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Simulating the impact of no-till systems on field water fluxes and maize productivity under semi-arid conditions

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ABSTRACT

Crop output from the smallholder farming sector in sub-Saharan Africa is trailing population growth leading to widespread household food insecurity. It is therefore imperative that crop production in semi-arid areas be improved in order to meet the food demand of the ever increasing human population. No-till farming practices have the potential to increase crop productivity in smallholder production systems of sub-Saharan Africa, but rarely do because of the constraints experienced by these farmers. One of the most significant of these is the consumption of mulch by livestock. In the absence of long term on-farm assessment of the no-till system under smallholder conditions, simulation modelling is a tool that provides an insight into the potential benefits and can highlight shortcomings of the system under existing soil, climatic and socio-economic conditions.

Thus, this study was designed to better understand the long term impact of no-till system without mulch cover on field water fluxes and maize productivity under a highly variable rainfall pattern typical of semi-arid South Africa. The simulated on-farm experiment consisted of two tillage treatments namely oxen-drawn conventional ploughing (CT) and ripping (NT). The APSIM model was applied for a 95 year period after first being calibrated and validated using measured runoff and maize yield data.

The predicted results showed significantly higher surface runoff from the conventional system compared to the no-till system. Predicted deep drainage losses were higher from the NT system compared to the CT system regardless of the rainfall pattern. However, the APSIM model predicted 62% of the annual rainfall being lost through soil evaporation from both tillage systems. The predicted yields from the two systems were within 50 kg ha^{-1} difference in 74% of the years used in the simulation. In only 9% of the years, the model predicted higher grain yield in the NT system compared to the CT system. It is suggested that NT systems may have great potential for reducing surface runoff from smallholder fields and that the NT systems may have potential to recharge groundwater resources through increased deep drainage. However, it was also noted that the APSIM model has major shortcomings in simulating the water balance at this level of detail and that the findings need to be confirmed by further field based and modelling studies.

Nevertheless, it is clear that without mulch or a cover crop, the continued high soil evaporation and correspondingly low crop yields suggest that there is little benefit to farmers adopting NT systems in semiarid environments, despite potential water resources benefits downstream. In such cases, the potential for payment for ecosystem services should be explored.

1. Introduction

The objective of improving household food security through uptake of crop improvement technologies in sub-Saharan Africa has been elusive due to the high variability of rainfall and associated risk to farmers in these largely semi arid areas. Crop production in semi-arid environments is heavily dependant on in-season spatial and temporal distribution of rainfall (Graef and Haigis, 2001). In southern Africa, the crop growing period typically extends from November to April and during this period rainfall normally occurs as short duration, heavy convective storms covering a few square kilometres (Tadross et al., 2005). Rainfall events are poorly distributed during the crop growing period, sometimes with more than 3 weeks between successive rainfall events in some seasons (Rockström et al., 2002). Such mid-season dry spells are characteristic feature of the semi-arid parts of southern Africa and their impact on smallholder crop production is sometimes more severe than that of drought (Cook et al., 2004; Usman and Reason, 2004; Twomlow et al., 2008a).

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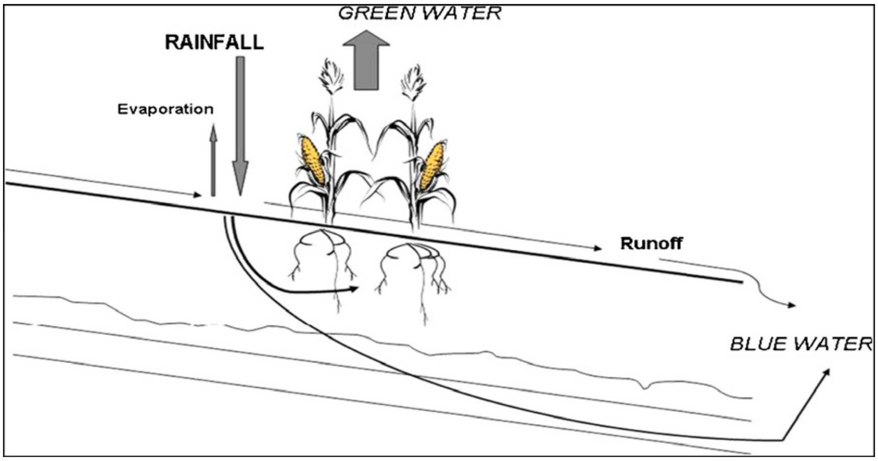

Fig. 1. Overview of rainfall partitioning into runoff, deep drainage, soil evaporation and transpiration (green water) (after Falkenmark and Rockström, 2004).

