Agricultural Systems 157 (2017) 185–192

Contents lists available at ScienceDirect

Agricultural Systems

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

Spatial evaluation of maize yield in Malawi

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ARTICLE INFO

Keywords:
Maize yield
Pigeonpea
Rotations
Residues incorporation
Crop modeling
SALUS, conservation agriculture

ABSTRACT

The objective of this research was to quantify the effects of climate, soil, and management on spatial and temporal variation of maize yields across Malawi. We simulated four different nitrogen (N) management strategies to evaluate the impact of mineral and organic N amendments on maize yield across the agricultural lands of Malawi. Maize yield increased when the crop was grown with pigeonpea, or if mineral N fertilizer was added, but yield improvements under these management strategies varied spatially as result of different soil biophysical and chemical properties, weather, and their interactions with management. The increased yield from N addition showed that a significant increase in food production could be achieved in Malawi to reduce food insecurity.

1. Introduction

Maize (*Zea mays*) is a staple crop in Malawi as it provides about 60% of daily caloric intake to the average Malawian's diet (Denning et al., 2009; Ortega et al., 2016). Maize monoculture is common in Malawi but, unfortunately, it contributes to soil nutrient depletion and reduced soil fertility levels (Thierfelder et al., 2013). Improving soil fertility for smallholder farmers in Malawi is critical because it leads to higher maize yield (Stoorvogel et al., 1993).

Conservation agriculture, characterized by minimal soil disturbance, crop rotation with legume crops, and soil protected by cover crops or previous crop residues, has been shown to increase soil water holding capacity and supply additional nutrients as a result of increased soil carbon (Giller et al., 2009; Thierfelder et al., 2013). Researchers and international organizations (e.g. Food and Agriculture Organization of the United Nations, FAO) have been promoting conservation agriculture practices, particularly the incorporation of fresh legume crops or legume crop residues to maize-centered cropping systems, in Malawi and across Africa (Ngwira et al., 2014; Rusinamhodzi et al., 2011). The feasibility of incorporating various legume crops, such as pigeonpea (*Cajanus cajan*), to the nutrient-poor farming systems in Malawi has been studied by various researchers (Snapp et al., 1998; Wani et al., 1995). Pigeonpea is a multi-purpose perennial legume crop that can be grown for food and fuel. As a legume crop, pigeonpea adds nitrogen (N) to soil through biological N fixation (Snapp et al., 1998; Wani et al., 1995). In recent years, maize-pigeonpea production systems have been promoted in Malawi. Researchers have demonstrated the benefits of soil fertility improvement on maize crop yield from maize-pigeonpea intercropping, maize-pigeonpea rotation and continuous maize with pigeonpea residue incorporation systems at research stations and in local farmers' fields in Malawi (Adu-Gyamfi et al., 2007; Snapp et al., 2010).

Crop systems models, designed to understand crop-soil-climate-management interactions, have been applied to maize-based cropping systems in southern and eastern Africa. The CERES-Maize model was used to simulate maize yield and N dynamics under the tropical conditions in Malawi and Kenya (Thornton, 1995). APSIM has been applied across Africa to simulate legume contribution to maize in Malawi, Kenya and Zimbabwe (Robertson et al., 2005; Whitbread et al., 2010; Robertson et al., 2001; Robertson et al., 2001). The contribution of pigeonpea to maize grain yield across the multiple different soil and weather regimes of Malawi agricultural lands has not been fully estimated.

The research questions we address in this paper are: what is the extent of the spatial and temporal variation of maize yield across Malawi? Can management lead to increased yield and overcome poor soil conditions? Is increased yield uniform across Malawi? What is the spatial variation of the main biophysical factors that contribute to maize yield?

The objectives of this study were: (1) to evaluate maize grain yield across cropland in Malawi in 1980–2010 under the following management strategies: i) continuous maize unfertilized, ii) pigeonpea in rotation with maize, and iii) continuous maize with addition of 3000 kg/ha pigeonpea residues and iv) continuous maize fertilized with 69 kgN/ha, and (2) to quantify the impact of biophysical factors (soil and weather) responsible to spatial variation of maize yield across

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http://dx.doi.org/10.1016/j.agsy.2017.07.014
Received 14 February 2017; Received in revised form 19 July 2017; Accepted 24 July 2017

Malawi. We chose these four strategies to capture management that is currently practiced on local farms. The baseline scenario in this study is continuous maize that is unfertilized, which represents the typical management in resource-constrained smallholder farming systems. Pigeonpea in rotation with maize and continuous maize with pigeonpea residue incorporated has been tested in both local farmers' fields and research stations (Snapp et al., 2002; Phiri et al., 2010; Gwenambira, 2015), and continuous maize fertilized with the addition of 69 kgN/ha has been practiced in researcher-managed fields (Thierfelder et al., 2013).

2. Material and methods

2.1. Study region and spatial distribution of cropland

Malawi is located in southeastern Africa, within the boundary of 9.4°S, 32.7°E and 17.1°S, 35.9°E. The western part of the country has a humid subtropical climate and the eastern part, near Lake Malawi, is considered a tropical savanna climate (Kottek et al., 2006). The main soil types in Malawi, Alfisols, Oxisols and Ultisols, characterized by low soil organic matter content, sandy/sandy loam texture, low water holding capability and high susceptibility to soil erosion (Buresh and Tian, 1997; Snapp, 1998).

