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Crop production and soil water management in conservation agriculture, no-till, and conventional tillage systems in Malawi

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ABSTRACT

Smallholder farming in southern and eastern Africa is constrained by low water-use efficiency, frequent dry spells, and drought. Conservation agriculture (CA), defined as minimal soil disturbance, year-round ground cover, and crop rotations, is being promoted as a way to sustainably improve water-use efficiency, reduce soil erosion, and boost crop production. In this study, three cropping systems – continuous no-till maize, CA rotation, and conventional tillage rotation – were established on smallholder farms in the Nkhotakota and Dowa districts, two distinct agroecological zones in Malawi. Three-year crop rotations of cassava, cowpea, and maize and cassava, soybean, and maize were implemented in CA and conventional tillage, respectively, in Nkhotakota. In Dowa, a 3-year rotation of sweet potato, bean, and maize was implemented in both CA and conventional tillage. Cropping systems were analyzed for their impact on infiltration, soil moisture content, sediment runoff, earthworm and termite abundance, and crop production from 2011 to 2014. In Nkhotakota, which had high potential evapotranspiration and low soil water-holding capacity, residue retention was positively correlated with infiltration and no-till and CA increased soil water content (0–60 cm) compared to conventional tillage by an average of 20 mm. In Dowa, which had lower potential evapotranspiration, eliminating tillage and retaining residue did not improve infiltration or soil water content. In 2013/2014, no-till and CA reduced sediment runoff by 1537 kg ha^{-1} and 1309 kg ha^{-1} in Nkhotakota and 346 kg ha^{-1} and 209 kg ha^{-1} in Dowa, respectively, compared to conventional tillage. Tillage and residue management did not have a significant impact on sweet potato, cassava, bean, soybean, or cowpea production. Crop rotations had the greatest impact on maize yields in 2013/14, with CA and conventional tillage rotations increasing maize yields compared to no-till maize by 2525 kg ha^{-1} and 2145 kg ha^{-1} in Dowa and 1364 kg ha^{-1} and 469 kg ha^{-1} in Nkhotakota, respectively. However, cumulative protein production was greater in no-till than CA and conventional tillage rotations in Dowa and greater than conventional rotations in Nkhotakota. Rotation crop productivity needs to be improved with better yielding grain legumes and other higher protein crops before widespread adoption of diverse rotations can occur on smallholder farms in eastern and southern Africa.

1. Introduction

Conservation agriculture (CA) is being promoted by international and non-governmental organizations as a means of overcoming agricultural production constraints, reversing soil degradation, and mitigating the impacts of climate change in southern and eastern Africa (Corbeels et al., 2013). Conservation agriculture is characterized by three principals: (1) continuous minimal soil disturbance, (2) year-round soil cover, and (3) crop rotations (FAO, 2001). Conservation agriculture provides many ecosystem services instrumental in improving agricultural productivity: reducing moisture deficits, breaking up pest and disease cycles, minimizing weeds, enhancing nutrient cycling and soil fertility, improving the biodiversity of soil biota, reducing soil erosion, and increasing carbon sequestration (Kassam et al., 2009; Palm et al., 2013). Increased agricultural productivity derived from these ecological services and lower production costs have led to widespread adoption of CA throughout North and South America and Australia, where agricultural systems are generally large-scale and highly mechanized (Kassam et al., 2009). However, CA has not consistently increased crop yields relative to conventional tillage globally, but rather is most effective in dry agroecosystems and

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when all three CA principles are implemented (Pittelkow et al., 2014; Rusinamhodzi et al., 2011).

Conservation agriculture's ability to transform smallholder agriculture in southern and eastern Africa, which is dominated by hand labor and animal traction, is highly debated (Giller et al., 2009). Concerns regarding CA include reduced yields in the first years of adoption, high labor demands when weeding is done exclusively by hand, increased input costs, competition for crop residue between livestock feed and surface mulch, and its promotion as a one-size-fits-all cropping system that ignores site-specific agroecological and socio-economic conditions (Baudron et al., 2012a; Brouder and Gomez-Macpherson, 2013; Corbeels et al., 2014; Giller et al., 2009; Valbuena et al., 2012 Giller et al., 2009; Valbuena et al., 2012). To date, CA adoption by smallholder farmers in Africa has been limited (Kassam et al., 2009). However, an increasing trend has been reported in Zambia, Malawi, and Zimbabwe (Wall et al., 2013).

Agricultural production in southern and eastern Africa suffers from many interrelated constraints including moisture deficits, low soil fertility, lack of access to credit, quality seed, and fertilizer, unsustainable management practices, and dysfunctional markets. Moisture deficits derive from low green water use efficiency (the amount of rainwater used for transpiration), frequent dry spells, and drought (Rockström et al., 2003; Stroosnijder, 2008). High rainwater runoff, poor water storage in soils, and large evaporative losses from soils result in green water use efficiencies of only 15–30% in much of southern and eastern Africa (Rockström et al., 2003; Stroosnijder, 2008). In-season dry spells that severely depress crop yields occur one or two years out of every five (Rockström et al., 2003). In addition to current challenges, moisture deficits are predicted to increase as the impacts of climate change increase, further depressing agricultural productivity in the region (Challinor et al., 2007; Lobell et al., 2008).

