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Interactive tillage & crop residue management effects on soil properties, crop nutrient uptake & yield in different weathered soils of West Africa

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Eusha Nafi

aus

Dhaka-Bangladesch

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Vorsitzender: Prof. Dr. Christian Borgemeister

Berichterstatter: Prof. Dr. Michael Frei

Berichterstatter: Prof. Dr. Gabriel Schaaf

Fachnahes Mitglied: Dr. Thomas Gaiser

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ABSTRACT

Sustainable crop production intensification in West Africa is hampered by constraints such as soil degradation, mainly due to excessive mining of soil nutrients, topsoil loss by surface runoff, and climatic factors like excessive rainfall, droughts, and high temperature. To counteract this problem, alternative management practices need to be adopted that have the potential to prevent and/or reduce the severity of soil degradation and could be suitable for buffering the future extreme climate effects on crop production in a sustainable manner. Considering this fact, the overarching aim of our study was to identify management options to improve crop productivity and livelihood among the farming population in the Sudan Savanna of West Africa under current and future climate conditions by using monitoring data from long-term field experiments on several sites over 5 years and additional simulation experiments.

Thus, this study was implemented stepwise: first, contour ridge tillage, reduced tillage, and crop residue management were assessed as an effective means to improve soil organic carbon stock, nutrient stocks, crop N uptake and N use efficiency (NUE) by setting up a field experiment on four sites [St1: Ferric Lixisol, footslope in Dano (Burkina-Faso); St2: Eutric Plinthosol, upslope in Dano (Burkina-Faso); St3: Haplic Lixisol, footslope in Dassari (Benin); and St4: Plinthic Lixisol, upslope in Dassari (Benin)] of West Africa from 2012 to 2016. On-farm trials were set up in a strip-split plot layout, where 2 levels of tillage (contour ridge tillage and reduced tillage) were considered as a main-plot factor, and sub-plot factors included 2 levels of crop residue management (with and without), and 2 levels of N fertilizer doses (control and recommended dose). In a second step, we calibrated and evaluated the CERES-Maize model in DSSAT and parameterized the tillage component of DSSAT using the experimental data of 2014 (calibration) and 2016 (validation). Finally, we used the calibrated model to assess the potential of contour ridge tillage and reduced tillage along with crop residue retention in terms of buffering the expected future climate change effects under a 2°C warming scenario

on crop yield and to provide a site-specific assessment of best management practices. For this purpose, we used the HAPPI weather dataset consisting of three GCMs (ECHAM6, MIROC5, NorESM1), and two climate scenarios: current baseline (2006–2015), and 2°C warmer than pre-industrial levels.

The field experiment demonstrated that in a gently undulated region (St2 and St4) subject to soil degradation through runoff and erosion, implementation of contour ridge tillage along with crop residue retention in upslope areas maintained soil fertility and sustained crop productivity. On the other hand, in footslope areas with well-drained soils and high water retention capacity (St3), the adoption of reduced tillage with crop residue retention could be more beneficial. Model simulations under future 2°C warming scenarios and cumulative probability distribution confirmed that contour ridge tillage along with crop residue application could lead to positive changes in maize yield at upslope field sites, where soil erosion and loss of water and nutrients through runoff is a serious risk. Simultaneously, reduced tillage with crop residue application could be a valuable alternative to farmers' practice in fields with deep soils and high water retention capacity at footslope position (St3), as it resulted in a higher increase of maize yield under future 2-degree warming compared to the baseline and could be preferred by risk-averse farmers. Maize production on gravelly soils with low water retention capacity (St1) may suffer from future 2-degree warming regardless of the tillage practice. Hence, the application of site-specific tillage operations and crop residue application has the potential to buffer future warming effects on maize yield as confirmed by DSSAT simulations. We must share this information with the local smallholders, policymakers, and scientific communities to adjust their decisions accordingly, and redirect their steps towards improving crop nitrogen use efficiency and soil fertility which in turn can sustain crop productivity.

ZUSAMMENFASSUNG

Die nachhaltige Intensivierung der Pflanzenproduktion in Westafrika wird durch Limitierungen wie die Verschlechterung der Bodenqualität, vor allem durch den übermäßigen Entzug von Bodennährstoffen, den Verlust des Oberbodens durch Oberflächenabfluss sowie durch klimatische Faktoren wie Dürren, Starkniederschläge und hohe Temperaturen behindert. Um diesem Problem entgegenzuwirken, müssen alternative Bewirtschaftungsweisen eingeführt werden, die das Potenzial haben, die Verschlechterung der Bodenqualität zu verhindern und/oder zu verringern, und die geeignet sein könnten, die künftigen extremen Klimaauswirkungen auf die Pflanzenproduktion nachhaltig abzufedern. Vor diesem Hintergrund war es das übergeordnete Ziel unserer Studie, mit Hilfe von Monitoringdaten aus Langzeit-Feldversuchen an mehreren Standorten über fünf Jahre und zusätzlichen Simulationsexperimenten Bewirtschaftungsoptionen zu identifizieren, die die Produktivität und die Lebensgrundlage der landwirtschaftlichen Bevölkerung in der westafrikanischen Sudan Savanne unter den aktuellen und zukünftigen Klimabedingungen verbessern.

Diese Studie wurde daher schrittweise durchgeführt: Zunächst wurden Konturliniendämme, die reduzierte Bodenbearbeitung und das Ernterückstandsmanagement als effektive Mittel zur Erhaltung des organischen Kohlenstoffvorrats, der Nährstoffvorräte, der N-Aufnahme und der N-Nutzungseffizienz (NUE) des Bodens durch einen Feldversuch an vier Standorten von Westafrika von 2012 bis 2016 bewertet [St1:Ferric Lixisol, Unterhang in Dano (Burkina-Faso); St2:Eutric Plinthosol, Oberhang in Dano (Burkina-Faso); St3:Haplic Lixisol, Unterhang in Dassari (Benin); und St4:Plinthic Lixisol, Oberhang in Dassari (Benin)]. Die Versuche wurden in einem streifenweise aufgeteilten Parzellenlayout angelegt, wobei zwei Varianten der Bodenbearbeitung (Konturliniendämme und reduzierte Bodenbearbeitung) als Hauptparzellenfaktor betrachtet wurden und die Faktoren der Nebenparzellen zwei Ebenen des Ernterückstandsmanagements (mit und ohne) und 2 Ebenen der N-Düngung (Kontrolle und

empfohlene Dosis) umfassten. In einem zweiten Schritt wurde das CERES-Maismodell im Modellsystem DSSAT kalibriert und evaluiert und die Bodenbearbeitungskomponente von DSSAT mit den experimentellen Daten von 2014 (Kalibrierung) und 2016 (Validierung) parametrisiert. Schließlich wurde das kalibrierte Modell verwendet, um das Potenzial der Konturliniendämme und der reduzierten Bodenbearbeitung sowie der Rückführung der Ernterückstände im Hinblick auf die Anpassung an den zu erwartenden Klimawandels unter einem Erwärmungsszenario von 2°C auf den Ernteertrag abzuschätzen und um eine standortspezifische Bewertung der besten Bewirtschaftungsmaßnahmen (Bodenbearbeitung und Ernterückstandsmanagement) zu ermöglichen. Zu diesem Zweck verwendeten wir den HAPPI-Wetterdatensatz, bestehend aus drei GCMs (ECHAM6, MIROC5, NorESM1), und zwei Klimaszenarien: das aktuelle Basisszenario (2006-2015) und 2°C wärmer als das vorindustrielle Niveau.

Das Feldexperiment zeigte, dass in einer leicht gewellten Region (St2 und St4), die der Bodendegradation durch Oberflächenabfluss und Erosion ausgesetzt ist, die Durchführung von Konturliniendämmen zusammen mit der Rückführung von Ernterückständen in Hanglagen die Bodenfruchtbarkeit und die nachhaltige Produktivität der Pflanzen aufrechterhält. In Hanglagen mit gut drainierten Böden und hohem Wasserrückhaltevermögen (St3) könnte dagegen die Anwendung einer reduzierten Bodenbearbeitung mit der Rückführung von Ernterückstanden vorteilhafter sein. Modellsimulationen unter zukünftigen 2°C-Erwärmungsszenarien und kumulativer Wahrscheinlichkeitsverteilung bestätigten, dass die Konturliniendämme zusammen mit der Ausbringung von Ernterückständen zu positiven Veränderungen des Maisertrags an Hanglagen führen könnte, wo die Bodenerosion und der Verlust von Wasser und Nährstoffen durch Oberflächenabfluss ein ernsthaftes Risiko darstellen. Gleichzeitig könnte die reduzierte Bodenbearbeitung mit der Ausbringung von Ernterückständen eine wertvolle Alternative zur Praxis der Landwirte auf Feldern mit tiefen

Böden und hohem Wasserrückhaltevermögen am Unterhang (St3) sein, da sie bei zukünftiger 2-Grad-Erwärmung zu einer höheren Steigerung des Maisertrags im Vergleich zur Ausgangssituation führt und von risikoscheuen Landwirten bevorzugt werden könnte. Die Maisproduktion auf kiesigen Böden mit geringem Wasserrückhaltevermögen (St1) wird unabhängig von der Bodenbearbeitungspraxis unter der zukünftigen 2-Grad-Erwärmung abnehmen. Daher hat die Anwendung von standortspezifischen Bodenbearbeitungsverfahren und die Ausbringung von Ernterückständen das Potenzial, zukünftige Erwärmungseffekte auf den Maisertrag zu puffern, wie durch DSSAT-Simulationen bestätigt wurde. Wir müssen diese Informationen an die lokalen Kleinbauern, politischen Entscheidungsträger und die Wissenschaft weitergeben, damit diese ihre Entscheidungen entsprechend anpassen und ihre Schritte zur Verbesserung der Stickstoffnutzung und der Bodenfruchtbarkeit neu ausrichten können, was wiederum die Pflanzenproduktivität nachhaltig steigern kann.

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Chapter 1

General Introduction

1. General Introduction

1.1. Problem Statement

Decline in agricultural production has become a global concern as it threatens food security by minimizing the availability of food. This issue is acute in many regions of West Africa, especially in Sudan Savanna areas. About 60% of tropical Africa is Savanna. Sudan Savanna covers the semi-arid portion of tropical Africa which has a typical rainfall of 600-900 mm per year and the number of growing days ranges from 90-140 (Ker, 1995). According to Callo-Concha et al. (2012), two major factors affect the agricultural productivity in this region; high rainfall variability and frequent droughts induced insufficient water availability (Challinor et al., 2007), and inherent poor soil fertility (Sanchez, 2002).

Among the most possible causes of soil degradation in West Africa, the existence of highly erodible soils (Angima et al., 2003), expansion of arable lands to steep slope areas (Young, 1999), increased population pressure on land and intensive cultivation by smallholder farmers without adequate nutrient management (Kalipeni, 1996) are predominant. Nutrient losses through soil erosion in combination with soil nutrient mining due to inadequate soil fertility management are the most striking factors of soil degradation in most of the areas in West Africa. Soil erosion by water and wind removes nutrients from the surface layers, reduces root depth, deteriorates soil structure and reduces soil infiltration capacity (Baptista et al., 2015; Tavares et al., 2015). As a consequence, negative nutrient balance and loss of crop yield were observed across entire West Africa. For example, the annual erosion rate from croplands in West Africa ranges from 0.1-90 Mg ha^{-1} (Morgan, 2005). Kiage (2013), demonstrated that human-induced factors like over-cultivation, overgrazing, deforestation and unskilled irrigation practice are also responsible for soil degradation in Western Africa.

In the last century, shifting cultivation, aeolian nutrient input from the Sahara and bush fires as well as nomadic grazing were sufficient to restore soil fertility in this region. However, this process has been slowed down in recent decades, as the potential carrying capacity of the land has already been exceeded, which results in the use of marginal and non-productive agricultural lands, such as steep slopes (Asiamah et al., 2000; Senayah et al., 2009). Moreover, agricultural production in this region is also limited by infrastructure (roads, storage facilities, input and sales markets), lack of access to information and extension services, and increasing pressure on land resources (Valbuena et al., 2015), of which degraded soils and low productivity are the ultimate consequences (Samaké et al., 2005).

On the other hand, the Sudan Savanna is a region where the ecosystem and arable lands are susceptible to climate change. Agricultural production in this area is particularly susceptible to climate change because of extensive dependence on rain-fed production and high climate variability (Boko et al., 2018). Between 1961 and 1990, West Africa faced a significant increase in temperature and the number of warmest days, a decrease in the frequency of warm nights, a decrease in heavy rainfall events, and an increase in rainfall intensity and dry spells (CDKN, 2012). Moreover, the future climate projection scenario for the period of 2071-2100 based on Global Circular Model (GCM) and Regional Climate Model (RCM) was concluded with an increase in warm days and nights, more frequent and longer heatwaves and dry spells, and slight to no change in heavy rainfall events (CDKN, 2012). Soil degradation together with climate change severely limits the agriculture production in this region and ultimately puts the food and livelihood security under insurmountable stress. The overall scenario has been illustrated in Figure 1

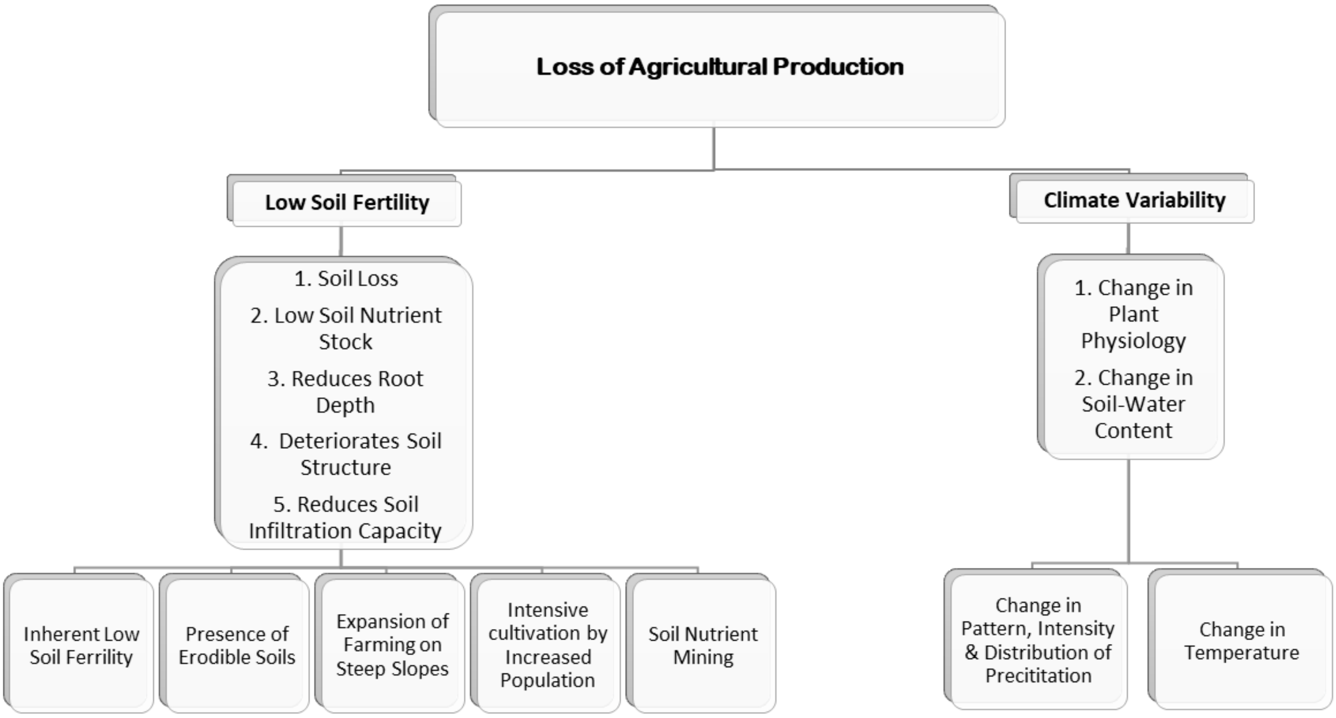

Figure 1: Drivers of low agricultural productivity in the Sudan Savanna (Source: Author)

1.2. Possible Technical Solutions

Soil degradation can technically be counterbalanced by a series of soil and water conservation management practices (for instance half-moons, Zai pits, stone or earth-based contour bounds conservation agriculture, and many more) aiming to arrest, prevent or even reverse soil degradation, which in turn will improve production and food security, leading to poverty reduction.

