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Accurate crop yield predictions from modelling tree-crop interactions in gliricidia-maize agroforestry

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ABSTRACT

Agroforestry systems, containing mixtures of trees and crops, are often promoted because the net effect of interactions between woody and herbaceous components is thought to be positive if evaluated over the long term. From a modelling perspective, agroforestry has received much less attention than monocultures. However, for the potential of agroforestry to impact food security in Africa to be fully evaluated, models are required that accurately predict crop yields in the presence of trees. The positive effects of the fertiliser tree gliricidia (*Gliricidia sepium*) on maize (*Zea mays*) are well documented and use of this tree-crop combination to increase crop production is expanding in several African countries. Simulation of gliricidia-maize interactions can complement field trials by predicting crop response across a broader range of contexts than can be achieved by experimentation alone. We tested a model developed within the APSIM framework. APSIM models are widely used for one dimensional (1D), process-based simulation of crops such as maize and wheat in monoculture. The Next Generation version of APSIM was used here to test a 2D agroforestry model where maize growth and yield varied spatially in response to interactions with gliricidia. The simulations were done using data for gliricidia-maize interactions over two years (short-term) in Kenya and 11 years (long-term) in Malawi, with differing proportions of trees and crops and contrasting management. Predictions were compared with observations for maize grain yield, and soil water content. Simulations in Kenya were in agreement with observed yields reflecting lower observed maize germination in rows close to gliricidia. Soil water content was also adequately simulated, except for a tendency for slower simulated drying of the soil profile each season. Simulated maize yields in Malawi were also in agreement with observations. Trends in soil carbon over a decade were similar to those measured, but could not be statistically evaluated. These results show that the agroforestry model in APSIM Next Generation adequately represented tree-crop interactions in these two contrasting agro-ecological conditions and agroforestry practices. Further testing of the model is warranted to explore tree-crop interactions under a wider range of environmental conditions.

1. Introduction

In much of sub-Saharan Africa there is a projected decline in per capita food availability (Rosen et al., 2012) that is exacerbated by land degradation already affecting a third of the land area (Bai et al., 2008; Tittonell and Giller, 2013; Vågen et al., 2016). Yields of staple crops remain well below those in other continents and what could be obtained with better water and nutrient management (Mueller et al., 2012). The gap between actual and potential yields could be reduced through more efficient use of resources. Agroforestry is increasingly promoted as an important tool in addressing soil fertility issues in Africa (Glover et al., 2012). This is because trees, when incorporated in crop fields, are often able to reduce soil erosion, improve water and nutrient cycling and increase both soil organic carbon and the abundance and

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activity of beneficial soil organisms (Barrios et al., 2012). However, trees can also compete with crops for water and nutrients and reduce the land area available for crops, so that the net effect of agroforestry on crop yields over time will depend on attributes and interactions of the trees, crops, soil, climate, and management (Bayala et al., 2012).

Fertiliser trees including gliricidia (*Gliricidia sepium*), intercropped or in improved fallows, have been shown to increase maize (*Zea mays*) yield over current farmer practice across sub-Saharan Africa (Sileshi et al., 2008), but with different performance across soil types, climates and fertiliser application (Sileshi et al., 2010). This variation in performance presents a major challenge in scaling up adoption of fertiliser trees in Africa, because it implies that there is a need to take into account fine scale variation in context amongst smallholder farmers, so that appropriate fertiliser tree options can be matched to sites and farmer circumstances (Coe et al., 2014). Addressing this need could greatly accelerate scaling up, through accurate simulation of crop yields obtainable from alternative fertiliser tree options in different locations, thereby reducing the risk to farmers adopting agroforestry (Coe et al., 2016). A key constraint with respect to addressing food security in previous attempts to model gliricidia-maize agroforestry in Malawi, has been a difficulty in accurately predicting crop yields (Chirwa et al., 2006; Kerr, 2012).

Scaling up the use of other agroforestry practices in Africa could also benefit from a field scale modelling capability. For example, the ACIAR (Australian Centre for International Agricultural Research)-funded ‘Trees for Food Security’ project, implemented by the World Agroforestry Centre (ICRAF), is developing such capabilities for *Alnus*-potato and *Grevillea*-maize in Rwanda, and for *Faidherbia*, *Croton* and other tree species grown with wheat, maize, or teff in Ethiopia (Muthuri et al., 2016). Evaluation of such diverse tree, crop, climate, soil and management conditions requires a highly flexible and robust modelling framework to be developed (Luedeling et al., 2016). In the Trees for Food Security project, the Rwandan and Ethiopian governments are keen to extend the use of agroforestry, but are unable to test all possible tree-crop-management combinations across the agro-ecologies that occur in each country. With validation at some contrasting sites, virtual experiments could be conducted using simulation models, to predict performance in untested circumstances, with enough confidence to guide the development of agricultural policies and the promotion of agroforestry practices. Yield forecasting to guide operations is a common use of APSIM (Agricultural Production Systems Simulator, www.apsim.info) and similar models by consultants or governments for crops like wheat, maize and soybean (Holzworth et al., 2014; Hoogenboom et al., 2015) that could be extended to include situations where crops are grown in agroforestry combinations through the use of a robust tree-crop interaction model.