The effect of low and highly variable rainfall on smallholder farming is further exacerbated by poor partitioning of rainfall into the productive transpiration (green water) pathway (Fig. 1). In sub-Saharan Africa (SSA) 25–30% of rainfall can be lost[2] as surface runoff (Rockström et al., 1999) while 40% flows from the farmland as soil evaporation (Wallace, 1991). In fact only a small proportion of rainfall received at field scale flows through the crop system as transpiration (Gregory et al., 1997) i.e. a water flux which is considered to be productive. Thus, there is much potential for yield improvement through farming practices that promote better retention of rainwater and improved transpiration on the farmer's field for both large and small scale farming systems.

One such farming practice is the no-till (NT) system which hinges on establishing a crop without any prior tillage operations (Erenstein et al., 2008). The benefits of the NT system have been widely demonstrated and include improved soil conditions, improved rainwater productivity and increased cereal and legume yields (Erenstein et al., 2008; Gan et al., 2008; Twomlow et al., 2008b). In the short term NT systems are reported to substantially increase crop yields and reduce surface runoff from farmer's fields under smallholder conditions of SSA (Vogel, 1992; Munodawafa and Zhou, 2008; Twomlow et al., 2008b). However, the findings reported in the available literature are based on short term study, often based on single seasons results and rarely beyond three growing seasons. In the absence of long term on-farm assessment of the NT system, simulation modelling can be used to provide an insight into the potential long term benefits of the NT system on rainwater partitioning and crop productivity under smallholder farming and socio-economic conditions (Mathews, 2002).

The Agricultural Production Simulator Model (APSIM), a deterministic and process based model, has been used extensively for assessing the impact of different management practices on the productivity of smallholder agroecosystems under semi-arid conditions (Shamudzarira and Robertson, 2002; Delve and Probert, 2004; Dimes and Malherbe, 2006; Ncube et al., 2009). The APSIM model has performed well in predicting crop production and its interaction with climate, soil and management factors (Keating et al., 2003). The soil water balance module in APSIM, i.e. SOILWAT, is less well developed and calculates runoff using the USDA Curve Number (CN) approach, drainage when soil water content is more than the drained upper limit (DUL) of a given soil layer, and direct evaporation from the soil (Probert et al., 1998; Keating et al., 2003). Nevertheless, it has been shown to perform adequately in several similar studies and is selected here because of its well reported strength in simulating smallholder crop production in similar environments.

Thus, this study was designed to assess the potential long term effect of CT and NT systems on surface runoff, deep drainage, soil evaporation and maize yield using a sandy clay loam soil (typically in the order of 65% sand, 25% clay and 10% loam/silt), typical of the semi-arid conditions experienced by smallholder farmers in the Potshini catchment in South Africa. Data obtained from ongoing on-farm experiments (Dlamini et al., in press; Kosgei, 2009; Mchunu et al., 2011) were used to calibrate and verify the model before the long term simulation was performed.

2. Materials and methods

2.1. Description of experimental site

Potshini catchment (29.37°E, 28.82°S) is located in the western headwaters of the Thukela River within the Emmaus Quaternary Catchment (V13D). The altitude ranges from 1100 to 1400 m above sea level (Kosgei, 2009) and the 95 year mean annual rainfall is 719 mm based on the Bergville weather station which lies 10 km from the experimental sites. Daily minimum and maximum temperatures average 10 and 24 °C. Experimental fields used in the study were at 3% slope (Kosgei, 2009) with soils penetrable to 1.2–1.5 m depth (Kongo and Jewitt, 2006). The soils in Potshini catchment are Hutton (Oxisols), Avalon (Ferrasols), Estcourt (Planosols) and Mispah (Lithosols) and the soils at the four experimental sites were predominantly sandy clay loams.

2.2. Summary of the field experiment

Two tillage systems namely conventional mouldboard ploughing (CT) and ripping (NT) were compared at four farms over three cropping seasons (2005/06, 2006/07 and 2007/08) on farmers' fields. Conventional ploughing to a depth of 0.15 m was performed using an oxen-drawn mouldboard plough (VS 100) while an animal drawn MacGoy ripper was used for opening furrows at 0.9 m spacing and to a depth of 0.15 m in the NT system. In the CT system two ploughing operations were conducted, the first at 3 weeks before planting and then again at planting.

Runoff plots measuring 10 m × 2.45 m plots were established in each tillage system and the runoff water generated in each treatment was measured using a tipping bucket system (HOBO data logger). Soil water was monitored weekly using a TDR tube probe (IMKO Trime-T3). Daily rainfall measurements were made using manual raingauges installed at each farm and an automatic weather station with a tipping bucket system that was located within the

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[2] i.e. In this paper, we consider that this is a loss to the crop, but recognise that this is actually a redistribution in the hydrological cycle at large scales.