1.2.1. Conceptual Framework

In this study, we explored possible options to alleviate the effects of soil degradation and future extreme climate change effects on crop productivity in this region; and that could be to couple soil-crop simulation models with field trials. Our study, therefore, aimed at combining crop model and field experiments to inform farmers and policymakers about the pros and cons of selected management options but aiming at alleviating the problem of soil nutrient loss and improve their livelihood through increasing actual yields. To this end, the experimental approach consisted of setting up field trails on four different soil types of West Africa and assessing the effects of implemented management practices such as contour ridge tillage, reduced tillage, crop residue incorporation on soil quality, crop N use efficiency, and crop yield.

In-field tillage experiments are typically long-term and costly (Khaledian et al., 2009), and are therefore not always practical or even possible. Also, field experiments remain time and resources consuming and often are limited to testing a smaller number of interventions and interactions only. To assess long-term impacts, select the most appropriate management options, field experiments are best complemented with model simulations. Hence, soil–crop simulation models have been developed as a rapid and economical means for approximating tillage effects on crop yield. The findings of crop models to elaborate simulations based on long-term data sets have the potential to advise farmers to adopt suitable and site-specific management options. However, recent studies underlined that the integration of crop models with field experiments has, in particular, a great potential to support farmers in adopting the best management options. But the inclusion of an experimental approach is important for two additional reasons: (1) to compile a source of primary data needed to run the crop models, and (2) for comparing the predicted value with the estimated value informative for the validation and evaluation of the model performance. It, therefore, was intended to use a data set of five years, from 2012 to 2016. This data set of 5 years is required since the effects of management options on soil characteristics such as soil organic matter dynamics often become effective after some years only, and these changes would, in turn, become the input for model simulations. The results of the experiment were interpreted by comparing the differences between mean values through statistics. Moreover, the mean values were used as the primary data to conduct the model simulation.

Several previous studies solely focused on the effects of tillage and crop residue management on crop yield and soil properties covering broader geographical boundaries using crop models like The Agricultural Production Systems sIMulator, APSIM (Mwansa, 2016; Yang et al., 2018); The Decision Support System for Agrotechnology Transfer, DSSAT (Corbeels et al., 2016; Joshi et al., 2017; Ngwira et al., 2014; Soldevilla-Martinez et al., 2013); Environmental Policy Integrated Climate, EPIC (Gaiser et al., 2008); The Agricultural Policy / Environmental eXtender, APEX (Wang et al., 2008); System Approach to Land Use Sustainability, SALUS (Cillis et al., 2018). Perhaps one of the most sophisticated and useful tools could be the tillage module of DSSAT v. 4.7.5. that has already been implemented to assess the conservation agriculture effects on crop yield in African regions.

At the beginning of constructing or modifying a model framework, it is important to define the Modelling objective as precisely as possible. Therefore, the aim was to calibrate and validate CERES-Maize model in DSSAT to assess the maize yield and to parameterize the tillage module of DSSAT v. 4.7.5 in a way to predict the impact of tillage and residue management practices on maize crop yield.

To run the model, estimate its parameters, and perform simulations, a minimum data set is needed. Generally, these data sets can be acquired in two ways: (1) screen for secondary data (e.g. available from the previously published literature), or (2) generate primary data through field experiments. The minimum data sets required for DSSAT are (1) weather, (2) soil, (3) crop, and (4) management data. Besides, the estimation of key parameters can help calibrating the model in the sense of matching the output of the model with empirically observed results. For this purpose, the model findings were compared to experimental results differing ideally in time and space, and other than those used for the parameterization of the model. In the absence of such data sets, the model validation can be done with the help of some common statistical procedures (described in chapter 3). HAPPI, which stands for Half a degree additional warming, prognosis and projected impacts daily climate data introduced by Mitchell et al. (2017) consisting of three GCMs (ECHAM6, MIROC5, NorESM1), and two climate scenarios: current baseline (2006–2015), and 2°C warmer than pre-industrial levels, were used for weather dataset. The summary of the proposed implementation has been presented in the following Figure 2.

1.3. State of the art

The study was implemented stepwise: first, the existing knowledge and the state of the art of contour ridge tillage, reduced tillage, crop residue management were assessed as an effective means to improve soil organic carbon stock, nutrient stocks, crop N uptake and N use efficiency (NUE). In a second step, we calibrated and evaluated CERES-Maize model in DSSAT and parameterized tillage component of DSSAT using the experimental data of 2014 (calibration) and 2016 (validation). Finally, we used the calibrated model to assess the potential of contour ridge tillage and reduced till1age along with crop residue incorporation in terms of buffering the expected future climate change effects on crop yield, and provide a site-specific assessment of best management practices (tillage and crop residue management).

1.3.1. Contour Ridge Tillage

According to the United Nations Environmental Program (UNEP 2001), “Contour ridges are small earthen ridges, 15 to 20 cm high, with an upslope furrow, which accommodates runoff from a catchment strip between the ridges. Sometimes, small earthen ties are made within the furrows at 4 to 5 m intervals to prevent lateral flow”. Hulugalle (1990) proposed the possibility of tied ridging in the Sudan Savanna region because this technology reduces soil bulk density, improves soil fertility, reduces soil nutrient loss and improves soil water holding capacity.

Moreover, contour ridge tillage (CRT) increases the depth of rooting for maize and cotton. Similar effects of CRT on the soil water regime, crop water use efficiency, and growth pattern has been evaluated for cowpea in the Sudan Savanna (Hulugalle, 1987). But despite these advantages, Hagmann (1996) documented huge soil loss and rill erosion due to improper and ineffective designs of contour ridge in areas with strong slopes. Such erosion and soil losses might be more intensive in middle and upper slope areas, whereas the deposition of eroded materials usually occurs in the lower part of sloping lands. Moreover, the eroded materials contain soil organic matter and essential plant nutrients, which may lead to low productivity and depletion of soil nutrient stocks on the upper parts of the slope. CRT with improved soil infiltration capacity has thus the potential to act as a conserving soil-water option. Many authors underscored the possibility to combine no/reduced tillage and mulching with contour ridge tillage.

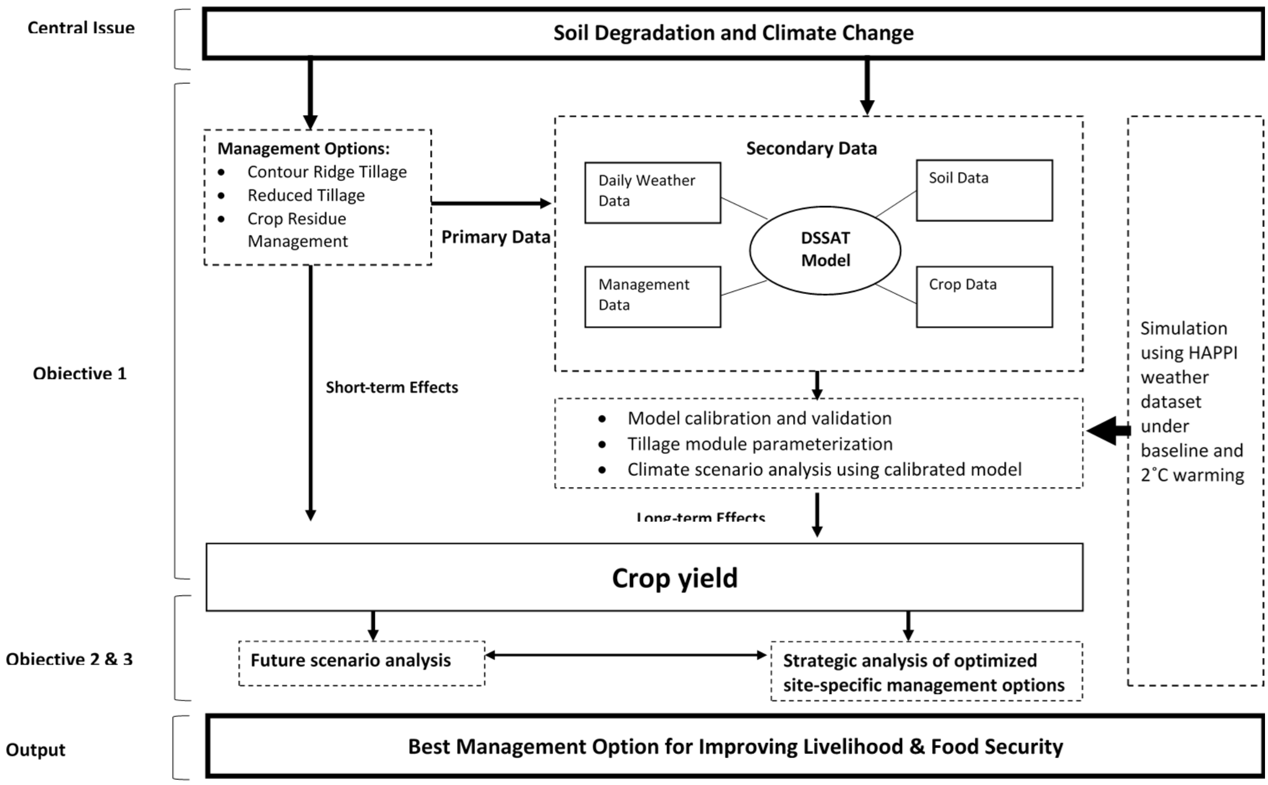

Figure 2: Proposed Implementation (Source: Author)

1.3.2. Reduced Tillage

Minimum tillage indicates a reduced level of soil manipulation, usually through ploughing, but also by using other tillage operations (Busari, et al. 2015). Furthermore, under reduced tillage systems, a minimum of 30% of the soil surface is covered usually with crop residues (Babalola and Opara-Nadi, 1993). As a consequence, the number of tillage operations can be reduced. The minimum tillage technology is considered highly effective in reducing soil loss, buffering soil evaporation and improving associated soil physical properties. Moreover, more water-stable aggregates are found in the upper layer of the soil under minimum tillage compared to tilled soils, resulting in a high total porosity (Blanco-Canqui and Lal, 2007). Minimum tillage, compared to conventional tillage practices, improves not only the soil aggregation but also increases the concentration of soil organic carbon and nitrogen associated with the surface soil aggregates (Jacobs et al., 2009). Besides, minimum tillage also positively affects other soil physical properties such as bulk density, infiltration and water content (Osunbitan et al., 2005). Compared to conventional tillage, the amount of Ca, Mg and K are significantly higher in the surface soil under reduced tillage practices (Ismail et al., 1994; Rahman et al., 2008). After two years of study, Busari et al., (2015) stated that the soil organic C (SOC) and the effective cation exchange capacity (ECEC) were significantly higher under reduced tillage. Under reduced tillage, the soil had increased SOC, microbial substrate availability, and microbial biomass. (Ghimire, et al. 2014).

1.3.3. Crop Residue Management

Under both reduced tillage and contour ridge tillage conditions, crop residues can be incorporated into the surface soil layers as a part of a conservation technique. The content of soil N, P, K, Ca, Mg, CEC, and SOC is significantly higher for the soils treated with straw residues (Ogbodo, 2011).

As evidenced by previous studies, crop residues are incorporated into the soil as a source of soil organic carbon, which can improve soil physical, chemical, and biological properties (Alvarez, 2006; Kumar and Goh, 1999). The incorporation of crop residues along with conservation tillage tends to reduce water and wind erosion (Lal, 2005). Furthermore, retaining crop residues allows greater accumulation of organic and inorganic phosphorus on the surface soil (Du Preez et al., 2001; Salinas-Garcia, et al. 2001), and this, in turn, alleviates soil loss and runoff. On the other hand, crop residues with higher decomposition rates can also cause N-losses through the process of denitrification and leaching (Kumar and Goh, 1999). A significant portion of K-demand by crops is supplied by the residues of the previous crops and the removal of crop residues may cause K deficiency in the growing crops (Whitbread et al., 2003). The incorporation of crop residues into the surface soil can also bring changes to soil pH (Butterly et al., 2013). Crop residues coupled with conservation tillage can improve soil hydraulic conductivity and infiltration capacity and reduce evaporation (Blanco-Canqui and Lal, 2009). An increase in organic matter content under this practice has the potential to decrease soil bulk density and increase macro-porosity (Shaver et al., 2002; Zeleke et al., 2004). Moreover, SOC can bind the soil primary particles into aggregates, and positively influence the formation and stabilization of soil aggregates and structure (Carrizo et al., 2015; Paul et al., 2013).

1.3.4. Crop Modelling

The complexity of food security, climate change impact and crop management practices demand an integrated assessment through the modelling of agro-ecosystems. Crop modelling tools have been developed to support discussions and improve decisions in the agricultural system. As mentioned above, long-term impacts of climatic conditions and management practices are unlikely to study successfully through experimental approaches to improve the understanding of the effects of tillage and crop residue management on yield and soil quality, unless field experiments are complemented with computer simulation models.

Crop models are used as a tool by scientists and researchers to find solutions to the complex problems of climate, soil, and crop management interaction faced by farmers while managing their crops (Houghton, 1986). On the other hand, the application of crop models can greatly contribute to identifying research gaps and assisting in efficient research planning (Rauff and Bello, 2015). Crop models can anticipate the status of future agroecosystems under climate change scenarios.

However, it is still believed that given the degraded soils and extreme climatic conditions of West Africa, crop models are not suitable for predicting crop response yet (MacCarthy et al., 2012). Various crop models that have been used for different purposes in many regions of West Africa are e.g., EPIC (Williams, 1990), SARRAH (Traoré et al., 2011), AGRHYMET, IMPACT-DSSAT (Nelson et al., 2009), CERES-maize (Jones et al., 2003), GEPIC (Liu et al., 2007), and Cropsyst (Tingem et al., 2009). The General Land Area Model (GLAM) was used to simulate maize yield in Burkina Faso (Waongo et al., 2015). The SARRA-H model was used for more than 7000 simulations of sorghum and millet yields over 35 research stations in West Africa, under different future climate conditions (Sultan et al., 2013). The EPIC model was used to simulate the sensitivity of maize, sorghum, and millet to seasonal rainfall in West Africa (Adejuwon, 2005). This model has also been used to simulate maize production in the semi-arid tropics of North-East Brazil (Gaiser et al., 2010).

