the production of maize under climate change scenarios in the Bethlehem District, South Africa would reduce by between 10 and 16% if no adaptation measures are employed (Beletse et al., 2015). In the case of Nkayi, Zimbabwe, the impact of climate change on the productivity of crops under current farmer practice was reported to be marginal (7%). The level of impact is low because the current production systems are low input characterized by depleted soils (Masikati et al., 2015).

Limitations and challenges to DST application in SSA

In spite of the evidence provided on the improvement in fertilizer use efficiency and reduction in production risks with the use of DST and modelling to inform agricultural management and planning, the use of DSTs to inform decision making is generally poor. This phenomenon is not peculiar to SSA alone. A recent study by Rose et al. (2016) reported of low uptake of DSTs for agricultural decision making in the United Kingdom. The lag in model use as tool for agricultural decision making in Africa may be attributed to several reasons. First, capacity for modelling use is and continues to be grossly lacking. A survey by Adiku (unpublished) on modelling-related publications from the SSA showed that by the year 2009, about 25, 15, 18 and 14 papers were published using DSSAT, APSIM, NUTMON and RUSLE/USLE, respectively. These papers, which emanated from collaborative works between advanced country researchers and SSA counterparts, appeared in reputable journals over a period of about 40 years. On the average, about two modelling papers or so are published annually from the region, with respect to these four models. Against the backdrop of the low capacity, the African Network for Soil Biology and Fertility (AfNet) and their collaborators organized a series of training that culminated in the publication of a book (Kihara et al., 2012).

Second, except for donor-funded projects, national support for crop modeling research and application for agriculture development is limited. Over the past 20 years of crop modeling activities within Ghana’s Universities and Research Institutes, for example, direct government funding is negligible. The funding support may appear to be somewhat better in Kenya and southern Africa, but generally not comparable to Europe, Australia, USA, among others. Therefore, as noted, the effect of many peculiar soil challenges of the SSA including soil acidity, phosphorous deficiency, Mn and Al toxicity, soil erosion and degradation, soil crusts that affect germination and emergence, among others, on crop yields cannot be simulated using the popular DSTs because these processes are not well represented in the models. As a result of the current models lack of sensitivity to these issues, their use in such situations would be limited. Apart, not many institutions in the SSA train expertise in crop modelling and DSTs. Researchers interested in crop modeling must seek training in advanced countries. Interest in modelling among the mainly biology-based students in agricultural sciences in SSA is low, especially because of the need for good mathematical background for modelling. As far back as 1997, the Department of Soil Science at the University of Ghana introduced a curriculum in agricultural systems simulation and modelling. To date, not more than 20 students have participated in the course and not more than 5 crop-modelling related thesis have been produced. There is no effort by SSA governments to financially support training in crop modelling. As indicated earlier, there is low capacity in the use of DST even among scientists. Skills on the use of decision support tools are still rare in Sub-Saharan Africa (Segda et al., 2005)

Third, data unavailability at suitable detail for model validation in particular under broader farm conditions continues to be a major handicap to model use. This requires the need for more research for new versions to include functions that can use routinely collected parameters to estimate those currently required. This will enhance their applicability. The emergence of technologies such as soil-scanners based on IR may be a game-changer for providing extra soil data for areas were data are lacking, particularly with large scale applications. Some efforts have been made to establish minimum data sets and also develop protocols to facilitate the use of DST by other potential users (Hoogenboom et al., 2012; Rosenzweig et al., 2013).

Fourth, the lack of knowledge of the usefulness of DST among agricultural stakeholders for policy formulation is a major handicap. Most DSTs require hardware and computational time and these are often not readily available to potential users in SSA. Organizations that introduce the use of DSTs in SSA often promote specifically those of interest to them whiles smallholder farmers challenges are complex hence require a set of DSTs (DST Toolbox) to adequately address their problems. Critical crops that contribute to food security such as cassava and yam in SSA are usually not adequately captured in most decision support tools. There is also the need to improve use of DST for spatial analysis as most of the existing ones are point based. This will require that they are coupled with geo-spatial tools. Such capabilities already exist in models such as APSIM and DSSAT (Huth et al., 2003) but have not yet been widely applied.