Table 1
Soil chemical and physical properties of the sandy clay loam soil used for calibrating the APSIM model. *Source*: Kosgei (2009), Dlamini et al. (in press), Mchunu et al. (2011).

Depth (cm)	pH (H_2O)	Organic carbon (%)	Bulk density (g cm^{-3})	SAT (mm mm^{-1})	DUL (mm mm^{-1})	LL (mm mm^{-1})
0–10	6.0	1.2	1.35	0.30	0.20	0.11
10–20	6.0	1.0	1.35	0.30	0.22	0.11
20–30	6.0	0.86	1.35	0.32	0.27	0.13
30–50	6.2	0.83	1.40	0.33	0.28	0.17
50–70	6.5	0.58	1.40	0.34	0.30	0.19
70–90	6.7	0.54	1.40	0.35	0.30	0.20
90–110	6.7	0.54	1.40	0.35	0.30	0.20
110–120	6.7	0.54	1.40	0.35	0.30	0.20

catchment. The full monitoring system is described in more detail by Kongo et al. (2010). In all tillage systems a short duration maize (*Zea mays* L.) variety PAN 6611 was planted in each seasons at 37,000 plants per-hectare. In all tillage systems the maize crop received 150 kg ha^{-1} fertilizer containing 18.5% nitrogen, 8.3% phosphate and 4.2% potassium. Weeds were controlled manually and also by herbicides (3% Senatar Extra-Glyphosate and 0.75% Dual Gold solution). The maize crop was harvested at maturity in all seasons.

2.3. Model parameterisation and calibration

APSIM performs crop production and water balance calculations at a daily time step, and thus requires input data at en equivalent time-step Daily rainfall, minimum and maximum temperatures, and solar radiation data were collected from South Africa Weather Services (SAWS) Bergville weather station which is located 10 km from Potshini experimental sites. Soil parameters used for calibrating the model (Table 1) were derived from field measurements made by Kosgei (2009), Dlamini et al. (in press) and Mchunu et al. (2011). For calibration purposes, a simulation was run from 1 October 2005 to 30 June 2008 and APSIM was reset at the start of the wet season on 1 October for soil water and nitrogen while organic carbon (OC) was allowed to accumulate in the soil with time because reducing tillage results in a buildup of soil organic matter (Derpsch, 2007). As the same sites were used in the three seasons of experimentation, plant available water capacity was set at 132 mm in the 0–1.2 m profile for a sandy clay loam soil. Default drained upper limit (DUL), lower limit (LL) and saturation (SAT) for maize grown on a sandy clay loam soil were adopted. The sandy clay loam soil had 68% sand, 22.5% clay and 9.5% silt (Kosgei, 2009). Initial soil nitrogen was set at 37 kg ha^{-1} (20 kg NO_3^- and 17 kg NH_4^+) based on data from Mchunu et al. (2011).

Runoff CN for bare soil was set at 75 according to the approach described by Littleboy et al. (1989). This accounts for the fact that the topography of the sites was relatively flat (<3% slope) and as highlighted by Kosgei (2009) that in both CT and NT systems the infiltration was generally high and runoff low – often lower than many would expect. The CT and NT tillage operations created surface roughness to varying degrees with the effect of furrows created by ripping on surface storage of rainwater lasting longer than in the CT system. The CN was therefore adjusted downwards by 10 and 20 units in the CT and NT systems respectively following the approach of Littleboy et al. (1989) and Littleboy et al. (1996), where the rainfall simulator conditions reported were felt to better reflect the conditions at Potshini than for example, the approach of Arabi et al. (2008) where the downward adjustment of CN is less, but where their SWAT application provides additional options to reflect changed runoff generation conditions. The first and second stage evaporation coefficients were set at 3 and 6 mm $day^{-0.5}$ which are recommended for medium to heavy textured soils in semi-arid environments (Chikowo et al., 2008; Ncube et al., 2009). The soil C:N ratio and SWCON coefficient were set at 15 at 0.5 respectively. The SWCON coefficient which indicates the proportion of water in excess of DUL that drains to the next soil layer (Keating et al., 2003) and is dependant on soil texture (Chikowo et al., 2008). Clay soils with poor drainage often have a SWCON coefficient of <0.5 while sandy soils can have values >0.8. The calibration process aimed at minimising the root mean square error (RMSE) between measured and predicted parameters. The root mean square error (RMSE) was calculated for comparison of observed and predicted data. A good model performance would be indicated by RMSE values as close to zero as possible. The RMSE was calculated as follows:

$$\mathrm{RMSE} = \left[1/n \sum (x_i - y_i)^2\right]^{0.5} \qquad (1)$$

where x_i is the predicted runoff or maize yield, y_i is the observed runoff or maize yield and n is the number of observations.