Many studies using crop models were limited to the assessment of rainfall and fertilizer inputs. But in reality, degraded soils have additional crucial parameters that interact and limit crop growth in complex ways. Under such conditions, it is important to test them in experiments during which measurements are taken to obtain information about all the necessary parameters permitting the model to make a firm prediction close enough to reflect reality. Validated crop models can anticipate the performance of technologies and hence offer an option to eliminate the need of conducting tedious, resource and time demanding crop experiments across regions (MacCarthy et al., 2012).

1.4. Innovation and Significance

The adoption of sustainable management practices e.g., contour ridge tillage, no-tillage, crop residue management can greatly reduce soil loss through surface runoff, improve crop nutrient uptake and use efficiency, and enhance crop productivity in degraded areas. Nevertheless, few studies have been conducted with contour ridge tillage and residue management in the Sudan Savanna regions. The available studies, however, revealed that the implementation of contour ridge tillage together with residue management can positively affect soil properties and hence production. Hulugalle (1987) stated that the use of contour and/or tied ridges in Burkina Faso increased root growth and yield of cowpea by improving the soil water availability and crop water use efficiency. Conservation tillage practices not only tended to reduce soil bulk density but also enhanced soil and nutrient use efficiency (Babalola and Opara-Nadi, 1993). Moreover, conservation tillage can also increase soil aggregation and associated SOC content (Mrabet, 2002). In Western Africa, crop residue management plays a vital role in improving soil-water balance, biological activities, SOC, and replenishing soil fertility in degraded croplands (Lahmar et al., 2012). Furthermore, there are major knowledge gaps when it comes to understanding the interactive effects when contour ridge tillage and crop residue management are combined in different soil types, which is typical for the Sudan Savanna region in West Africa. Therefore, aiming at understanding the interactive effects of tillage and crop residue management on productivity and soil properties in four different soil types is the major innovative approach of this study. However, to anticipate the future response of crops under different climatic, biophysical conditions and management practices, crop modelling is more effective than experiments.

Modelling is needed also to assess numerous management practices for sustainable crop production and soil productivity, as it is not feasible to conduct such field experiments with sufficient detail in space and time and across a variety of agro-ecological conditions (Basso and Ritchie, 2015). Although scientific knowledge of tillage effects on soil properties and crop yield or of crop residues or other water and soil conservation measures is extensive, modelling of the combined impacts of for instance tillage and crop residue management still is underdeveloped. Some existing models can evaluate tillage and crop residue effects on soil properties simultaneously, but they are very limited in number and application. Most of the models used to predict the effects of tillage on soil properties and processes have been developed during the 70s and 80s (Gupta et al., 1991). The CERES-Till model, for instance, was developed by Dadoun, (1994) to anticipate the effects of crop residue on soil surface properties and crop growth. Mkoga et al. (2010) reported on simulated results indicating the effects of conservation tillage on soil moisture, yield, and water productivity for 24 years in the Mkoji sub-catchment in Tanzania using the APSIM model framework. The SALUS model has been used to simulate the effects of tillage on SOC, bulk density, drainage, evaporation, and surface runoff (Basso et al., 2006). Modification within the SALUS model framework allowed evaluating the effects of agronomic management practices on crop yield, carbon and nitrogen dynamics, and environmental performance (Basso and Ritchie, 2015). Simulation of effects of different tillage operations, such as conventional, reduced and no-tillage on soil hydraulic properties and their temporal dynamics using the VGM model in Lower Austria has been demonstrated as well (Bodner et al., 2013).

In spite of having crop models capable of simulating the effects of tillage and crop residue management on crop yield and soil properties, only a few studies have been conducted to simulate the effect of crop response to the changing climate in Sudan Savanna Africa. None of these studies have simulated effects of tillage and residue management on crop yield, nutrient uptake, and soil properties in this region. Mkoga et al. (2010) used the APSIM model to assess conservation tillage effects on maize yield in Tanzania. A study by Gerardeaux et al. (2012) in Madagascar illustrated the effects of tillage and N fertilizer on rice yield using CERES-Rice in DSSAT. In Malawi, the effects of conservation tillage on maize yield was modelled using DSSAT model (Ngwira et al., 2014). Long-term effects of conservation tillage on maize yield in Zambia was assessed using DSSAT by Corbeels et al. (2016). However, none of the studies demonstrated the potential of different tillage and crop residue management options to buffer climate change effects on crop yield in West Africa. Thus, we lack knowledge of the crop production losses induced by climate change that can be offset by introducing optimized management practices consisting of tillage and crop residue management. This justifies the second innovative goal of this study: to use the tillage module of DSSAT model to simulate tillage and crop residue management effects on crop yield in Sudan Savanna Africa. Keeping this in mind, we intended to calibrate and validate the tillage module of DSSAT v. 4.7.5 to complement tillage and crop residue effects on maize yield, and further using the model to assess future climate change impacts on maize yield under different soil types.

The overarching aim of the study is to identify management options to improve crop productivity and livelihood among the farming population in the Sudan Savanna of West Africa under current and future climate conditions by using monitoring data from long-term field experiments on several sites over 5 years and additional simulation experiments.

The working objectives in detail are:

1. To assess the single and interactive effects of tillage and crop residue management on crop nitrogen uptake and nitrogen use efficiency (Chapter 2),

2. To assess the single and interactive effects of tillage and crop residue management on soil nutrient stocks and soil organic carbon in four different soil types of West Africa (Chapter 3).
3. To calibrate and validate CERES-Maize model using the dataset of 2014 and 2016 (chapter 4).
4. To use the validated model under future climate scenario, and identify management practices which offsets or take advantage of the future extreme climate effects on crop productivity based on different soil types (Chapter 4).

1.5. Research Questions:

This research is aimed at answering the following questions:

1. How the implemented management practices affect soil quality and crop nutrient uptake in different soil types?
2. Can DSSAT reproduce the effects of contour ridge tillage and reduced tillage along with crop residue on crop yield?
3. Can different tillage along with residue management buffer the future climate effects on crop yield on different soil types?

Chapter 2

Soil tillage, residue management and site interactions affecting nitrogen use efficiency in maize and cotton in the Sudan Savanna of Africa

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1. Introduction

Western Africa remains one of the poorest regions in the world and is constantly challenged with food security and poverty. Increased crop production in a sustainable manner could play an important role towards eliminating poverty and hunger, and to drive farm incomes and economic growth. West African agriculture consists mainly of subsistence smallholder farmers who contribute to food security through the production of major food crops like maize and cash crops like cotton (Vanlauwe et al., 2014). However, both maize and cotton production in West Africa is hampered to a large extent by poor nitrogen (N) fertilizer management (Webber et al., 2014).

Nitrogen is the single most important nutrient that constitutes slightly more than 50% of all nutrients applied to maximize crop production in West Africa (Bumb, 1989). Benin and Burkina-Faso are among the countries with the most severe soil nitrogen depletion in West Africa, with an annual nitrogen loss from agricultural soils of 22.7 and 27.6 kg N ha yr^{-1}, respectively (Henao and Baanante, 1999). To this end, it is necessary to optimize the use of N fertilizer to reduce N losses and sustain crop production in this particular region. Nitrogen use efficiency (NUE) is a term often used to indicate the efficient utilization of applied N by crops and plays a vital role in maximizing economic yield (Lassaletta et al., 2014). Although, various indices are commonly proposed in different studies to evaluate NUE in crops, we only presented the indices that are calculated based on differences in yield or nitrogen uptake (NU) between fertilized plots and control plots, such as, nitrogen agronomic efficiency (AE), nitrogen fertilizer recovery efficiency (NFR), and partial factor productivity (PFP_n) (Baligar et al., 2001; Baligar and Duncan, 1990; Craswell and Godwin, 1984; Dobermann, 2007).

In recent decades, improving NUE with new techniques has been a major challenge. Among the different techniques, conservation agriculture (conservation tillage and crop residue retention) is widely known as a viable option for sustainable crop production (Lee and

Thierfelder, 2017) and efficient management of applied N (Mohammad et al., 2012). The main advantages of conservation or reduced tillage is to minimize soil erosion, restrict the loss of soil organic carbon (C) and N (Awale et al., 2017, 2013; Chen et al., 2009; Dou et al., 2008; Machado et al., 2006), and improve inorganic soil N content and potential C and N mineralization (Salinas-Garcia et al., 1997). Also, conservation or reduced tillage has been shown to ameliorate NU and NUE in both maize (Al-Kaisi and Kwaw-Mensah, 2007; Habbib et al., 2016; Halvorson et al., 2001) and cotton (Khan et al., 2018). On the other hand, in steep hillslope regions, where erosion plays a more important role, conservation techniques like contour ridges have become popular among the farmers of West Africa (Gigou et al., 2006) which led to reduced soil erosion and sediment loss (Gathagu et al., 2018; Zhang et al., 2004). Numerous studies carried out in West Africa also hold the view that the retention of crop residues on the soil surface along with reduced tillage could contribute to improved nutrient cycling, crop yield, plant NU and NUE (Dossou-Yovo et al., 2016; Kouelo et al., 2014; Malhi et al., 2006).

However, most previous studies have reported single and/or interactive effects of tillage and crop residue incorporation on plant NU and NUE under a mono-cropping system with a single location and soil type (Chandrika et al., 2016; Malhi et al., 2006a, 2006b; Sainju et al., 2005). Amouzou et al. (2018) assessed the effects of different soil management strategies on NUE of maize, sorghum and cotton under three different soil types in Benin and concluded that the greatest AE and NFR of applied N were obtained under integrated soil-crop management practices. Also, Dossou-Yovo et al. (2016) conducted a study in Lixisol and Gleyic Luvisol of Benin to determine the effects of tillage, crop residue and N fertilizer on NFR of upland rice, and found that no-tillage together with crop residue and judicial N application could improve soil quality as well as crop yield. A comprehensive evaluation of the interactive effects of tillage practices and crop residue incorporation on NUE of cotton-maize rotation system under different soil types in West Africa is scarce. Therefore, more research is needed for a deeper understanding of whether different soil conservation management practices, such as contour ridge tillage, reduced tillage, and crop residue retention could improve NUE of maize-cotton rotation systems on different soil types in West Africa. Such an understanding can also serve as the basis for site-specific soil conservation measures by local smallholder farmers growing maize and cotton crops to overcome the adverse impacts of improper N fertilizer management through mitigating their loss and making mineral N more available. To this end, we hypothesized that reduced tillage along with crop residue retention could benefit NUE of both maize and cotton by increasing soil mineral N. However, we also anticipated that such effect could also be site-specific. Thus, we aimed to investigate the single and interactive effects of tillage and crop residue management on NU and NUE indices of both maize and cotton on different weathered soils of West Africa.

2. Materials and methods

2.1. Site description

Two experiments were conducted as on-farm trials in the Sudan Savanna agro-ecological zone of the Republic of Benin and Burkina-Faso during the growing seasons of 2013 and 2014. The study locations (Figure. 1) were: Tambiri (11˚10´N, 2˚38´W) in Dano watershed of Burkina Faso; and Ouriyouri (10˚49´N, 1˚04´E) in Dassari watershed of Republic of Benin (Danso et al., 2018).

The climate is semi-arid with a mean rainfall between 900 and 1000 mm mostly from May to October and the temperature varies from 15 ˚C during the night to 40 ˚C during the day in the rainy season (Danso et al., 2018; Kpongor, 2007). The amount of total rainfall during the 2013 cotton season (June-November, 2013) was 766.4 mm and 777.9 mm (Figure. 2b) in Dano and Dassari, respectively. Most of the rainfall occurred from June to September in Dano, while

Dassari received most of the rainfall from June to October. During the 2014 maize season, Dano received a total of 860 mm rainfall throughout the growing season while Dassari received a total of 731 mm rainfall. The maximum air temperature during June to November in 2013 remained between 27 ˚C to 30.5 ˚C in both sites, while the minimum air temperature ranged between 23 ˚C to 25.5 ˚C and 21 ˚C to 24.8 ˚C in Dano and Dassari, respectively (Figure. 2a). Maximum monthly air temperature in 2014 ranged between 27.8 ˚C to 31.6 ˚C in Dano and between 29.2 ˚C to 31.8 ˚C in Dassari, while the Monthly minimum air temperature tended to remain between 24.2 ˚C to 25.7 ˚C in Dano and 24.8 ˚C to 26.3 ˚C in Dassari.

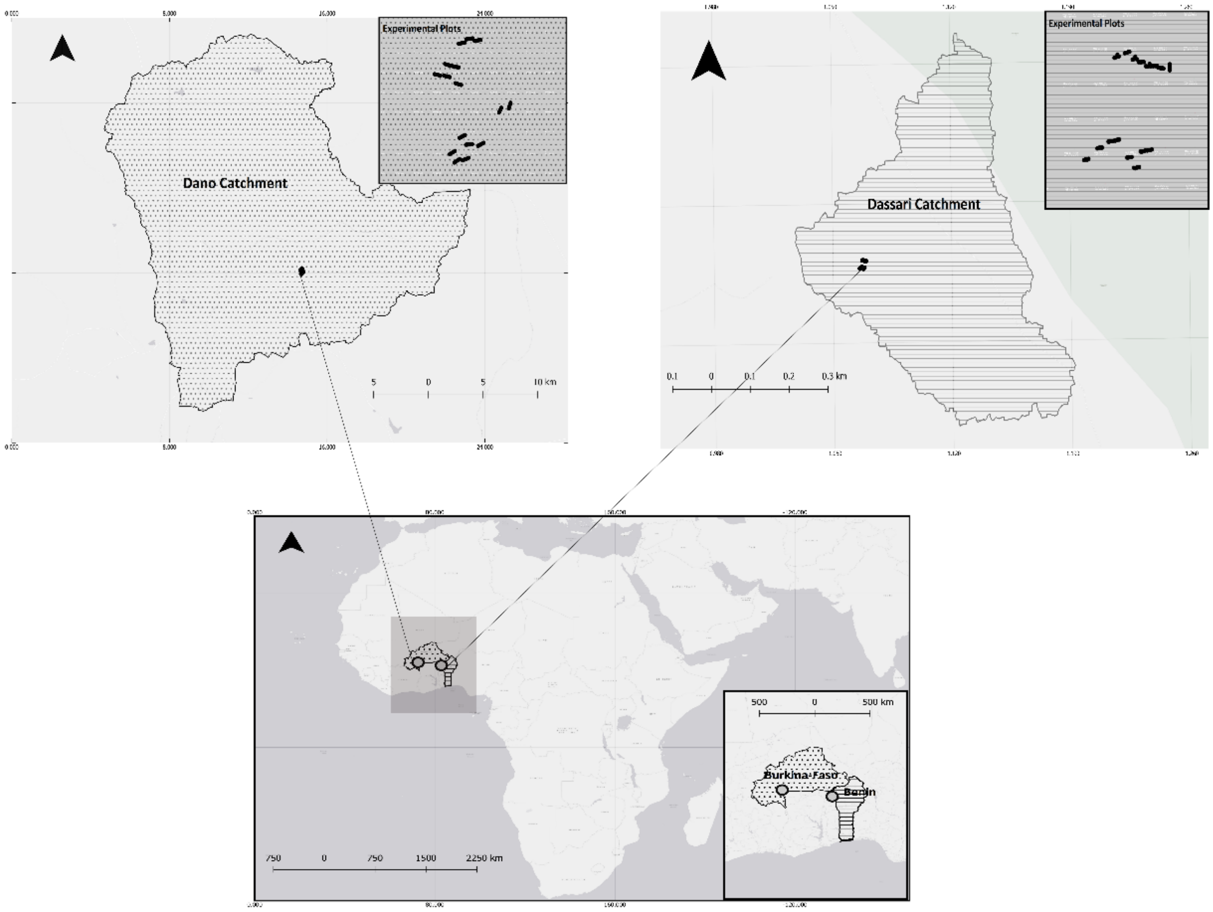

Figure 1. Locations of study and the corresponding experiment plots

Soils in these two experimental locations vary based on topography (upslope and footslope) and in many characteristics (topsoil layer, 0-20 cm) like gravel content, texture, maximum rootable depth, and water content (Table 1) such that the study was conducted on four different soil types. An average of 3% slope existed between the footslope and upslope soils. The soils can be classified as Eutric Plinthosol (EP) for Dano and Plinthic Lixisol (PL) for Dassari in the upslope position, and as Ferric Lixisol (FL) for Dano and Haplic Lixisol (HL) for Dassari in the footslope position (Danso et al., 2018). The HL in Dassari and the FL in Dano can be classified as deep soils, located in a downslope position with a maximum rooting depth of 90 cm and 75 cm, respectively. Both soils (0-20 cm) have low clay content and high sand content, and texture class of sandy loam and sandy, respectively. On the other hand, EP and PL can be classified as shallow soils, located in an upslope position with a maximum of 65 cm rootable depth. EP (0-20 cm) has high clay content and low sand content with a texture class of sandy clay loam. PL (0-20 cm) is similar to HL in terms of clay content and texture class, however, the rootable depth is smaller. Total available water capacity (up to rootable depth) of these soils exhibits the following rank: FL (29.1 mm) < PL (43.8 mm) < EP (51.2 mm) < HL (54.1 mm). Such a difference in soil water content within the soil profile caused mainly due to variations in gravel content among these soil types. Based on gravel content by mass percentage, soils in our study can be ranked as FL (47%) > EP (26%) > PL (24%) > HL (13%).