Conclusions and the way forward

Sub-Saharan Africa lags in the use of decision support tools for agricultural decision support even though it is increasingly used in developed countries to support agricultural planning. A great deal of modelling work in SSA has been limited to calibration and validation. Where models were applied to support decision making process, they were hardly used to inform site specific fertilizer recommendation. Inability to capture in models the SSA-peculiar yield limiting factors such as aluminum toxicity, phosphorous deficiency, weeds, and deficiencies of micronutrients limits the application of most of the current models both in representing the real situations and also in making recommendations. The application of models as DST for formulating fertilizer recommendations in the SSA requires much more funding and capacity building support, especially from the national governments and regional bodies in SSA. In sum, for DST to become effective tools for agricultural planning, the following must be achieved:

(i) Capacity building: The introduction of the use of DST in tertiary school curriculum, with a focus on the training especially the next generation not only in model use but more importantly model development. In particular, support from the mathematical disciplines to biological sciences will be required. The setting up of special funds to support students willing to engage in modelling work would be important.

(ii) Demonstration of the utility of DSTs beyond research to policy formulation domain

(iii) Address peculiar tropical soil and cropping system challenges such as phosphorus deficiency, aluminum toxicity, soil acidity, weed competition, mixed cropping among others to enhance their applicability in SSA.

(iv) Development of DST for other important food crops such as cassava and yam.

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List of figure captions

Fig. Response curve of maize yield to different levels of nitrogen application over 30 years (1980-2009) simulation period for Tamale, Ghana.

Fig. 2: Monetary returns on the use of inorganic fertilizer in maize production at a site in Tamale, Ghana

Fig. 3: Simulated maize grain and stover yields in response to mineral N fertilization in 3 countries in southern Africa.

Fig. 4: The Simulated effect of soils from Koutiala, Mali with different water holding capacity on the response of maize yield to mineral nitrogen fertilization. WHC is water holding capacity.

Fig. 5: The simulated effect of sowing dates on the response of maize yield to mineral fertilizer application in Nioro. Senegal.

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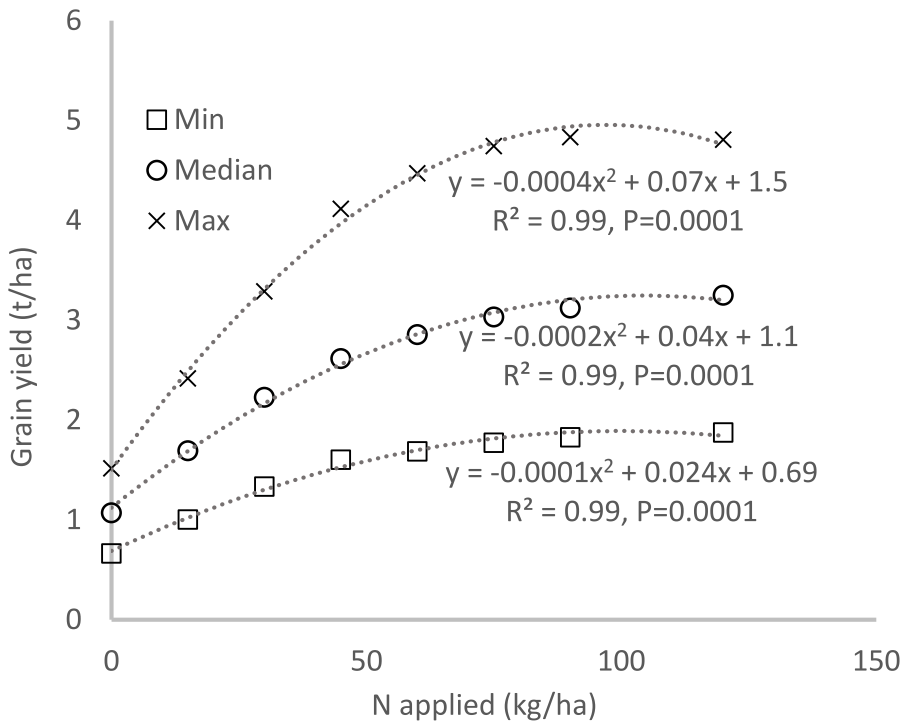