2.4. Model evaluation

Model evaluation was performed for each tillage system using the three seasons data for runoff (2005/06, 2006/07 and 2007/08) and two seasons data for maize yields (2005/06 and 2006/07). The predicted and observed data sets were compared statistically using the Index of Agreement (Willmott et al., 1985). The Index of Agreement (d) was calculated as follows:

$$d = 1 - \left\{ \frac{\sum_{i=1}^{n} (X_I - Y_I)^2}{\sum_{i=1}^{n} (|X_I| - |Y_I|)^2} \right\} \qquad (2)$$

where x_I and y_I are predicted and observed values respectively.

2.5. Model application

The long term simulation was run using soil properties of a sandy clay loam (Table 1). The 95 year climate record (1905–2000) derived from the SAWS Bergville weather station was used and the following scenarios were simulated:

- Double conventional mouldboard ploughing (CT) to a depth of 0.15 m, first ploughing on 1 November and second ploughing at planting every year.
- Oxen-drawn ripping (NT) to a depth of 0.15 m at planting every year.

In both tillage systems no mulch was applied as is the case in Potshini where crop residues are grazed *in situ* by livestock during winter months. Planting was done on 29 November each year and a density of 37,000 plants per-hectare was used in the simulation. All the other crop, soil and management conditions were set as described in the calibration process.

2.6. Reporting frequency

The APSIM model was set to report selected variables on a daily time step. The reported variables for the APSIM calibration stage were surface runoff, total biomass and grain yields. In the long term simulation the model was set up to report variables on a daily basis and the predicted variables were annual surface runoff, deep drainage, soil evaporation and maize grain yield. Predicted parameters from the CT and NT systems were compared using *t-tests* in Genstat Discovery Edition 3 (www.vsni.co.uk).

3. Results and discussion

3.1. APSIM calibration

3.1.1. Seasonal runoff

The APSIM model predicted surface runoff closely ($d = 0.97$; RMSE = 6.58 mm) in 2005/06 and 2006/07 seasons in the CT system (Fig. 2). The model also predicted well ($d = 0.72$; RMSE = 10.2 mm) surface runoff from the NT system in 2005/06 and 2007/08 seasons. Whilst the results can be considered reasonable for the short calibration period, some problem areas are noted. The over prediction of surface runoff from the CT system can be attributed to the fact that the October–April period received an unusually high 1010 mm which was well distributed throughout the 5 months. Antecedent soil water before each rainfall event was relatively high allowing more overland flow to be generated from the CT system. Soils with high antecedent soil water content often promote high generation of overland flow (Choudhary et al., 1997), but the CN based runoff generation approach used by APSIM is not able to account for this adequately. Similarly the under prediction of surface runoff from the NT system in 2006/07 season can be attributed to the fact that the APSIM model failed to take into account the high intensity (>10 mm h^{-1}) of some rainfall events that occurred between November and February during the 2006/07 season (Kosgei, 2009). In addition to total amount of a rainfall event, the intensity of the rainfall plays a substantial role in the generation of surface runoff (Rao et al., 1998b).

3.1.2. Maize yields

The predicted maize grain yield was consistent with measured values in the CT system ($d = 0.94$; RMSE = 0.45 tha^{-1}) in the two seasons (Fig. 3). However, in the NT system, APSIM predicted closely ($d = 0.81$; RMSE = 1.08 tha^{-1}) maize grain production in the 2006/07 season only. In both tillage systems the model under-predicted biomass production during the 2005/06 and 2006/07 seasons (Fig. 4). The values for d and RMSE were 0.96 and 1.32 tha^{-1} for the CT system while in the NT system the d and RMSE values were 0.52 and 3.47 tha^{-1}. Under prediction of grain and stover production in 2005/06 season which received 962 mm of rain can be attributed to the fact that soil nutrients could have limited growth of the simulated crop in a season with no soil moisture constraints. This suggests that initial N set in the model (37 kg ha^{-1}) and the N applied as inorganic fertilizer might not have been enough for the simulated maize crop when soil moisture was not limiting. The under prediction of both grain and biomass yields in 2006/07 season which received 336 mm of rainfall between planting and harvest (Kosgei, 2009) could be an indication of soil moisture limiting maize growth which the model was not able to account for.

