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Integrated soil fertility management sequences for reducing climate risk in smallholder crop production systems in southern Africa

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ABSTRACT

Climate change, increased climate variability and poor soil fertility are major bio-physical constraints to cropping on smallholder farms in southern Africa. We used the Agricultural Production Systems sIMulator (APSIM) to assess maize yield response to integrated soil fertility management (ISFM) rotational sequences of low-quality organic resources, nitrogen-fixing green manure and grain legumes, and mineral fertilizers under baseline (1960–2005) and projected (2040–2069) climates. APSIM was also employed to evaluate the response of maize yield to the ISFM sequences under a combination of a changing climate, and typical sowing dates and mineral fertilizer application rates for smallholder households of varying resource endowment. The ISFM sequences were ‘Fertilizer-start’ [a sunnhemp (*Crotalaria juncea* (L.)-based sequence], ‘Litter-start’ (a woodland litter-based sequence), and ‘Soya-start’ and ‘Manure-start’ (cattle manure-based sequences). The simulated maize grain yields were used to analyze agronomic and economic risks of maize productivity. Agronomic risk was evaluated on the basis of sufficiency of the maize grain yield to meet annual household calorie (energy) requirements, while economic risk was assessed using gross margins. For model evaluation, the simulated maize yields compared well with those measured from the field experiment (RMSE = 0.11–0.55; R^2 = 0.55–0.93). Under the baseline climate, ‘Soya-start’ was the least risky ISFM option as only one (2.2%) of the 45 years had calories lower than the minimum acceptable limit of 4,872,750 kcal required to meet household food self-sufficiency for a family of six people. Conversely, continuous fertilized maize and ‘Litter-start’ were the most risky options among the fertilized treatments as three (6.7%) and four (8.9%) of the 45 years, respectively, yielded calories that were below the threshold. Across treatments, the number of years with maize grain yield exceeding 2.3 t ha^{-1} was higher under baseline compared with future climate. However, ‘Soya-start’ and ‘Manure-start’ were consistently the least risky options under the future climate. The cattle manure-based sequences also had the lowest economic risk under both baseline and future climates. Over the 45-year period under baseline climate, ‘Soya-start’ only had two years with negative gross margins compared with six and nine for ‘Litter-start’ and continuous fertilized maize, respectively. A similar trend was observed under future climate. Overall, agronomic risk was lowest under sowing dates and mineral fertilizer application rates for resource-endowed (RG1) farmers compared with their resource-constrained (RG3) counterparts. Agronomic risk was higher under the representative concentration pathway (RCP) 8.5 compared with RCP4.5, with an average increase of 6, 4 and 6% for RG1, resource-intermediate (RG2) and RG3 management, respectively. Under the typical farmer management practices, the cattle manure-based sequences gave lower agronomic risk than continuous fertilized maize. Economic risk under the farmer management scenarios overly mirrored trends observed for agronomic risk. We conclude that sequenced ISFM combinations of organic resources, nitrogen-fixing green manure and grain legumes, and mineral fertilizers reduce climate risk in smallholder rainfed crop production systems in southern Africa, and similar agroecologies.

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1. Introduction

Southern Africa is projected to experience a sharp decline in crop yields by 2100 because of climate change and increased climate variability (IPCC, 2013, 2014; Lobell et al., 2008; Rurinda et al., 2015). The region is already grappling with warming temperatures, heat waves, frequent intra-seasonal rainfall variability and droughts, and recurrent episodes of floods and cyclones (IPCC, 2013; Rurinda et al., 2015; Zinyengere et al., 2013). Besides climate change, poor and declining soil fertility has been a major limitation to cropping on smallholder farms in southern Africa (Mapfumo and Giller, 2001; Ngwira et al., 2012). A combination of negative impacts of a changing climate and poor soil fertility has thus significantly reduced crop productivity in southern Africa, further rendering many smallholder farmers food insecure as the majority depends on climate sensitive rainfed agriculture. Alternative sources of food outside agriculture such as common natural resource pools (e.g. woodlands, wetlands and rangelands) have continued to dwindle largely due to land degradation and over-extraction (Chagumaira et al., 2015; Millennium Ecosystem Assessment, 2005), while income from off-farm activities and remittances has been declining because of limited employment opportunities and rising poverty, among other challenges (Anderson, 2001; Jayne et al., 2010). The food insecurity situation is likely to be worsened by rising food demands due to human population growth and changes in dietary patterns (HLPE, 2017). In most African countries the increased demand for food inevitably leads to importation, placing an extra burden on already meagre financial resources (Jayne et al., 2006). Appropriate agronomic management techniques that can simultaneously address poor and declining soil fertility, and reduce climate risks are thus key for improved and sustained crop productivity.