A recent evaluation of tree-crop interaction modelling at field scale (Luedeling et al., 2016), concluded that it would be useful to adapt the widely-used crop modelling framework in APSIM (Holzworth et al., 2014, 2015), that can reliably predict yields of major staple crops across a wide range of sites globally. Here we report on the first attempts to simulate tree-crop interactions and crop yield using APSIM Next Generation. The agroforestry practices that we simulated were gliricidia-maize intercropping at two contrasting sites in Kenya and Malawi, for which there were sufficient historical data to both parameterise the model and evaluate model performance. Gliricidia is a nitrogen-fixing tree native to Central America that is widely promoted as a fertiliser tree in Africa (Wise and Cacho, 2005). In Malawi and Zambia, gliricidia-maize intercropping is widely practiced (Akinnifesi et al., 2010; Sileshi and Mafongoya, 2006). The specific aim of the research reported here was to evaluate the new agroforestry model incorporated within the APSIM Next Generation modelling framework for simulating interactions in gliricidia-maize intercropping at two contrasting sites in Africa: Machakos in Kenya, and Makoka in Malawi, with a focus on maize yields, short-term soil water dynamics, and long-term soil carbon concentrations.

2. Materials and methods

2.1. Site description

2.1.1. Machakos, Kenya

The Machakos site (1° 33′ S, 37° 08′ E, 1600 m elevation) is located 56 km southeast of Nairobi, Kenya. This site was chosen because water was usually more limiting to maize growth than nutrients. This is a semi-arid tropical site with mean annual rainfall of 740 mm. The climate is relatively cool, with an annual mean daily temperature of 20.1 °C. Rainfall has a bimodal distribution with one rainy season from October to December and the other from March to May. Soils are classified as Haplic Lixisols (WRB classification; Dewitte et al., 2013), which predominate in the area. Top soil (0–15 cm) comprised 1.0–1.5% organic carbon with a pH of 6.0 to 6.5, and base saturation ranging from 50 to 80% (Mathuva et al., 1998, Odhiambo et al., 2001, Wilson et al., 1998). Surface texture was sandy clay loam. The soil was of variable depth averaging 1.6 m, with bulk density increasing with depth from 1.19 to 1.67 g cm^{-3} (Ong et al., 2000). The availability of nitrogen, phosphorus and other nutrients was considered adequate for maize, and generally the site was considered to be more water-limited than nutrient-limited for maize growth. Govindarajan et al. (1996) observed strong competition for water between the gliricidia and crops, because of the concentration of tree roots in the top 0.5 m of soil where crop roots are also predominantly found.

2.1.2. Makoka, Malawi

The Makoka site (15° 30′ S, 35° 15′ E, 1030 m elevation) is located 20 km south of Zomba, Malawi. This site was chosen because N was more limiting to maize growth than other nutrients or water. This is a sub-humid sub-tropical site with mean annual rainfall of 1024 mm. Mean daily temperature varies between 16 and 24 °C. Unlike the Machakos site, Makoka has a unimodal distribution of rainfall from November to April. Soils are classified as Ferric Lixisols (WRB classification). Top soil (0–20 cm) comprised 0.88% organic carbon, with total N at 0.07%, and pH 5.9 (Ikerra et al., 1999). Surface texture was sandy clay. Soil was at least 1.2 m deep, with plant available water capacity 118–161 mm (Robertson et al., 2005). Low availability of nitrogen was the main limitation to maize growth, as well as seasonal variations in soil water content (droughts and saturation). Phosphorus was thought to be non-limiting to maize growth during the first few years of the experiment, but became co-limiting during the last few years (Akinnifesi et al., 2007).

2.2. Experiments

2.2.1. Machakos, Kenya

The experiment at Machakos consisted of three treatments in a randomized block design with four replicates. Two treatments are considered in this paper: (1) sole maize crop, and (2) maize grown between gliricidia trees. A treatment not used was maize grown with grevillea trees. There were two crops per year: maize (cultivar Katumani composite) during the long season, and beans during the short season. The experiment commenced in 1993, but only the two maize crops in the period March 1996 to July 1997 were reported by Odhiambo et al. (2001) and used here. Plots were 20 m × 18 m with maize planted 1 m apart between rows and 30 cm apart within rows. In plots with gliricidia, trees replaced the middle row of maize. No fertilisers were applied, and weeds were removed manually, twice each season. Gliricidia was side-pruned to leave branch-free stems to a height of 2.5 m; residues were removed from the experiment. Between March 1996 and July 1997, gliricidia grew in height from about 4.0 to 4.5 m (Wilson et al., 1998). Key measurements for this paper included maize germination percentage (1996 only) and grain yield, gliricidia height and root-length-density, and soil water content at 35 cm depth. Data were provided by Wilson et al. (1998) and Odhiambo et al. (2001).