Fig 1

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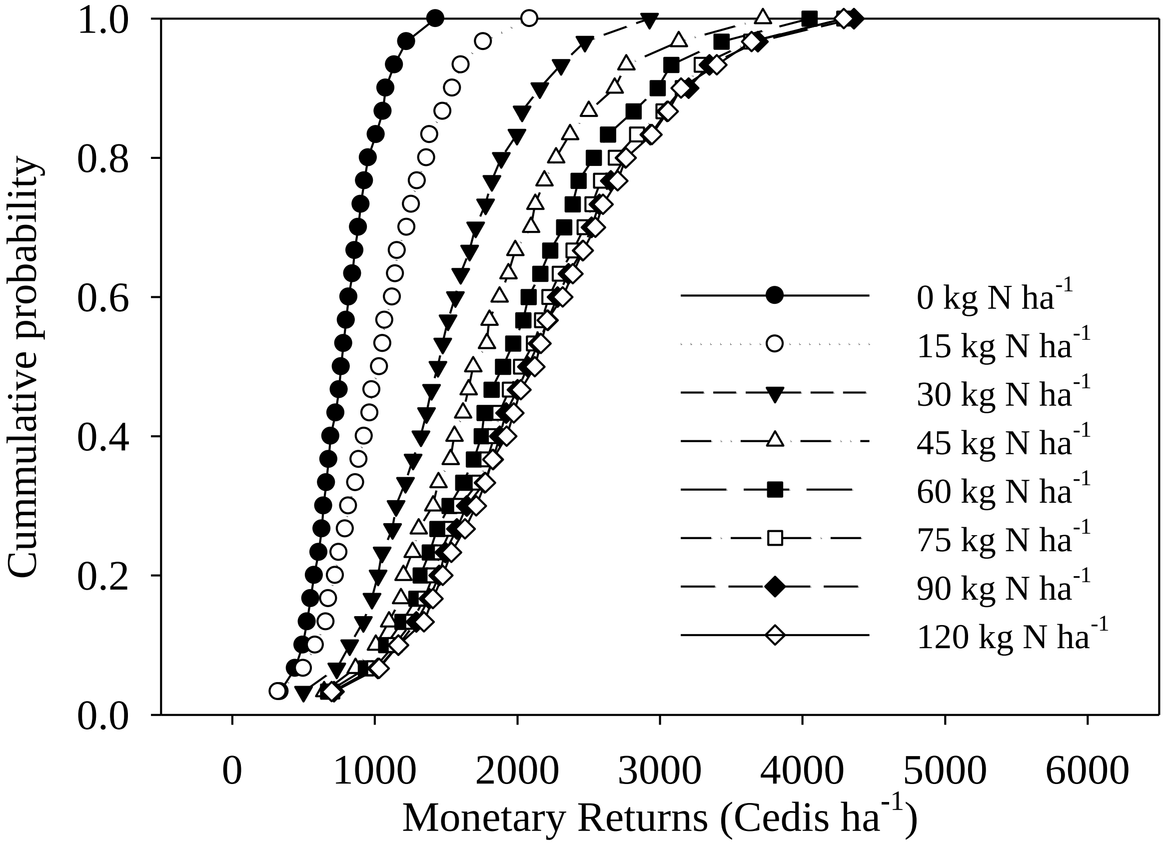

