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Multi-scale trade-off analysis of cereal residue use for livestock feeding vs. soil mulching in the Mid-Zambezi Valley, Zimbabwe

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ABSTRACT

Cereal residues represent a major resource for livestock feeding during the dry season in southern Africa. When kept on the soil surface instead of feeding them to livestock, crop residues can contribute to increasing soil fertility and maintaining crop productivity in the short- and the long-term. We explored these trade-offs for smallholder cotton–sorghum farming systems in the semi-arid Zambezi Valley, northern Zimbabwe. The analysis was done using simulation models at three scales, the plot, the farm and the territory, to simulate the effects of different sorghum residue allocations to livestock feeding vs. soil mulching, in combination with different application rates of mineral nitrogen fertilizer on crop productivity. The plot-scale simulations suggest that without N fertilization soil mulching has a positive effect on cotton yields only if small quantities of sorghum residues are used as mulch (average cotton yields of 2.24 ± 0.41 kg ha^{-1} with a mulch of 100 kg ha^{-1} vs. 1.91 ± 0.29 kg ha^{-1} without mulch). Greater quantities of mulch have a negative effect on cotton yield without N fertilization due to N immobilization in the soil microbial biomass. With applications of 100 kg N ha^{-1}, quantities of mulch up to 3 t ha^{-1} have no negative effect on cotton yield. Results at farm-scale highlight the fundamental role of livestock as a source of traction, and the need to feed a greater proportion of sorghum residues to livestock as herd and farm sizes increase. Farmers with no livestock attained maximum crop production when 100% of their sorghum residue remained in the field, as they do not have access to cattle manure. The optimum fraction of crop residue to be retained in the fields for maximum farm crop production varied for farmers with 2 or less heads of cattle (80% retention), with 2–3 heads (60–80%), with 4 or more heads (40–60%). At the scale of the entire territory, total cotton and sorghum production increased with the density of cattle, at the expense of soil mulching with crop residues. The results of our simulations suggest that (i) the optimum level of residue retention depends on the scale at which trade-offs are analyzed; (ii) the retention of all of the crop residue as mulch appears unrealistic and undesirable in farming systems that rely on livestock for traction; and (iii) crop residue mulching could be made more attractive to farmers by paying due attention to balancing C to N ratios in the soil and by promoting small-scale mechanization to replace animal traction.

1. Introduction

In most farming systems of sub-Saharan Africa (SSA), livestock provide a number of key functions that are crucial to rural livelihoods. These include the provision of nutritious animal products, the generation of income, the cycling of nutrients, the provision of traction for land cultivation, inflation-proof saving, insurance, and the display of status (Schiere et al., 2002; Powell et al., 2004). In many farming systems of SSA, crop residues represent a major resource for feeding of livestock during the dry season (Valbuena et al., 2012).

A major cause of low crop productivity in SSA is soil degradation (e.g., Sanchez, 2002). Conservation agriculture (CA) is currently being widely promoted to attempt to avert this, while increasing

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food security (www.fao.org/ag/ca). Retention of crop residues as mulch is a fundamental component of CA. CA may significantly increase water available to the crop by reducing water runoff and soil evaporation (Thierfelder and Wall, 2012; Mupangwa et al., 2011). CA may also enable early planting (Haggblade and Tembo, 2003), which may result in a more efficient use of rainfall by the crops. Thus, CA may reduce the risk of crop failure during times of inadequate rainfall, and may stabilize crop yields when rains are poorly distributed (e.g., Mkoga et al., 2010; Thierfelder and Wall, 2012).

In the mixed crop–livestock systems of SSA, smallholders face important trade-offs in the allocation of crop residues for livestock feeding during the dry season on the one hand, and for soil fertility maintenance and crop production on the other (cf. Baudron et al., 2013). Due to the interconnectedness between the crop and the livestock sub-systems (Schiere et al., 2002), changes in crop residue allocation may impact the overall farming system and have important consequences for smallholder livelihoods. Yet, most agricultural experiments have a narrow technological focus and are short-lived, which makes long-term effects uncertain (Powell et al., 2004; Schlecht et al., 2004; Mkoga et al., 2010). The use of simulation models is an effective way to explore the impact of different crop or livestock management options at the scale of the farm or territory, and in the long-term (e.g., Giller et al., 2010).

Several studies have used simulation models to explore the impacts of different crop residue management options at plot-scale (e.g., Mkoga et al., 2010), while few studies have used simulation models at higher scales (e.g., Belem et al., 2011; Rufino et al., 2011; Zingore et al., 2011). However, the consequences of different residue management options on agricultural productivity across scales have been little studied. Moreover, studies using simulation models at territory-scale have often considered livestock as being managed collectively (e.g., Rufino et al., 2011; Zingore et al., 2011), while here we study the effects of competition between herds of individual farmers for common biomass resources.