To ease challenges of nutrient resource scarcity as well as redress soil degradation on smallholder farms in southern Africa, many studies have explored how nitrogen fixing (N_2)-legumes, and combinations of locally-available organic resources and mineral fertilizers could be integrated and managed to sustain crop productivity (Waddington, 2003; Waddington et al., 1998). These nutrient management technologies are collectively classified under integrated soil fertility management (ISFM) (Mapfumo et al., 2013; Vanlauwe et al., 2010). The soil quality and productivity benefits of ISFM rotational sequences such as enhanced nutrient cycling and soil biological activity, and the underlying mechanisms, have been widely reported in many studies (e.g. Gentile et al., 2009; Swift et al., 1994; Vanlauwe et al., 2001). In southern Africa, ISFM has been found to increase yields of maize (*Zea mays* L.) and grain legumes on sandy soils from less than 1 t ha^{-1} under typical farmer management practices to 5 t ha^{-1} and 2 t ha^{-1}, respectively (Kamanga et al., 2014; Mapfumo et al., 2013; Nezomba et al., 2015a). However, there is a need to re-evaluate the resilience of the ISFM options for sustainable intensification of crop production in the wake of new threats posed by a changing climate. ISFM includes use of mineral fertilizers coupled with appropriate choices of locally adapted improved seed varieties among other external inputs, and these resources constitute significant costs to farmers. Because of the changing rainfall patterns, the use of these inputs has also become increasingly risky to farmers.

A few studies have been conducted on the technical feasibility of managing ISFM options to increase crop yields and economic benefits under rising temperatures and changing rainfall patterns in the region (Rurinda et al., 2013; Mapfumo et al., 2013). Most of these studies were conducted for less than three years, a time frame that could be too short to derive tangible conclusions given the increasing seasonal rainfall variability currently being experienced. Assessing the effects of ISFM on crop yields under long-term climate is thus critical in identifying options that can increase the adaptive capacity of farmers to the changing climate and land degradation. Agronomic and economic benefits of ISFM are highly likely to vary from farm to farm because different households are exposed to different climate variables, and have access to different farm level resources (Kamanga et al., 2010; Rurinda et al., 2014). Access to seed, nutrient inputs, labour and draught power are some of the resources that vary between smallholder households in southern Africa (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007). This suggests that the performance of ISFM technologies should also be assessed under typical agronomic management practices suitable for different farm types. Tailoring of technologies such as ISFM to different farm types as well as assessment of climate risk can be explored through characterization of farming systems, field experimentation and simulation modelling (Tittonell et al., 2009; Zingore et al., 2009). Simulation modelling and field experimentation compliment each other to further understand the complexity of interactions between crop-soil processes, as driven by management and climate (Whitbread et al., 2010).

In this study, we used simulation modelling and farm characterization surveys to assess maize yield response to different ISFM rotational sequences of low-quality organic resources, N_2-fixing green manure and grain legumes, and mineral fertilizers under rising temperatures and changing rainfall patterns, and to typical crop management practices by different farmer resource categories. Our assessment was envisaged to enable identification of ISFM sequencing options that would allow different farm types to attain maize grain yield sufficient to meet their household food needs under variable climatic conditions. The specific objectives of the study were to: (i) analyze agronomic and economic risks of maize productivity for different ISFM sequences under baseline (1960–2005) and future (2040–2069) climate, and (ii) evaluate maize grain yield response to ISFM sequences under typical agronomic management practices by smallholder households of different resource endowments, for baseline and future climates.

2. Materials and methods

2.1. Study site

The study was conducted in Hwedza (18°41′S; 31°42′E) smallholder farming area located in eastern Zimbabwe. This study area was purposefully selected to represent most of the smallholder farming areas in southern Africa, and other parts of sub-Saharan Africa (SSA), with regards to climate and soils. Hwedza is predominantly characterized by a dry sub-humid to semi-arid climate. This climate is representative of the larger part of southern Africa (https://public.world meteorological organization.int/en). Hwedza receives 500–800 mm rainfall $annum^{-1}$ between November and March (Rurinda et al., 2013). While the area has not recorded significant changes in total seasonal rainfall over the past five decades, emerging evidence show increased frequency of dry spells, late on-set of rainfall seasons and reduced number of rainy days (IPCC, 2013; Mtambanengwe et al., 2012; Rurinda et al., 2013). The dominant soils in Hwedza are sands (Lixisols and Arenosols) typified by low nutrient reserves and poor water holding capacity (FAO/ISRIC/ISSS, 2006; Nyamapfene, 1991). Arenosols cover 13% of the land area in SSA (FAO/ISRIC/ISSS, 2006). In southern Africa alone, approximately 6.5 million ha are under Arenosols, with the largest spatial coverage being in Angola, Botswana and South Africa (Hartemink and Huting, 2008). Lixisols occupy approximately 220 million ha of land in SSA, with more than half of the area under agriculture. As in smallholder farming systems of southern Africa (Waddington et al., 1998), maize is the dominant crop grown in Hwedza, with grain legumes such as Bambara nuts (*Vigna subterranea* L.), cowpea (*Vigna unguiculata* L Walp), groundnut (*Arachis hypogaea* L.) and soyabean (*Glycine max* [L.] Merr.) allocated to smaller land areas. Cattle manure, composted woodland litter and NPK fertilizers are the major nutrient inputs used in crop production, but amounts applied vary across households.

2.2. Overview of the ISFM sequences experiment

This study builds on an earlier four-year experiment conducted in