Fig. 2

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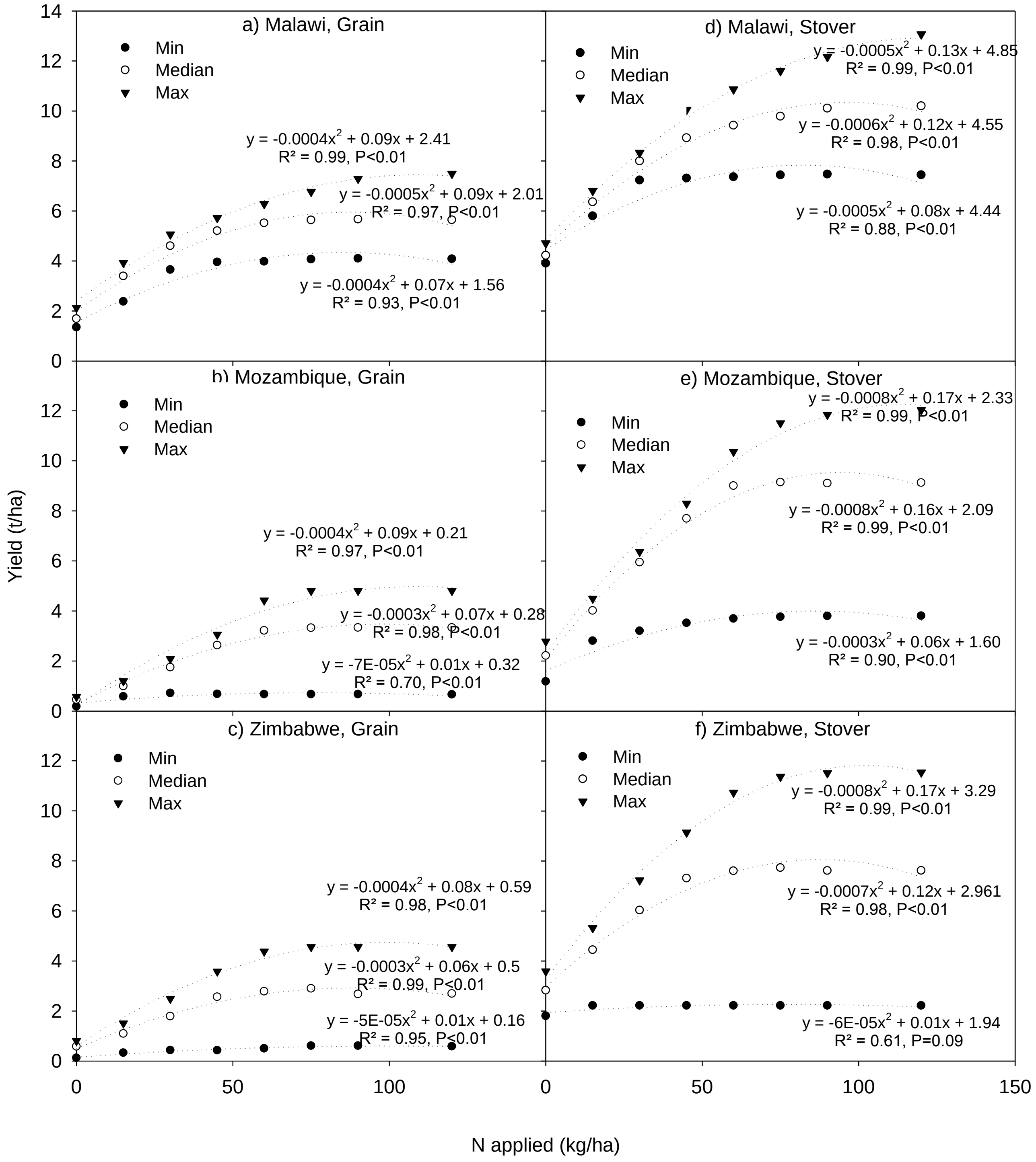