Overall, our study involved four different sites, each consisting of a combination of weather conditions (similar within a location) and unique soil type. Thus, the sites were named as S1 (Dano village on Ferric Lixisol), S2 (Dano village on Eutric Plinthosol), S3 (Dassari village on Haplic Lixisol), and S4 (Dassari village on Plinthic Lixisol). Since, our study used weather data only for two consecutive years (2013-2014) and interestingly, no differences were observed among the weather parameters (rainfall and temperature) between these two years (Figure. 2), the main criteria that caused the variation among the sites was soil types.

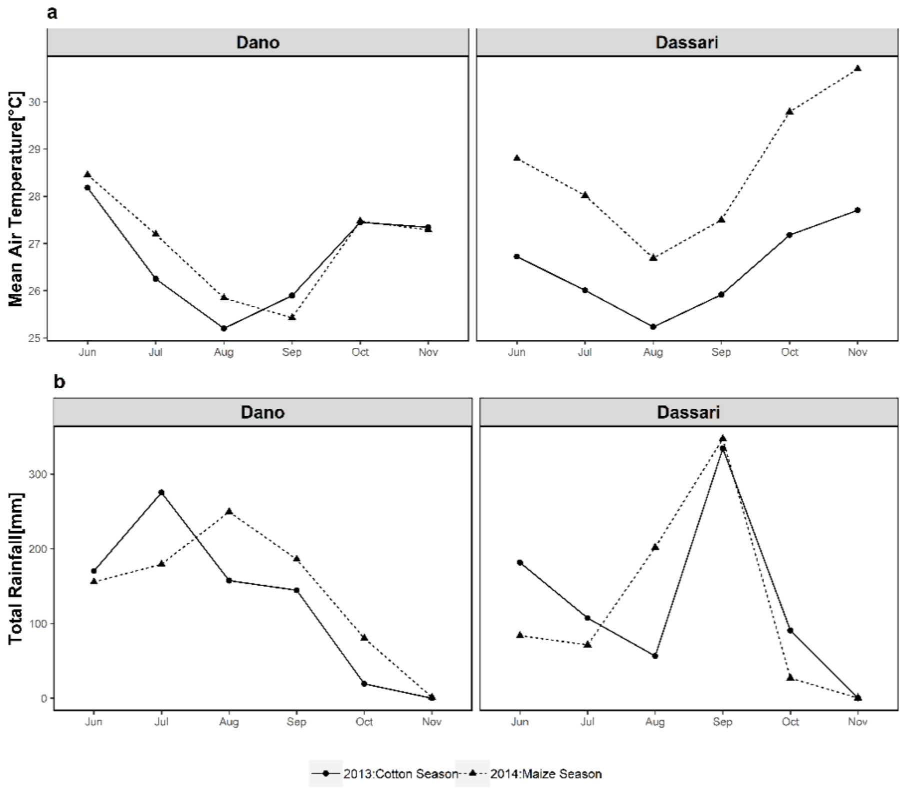

Figure 2: Climatic conditions during the growing seasons of 2013 and 2014 in experimental sites of Dano and Dassari; [a] Mean monthly air temperature (˚C), [b] Total monthly rainfall (mm). The numbers within the figures indicate the total and/or mean value of the respective weather parameter.

2.2. Experimental design and treatments

The experiments were set up as a strip-split plot design with four replications. At both locations, a similar experiment was established on both upslope and footslope positions in the landscape. As mentioned previously, each of the sites consisted of a combination of particular weather and soil type, and thus sites were considered as the strip factor. In each strip, eight main plots were randomly distributed. Two levels of tillage, contour ridge tillage, and reduced tillage, were applied as main plot treatments with four replicated in each strip. Subplot treatments included crop residue management (with crop residue and without crop residue) and a nitrogen fertilizer treatment (no nitrogen application and recommended dose of nitrogen: 45 kg N ha^{-1}

for cotton and 60 kg N ha^{-1} for maize). The subplot factors were randomized within the main plot. A total of 48 (2 x 2 x 2 x 4) sub-plots were set up at each of the sites. At planting, the previous year's residues were distributed evenly to the sub-plots receiving crop residue retention treatments. The C:N ratio of the incorporated residue of cotton and maize were 30 and 70, respectively. The size of each main and subplot was 30 m x 10 m and 10 m x 5 m, respectively.

Table 1: Major soil characteristics of all four soil types at the top 20 cm **(**adapted from Danso et al., 2018)

Properties	**Units**	**location/slope/Soil Type**			
		Dano/Footslope/Ferric Lixisol	**Dano/Upslope/ Eutric Plinthosol**	**Dassari/Footslope/ Haplic Lixisol**	**Dassari/Upslope/Plinthic Lixisol**
pH	1:2.5 H_2O	6.5	6.5	6.16	6.58
Organic C	%	0.65	0.63	0.81	0.69
Total N	%	0.05	0.05	0.08	0.06
Bray P	mg kg^{-1}	2.3	2.8	5.9	7.5
Bray K	mg kg^{-1}	36	33	56	36
Sand	%	52.9	32.8	66.4	56.9
Silt	%	43.1	17.1	32.5	40.1
Clay	%	3.0	50.0	1.1	2.0
Texture		Sandy	Sandy clay loam	Sandy Loam	Sandy Loam
Gravel content	%	47	26	13	24
Permeability Class	-	Rapid	Moderately Slow	Moderately Rapid	Moderately Rapid

2.3. Crop and soil management

Maize (short-season variety: Dorke SR, 90 days) was sown in late June and harvested in mid-October of the same year (2014) in both locations. Cotton (variety: FK 37) was sown mid-June and harvested in mid-October and mid-November of the same year (2013) in Dano and Dassari, respectively. An amount of 2.1-liter ha^{-1} glyphosate was applied before tillage operations to kill the weeds. Contour ridges were developed by using animal-drawn moldboard ploughs.

Maize was planted with a density of 62,500 plants ha^{-1} and with a 0.8 m of inter-row and 0.4 m of intra-row spacing. Cotton was planted at a density of 83,333 plants ha^{-1} and inter-row and intra-row spacing of 0.8 m and 0.3 m, respectively. Weeds were cleared by using a hand hoe and the pesticide “Super Lambda” was sprayed 5-6 times to protect the cotton bolls against pests. For the plots receiving N fertilizer, applied rates for cotton and maize were 45 kg ha^{-1} and 60 kg ha^{-1}, respectively. All plots received 60 Kg ha^{-1} of each P_2O and K_2O fertilizer. All the P and K and 50 % N were broadcasted 25 days after planting and the rest 50 % of N was applied 45 days after planting.

2.4. Sampling, measurements, and calculations

Cotton and maize yield samples and total aboveground biomass were collected at harvest. Cotton yield was determined by handpicking all open bolls from an area of 9 m^2 at harvest. The lint yield was calculated after ginning. Maize yield was measured by harvesting all plants from an area of 9 m^2 at maturity. The collected plant samples were cleaned, separated into parts (shoot and storage organ), and left for air-drying in the laboratory for 48 hours. Later, the air-dried sub-samples were placed in paper bags and oven-dried at 80 ˚C (Isaac and Jones, 1972) for at least 24 hours to remove residual moisture and to calculate the dry matter content in kg ha^{-1}. The dried samples were then mechanically chopped into small pieces to fit them into a ball mill. In order to reduce the particle size of plant tissue and to ensure a greater degree of uniformity in the sample composition, ball milling was carried out in a Mixer Mill MM 400 at 400 rpm for a maximum of one minute per sample (Jones, 2001). The milled fine plant tissue samples were then preserved in 250 ml glass vials for chemical analysis. The nitrogen content of the plant tissue was determined by combustion in Autoanalyzer (CHN model EA 1108).

Various NUE indices were calculated based on the data collected for yield, aboveground biomass, and N concentrations in both cotton and maize using the following formulas:

$$\textbf{NU}\ (\text{kg ha}^{-1}) = \frac{\%\ \text{N in storage organs x Yield in kg ha}^{-1}}{100} \quad (1)$$

$$\textbf{NFR}\ (\%) = \frac{TNU_f - TNU_0}{N_{apply}} \times 100 \quad (2)$$

$$\textbf{AE}\ (\text{kg kg}^{-1}\ \text{N applied}) = \frac{Yield_f - Yield_0}{N_{apply}} \quad (3)$$

$$\textbf{PFP}\ (\text{kg kg}^{-1}\ \text{N applied}) = \frac{Yield}{N_{apply}} \quad (4)$$

Where, TNU= total nitrogen uptake in plant biomass, TAGB= total above-ground biomass, f=fertilizer plots, 0=control plots, N_{apply} = rate of applied nutrient (N/P/K)

2.5. Statistical analysis

R Development Core Team (2011) was used to perform all the statistical analyses. Variables like NFR, AE, PFP_n, and NU were analyzed using a mixed model for strip-split plot layout described by Gomez et al. (1984) using the "lme" function in the "nlme" package in R. We considered sites, tillage, and crop residue as fixed factors, while replication and replication × tillage were included as random factors. Sites were chosen to represent specific soils among which comparisons were to be made, which means they should be treated as fixed factors (Piepho et al., 2003). We also opted out N as an experimental factor because NFR, and AE was calculated based on the difference method (the difference between fertilizer plots and unfertilized plots). Therefore, our statistical model deviates from the one used in a previous study by Danso et al. (2018). Mean values were compared using the Tukey test at $p < 0.05$ level using "lsmeans" function. All the figures illustrating the differences among different treatments were produced using "ggplot2" package.

3. Results

We first conducted analysis of variance (ANOVA) to identify factors significantly affecting the NUE in the different crops. In cotton, illustrated that NU and NUE indices (NFR, AE, and

PFP_n) significantly varied according to the individual effects of tillage and crop residue (Table 2). A significant effect of site × tillage interaction was observed for NU and all NUE indices of cotton, whereas site × crop residue interaction was significant only for NFR of cotton. No three-way or four-way interactions were observed for cotton NUE indices. In maize, NU and NUE indices of maize followed a similar trend (Table 3). Thus, NU and NUE indices of maize were significantly affected by the single effect of tillage and the interactive effects of site × tillage. However, the effect of crop residue on NU and NUE of maize was marginal and only NFR was significantly influenced by crop residue and site × crop residue interaction effects. Together these data suggest that both crops showed a similar trend in terms of factors significantly affecting NUE indices.

3.1. Effects of management practices on NUE indices

3.1.1. Effects on NFR

First, we analyzed the effects of tillage on NUE indices. Compared to reduced tillage, contour ridge tillage increased NFR of cotton significantly on all sites except S1. When averaged across sites (Table 2), contour ridge tillage tended to increase NFR of cotton markedly by 32.6% compared to reduced tillage. For the effects of crop residue (on average of all treatments), an increase in NFR of cotton by 14.6% was observed when crop residues were added to the surface soil (Table 2), an effect that was significant on S2 and S4 (Figure. 5a).

Next, we analyzed whether maize followed a similar trend as cotton. The superiority of contour ridge tillage over reduced tillage was seen on all sites except S3, although NFR was slightly increased by contour tillage (Figure. 4a). When averaged across sites, contour ridge tillage contributed to 29.4% higher NFR of maize compared to reduced tillage. Incorporation of crop residues positively affected NFR of maize only on S2 (Figure. 6a). In general, an overall 14% increase in NFR of maize was recorded under crop residue retention. In summary, contour ridge tillage proved and incorporation of crop residue proved to be superior on most sites in both crops with some exceptions.

Table 2: Mean effects (single main effects) and summary of ANOVA output of the generalized linear model for the effect of sites, tillage, and crop residue on the traits measured for cotton.

Factors/Levels	NU ($kg\ ha^{-1}$)	NFR (%)	AE ($kg\ kg^{-1}$)	PFP_n ($kg\ kg^{-1}$)	PFP_p ($kg\ kg^{-1}$)	PFP_k ($kg\ kg^{-1}$)
			Sites			
Eutric Plinthosol	27.2±0.7 a	25.4±0.7 a	5.5±0.3 a	37.7±0.9 a	29.6±0.7 a	15.6±0.4 a
Ferric Lixisol	28.1±0.7 a	27.6±0.8 ab	5.8±0.3 a	37.7±1.0 a	29.6±0.6 a	15.6±0.4 a
Plinthic Lixisol	34.3±0.9 b	30.5±1.0 b	5.9±0.4 ab	50.8±1.2 b	39.8±0.9 b	21.1±0.5 b
Haplic Lixisol	42.3±0.8 c	34.8±0.8 c	7.3±0.3 b	57.9±1.0 c	45.4±0.8 c	24.0±0.4 c
			Tillage			
Reduced Tillage	28.4±0.5 a	24.7±0.5 a	5.6±0.2 a	41.4±0.7 a	32.5±0.5 a	17.2±0.3 a
Contour Ridge	37.5±0.5 b	34.4±0.6 b	6.7±0.2 b	50.6±0.7 b	39.7±0.6 b	21.0±0.3 b
			Crop Residue			
Residues Removed	31.7±0.5 a	27.4±0.6 a	5.8±0.2 a	44.8±0.7 a	35.1±0.5 a	18.6±0.3 a
Residues Incorporated	34.2±0.5 a	31.7±0.6 b	6.4±0.2 a	47.3±0.7 a	37.0±0.6 a	19.6±0.3 a
			Analysis of Variance			
Site	<.0001***	<.0001***	0.0036**	<.0001***	<.0001***	<.0001***
Tillage	<.0001***	<.0001***	0.0026**	<.0001***	<.0001***	<.0001***
Residue	ns	<.0001***	ns	0.0462*	ns	0.0462*
Site:Tillage	0.0003***	0.0225*	0.0283*	0.0095**	0.0095**	0.0095**
Site:Residue	ns	0.0128*	ns	ns	ns	Ns
Tillage:Residue	ns	ns	ns	ns	ns	Ns
Site:Tillage:Residue	ns	ns	ns	ns	ns	Ns

The values are presented as lsmean±standard error. For each main treatment effect, values within a column followed by the same letters are not significantly different at $P \leq 0.05$. The amount of N fertilizer for cotton was 45 kg ha^{-1} and for maize was 60 kg ha^{-1}. In both cases (cotton and maize), the amount of P_2O_5 and K_2O fertilizer applied was 60 kg ha^{-1} each.