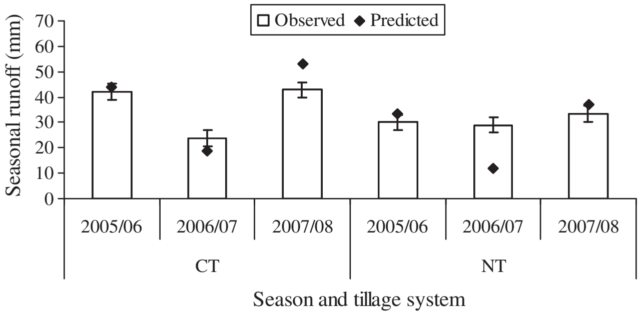

Fig. 2. Observed and predicted seasonal runoff from the CT and NT systems for 2005/06, 2006/07 and 2007/08 growing seasons in Potshini, South Africa. Vertical bars are standard errors of means.

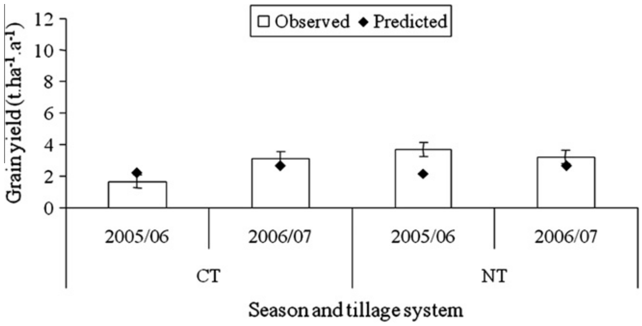

Fig. 3. Observed and predicted maize grain yield from CT and NT systems for 2005/06 and 2006/07 growing seasons in Potshini, South Africa. Vertical bars are standard errors of means.

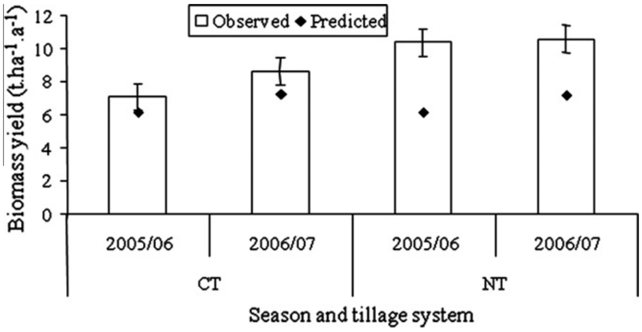

Fig. 4. Observed and predicted above-ground maize biomass yield from CT and NT systems for 2005/06 and 2006/07 growing seasons in Potshini, South Africa. Vertical bars are standard errors of means.

3.2. Long term simulation

3.2.1. Annual rainfall

Total annual rainfall used in the long term simulation varied from 356 to 1330 mm (Fig. 5) with a standard deviation and coefficient of variation of 235 mm and 33% respectively. Coefficients of variation (CV) for seasonal rainfall in Southern Africa range from 20% to 40% and often increase as seasonal rainfall amounts decrease and are reported to be the highest in sub-Saharan Africa (Nicholson, 2000; Rockström et al., 2002; Cooper et al., 2008;).

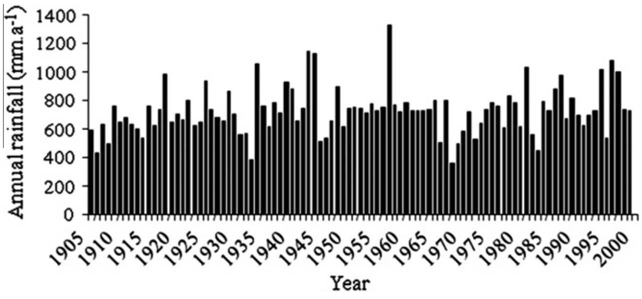

Fig. 5. Total annual rainfall measured at Bergville weather station between 1905 and 2000.

The driest and wettest years were 1968 and 1957 respectively with 52% of the years receiving more than the 95 year average rainfall for the Bergville weather station. The 95 year average rainfall (716 mm) was higher than the national average (464 mm) and lower than the world average rainfall (860 mm).