Fig. 3

Figure 4

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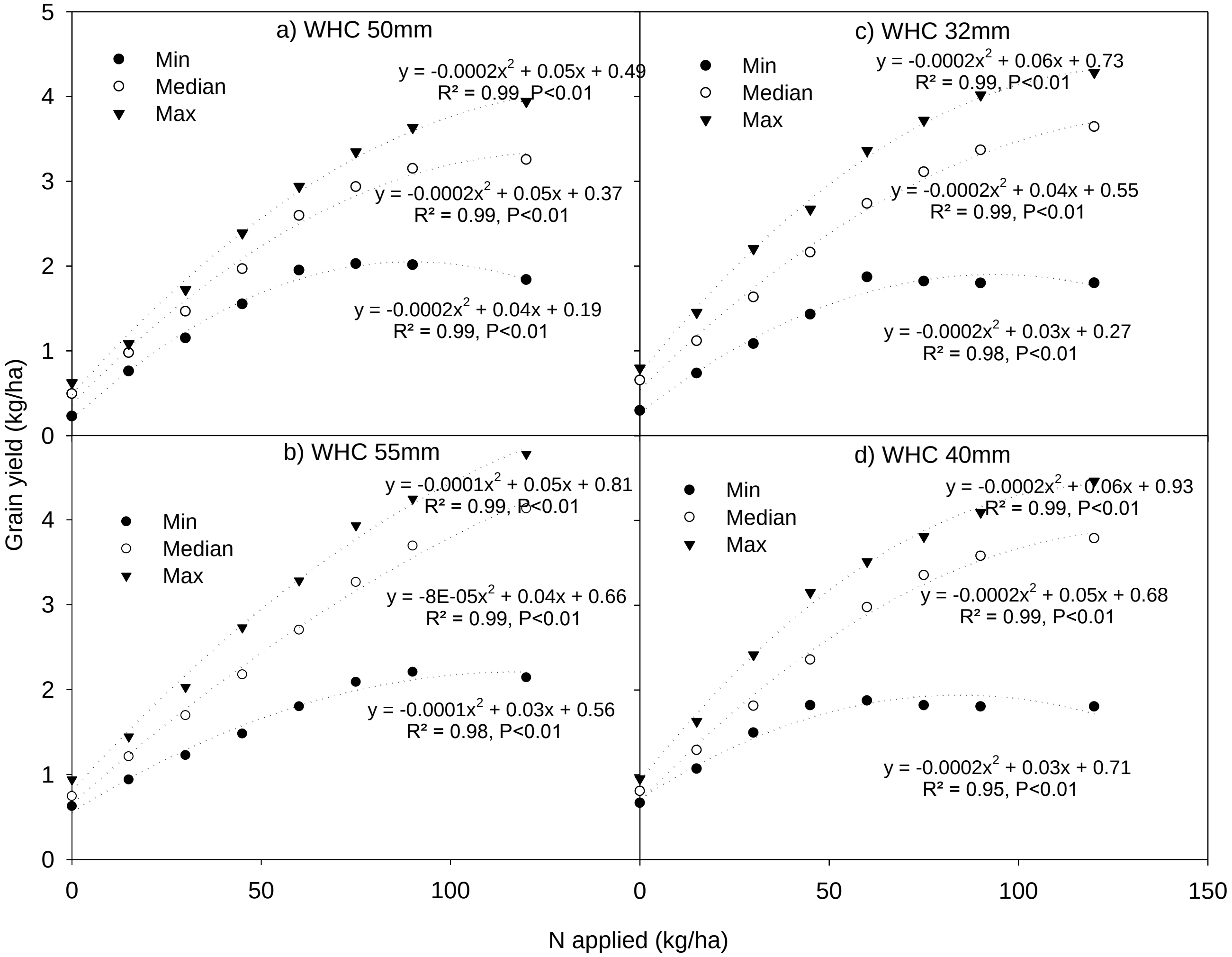