2. Material and methods

2.1. Study area

The study was conducted in the Mbire District in northern Zimbabwe, an area located between 30°00 and 31°45′ E and 16°00 and 16°30′ S. Mbire District is part of the Mid-Zambezi Valley, a formation characterized by the former floodplains of the Zambezi River, at an average altitude of 400 m above sea level. The area is characterized by low rainfall, and severe dry spells during the growing season, resulting in a low agricultural production potential (Baudron et al., 2011a). There are two clearly defined seasons: a short rainy season with 110–140 days of rainfall from December to March and a long dry season from April to November. Rainfall is highly variable within seasons, and across small distances. Sorghum (*Sorghum bicolor* (L.) Moench) is the major cereal crop and is grown in rotation with cotton (*Gossypium hirsutum* L.) on the interfluves, while maize (*Zea mays* L.) is mostly grown along river banks.

2.2. Modeling approach

We analyzed through simulation modeling the impact of sorghum residue management at three scales: plot, farm and village territory. At plot-scale, we quantified the effects of the retention of sorghum residues as mulch on the productivity of the following cotton crop. At farm- and territory-scale, we analyzed trade-offs in the use of sorghum residues between crop production and animal keeping in the long-term (150 years for the farm-scale and 10 years for the landscape-scale). At these scales, we used the farm typology developed in the study area by Baudron et al. (2011a), which is based on the importance of animal draught power and cotton as the main cash crop. The four farm types are: hand-hoe farmers not growing cotton (Type 1), hand-hoe farmers growing cotton (Type 2), ploughing farmers owning less than two pairs of draught animals (Type 3), and ploughing farmers owning two or more pairs of draught animals (Type 4). Selected characteristics of these four farm types are shown in Table 1. Three types of fields were considered: fields under sorghum–cotton rotation, fields under sorghum monocropping (the case of Type 1 farmers who do not grow cotton), and fields under cotton monocropping (the case of Type 4 farmers that grow more cotton than sorghum).

The overall approach used in the study follows the principles of *ad hoc* modeling (Affholder et al., 2012). At plot-scale we used a process-based, detailed crop growth model to simulate cotton and sorghum yields over one growing season. At higher spatial or temporal scales (i.e., farm and territory, and/or over several years) we used simplified summary models instead of more complex and detailed process-based models (as in Chikowo et al., 2008). In general, as the scale of analysis becomes coarser, and larger systems are considered, smaller components and more detailed processes have to be aggregated to maintain manageable complexity in models (Rastetter et al., 1992).

2.2.1. Short-term simulations at plot-scale: APSIM

To explore the short-term effects of different sorghum residue and fertilizer management on the productivity and water and nitrogen (N) use efficiency of cotton we used the Agricultural Production Systems Simulator 7.3 (APSIM, Keating et al., 2003). A number of studies (e.g., Probert, 2007; Chikowo et al., 2008; Mupangwa et al., 2011) have demonstrated that APSIM predicts reasonably well crop yields under the farming conditions of Southern Africa, including under CA management.

2.2.2. Long-term simulation at farm-scale: CLIF

To explore the long-term effects of different sorghum residue, fertilizer and manure management on farm productivity, a simple farm-scale model was developed: the Crop–Livestock Interaction at Farm-scale (CLIF) model. In CLIF, crop yields are calculated through summary functional relationships obtained from a sensitivity analysis of APSIM calibrated for the study area (as in Chikowo et al. (2008)). CLIF incorporates the soil organic C module of FIELD (Tittonell et al., 2010). Livestock feeding and manure production on sorghum residues are represented by simple equations that were derived from empirical data (Fig. 1). The crop and livestock subsystems are linked by feedbacks through which (1) cattle are fed during the dry season by the fraction of sorghum residues not used as mulch, while (2) the provision of manure and traction by cattle affect crop yield and crop area, respectively. CLIF uses a seasonal time-step.

2.2.3. Long-term simulation at territory-scale: the SABLE model

To analyze interactions between farms – in particular through e competition for sorghum residues in a context of communal grazing – a simple agent-based model was developed using the software NetLogo (version 4.1.3, 2011): the Simplified Agent Based Land use Exploration (SABLE) model (Fig. 2). NetLogo is a multi-agent programmable modeling environment well suited to the exploration of the connection between the micro-level behavior of individuals and the macro-level patterns that emerge from the interactions between these individuals (Wilensky and Resiman, 2006). SABLE uses a weekly time-step.

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