*, **, and *** denote the significance of the factor at $P \leq 0.05$, 0.01, and 0.001, respectively; ns, not significant at $P \leq 0.05$

NU= Nitrogen Uptake, NFR= Nitrogen Fertilizer Recovery Efficiency, AE= Agronomic Efficiency, PFP_n= Partial Factor Productivity of Nitrogen, PFP_p= Partial Factor Productivity of phosphorus, PFP_k= Partial Factor Productivity of potassium

3.1.2. Effects on AE

Tillage operations and tillage × site interactions had significant effects on AE of cotton. On average, the application of contour ridge tillage significantly improved (+18.6%) AE of cotton compared to reduced tillage. This was true for all sites (Figure. 3b), but the magnitude was significantly higher on S2 (+47%). For the effects of crop residue, residue application had no significant effect on AE of cotton across the sites. However, AE tended to be slightly higher when crop residues were incorporated, yet not significant.

Again, we determined the AE of maize in order to identify whether it followed a similar trend as cotton. The highest AE of maize occurred under the contour ridge tillage system. When averaged across sites (Table 3), the implementation of contour ridge tillage caused a 25.8% increase in AE of maize compared with reduced tillage. Also, the factor tillage × site interaction showed significant effects on AE of maize. Contour ridge tillage significantly improved AE of maize on all soils except S3 (Figure. 4b). Together these results illustrated higher AE of both cotton and maize under contour ride tillage compared to reduced tillage, and with crop residue retention on all sites, although the effect was not significant on all sites.

Table 3: Mean effects (single main effects) and summary of ANOVA output of the generalized linear model for the effect of sites, tillage, and crop residue on the traits measured for maize.

Factors/Levels	NU (kg ha^{-1})	NFR (%)	AE (kg kg^{-1})	PFP$_n$ (kg kg^{-1})	PFP$_p$ (kg kg^{-1})	PFP$_k$ (kg kg^{-1})
			Sites			
Ferric Lixisol	59.5± 5.2 a	45.1±2.3 a	10.2±1.0 a	67.9±3.3 a	70.2±3.4 a	37.7±1.8 a
Eutric Plinthosol	84.1± 5.2 b	53.5±2.3 b	16.5±1.0 b	93.1±3.3 b	97.0±3.4 b	51.3±1.8 b
Plinthic Lixisol	92.3± 5.2 b	60.6±2.3 b	18.0±1.0 b	110.2±3.3 b	115.3±3.4 b	61.1±1.8 b
Haplic Lixisol	133.3± 5.2 c	76.0±2.3 c	28.1±1.0 c	174.7±3.3 c	182.7±3.4 c	96.8±1.8 c
			Tillage			
Reduced Tillage	84.3±3.6 a	51.4±1.8 a	15.8±0.7 a	105.1±3.4 a	110.7±3.6 a	58.6±1.9 a
Contour Ridge	100.5±3.6 b	69.2±1.8 b	20.6±0.7 b	117.9±2.1 b	122.3±2.2 b	65.4±1.1 b
			Crop Residue			
Residues Removed	88.1±3.6 a	54.2±1.8 a	17.7±0.7 a	110.5±2.5 a	115.8±2.6 a	61.1±1.4 a
Residues Incorporated	95.5±3.6 a	62.4±1.8 b	18.7±0.7 a	112.4±2.5 a	117.3±2.6 a	62.4±1.4 a
			Analysis of Variance			
Site	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***
Tillage	0.0047**	<.0001***	0.0006***	0.0006***	0.0006***	0.0006***
Residue	ns	0.0001***	Ns	ns	ns	Ns
Site:Tillage	0.0416*	0.0002***	0.0436*	<.0001***	<.0001***	<.0001***
Site:Residue	ns	0.0002***	ns	ns	ns	0.0044**
Tillage:Residue	ns	ns	ns	ns	ns	Ns
Site:Tillage:Residue	ns	ns	ns	ns	ns	Ns

The values are presented as lsmean±standard error. For each main treatment effect, values within a column followed by the same letters are not significantly different at $P \leq 0.05$. The amount of N fertilizer for cotton was 45 kg ha^{-1} and for maize was 60 kg ha^{-1}. In both cases (cotton and maize), the amount of P_2O_5 and K_2O fertilizer applied was 60 kg ha-$^{-1}$ each.

*, **, and *** denote the significance of the factor at P ≤0.05, 0.01, and 0.001, respectively; ns, not significant at $P \leq 0.05$

NU= Nitrogen Uptake, NFR= Nitrogen Fertilizer Recovery Efficiency, AE= Agronomic Efficiency, PFP$_n$= Partial Factor Productivity of Nitrogen, PFP$_p$= Partial Factor Productivity of phosphorus, PFP$_k$= Partial Factor Productivity of potassium

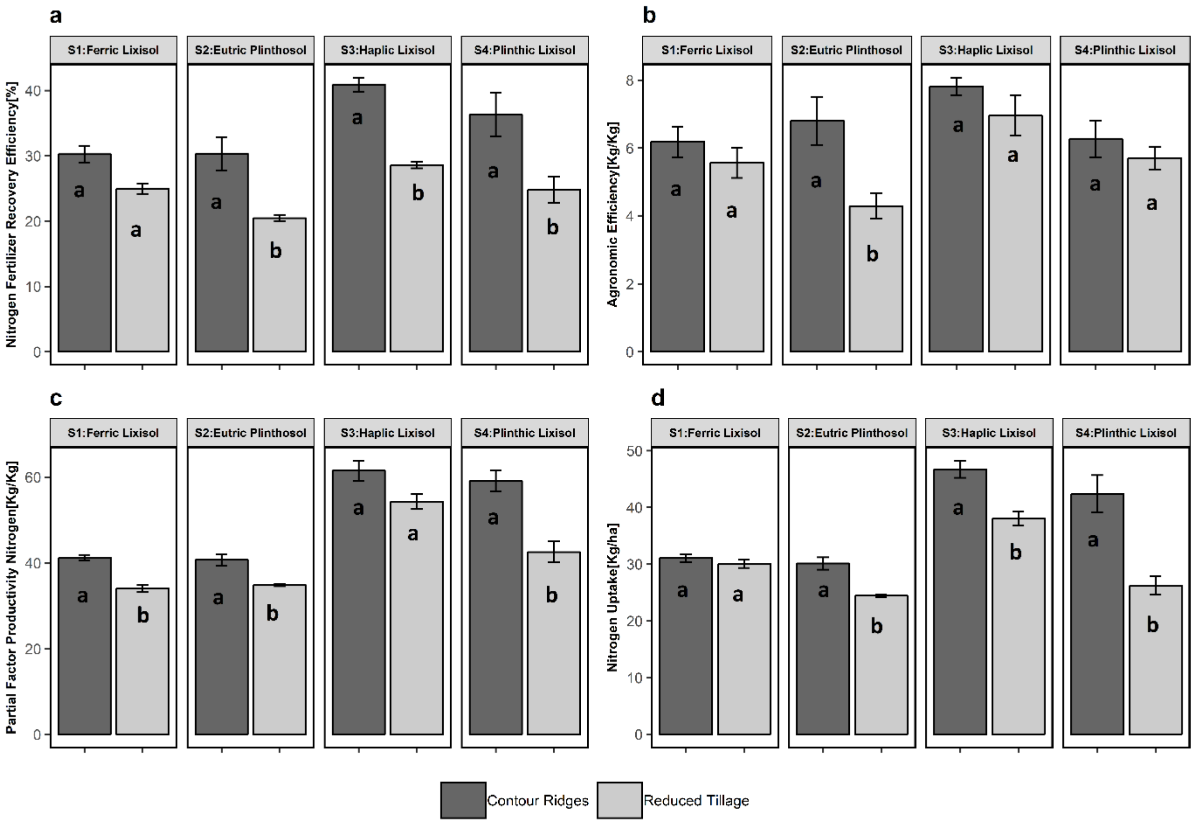

Figure 3: Nitrogen fertilizer recovery efficiency (%) [a], agronomic efficiency (kg kg^{-1}) [b] partial factor productivity nitrogen (kg kg^{-1}) [c], and nitrogen uptake (kg ha^{-1}) [d] in cotton as affected by contour ridge tillage and reduced in four sites. Each bar is a mean of 8 values (1 tillage×2 crop residue×4 replications). Vertical bars indicate mean standard error (±) at P=0.05. Bars belonging to the same variable within a site group followed by the same letter (s) are not significantly different at P ≤0.05 level according to Tukey test.

3.1.3. Effects on PFP_n

The difference in PFP_n of cotton between tillage systems was consistent over the sites. Contour ridge tillage was superior on all sites except S3. When averaged across sites, PFP_n of cotton improved from 41.4 kg kg^{-1} to 50.6 kg kg^{-1} under contour ridge tillage than reduced tillage (Table 2). Although not significant, incorporation of crop residue irrespective of sites and tillage systems led to a 5.4% increase in PFP_n of cotton.

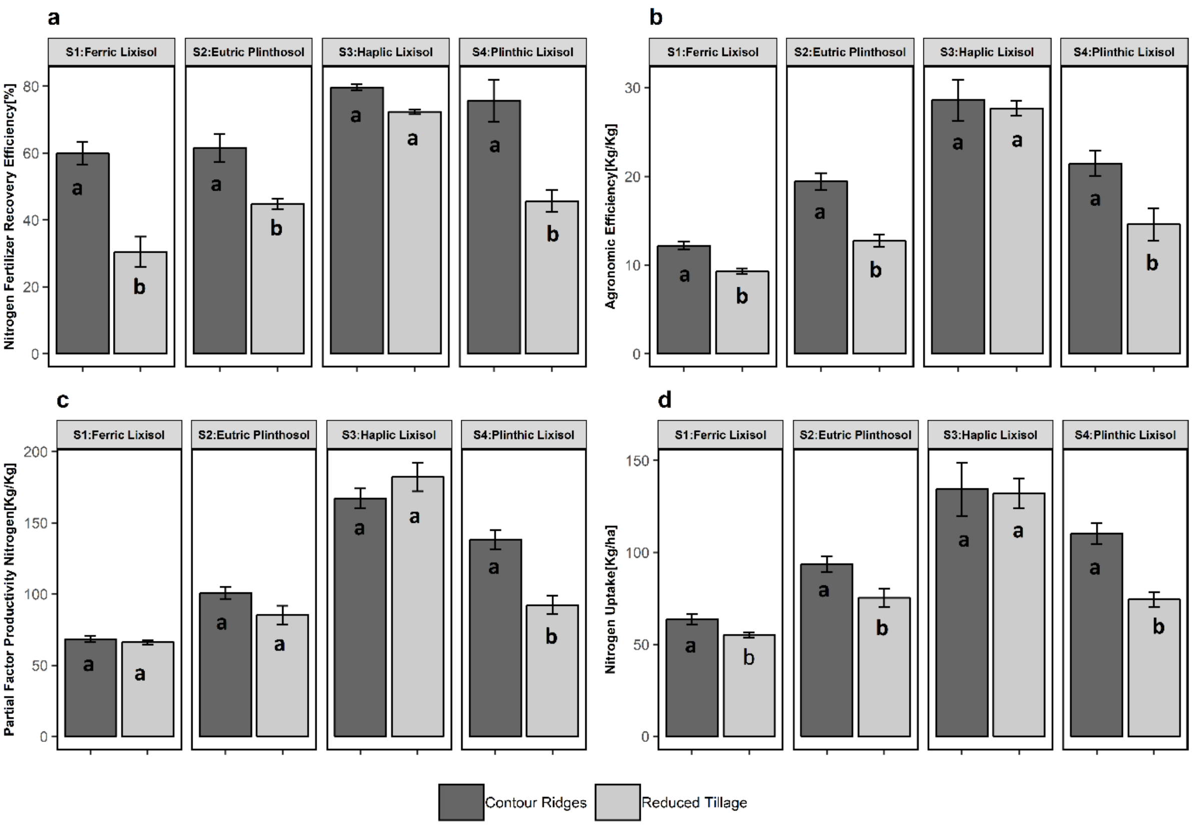

Figure 4: Nitrogen fertilizer recovery efficiency (%) [a], agronomic efficiency (kg kg^{-1}) [b] partial factor productivity nitrogen (kg kg^{-1}) [c], and nitrogen uptake (kg ha^{-1}) [d] in maize as affected by contour ridge tillage and reduced in four sites. Each bar is a mean of 8 values (1 tillage×2 crop residue×4 replications). Vertical bars indicate mean standard error (±) at P=0.05. Bars belonging to the same variable within a site group followed by the same letter (s) are not significantly different at P ≤0.05 level according to Tukey test.

Subsequently, we assessed the PFP_n of maize in order to identify whether it follows a similar trend as cotton. The difference in PFP_n of maize between the tillage systems was significant only on the site upslope of Dassari (S4), but not on the other sites. On S2, and S1 (Figure. 4c), contour ridge tillage did not markedly improve PFP_n of maize and on S3, reduced tillage was even slightly superior, yet not significant. For the effects of crop residue, returning crop residue had no significant on any site at all (Figure. 6c). On average, incorporation of crop residue did not significantly increase (112.4 kg kg^{-1} versus 110.5 kg kg^{-1}) PFP_n of maize over crop residue removal (Table 3).

These results indicated that in comparison to reduced tillage, PFP_n of both cotton and maize were high under contour ridge tillage practice on all sites except S3. Incorporation of crop residue did not significantly affect PFP_n of cotton and maize at any site.