Fig. 4

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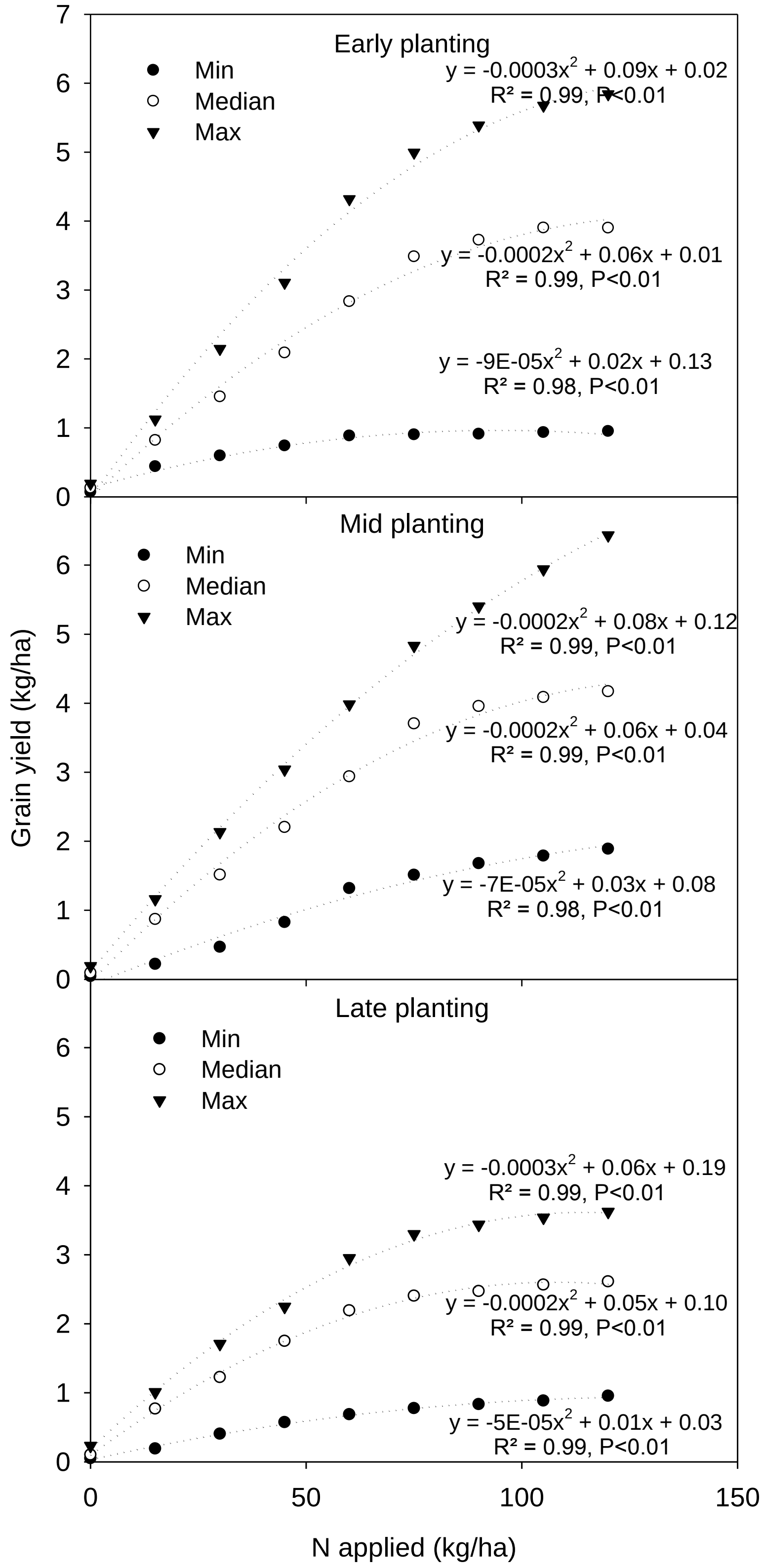

Fig. 5

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Table 1. Selected publication on the use of Decision support tools in Sub Sahara Africa (SSA).

Source	Crop	Treatment	Application	Location
MacCarthy et al. 2012	Maize	N	CSM-CERES (DSSAT v 4.0)	Ghana
Fatondji et al. 2012	Millet	Manure	CSM-CERES (DSSAT v 4.0)	Niger
Fosu et al. 2012	Maize	N	CSM-CERES (DSSAT v 4.0)	Ghana
Zinyengere et al. (2015)	Maize	Variable	CSM-CERES (DSSAT v 4.0)	Malawi
Zinyengere et al. (2015)	Groundnut	None	CropGro (DSSAT v 4.0)	Malawi
MacCarthy et al 2009	Sorghum	N & P	APSIM v 4.0	Ghana
MacCarthy et al 2015	Maize	N	APSIM v 7.4	Ghana
Fosu-Mensah et al. 2013	Maize	N & P	APSIM v 6.1	Ghana
Tetteh and Nurudeen (2015)	Maize	N & P	CSM-CERES (DSSAT v 4.0)	Ghana
Chisanga 2014	Maize	N and planting dates	CSM-CERES (DSSAT v 4.0)	Zambia
Kisaka et al. 2015	Maize	N and manure	APSIM	Kenya
Delve et al. 2009	Maize	P	APSIM	Kenya
Delve et al. 2009	Maize	P	APSIM	Kenya
Delve et al. 2009	Bean	P	APSIM	Kenya
Chimonyo et al. 2016	Sorghum	Water regime	APSIM	South Africa
Chimonyo et al. 2016	Cowpea	Water regime	APSIM	South Africa
Robertson et al. 2005	Velvet bean	N and velvet bean as previous crop	APSIM	Malawi
Chikowo et al. 2008	Maize	Fertilizer and rainfall	APSIM	Kenya
Katambara et al. 2013	Rice	Water productivity and efficiency	AQUACROPP	Tanzania
Ngwira et al. 2014	Maize	Climate change, CA, CT	CSM-CERES DSSAT	Malawi
Estes et al. 2013	Maize, Wheat	Climate impacts, N	CSM-CERES DSSAT v 4.5.0.047	South Africa
Estes et al. 2013	Wheat	Climate impacts	GAM model	South Africa
Bontkes et al. 2003	Maize	N, P, K	QUEFTS	Togo
Micheni et al. 2004	Sorghum, cowpea, pearl millet	Manure	APSIM	Kenya
Tsubo et al. 2004	Maize	Cereal-legume intercropping	APSIM	South Africa
Tsubo et al. 2004	Beans	Cereal-legume intercropping	APSIM	South Africa
Smaling and Janssen, 1993	Maize	N, P, K	QUEFTS	Kenya
Okwach and Simiyu 1999	Maize	Land management practices	APSIM	Kenya
Gaiser et al. 20010	Maize (West Africa)	Improved varieties, soils	EPIC	West Africa