Cropland distributions in Malawi were derived from the 1-km-resolution global cropland product developed by the International Institute for Applied Systems Analysis-International Food Policy Research Institute (Fritz et al., 2015). We extracted the likelihood of each pixel being cropland by using a scoring system that measured the agreement between multiple land cover products. A value of 1 in this global cropland product represented the highest likelihood of being cropland and the value of 0 represented the lowest likelihood. We included pixels with likelihoods of at least 0.6 as cropland (Fig. S1).

2.2. Systems approach to land use sustainability (SALUS) model overview

SALUS is a process-based crop system model designed to simulate climate-soil-crop-management interactions and their impacts on crop growth and development, water and nutrient cycles (Fig. 1). The model stems from the well-known Crop Environment Resource Synthesis (CERES) model with various improvements in crop growth, nutrient- and water-cycle (Basso and Ritchie, 2015; Basso et al., 2016). SALUS uses a minimum dataset of soil information at each layer, daily weather information, crop genetics parameters and management data as input, and runs on a daily time step for multiple years. SALUS contains two approaches to calculate crop development and growth. A simple approach based on leaf area index curve, crop durations and harvest index. LAI and biomass are adjusted to account for temperature effects on development, and stresses (water and nitrogen) on crop growth to capture environmental conditions occurring during the season (Dzotsi et al., 2013; Liu and Basso, 2017). The complex approach uses a series of genetic coefficients to calculate crop development and growth. In this paper, we used the complex model to simulate maize growth, and the simple model to simulate pigeonpea growth.

The nutrient cycle module was adapted from the Century model (Parton et al., 1988) with modifications to temperature, clay and water functions. Soil organic matter (SOM) decomposition, N mineralization, N immobilization and transformation to gaseous N, and three pools of phosphorous (P) are considered in the module. Three soil organic carbon pools - active, slow and passive - with varied turnover rates and C:N ratio are considered in the model to simulate SOM and N immobilization and mineralization. Fresh organic matter (i.e. crop residue) is divided into two pools, structural and metabolic, based on residue lignin and N content. SOC pools are initialized using the method presented by Basso et al. (2011). Results of SALUS SOC decomposition are presented in Senthilkumar et al. (2009).

The water balance module is based on Ritchie method similar to the one in the CERES models with new algorithms for runoff, infiltration, soil evaporation, plant transpiration and water redistributions (Suleiman and Ritchie, 2003). The SALUS model does not simulate weeds, pest or disease.

2.3. SALUS calibration

SALUS has been tested under numerous different climate and cropping systems. The simulated grain yield of cereal crops matched the field observations under a humid subtropical climate in Argentina (Albarenque et al., 2016), a Mediterranean environment in Italy (Basso et al., 2011; Pezzuolo et al., 2014) and a warm humid continental climate in the US (Basso and Ritchie, 2015). The model has been tested and used to simulate non-cereal crops, such as switchgrass, alfalfa and poplar (Liu and Basso, 2017; Syswerda et al., 2012). In addition, SALUS has been tested for SOC dynamics (Senthilkumar et al., 2009; Basso and Ritchie, 2015), plant N uptake and phenology (Basso et al., 2010), nitrate leaching (Giola et al., 2012; Syswerda et al., 2012), and tillage effects and management on yield and soil properties (Basso et al., 2015; Basso and Ritchie, 2012; Basso et al., 2006).

To validate the capability of SALUS to represent maize growth under Malawi's climatic conditions, we compared the SALUS-simulated results with field observations at four locations across Malawi in 1998–1999, shown in Robertson et al. (2000) (Fig. S1). For the validation simulation, we used soil parameter values and management information at each location as reported by Robertson et al. (2000). We

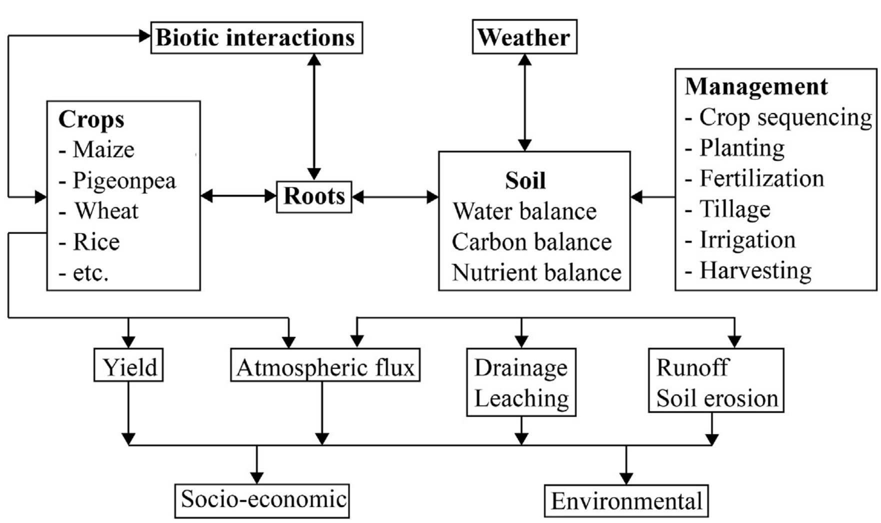

Fig. 1. Overview of the systems approach to land use sustainability (SALUS) model (Basso et al., 2006).