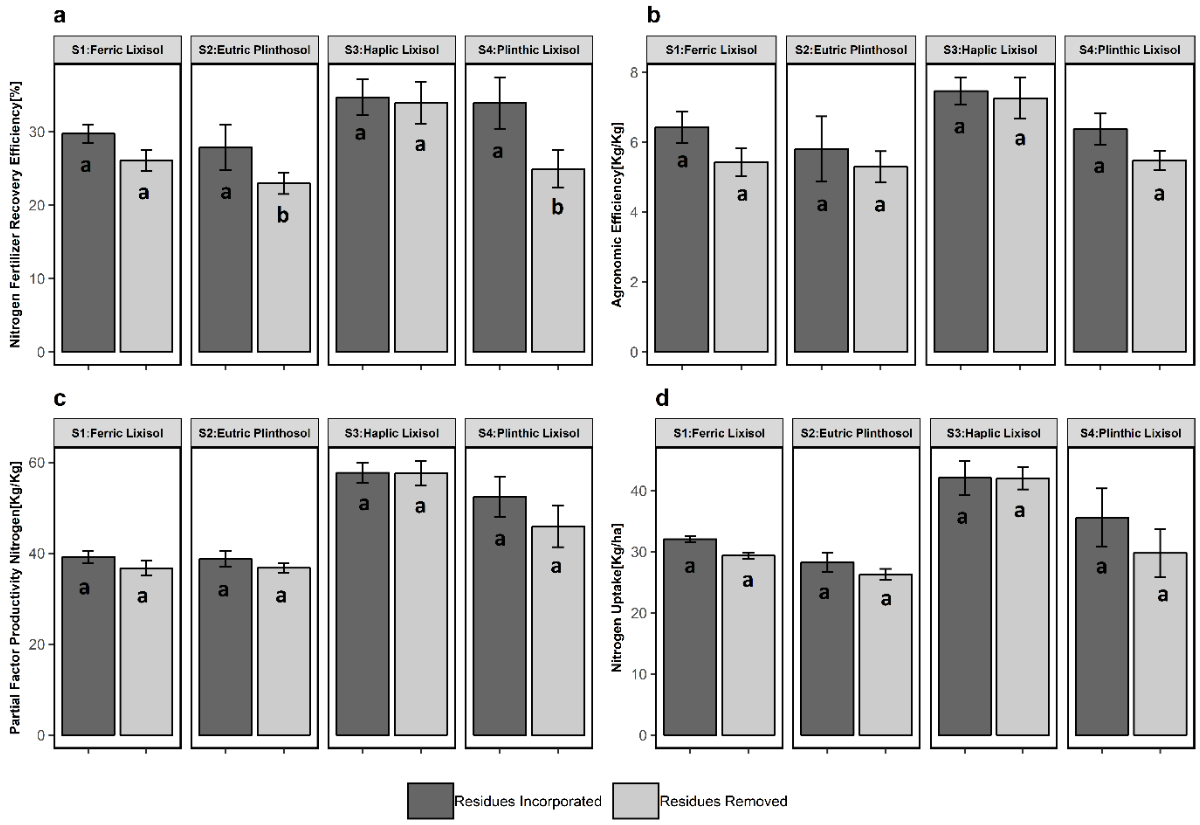

Figure 5: Nitrogen fertilizer recovery efficiency (%) [a], agronomic efficiency (kg kg^{-1}) [b] partial factor productivity nitrogen (kg kg^{-1}) [c], and nitrogen uptake (kg ha^{-1}) [d] in cotton as affected by crop residue in four sites. Each bar is a mean of 8 values (1 crop residue×2 tillage×4 replications). Vertical bars indicate mean standard error (±) at P=0.05. Bars belonging to the same variable within a site group followed by the same letter (s) are not significantly different at P ≤0.05 level according to Tukey test.

3.2. Effects on NU

Finally, we analyzed NU as a product of N concentrations and yields, which are reported elsewhere (equation 1). Contour ridge tillage significantly improved NU in cotton on all sites except S1 (Figure. 3d). On average across all sites, contour ridge tillage increased NU in cotton by 27.6% (Table 2). Similarly, crop residue had no significant effects on NU in cotton, but the removal of crop residue contributed to a gradual decrease in NU in cotton by 7.6% compared to crop residue incorporation (on average). Similarly, we assessed the NU in maize in order to identify whether it follows a similar trend as cotton. Contour ridge tillage increased NU on all sites except S3 (Figure. 4d). When averaged across all treatments (sites and crop residue), contour ridge tillage significantly improved NU in maize by 17.5% compared to reduced tillage system. Although not significant, NU in maize increased by 8% with crop residue incorporation. Taken together contour ridge tillage led to higher NU in both cotton and maize (on most sites with some exceptions, while the effects of crop residue retention were not significant.

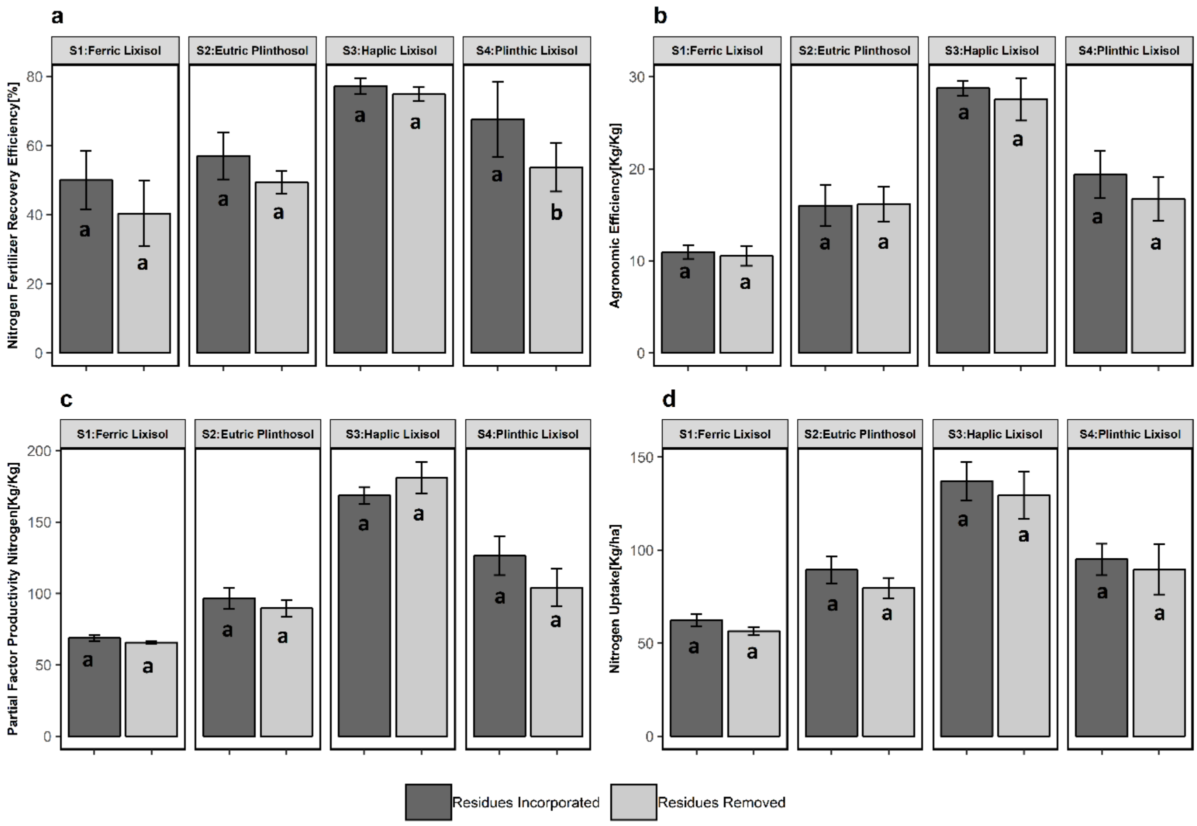

Figure 6: Nitrogen fertilizer recovery efficiency (%) [a], agronomic efficiency (kg kg^{-1}) [b] partial factor productivity nitrogen (kg kg^{-1}) [c], and nitrogen uptake (kg ha^{-1}) [d] in maize as affected by crop residue in four sites. Each bar is a mean of 8 values (1 crop residue×2 tillage×4 replications). Vertical bars indicate mean standard error (±) at P=0.05. Bars belonging to the same variable within a site group followed by the same letter (s) are not significantly different at P ≤0.05 level according to Tukey test.

Overall, our results suggest that the implementation of contour ridge tillage instead of reduced tillage and crop residue retention could be beneficial in terms of improving crop (both cotton and maize) NUE and NU across sites. However, such differences between tillage operations and crop residue management were not significant on all sites.

4. Discussion

One of the most important steps towards achieving sustainable crop production is to improve crop NUE (Lammerts van Bueren and Struik, 2017). Our study contributes to the understanding of how tillage and crop residue application interact with soil conditions on different NUE indicators in the sub-humid savanna of West Africa. Thus, our goal was to identify management options that enable efficient use of synthetic N fertilizers and at the same time, could potentially intensify crop production in a sustainable manner.

We used three major indicators, NFR, AE, and PFP_n to evaluate NUE. According to Dobermann (2007) and Fixen et al. (2014), PFP_n corresponds to the crop yield per unit of N applied and answers the question, "How productive is this cropping system in comparison to its N input?"; AE is the increase in crop yield per unit of N applied and answers the question, "How much productivity improvement was gained by use of N input?"; and NFR is the increase in NU in response to applied nutrients and answers the question, "How much of the N applied did the plant take up?". Since each of the indices has different interpretation values, it is recommended to include all of them in order to better understand the possible causes of variations in NUE (Dobermann, 2005). Generally, the ranges of NFR, AE and NU measured for both cotton and maize in our study are in agreement with the results from a study carried out by Amouzou et al. (2018) in Benin.

4.1. Effect of tillage on NUE indices

Our research suggests that the contour ridge tillage may be a valuable alternative to reduced tillage in most sites of West Africa, as NUE and NU (on average of sites and crop residue) of both cotton and maize cropping systems were higher in soils treated with contour ridge tillage compared to reduced tillage (Figure. 3 and 4). This effect may have occurred for the following reasons.

Firstly, enhanced soil water availability under contour ridge tillage system could lead to increased uptake of soil available N and improved NUE. Restoration of soil water storage under contour and tied ridge tillage compared to minimum tillage was demonstrated previously (1978) in Chromic Luvisol. Another study performed by Brhane et al. (2006) in Typic Pellustert, illustrated the importance of contour or tied ridge tillage in improving soil moisture storage as well as crop yield. Shaxson et al. (2003) reflected the convenience of tied contour ridge to confine rainfalls where it occurs so that there is more opportunity for soil to absorb and store it, and to prevent runoff.

Secondly, loss of surface soil particles and runoff in semi-arid regions can be greatly reduced or even eliminated by applying contour or tied ridge (Hatfield et al., 1998; Lal, 1990; Mohamoud, 2012). Contouring provides enough time for soil water infiltration, thus controlling runoff and water erosion (Unger et al., 1991). Such measures are traditionally adopted by the farmers of West Africa to check soil erosion and trap soil and moisture (Tengberg et al., 1998). A study carried out by Thapa et al. (1999) in Oxisol also confirmed the use of contour ridge tillage as an effective practice to mitigate soil loss from steep slope areas. Considering the reduced soil erosion and increased soil water availability associated with contour ridge tillage compared to reduced tillage, it is not surprising that higher NU and NUE of both cotton and maize (on average) were recorded under the contour ridge tillage system in this study (Table 2 and 3).

We also found a site × tillage interactive effects on crop NU and NUE indices (Figure. 3 and 4). Implementation of contour ridge tillage was found effective mainly on sites in upslope of Dano (S2, Eutric Plinthosol) and Dassari (S4, Plinthic Lixisol). From the aforementioned discussion, it is clear that contour ridge tillage in steep slope areas is likely to restrict horizontal water movement and soil loss, and increase soil water storage that results in increased soil available N content and NU. In that regard, improved crop NUE under contour ridge tillage compared to reduced tillage on sites in upslope (S2 and S4) is plausible. On the other hand, contour ridge tillage was not effective in improving crop NUE on S3 (Haplic Lixisol, footslope Dassari). Greater NUE indices in S3 under both tillage operations could be attributed to the inherent fertility status (Table 1) of this site as it has the highest available water content (54.1 mm) due to increased rooting depth (90 cm), low gravel content (13%), and high organic carbon (0.81%). On the other hand, S1 also did not exhibit any difference between tillage practices (in particular cases) as it is located in the footslope slope of Dano that makes it less prone to topsoil erosion and, thus the effectiveness of contour ridge tillage was less pronounced. Further, increased N leaching with rapid vertical soil water movement due to high gravel content (Table 1) on S1 could also lead to such observation.

4.2. Effect of crop residue on NUE indices

Keeping crop residues on surface soil also significantly increased average NU and NUE indices (mainly NFR) of cotton and maize (across sites) compared with the removal of crop residue. This result is in agreement with other studies where improved crop yield and NUE were observed under crop residue incorporation (Kaleeem Abbasi et al., 2015; Kumar, 1998; Nishigaki et al., 2017; Sharma and Prasad, 2008).

The efficiency of crop residue incorporation in terms of improving NU and NUE in this study could be explained by the following phenomena. Generally, release of available N through crop residue decomposition depends on the quality of the returned crop residue (its N content, C:N ratio and other plant constituents N), and the rate of N release through mineralization (Baijukya et al., 2006; Nicolardot et al., 2001; Palm et al., 2001). Although other studies demonstrated that incorporating low-quality crop residue with high C:N ratios and high lignin concentrations might reduce soil N availability to plants by markedly increasing soil N immobilization (Chaves et al., 2004; Chen et al., 2014; Gentile et al., 2009; Manzoni et al., 2008), greater NFR under both maize (high C:N ratio, 70) and cotton (low C:N ratio, 30) residue retention was observed. This could be attributed to the slow and continuous release of N from the applied crop residue during the growing seasons of both cotton and maize. Moreover, the application of crop residue has the potential to increase soil N availability by improving soil water storage and soil water infiltration and reducing soil water evaporation (Melaj et al., 2003).

An interaction effect of site and crop residue was also observed for both cotton and maize (Table 2 and 3). Greater NUE indices (mainly NFR) of cotton was observed under maize crop residue incorporation on S2 (Eutric Plinthosol, upslope in Dano), and S4 (Plinthic Lixisol, upslope in Dassari), while the NFR of maize was higher under cotton residue retention was only on S2. Keeping residue could improve soil particle protection and act as a barrier against surface runoff and erosion. Moreover, soils with a greater content of clay particles provide physical protection to soil organic matter (crop residues) that reduce the pace of soil organic matter decomposition (Jenkinson, 1977; Merckx et al., 1985). These observations suggest that restricted soil loss and steady rate of soil organic matter decomposition resulted in slow and continuous release of soil N and increased soil N availability on S2 and S4 under crop residue retention. However, this statement is not true for S4 under cotton residue retention which could be due to increased N leaching loss with a greater content of sand particles in the soils (Table 1). As mentioned earlier, the lack of significant effects of crop residue retention on S3 (Haplic Lixisol, footslope in Dassari) could be attributed to its pre-existing improved hydrological and other soil properties that resulted in a slow and continuous N supply to crops and improved crop NUE regardless of implemented management practices.

Irrespective of our results, there are certain technological barriers to contour ridge tillage and crop residue application. One is the difficulty of implementing animal traction for contour ridge tillage. Also, several factors keep smallholder farmers from incorporating crop residues in this region. Crop residues are greatly used as livestock feed in this region and the demand for it rises during the dry season when feed shortages become more acute (Jimma et al., 2016). Moreover, improper management of crop residues in wet soils could also lead to disease transmission to the following crop.

5. Conclusions

This study evaluated the single and interactive effects of tillage and crop residue retention on NUE of maize and cotton on different weathered soils of West Africa. Among four representative sites tested, the NUE of both crops was best under contour ridge tillage with an exception of S3 (Haplic Lixisol, footslope in Dassari) presumably due to its pre-existing improved hydrological properties and fertility. Application of crop residues also showed pronounced effects on NUE (mainly NFR) of both crops, however not on all sites. While the observed trend of improved NUE with contour ridge tillage is not in accord with our hypothesis, it can be explained with increased soil water content, restricted horizontal movement and soil loss. Taken together, our results, therefore, suggest that contour ridge tillage with crop residue retention generally resulted in improved NUE of both maize and cotton by improving soil N availability and soil water content in a site-specific manner. The results of this study are therefore targeted at extension agents and cotton and maize farmers in these regions to maintain proper and efficient N fertilizer management strategies.