3.2.2. Surface runoff

In all the years the model predicted higher ($P < 0.05$) surface runoff from the CT system compared to the NT system (Fig. 6), a trend consistent with field measurements (Kosgei, 2009; Mchunu et al., 2011) and observations made elsewhere (Choudhary et al., 1997; Zheng et al., 2004). The APSIM model predicted a 28% reduction in surface runoff due to the use of no-till system compared to the CT system under similar soil, climatic and field management conditions. Under semi-arid conditions 25–30% of rainfall received can be lost as surface runoff from conventional systems (Rao et al., 1998b; Rockström et al., 1999) or no-till systems without mulch (Rao et al., 1998a). Even in the drought years such as 1968 (Fig. 5) the model predicted higher water losses from the CT system through surface runoff relative to the NT system. The model also predicted that 3% and 1% of the rainfall received in the driest year (1968) can be lost as runoff from CT and NT systems respectively. In wetter years, illustrated by 1957 (Fig. 5), the CT system would lose 25% more water as surface runoff compared to the NT system. In a wet year the predicted proportion of rainfall forming surface runoff is 18% and 13% from the CT and NT systems respectively.

A reduction in surface runoff signals reduced soil and nutrient losses from farmers' fields. Consequently this reduces siltation and water pollution of local and downstream water bodies. There is also a need for eliminating other constraints such as soil fertility through use of livestock manure and fertilizers in order to improve rainwater productivity which currently stands at only 30% under smallholder conditions in SSA (Rockström et al., 2010).

3.2.3. Deep percolation

The APSIM model predicted higher ($P < 0.05$) deep drainage from the NT system than CT in all years regardless of the rainfall received (Fig. 7). When averaged across years used in this simulation, the model predicted 19% more deep drainage from NT system than CT system. In the wettest year, illustrated by 1957, predicted drainage was 21% higher in the NT system compared to the conventional practice. However, the highest predicted deep drainage was 388 and 451 mm from CT and NT systems in 1934 with 1061 mm of rain. Daily rainfall distribution during 1934 was characterised by seven rainfall events of 40–60 mm and nine events of 20–32 mm. In the wettest year (1957 with 1330 mm), there were only four events of 40–65 mm and sixteen events of 20–39 mm.

In West Africa Rockström et al. (1999) reported deep drainage values of 200–330 mm in average years and 160 mm in drought years under smallholder farming conditions. Higher deep drainage, despite being a loss from a farmer's standpoint, can contribute immensely to local water resources through groundwater recharge. This is critical for communities in semi-arid environments who rely on borehole water for domestic use and livestock watering. However, there is high risk of groundwater pollution in the event of intense use of herbicides in the smallholder agroecosystems.

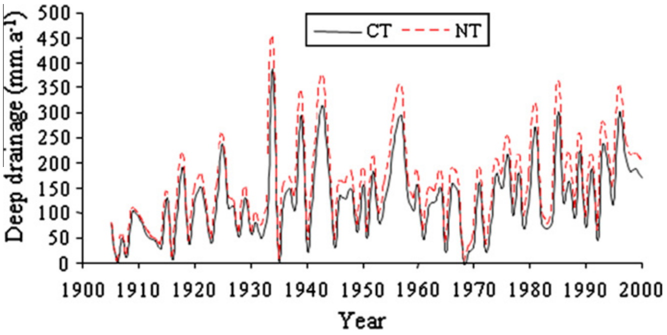

Fig. 7. Predicted deep drainage from the 0–1.2 m profile under CT and NT systems in semi-arid Potshini catchment, South Africa.

3.2.4. Soil evaporation

Under the unmulched conditions of the simulated experiment, APSIM predicted similar ($P > 0.05$) water losses from the CT and NT systems through soil evaporation in all years (Fig. 8). When averaged across the years, the model predicted 62% of the annual rainfall being lost through soil evaporation from both tillage systems. Predicted soil evaporation is consistently high despite differences in annual rainfall recorded at the Bergville weather station. This can be attributed to high soil evaporation soon after some rainfall events and the rapid drying of soil under semi-arid conditions (Rockström et al., 1999), highlighting the scope for introducing mulching and/or cereal-legume intercropping as these practices will aid in the partitioning of more rainwater into infiltration (Valentin et al., 2008) and aid in reducing soil evaporation particularly early in the growing season when crop leaf area is still small (Adams et al., 1976).

3.2.5. Maize productivity

The predicted grain yield from CT and NT systems are given in Fig. 9. The predicted yields from the two systems were within 50 kg ha^{-1} difference in 74% of the years used in the simulation. In only 9% of years did the model predict higher grain yield in the NT system compared to the CT system. Based on the climate record used for the simulation, the CT system outperforms the NT system in some years that receive above average rainfall. However, the NT system does outperform the CT in some years with below

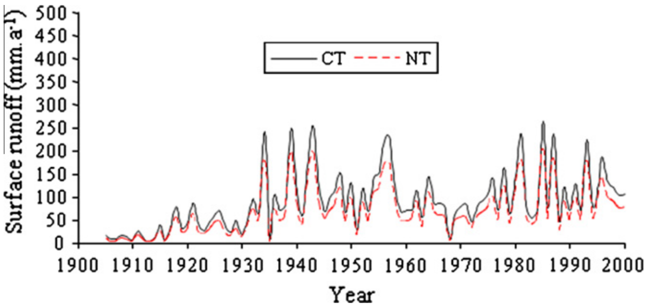

Fig. 6. Predicted surface runoff from fields under CT and NT systems using climatic and soil conditions of Potshini, South Africa.