Conservation agriculture can offer immediate advantages to smallholder farmers by increasing rainwater harvesting and serving as a mitigation strategy against climate change and late or variable rainfall (Pittelkow et al., 2014; Rockström et al., 2009; Thierfelder and Wall, 2010). Long-term studies in Zimbabwe and Zambia reported that eliminating tillage and retaining residue can quadruple rainwater infiltration relative to conventional tillage (Thierfelder et al., 2012a,b). Increased soil water content and crop yields have been reported in Kenya, Zimbabwe, Zambia, and Malawi when these two CA principles are implemented (Gicheru et al., 2006; Thierfelder et al., 2009, 2010, 2012c). Conversely, Ito et al. (2006) found that the CA principles of no-till and residue retention positively impacted maize yields in only two of five districts in Malawi after 3 years. In Zambia, no-till and residue retention had no impact on continuous maize yields in three out of four years (Thierfelder and Wall, 2010). Baudron et al. (2012b) reported that CA increased rainwater runoff and reduced cotton yields compared to conventional tillage in sorghum–cotton rotations on soils prone to compaction and surface crusting in a three year study.

In Malawi and Zimbabwe, smallholder farmers who have adopted at least one CA principle have predominately adopted reduced tillage and residue retention; with more than 90% practicing no-till, 70–90% retaining crop residue, but less than 30% practicing crop rotation (Mazvimavi and Twomlow, 2009; Ngwira et al., 2014a,b). Reluctance to adopt diverse crop rotations stems from limited landholding sizes combined with an emphasis on planting staple grain crops, a lack of quality seed and soil inoculants for legumes, and poor markets for alternative crops (Ellis et al., 2003; Mloza-Banda and Nanthambwe, 2010; Snapp et al., 2002; Wall et al., 2013). When crop rotations are practiced by smallholder farmers they generally include grain legumes, green manure cover crops, or cash crops (Thierfelder et al., 2014). Grain legumes, in particular, are a crucial component of robust crop rotations, increasing soil N, fertilizer-use efficiency, agricultural productivity, and protein output (Franke et al., 2014; Snapp et al., 2010). Green manure cover crops can have significant long-term soil fertility benefits but smallholder farmers prefer crops that increase food production in the short-term (Bezner-Kerr et al., 2007). Adapting diverse crop rotations to smallholder farms in southern and eastern Africa will require that alternative food crops are incorporated into rotations. However, little research has been conducted on CA rotations or on integrating alternative food crops, such as sweet potato and cassava, into CA systems in southern and eastern Africa (Brouder and Gomez-Macpherson, 2013; Wall et al., 2013).

The hypothesis of this study was that smallholder farmers would improve soil–moisture relations and crop production by shifting from continuous maize-based no-till cropping systems to diverse CA rotations. Diverse CA and conventional tillage rotations were established on smallholder farms by incorporating different combinations of sweet potato, cassava, common bean, cowpea, soybean, and pigeonpea into existing maize-based CA and conventional tillage systems. The specific objectives of this study were to investigate the effects of continuous no-till maize and diversified CA and conventional tillage rotations on soil–water relations and crop production in two agroecological zones in Malawi.

2. Materials and methods

2.1. Experimental sites

This study was carried out during the 2011/12, 2012/13, and 2013/14 growing seasons in the Central region of Malawi. Malawi is a subtropical country located in south-eastern Africa with a sub-humid climate. Maize (*Zea mays* L.) is the primary food crop grown in the region and other important food crops are cassava (*Manihot esculenta* Crantz) and sweet potato (*Ipomea batatas* L.). Grain legumes grown in the area, either as intercrops or in rotation, include soybean (*Glycine max* L.), cowpea (*Vigna unguiculata* (L.) Walp), common bean (*Phaseolus vulgaris* L.), groundnut (*Arachis hypogaea* L.), and pigeonpea (*Cajanus cajan* (L.) Millsp.). Tobacco (*Nicotiana tabacum* L.), cotton (*Gossypium hirsutum* L.), and rice (*Oryza sativa* L.) are cultivated as cash crops.

Research sites were established in two districts, Nkhotakota (−13.06 S, 34.3 E; altitude: 498 masl) and Dowa (−13.47 S, 33.71 E; altitude: 1146 masl). During the course of the study, annual rainfall averaged 1450 mm and 834 mm at the Nkhotakota and Dowa research sites, respectively and had a unimodal rainfall distribution from November to April (Fig. 1a). Average daily temperatures were 26.6 °C and 21.0 °C in Nkhotakota and Dowa, respectively. Soils at Nkhotakota and Dowa research sites were coarse textured haplic *Luvisols* and haplic *Lixisols*,respectively (WRB, 1998).

2.2. Experimental design

Research plots were established on four smallholder farms in each district in November 2011. Representative smallholder farms were identified with the help of Total LandCare, a regional non-government organization headquartered in Malawi (www.totallandcare.org). All four study farms within each of the two districts had similar soil types and had already adopted CA principles, eliminating tillage and/or maintaining residue cover, on at least one field two years prior to November 2011. On each farm three plots were established: continuous no-till maize (NTM), conservation agriculture rotation (CAR), and conventional tillage rotation (CTR). The three plots on each farm were chosen so that they each had the same microclimate, slope, soil profile, and soil