6. References

Adediran, J.A., Banjoko, V.A., 1995. Response of maize to nitrogen, phosphorus, and potassium fertilizers in the savanna zones of Nigeria. Commun. Soil Sci. Plant Anal. 26, 593–606. https://doi.org/10.1080/00103629509369320

Aina, P.O., Lal, R., Roose, E.J., 1991. Tillage methods and soil and water conservation in West Africa. Soil Tillage Res. 20, 165–186. https://doi.org/10.1016/0167-1987(91)90038-Y

Al-Kaisi, M., Kwaw-Mensah, D., 2007. Effect of Tillage and Nitrogen Rate on Corn Yield and Nitrogen and Phosphorus Uptake in a Corn-Soybean Rotation. Agron. J. 99, 1548. https://doi.org/10.2134/agronj2007.0012

Amouzou, K.A., Naab, J.B., Lamers, J.P.A., Becker, M., 2018. Productivity and nutrient use efficiency of maize, sorghum, and cotton in the West African Dry Savanna. J. Plant Nutr. Soil Sci. 181, 261–274. https://doi.org/10.1002/jpln.201700139

Angás, P., Lampurlanés, J., Cantero-Martínez, C., 2006. Tillage and N fertilization: Effects on N dynamics and Barley yield under semiarid Mediterranean conditions. Soil Tillage Res. 87, 59–71. https://doi.org/10.1016/J.STILL.2005.02.036

Araya, A., Stroosnijder, L., 2010. Effects of tied ridges and mulch on barley (Hordeum vulgare) rainwater use efficiency and production in Northern Ethiopia. Agric. Water Manag. 97, 841–847. https://doi.org/10.1016/J.AGWAT.2010.01.012

Aulakh, M.S., Rennie, D.A., Paul, E.A., 1982. Gaseous nitrogen losses from cropped and summer-fallowed soils. Can. J. Soil Sci. 62, 187–196. https://doi.org/10.4141/cjss82-020

Awale, R., Chatterjee, A., Franzen, D., 2013. Tillage and N-fertilizer influences on selected organic carbon fractions in a North Dakota silty clay soil. Soil Tillage Res. 134, 213–222. https://doi.org/10.1016/J.STILL.2013.08.006

Awale, R., Emeson, M.A., Machado, S., 2017. Soil Organic Carbon Pools as Early Indicators for Soil Organic Matter Stock Changes under Different Tillage Practices in Inland Pacific Northwest. Front. Ecol. Evol. 5, 96. https://doi.org/10.3389/fevo.2017.00096

Baijukya, F.P., de Ridder, N., Giller, K.E., 2006. Nitrogen Release from Decomposing Residues of Leguminous Cover Crops and their Effect on Maize Yield on Depleted Soils of Bukoba District, Tanzania. Plant Soil 279, 77–93. https://doi.org/10.1007/s11104-005-2504-0

Baligar, V.C., Duncan, R.R., 1990. Crops as enhancers of nutrient use. Academic.

Baligar, V.C., Fageria, N.K., He, Z.L., 2001. Nutrienr use efficiency in plants. Commun. Soil Sci. Plant Anal. 32, 921–950. https://doi.org/10.1081/CSS-100104098

Barber, S.A., 1971. Effect of Tillage Practice on Corn (Zea mays L.) Root Distribution and Morphology1. Agron. J. 63, 724. https://doi.org/10.2134/agronj1971.00021962006300050020x

Brennan, J., Hackett, R., McCabe, T., Grant, J., Fortune, R.A., Forristal, P.D., 2014. The effect of tillage system and residue management on grain yield and nitrogen use efficiency in winter wheat in a cool Atlantic climate. Eur. J. Agron. 54, 61–69. https://doi.org/10.1016/J.EJA.2013.11.009

Brhane, G., Wortmann, C.S., Mamo, M., Gebrekidan, H., Belay, A., 2006. Micro-basin tillage for grain sorghum production in semiarid areas of Northern Ethiopia. Agron. J. 98, 124–128. https://doi.org/10.2134/agronj2005-0148

Bumb, B.., 1989. Global fertilizer perspective 1960-95: The dynamics of growth and structural change.Report T-34 and T-35. Muscle Shoals, Ala., U.S.A.

Bumb, B.L., Johnson, M.E., Fuentes, P.A., 2011. Policy Options for Improving Regional Fertilizer Markets in West Africa.

Chandrika, D.S., K.L. Sharma, Vidyavathi, S., Munnala, Kumar, T.S., Rani, K.U., 2016. Effect of conservation tillage, residue and nitrogen levels on soil nitrogen fractions and their contributions in nitrogen uptake in castor (Ricinus communis). Indian J. Agric. Sci. .

Chaves, B., De Neve, S., Hofman, G., Boeckx, P., Van Cleemput, O., 2004. Nitrogen mineralization of vegetable root residues and green manures as related to their (bio)chemical composition. Eur. J. Agron. 21, 161–170. https://doi.org/10.1016/J.EJA.2003.07.001

Chen, B., Liu, E., Tian, Q., Yan, C., Zhang, Y., 2014. Soil nitrogen dynamics and crop residues. A review. Agron. Sustain. Dev. 34, 429–442. https://doi.org/10.1007/s13593-014-0207-8

Chen, H., Hou, R., Gong, Y., Li, H., Fan, M., Kuzyakov, Y., 2009. Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. Soil Tillage Res. 106, 85–94. https://doi.org/10.1016/J.STILL.2009.09.009

Costa, André da, Albuquerque, J.A., Costa, Adriano da, Pértile, P., Silva, F.R. da, 2013. Water retention and availability in soils of the State of Santa Catarina-Brazil: effect of textural classes, soil classes and lithology. Rev. Bras. Ciência do Solo 37, 1535–1548. https://doi.org/10.1590/S0100-06832013000600010

Cousin, I., Nicoullaud, B., Coutadeur, C., 2003. Influence of rock fragments on the water retention and water percolation in a calcareous soil. CATENA 53, 97–114. https://doi.org/10.1016/S0341-8162(03)00037-7

Craswell, E.T., Godwin, D.C., 1984. Advances in plant nutrition., Advances in plant nutrition (USA). Praeger.

Crawford, E.W., Jayne, T.S., Kelly, V.A., 2006. Alternative approaches for promoting fertilizer use in Africa.

Cruse, R.M., Herndl, C.G., 2009. Balancing corn stover harvest for biofuels with soil and water conservation. J. Soil Water Conserv. 64, 286–291. https://doi.org/10.2489/jswc.64.4.286

Danso, I., Gaiser, T., Webber, H., Naab, J., Ewert, F., 2018. Response of Maize to Different Nitrogen Application Rates and Tillage Practices Under Two Slope Positions in the Face of Current Climate Variability in the Sudan Savanna of West Africa. Springer, Singapore, pp. 41–58. https://doi.org/10.1007/978-981-10-4796-1_3

Danso, I., Webber, H., Bourgault, M., Ewert, F., Naab, J.B., Gaiser, T., 2018. Crop management adaptations to improve and stabilize crop yields under low-yielding conditions in the Sudan Savanna of West Africa. Eur. J. Agron. 101, 1–9. https://doi.org/10.1016/J.EJA.2018.08.001

Dijkstra, F.A., Cheng, W., 2008. Increased soil moisture content increases plant N uptake and the abundance of 15N in plant biomass. Plant Soil 302, 263–271. https://doi.org/10.1007/s11104-007-9477-0

Dobermann, A., 2007. Nutrient use efficiency. Measurement and management, in: Kraus, A., Isherwood, K. and Heffer, P., Eds., Fertilizers Best Management Practices. Proceeding of International fertilizer Industry Association, Brussels, Belgium, pp. 1–22.

Dobermann, A.R., 2005. Nitrogen Use Efficiency-State of the Art, in: IFA International Workshop on Enhanced-Efficiency Fertilizers. Frankfurt, Germany, pp. 1–18.

Dong, W., Qin, J., Li, J., Zhao, Y., Nie, L., Zhang, Z., 2011. Interactions between soil water content and fertilizer on growth characteristics and biomass yield of Chinese white poplar (*Populus tomentosa* Carr.) seedlings. Soil Sci. Plant Nutr. 57, 303–312. https://doi.org/10.1080/00380768.2010.549445

Doran, J.W., 1980. Soil Microbial and Biochemical Changes Associated with Reduced Tillage1. Soil Sci. Soc. Am. J. 44, 765. https://doi.org/10.2136/sssaj1980.03615995004400040022x

Dossou-Yovo, E.R., Ampofo, E., Igue, A.M., Sintondji, L.O., Agbossou, E.K., 2016. Tillage , Rice Straw Mulch and Nitrogen Fertilization Effects on Upland Rice Yield in Northern Benin 6, 107–117.

Dou, F., Wright, A.L., Hons, F.M., 2008. Sensitivity of Labile Soil Organic Carbon to Tillage in Wheat-Based Cropping Systems. Soil Sci. Soc. Am. J. 72, 1445. https://doi.org/10.2136/sssaj2007.0230

Fixen, P.E., Brentrup, F., Bruulsema, T., Garcia, F.S., Norton, R., Zingore, S., 2014. Nutrient / fertilizer use efficiency : measurement , current situation and trends.

Fixen, P., Brentrup, F., Bruulsema, T., Garcia, F., Norton, R., Zingore, S., n.d. Chapter 1. Nutrient/fertilizer use efficiency: measurement, current situation and trends.

Fox, R.H., Piekielek, W.P., 1993. Management and Urease Inhibitor Effects on Nitrogen Use Efficiency in No-Till Corn. jpa 6, 195. https://doi.org/10.2134/jpa1993.0195

Gaiser, T., Graef, F., Cordeiro, J.C., 2000. Water retention characteristics of soils with contrasting clay mineral composition in semi-arid tropical regions. Aust. J. Soil Res. 38, 523. https://doi.org/10.1071/SR99001

Gardner, W.H., 1986. Water Content, in: Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods. American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 493–544. https://doi.org/10.2136/sssabookser5.1.2ed.c21

Gathagu, J.N. ang a., Mourad, K.A., Sang, J., 2018. Effectiveness of contour farming and filter strips on ecosystem services. Water (Switzerland) 10. https://doi.org/10.3390/w10101312

Gauer, E., Shaykewich, C.F., Stobbe, E.H., 1982. SOIL TEMPERATURE AND SOIL WATER UNDER ZERO TILLAGE IN MANITOBA. Can. J. Soil Sci. 62, 311–325. https://doi.org/10.4141/cjss82-035

Gentile, R., Vanlauwe, B., van Kessel, C., Six, J., 2009. Managing N availability and losses by combining fertilizer-N with different quality residues in Kenya. Agric. Ecosyst. Environ. 131, 308–314. https://doi.org/10.1016/J.AGEE.2009.02.003

Ghimire, R., Norton, J.B., Stahl, P.D., Norton, U., 2014. Soil Microbial Substrate Properties and Microbial Community Responses under Irrigated Organic and Reduced-Tillage Crop and Forage Production Systems. PLoS One 9, e103901. https://doi.org/10.1371/journal.pone.0103901

Gigou, J., Traoré, K., Giraudy, F., Coulibaly, H., Sogoba, B., Doumbia, M., 2006. Farmer-led contour ridging can reduce water runoff in African savannahs. Cah. Agric. 15, 116–122.

Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C., Vanlauwe, B., 2011. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agric. Syst. 104, 191–203. https://doi.org/10.1016/j.agsy.2010.07.002

Gomez, K.A., Gomez, A.A., Gomez, K.A., 1984. Statistical procedures for agricultural research. Wiley.

Habbib, H., Verzeaux, J., Nivelle, E., Roger, D., Lacoux, J., Catterou, M., Hirel, B., Dubois, F., Tétu, T., 2016. Conversion to No-Till Improves Maize Nitrogen Use Efficiency in a Continuous Cover Cropping System. PLoS One 11, e0164234. https://doi.org/10.1371/journal.pone.0164234

Halvorson, A., Wienhold, B.J., Black, A., 2001. Tillage and Nitrogen Fertilization Influence Grain and Soil Nitrogen in an Annual Cropping System. Publ. from USDA-ARS / UNL Fac.

Hatfield, J.L., Allmaras, R.R., Rehm, G.W., Lowery, B., 1998. Ridge tillage for corn and soybean production: environmental quality impacts. Soil Tillage Res. 48, 145–154. https://doi.org/10.1016/S0167-1987(98)00141-X

Heidari, G., Mohammadi, K., Sohrabi, Y., 2016. Responses of Soil Microbial Biomass and Enzyme Activities to Tillage and Fertilization Systems in Soybean (Glycine max L.) Production. Front. Plant Sci. 7, 1730. https://doi.org/10.3389/fpls.2016.01730

Houben, D., Faucon, M.-P., Mercadal, A.-M., Houben, D., Faucon, M.-P., Mercadal, A.-M., 2018. Response of Organic Matter Decomposition to No-Tillage Adoption Evaluated by the Tea Bag Technique. Soil Syst. 2, 42. https://doi.org/10.3390/soilsystems2030042

Hu, G., Liu, X., He, H., Zhang, W., Xie, H., Wu, Y., Cui, J., Sun, C., Zhang, X., 2015. Multi-Seasonal Nitrogen Recoveries from Crop Residue in Soil and Crop in a Temperate Agro-Ecosystem. PLoS One 10, e0133437. https://doi.org/10.1371/journal.pone.0133437

Hu, W., Tian, S., Di, Q., Liu, J., Zhang, S., 2018. Nitrogen mineralization simulation dynamic in tobacco soil, Journal of Soil Science and Plant Nutrition.

Hulugalle, N.R., 1987. Effect of tied ridges on soil water content, evapotranspiration, root growth and yield of cowpeas in the Sudan Savanna of Burkina Faso. F. Crop. Res. 17, 219–228. https://doi.org/10.1016/0378-4290(87)90036-0

Isaac, R.A., Jones, J.B., 1972. Effects of various dry ashing temperatures on the determination of 13 nutrient elements in five plant tissues. Commun. Soil Sci. Plant Anal. 3, 261–269. https://doi.org/10.1080/00103627209366375

Jenkinson, D.S., 1977. Studies on the decomposition of plant material in soil. V. The effects of plant cover and soil type on the loss of carbon from 14C labelled ryegrass decomposing under field conditions. Eur. J. Soil Sci. 28, 424–434. https://doi.org/10.1111/j.1365-2389.1977.tb02250.x

Jimma, A., Tessema, F., Gemiyo, D., Bassa, Z., 2016. Assessment of Available Feed Resources, Feed Management and Utilization Systems in SNNPRS of Ethiopia. J. Fish. Livest. Prod. 4, 1–9. https://doi.org/10.4172/2332-2608.1000183

Johnson, J.M.F., Karlen, D.L., Andrews, S.S., 2010. Conservation considerations for sustainable bioenergy feedstock production: If, what, where, and how much? J. Soil Water Conserv. 65, 88A-91A. https://doi.org/10.2489/jswc.65.4.88A

Jones, J.B., 2001. Laboratory guide for conducting soil tests and plant analysis. CRC Press.

Kabiri, V., Raiesi, F., Ghazavi, M.A., 2016. Tillage effects on soil microbial biomass, SOM mineralization and enzyme activity in a semi-arid Calcixerepts. Agric. Ecosyst. Environ. 232, 73–84. https://doi.org/10.1016/J.AGEE.2016.07.022

Kaleeem Abbasi, M., Mahmood Tahir, M., Sabir, N., Khurshid, M., 2015. Impact of the addition of different plant residues on nitrogen mineralization–immobilization turnover and carbon content of a soil incubated under laboratory conditions. Solid Earth 6, 197–205. https://doi.org/10.5194/se-6-197-2015

Khan, N.U., Khan, F., Kashan, M., Ullah, Q., Rauf, A., 2018. Nitrogen Use Impact on Nitrogen Use Efficiency and Lint Yield in Zero Tillage Cotton. Pakistan J. Agric. Res. 31, 45–54.