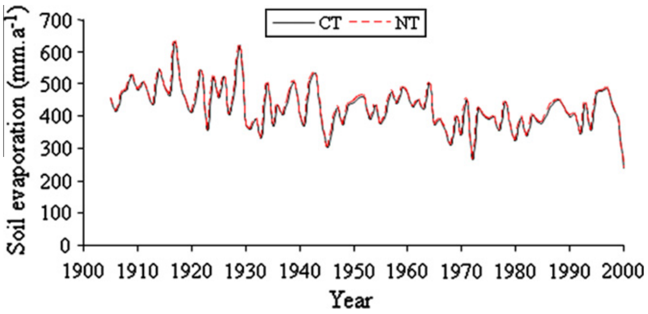

Fig. 8. Predicted soil evaporation from CT and NT systems under unmulched conditions in semi-arid Potshini catchment, South Africa.

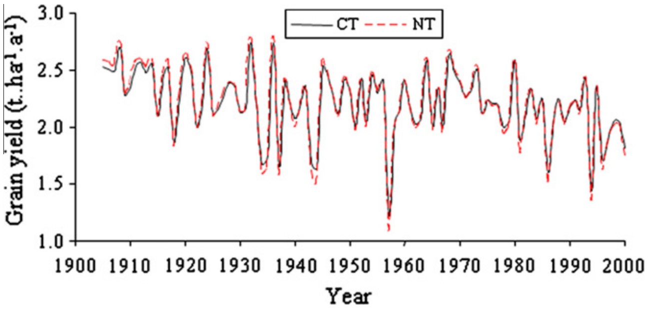

Fig. 9. Predicted maize grain yields from the CT and NT systems under the soil and climatic conditions of Potshini catchment over 95 years.

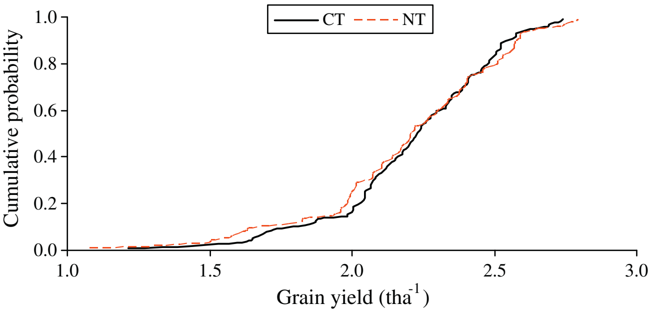

Fig. 10. Probability of producing maize grain from CT and NT systems based on daily rainfall, temperature and solar radiation values of Bergville SAWS in semi-arid South Africa.

average rainfall. The predicted grain yields from both systems are within the range of national average of <2–3 tha^{-1} for South Africa (FAO, 1997). In circumstances where smallholder farmers have resources to achieve yields of more than 2.5 tha^{-1}, the NT system appears to be a better option as illustrated in Fig. 10. Assuming no other management interventions, in areas where maize yield potential is less than 2.5 t ha^{-1}, and in the absence of mulch or some other cover, it makes no difference whether smallholder farmers use either CT or NT system. Many studies have shown that in NT systems inclusion of surface cover through mulching with stover, cereal-legume intercropping, crop rotation and the judicious use of organic and inorganic fertilisers bring about yield and soil productivity gains (Salinas-Garcia et al., 1997; Arshad et al., 1999; Halvorson et al., 2002; Erenstein et al., 2008). The high soil evaporation simulated by the model in this study, clearly shows the opportunity for the growth of cover crops or some other form of cover to limit soil evaporation and enhance transpiration and thus biomass yield. However, it should be noted that the modelled separation between soil evaporation and deep drainage could not be adequately calibrated and the relative portions of these two components of the water balance could differ significantly from the simulation results. Furthermore, the complexity of the socio-economic systems in which these smallholder farmers operate, and in this context, particularly the issue of livestock grazing and the resource constraints under which the farmers operate mean that there is little incentive to the farmer of adopting NT practices. However, the simulated results clearly indicate that improved infiltration and correspondingly less runoff and improved drainage through the soil occurs when NT is adopted. This could provide an opportunity for other stakeholders in the catchment to explore payment for ecosystem services type approaches to support smallholder farmers to adopt NT systems, address the issue of mulching and/or cover crops and so provide a catchment wide benefit.