Folberth et al. 2013	Maize	N, P, improved seeds	GEMIC	Sub-Sahara Africa
O’Leary, 2000	Sugarcane	N, water, temperature	APSIM	South Africa
O’Leary, 2000	Sugarcane	N, water, temperature	CANEGRO	South Africa
O’Leary, 2000	Sugarcane	N, water, temperature	QCANE	South Africa
Ncube et al. 2009	Sorghum	N uptake	APSIM	Zimbabwe
Srivastava et al. 2012	Yam	Fallow	EPIC	Benin
Jansen 2010	Maize	SOM, residual P, N	NUE	Kenya
Tittonell et al. 2013	Maize	N, P, K manure	QUEFTS	Kenya
Tittonell et al. 2008	Maize	Fertilizer, Manure	FIELD	Kenya
Kurwakumire et al. 2014	Maize	N, P, K, water use efficiency	QUEFTS	Zimbabwe
Mowo et al. 2006	Maize	N, P, K	QUEFTS	Tanzania
Araya et al. 2010	Barley	Water regime, planting dates	AQUACROP v 3.0	Ethiopia
Mabhaudhi et al. 2014a	Taro	Water regime, Taro landraces	AQUACROP	South Africa
Mabhaudhi et al. 2014b	Groundnut	Water regime	AQUACROP	South Africa
Karunaratne et al. 2011	Groundnut	Soil moisture regime	AQUACROP	Swaziland & Botswana
Beletse et al. 2012	Sweet potato	Irrigation treatment	AQUACROP	South Africa
Kipkorir et al. 2010	Maize	Water regime	AQUACROP	Kenya
Mugalavai and Kikorir et al. 2015	Maize		AQUACROP	Kenya
Mhizha et al. 2014	Maize	Sowing management options	AQUACROP	Zimbabwe
Nyakudya and Stroosnijder, 2014	Maize	Rooting depth, planting density, planting date	AQUACROP	Zimbabwe
Masanganise et al. 2013	Maize	Cultivars, planting dates, climate	AQUACROP	Zimbabwe
Singels and Bezuidenhout, 2002	Sugarcane	Temperature and water stress	CANEGRO	South Africa
Dzotsi et al. 2003	Maize	Cultivar, sowing date	DSSAT (CERES-Maize)	Togo
Dzotsi et al. 2010	Maize	N, P	DSSAT	Ghana
Jagtap et al. 1999	Maize	N, varieties	DSSATv2.1 (CERES- Maize)	Nigeria
Hansen et al. 2009	Maize (Kenya)	Precipitation, fertilizer management	GCM	Kenya
Mupangwa and Jewitt, 2011	Maize (South Africa)	No-till (NT) and CT systems	APSIM	South Africa
Adnan et al. 2017	Maize	N	DSSAT v 4.6 (CERES-Maize)	Nigeria