4. Conclusion and recommendations

The APSIM model was calibrated using measured data and then applied to assess the long term impact of no-till system on field water fluxes and maize productivity under semi-arid conditions of South Africa. The long term simulation indicated that the no-till system has greater potential of reducing surface runoff from cropped smallholder fields. Rainwater and plant nutrients will therefore be retained in the field thereby increasing chances of improved water and crop productivity under semi-arid smallholder conditions. In these conditions, the long term simulation also suggested that the NT system can recharge the groundwater resources through increased deep drainage out of the rooting zone. Based on the runoff and deep drainage simulations, the large scale uptake of NT system could have large and significant on-site (farmer's field) and downstream impacts on water availability and use. Soil water losses through evaporation from CT and NT systems are high under unmulched conditions in the semi-arid environment used in the current study.

The CN based approach to runoff generation used by the APSIM model has some major limitations. It was noted that the model was not able to adequately account for antecedent moisture conditions in the calibration period, and this shortcoming is most likely carried through to the simulation of the longer time period. The approach cannot effectively distinguish between crust or sub-surface controls on infiltration and the assumption that CN is static through the growing season is not correct as both the kinetic energy of the rainfall and the growth of the crop will change the surface conditions through the growing season Furthermore, the relatively simple soil water balance approach inherent in the model, limits the extent to which the model can represent the suppression of soil evaporation and the partitioning of water between soil evaporation and drainage to groundwater. Interception is not considered at all. Therefore, there are high levels of uncertainty in the water balance aspects of this study, which may in turn compromise the crop yield estimates, despite the process based nature of those components of the model. Thus, it is recommended that further studies of this nature carefully consider the need for both sound hydrological and crop yield modelling.

Models such as HYDRUS (Gates et al., 2011) and SWAT (Andersson et al., 2009) have been applied in similar studies, but in the case of HYDRUS, crop yield estimation is not possible and root water uptake simulation is fairly rudimentary, and SWAT has the same limitations as APSIM in relying on CNs to control runoff generation and the subsequent soil water processes. For example, Garg et al. (2011) noted that different types of *in situ* agricultural management are parameterised in the same way with the same values leading to some uncertainty in such studies. The ACRU Agrohydrological Modelling System (Schulze, 1995) has both sophisticated rainfall-runoff and crop yield routines, has been applied in similar studies elsewhere (Lumsden et al., 2003) and is strong candidate model for future studies of this nature.

Over the time period simulated, there was no significant improvement in crop yield under the NT system. However, the predicted grain yield indicates that the effect of the NT system on crop productivity depends on the rainfall pattern. In some years with below average rainfall, the NT system as adopted is a better option for smallholder farmers at Potshini.

The study clearly shows that without management practices which limit soil evaporation, there is little benefit to the farmer. The adoption of NT does have important larger scale benefits through improved drainage through the soil and potentially for groundwater recharge. To combat the high water losses through soil evaporation, other components of NT systems that were not included in the simulated experiment could be explored. With the crop-livestock smallholder farming inherent in Potshini and indeed many other smallholder systems throughout sub Saharan Africa where most of the crop residue is reserved for livestock feeding, the use of cereal-legume intercropping and cover cropping could have some crop yield benefits in that much of the soil evaporation taking place could be shifted into transpiration and production of a useful cover crop which can be used as fodder which is grazed in preference to the much. Implementation of agroforestry with tree species such as *Cassuarina cunninghamiana* (L.) and *Grevillea robusta* (L.) (ICRAF, 1992) whose leaves can be used for mulching and fodder could also be explored to accompany the promotion of no-till systems in smallholder agroecosystems. There is scope in using both fertilizer and livestock manure in the cropping system in order to eliminate the soil fertility constraint and increase the productivity of rainwater retained in fields under NT systems. It is also imperative to conduct long term experimentation to understand the impact of NT systems on water fluxes, rainwater and crop productivity if other components of NT systems that were not included in the simulated experiment are to be introduced.

From a larger scale water resources perspective, the study suggests that there could be benefits in terms of less surface runoff, potentially less soil erosion, and improved recharge under NT conditions, but more sophisticated soil water and runoff modelling approaches which build on the available field studies are required to confirm this. Given that the livestock-mulch conundrum is driven by available resources, where a market exists, payment for ecosystem services type approaches could be explored as a means of ensuring that the benefits of NT accrue to both the farmer and the other stakeholders in the catchment.

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