Kpongor, D.S., 2007. Spatially explicit modeling of sorghum (Sorghum bicolor (L.) Moench) production on complex terrain of a semi-arid region in Ghana using APSIM. University of Bonn, Germany.

Kumar, K., 1998. Effects of different crop residues and management practices on soil nitrogen dynamics, yield and recovery of nitrogen by wheat. Lincoln University.

Ladha, J.K., Pathak, H., J. Krupnik, T., Six, J., van Kessel, C., 2005. Efficiency of Fertilizer Nitrogen in Cereal Production: Retrospects and Prospects. Adv. Agron. 87, 85–156. https://doi.org/10.1016/S0065-2113(05)87003-8

Lal, R., 1990. Ridge-tillage. Soil Tillage Res. 18, 107–111. https://doi.org/10.1016/0167-1987(90)90053-G

Lamers, J.P.A., Bruentrup, M., Buerkert, A., 2015. Financial performance of fertilisation strategies for sustainable soil fertility management in Sudano-Sahelian West Africa 1: profitability of annual fertilisation strategies. Nutr. Cycl. Agroecosystems 102, 137–148. https://doi.org/10.1007/s10705-015-9673-x

Lammerts van Bueren, E.T., Struik, P.C., 2017. Diverse concepts of breeding for nitrogen use efficiency. A review. Agron. Sustain. Dev. 37, 50. https://doi.org/10.1007/s13593-017-0457-3

Lascano, R.J., Krieg, D.R., Baker, J.T., Goebel, T.S., Gitz III, D.C., 2015. Planting Cotton in a Crop Residue in a Semiarid Climate: Water Balance and Lint Yield. Open J. Soil Sci. 05, 236–249. https://doi.org/10.4236/ojss.2015.510023

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 9, 105011. https://doi.org/10.1088/1748-9326/9/10/105011

Lee, N., Thierfelder, C., 2017. Weed control under conservation agriculture in dryland smallholder farming systems of southern Africa. A review. Agron. Sustain. Dev. 37, 48. https://doi.org/10.1007/s13593-017-0453-7

Liang, A., Chen, S., Zhang, X., Chen, X., 2014. Short-term effects of tillage practices on soil organic carbon turnover assessed by δ13C abundance in particle-size fractions of black soils from northeast China. ScientificWorldJournal. 2014, 514183. https://doi.org/10.1155/2014/514183

Liu, X., Herbert, S.J., Hashemi, A.M., Zhang, X., Ding, G., 2006. Effects of agricultural management on soil organic matter and carbon transformation - A review. Plant, Soil Environ. 52, 531–543. https://doi.org/10.17221/3544-PSE

López-Bellido, R.., López-Bellido, L., 2001. Efficiency of nitrogen in wheat under Mediterranean conditions: effect of tillage, crop rotation and N fertilization. F. Crop. Res. 71, 31–46. https://doi.org/10.1016/S0378-4290(01)00146-0

Lü, X.-T., Dijkstra, F.A., Kong, D.-L., Wang, Z.-W., Han, X.-G., 2014. Plant nitrogen uptake drives responses of productivity to nitrogen and water addition in a grassland. Sci. Rep. 4, 4817. https://doi.org/10.1038/srep04817

Lundy, M.E., Pittelkow, C.M., Linquist, B.A., Liang, X., van Groenigen, K.J., Lee, J., Six, J., Venterea, R.T., van Kessel, C., 2015. Nitrogen fertilization reduces yield declines following no-till adoption. F. Crop. Res. 183, 204–210. https://doi.org/10.1016/J.FCR.2015.07.023

Machado, S., Rhinhart, K., Petrie, S., 2006. Long-Term Cropping System Effects on Carbon Sequestration in Eastern Oregon. J. Environ. Qual. 35, 1548. https://doi.org/10.2134/jeq2005.0201

MacKenzie, A.F., Fan, M.X., Cadrin, F., 1997. Nitrous oxide emission as affected by tillage, corn-soybean-alfalfa rotations and nitrogen fertilization. Can. J. Soil Sci. 77, 145–152. https://doi.org/10.4141/S96-104

Malhi, S.S., Lemke, R., Wang, Z.H., Chhabra, B.S., 2006. Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. Soil Tillage Res. 90, 171–183. https://doi.org/10.1016/J.STILL.2005.09.001

Malhi, S.S., Nyborg, M., 1990. Effect of tillage and straw on yield and N uptake of barley grown under different N fertility regimes. Soil Tillage Res. 17, 115–124. https://doi.org/10.1016/0167-1987(90)90010-B

Manns, H.R., Parkin, G.W., Martin, R.C., 2016. Evidence of a union between organic carbon and water content in soil. Can. J. Soil Sci. 96, 305–316. https://doi.org/10.1139/cjss-2015-0084

Manzoni, S., Jackson, R.B., Trofymow, J.A., Porporato, A., 2008. The Global Stoichiometry of Litter Nitrogen Mineralization. Science (80-.). 321, 684–686. https://doi.org/10.1126/science.1159792

Marimi, A.M., 1978. The effects of tillage methods and cropping systems for conserving rainfall in a semiarid area of eastern Kenya, In Soil and WaterConservation in Kenya. Kenya.

Masle, J., Passioura, J.B., 1987. The Effect of Soil Strength on the Growth of Young Wheat Plants, Aust. J. Plant Physiol.

Mathew, R.P., Feng, Y., Githinji, L., Ankumah, R., Balkcom, K.S., 2012. Impact of No-Tillage and Conventional Tillage Systems on Soil Microbial Communities. Appl. Environ. Soil Sci. 2012, 1–10. https://doi.org/10.1155/2012/548620

McConkey, B.G., Curtin, D., Campbell, C.A., Brandt, S.A., Selles, F., 2002. Crop and soil nitrogen status of tilled and no-tillage systems in semiarid regions of Saskatchewan. Can. J. Soil Sci. 82, 489–498. https://doi.org/10.4141/S01-036

Melaj, M.A., Echeverría, H.E., López, S.C., Studdert, G., Andrade, F., Bárbaro, N.O., 2003. Timing of Nitrogen Fertilization in Wheat under Conventional and No-Tillage System. Agron. J. 95, 1525. https://doi.org/10.2134/agronj2003.1525

Merckx, R., den Hartog, A., van Veen, J.A., 1985. Turnover of root-derived material and related microbial biomass formation in soils of different texture. Soil Biol. Biochem. 17, 565–569. https://doi.org/10.1016/0038-0717(85)90026-4

Mohamoud, Y.M., 2012. Effect of contour ridging on runoff and soil loss. African J. Agric. Res. 7, 6115–6124. https://doi.org/10.5897/AJAR11.2307

Moroizumi, T., Horino, H., 2002. The effects if tillage on soil temperature and soil water. Soil Sci. 167, 548–559.

Motavalli, P.P., Palm, C.A., Elliott, E.T., Frey, S.D., Smithson, P.C., 1995. Nitrogen Mineralization in Humid Tropical Forest Soils: Mineralogy, Texture, and Measured Nitrogen Fractions. Soil Sci. Soc. Am. J. 59, 1168. https://doi.org/10.2136/sssaj1995.03615995005900040032x

Mthandi, J., Kahimba, F.C., Tarimo, A., Salim, B.A., Lowole, M., 2013. Nitrogen movement in coarse-textured soils and its availability to maize (<i>Zea mays</i> L.) plant. Agric. Sci. 04, 30–35. https://doi.org/10.4236/as.2013.48A005

Muñoz-Romero, V., Lopez-Bellido, L., Lopez-Bellido, R.J., 2015. Effect of tillage system on soil temperature in a rainfed Mediterranean Vertisol. Int. Agrophysics 29, 467–473. https://doi.org/https://doi.org/10.1515/intag-2015-0052

Nguyen, D.H., Scheer, C., Rowlings, D.W., Grace, P.R., 2016. Rice husk biochar and crop residue amendment in subtropical cropping soils: effect on biomass production, nitrogen use efficiency and greenhouse gas emissions. Biol. Fertil. Soils 52, 261–270. https://doi.org/10.1007/s00374-015-1074-4

Nicolardot, B., Recous, S., Mary, B., 2001. Simulation of C and N mineralisation during crop residue decomposition: A simple dynamic model based on the C:N ratio of the residues. Plant Soil 228, 83–103. https://doi.org/10.1023/A:1004813801728

Nishigaki, T., Sugihara, S., Kilasara, M., Funakawa, S., 2017. Soil nitrogen dynamics under different quality and application methods of crop residues in maize croplands with contrasting soil textures in Tanzania. Soil Sci. Plant Nutr. 1–12. https://doi.org/10.1080/00380768.2017.1332454

Nunes, M.R., Denardin, J.E., Pauletto, E.A., Faganello, A., Pinto, L.F.S., 2015. Effect of soil chiseling on soil structure and root growth for a clayey soil under no-tillage. Geoderma 259–260, 149–155. https://doi.org/10.1016/J.GEODERMA.2015.06.003

Onchere, J., 1977. Infiltration rates and related soil properties as influenced by seedbed preparation and time of the year.

Oorts, K., Nicolardot, B., Merckx, R., Richard, G., Boizard, H., 2006. C and N mineralization of undisrupted and disrupted soil from different structural zones of conventional tillage and no-tillage systems in northern France. Soil Biol. Biochem. 38, 2576–2586. https://doi.org/10.1016/J.SOILBIO.2006.03.013

Ourrry, A., Gordon, A.J., Machduff, J.H., 1997. Nitrogen uptake and assimilation in roots and root modules, in: Foyer, C. (Ed.), A Molecular Approach To Primary Metabolism In Higher Plants. Taylor and Francis, London, pp. 237–254.

Palm, C.A., Giller, K.E., Mafongoya, P.L., Swift, M.J., 2001. Management of organic matter in the tropics: translating theory into practice. Nutr. Cycl. Agroecosystems 61, 63–75. https://doi.org/10.1023/A:1013318210809

Pandiaraj, T., Selvaraj, S., Ramu, N., 2015. Effects of crop residue management and nitrogen fertilizer on soil nitrogen and carbon content and productivity of wheat (triticum aestivum L.) in two cropping systems. J. Agric. Sci. Technol. 17, 249–260. https://doi.org/10.1158/1078-0432.CCR-04-0265

Pereira, H.C., Hosegood, P.H., Dagg, M., 1967. Effects of Tied Ridges, Terraces and Grass Leys on a Lateritic Soil in Kenya. Exp. Agric. 3, 89. https://doi.org/10.1017/S0014479700021839

Piepho, H.P., Buchse, A., Emrich, K., 2003. A Hitchhiker's Guide to Mixed Models for Randomized Experiments. J. Agron. Crop Sci. 189, 310–322. https://doi.org/10.1046/j.1439-037X.2003.00049.x

Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., van Groenigen, K.J., Lee, J., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015. When does no-till yield more? A global meta-analysis. F. Crop. Res. 183, 156–168. https://doi.org/10.1016/J.FCR.2015.07.020

Ramirez-Garcia, J., Martens, H.J., Quemada, M., Thorup-Kristensen, K., 2015. Intercropping effect on root growth and nitrogen uptake at different nitrogen levels. J. Plant Ecol. 8, 380–389. https://doi.org/10.1093/jpe/rtu024

Rasmussen, K.J., 1999. Impact of ploughless soil tillage on yield and soil quality: A Scandinavian review. Soil Tillage Res. 53, 3–14. https://doi.org/10.1016/S0167-1987(99)00072-0

Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., 2003. Effect of soil organic carbon on soil water retention. Geoderma 116, 61–76. https://doi.org/10.1016/S0016-7061(03)00094-6

Reichmann, L.G., Sala, O.E., Peters, D.P.C., 2013. Water controls on nitrogen transformations and stocks in an arid ecosystem. Ecosphere 4, art11. https://doi.org/10.1890/ES12-00263.1

Rochester, I., Constable, G., Macleod, D., 1993. Cycling of fertilizer and cotton crop residue nitrogen. Soil Res. 31, 597. https://doi.org/10.1071/SR9930597

Sahrawat, K.L., Narteh, L.T., 2001. ORGANIC MATTER AND REDUCIBLE IRON CONTROL OF AMMONIUM PRODUCTION IN SUBMERGED SOILS. Commun. Soil Sci. Plant Anal. 32, 1543–1550. https://doi.org/10.1081/CSS-100104211

Sainju, U.M., Singh, B.P., Whitehead, W.F., 2005. Tillage, Cover Crops, and Nitrogen Fertilization Effects on Cotton and Sorghum Root Biomass, Carbon, and Nitrogen. Agron. J. 97, 1279. https://doi.org/10.2134/agronj2004.0213

Saleem, M.F., Bilal, M.F., Awais, M., Shahid, M.Q., Anjum, S.A., 2006. Journal of animal and plant sciences., JAPS, Journal of Animal and Plant Sciences. Pakistan Agricultural Scientists Forum.

Salinas-Garcia, J.R., Hons, F.M., Matocha, J.E., Zuberer, D.A., 1997. Soil carbon and nitrogen dynamics as affected by long-term tillage and nitrogen fertilization. Biol. Fertil. Soils 25, 182–188. https://doi.org/10.1007/s003740050301

Sauer, T.J., Logsdon, S.D., 2002. Hydraulic and Physical Properties of Stony Soils in a Small Watershed. Soil Sci. Soc. Am. J. 66, 1947. https://doi.org/10.2136/sssaj2002.1947

Schlüter, S., Großmann, C., Diel, J., Wu, G.-M., Tischer, S., Deubel, A., Rücknagel, J., 2018. Long-term effects of conventional and reduced tillage on soil structure, soil ecological and soil hydraulic properties. Geoderma 332, 10–19. https://doi.org/10.1016/J.GEODERMA.2018.07.001

Sharma, S.N., Prasad, R., 2008. Effect of crop-residue management on the production and agronomic nitrogen efficiency in a rice–wheat cropping system. J. Plant Nutr. Soil Sci. 171, 295–302. https://doi.org/10.1002/jpln.200700144

Shaxson, T.F., Barber, R.G., Food and Agriculture Organization of the United Nations., 2003. Optimizing soil moisture for plant production : the significance of soil porosity. Food and Agriculture Organization of the United Nations.

Sui, R., Byler, R.K., Fisher, D.K., Barnes, E.M., Delhom, C.D., 2014. Effect of Supplemental Irrigation and Graded Levels of Nitrogen on Cotton Yield and Quality. J. Agric. Sci. 6, p119. https://doi.org/10.5539/jas.v6n2p119

Tengberg, A., Ellis-Jones, J., Kiome, R., Stocking, M., 1998. Applying the concept of agrodiversity to indigenous soil and water conservation practices in eastern Kenya. Agric. Ecosyst. Environ. 70, 259–272. https://doi.org/10.1016/S0167-8809(98)00153-4

Thapa, B.B., Cassel, D.K., Garrity, D.P., 1999. Ridge tillage and contour natural grass barrier strips reduce tillage erosion. Soil Tillage Res. 51, 341–356.

Tosti, G., Thorup-Kristensen, K., 2010. Using coloured roots to study root interaction and competition in intercropped legumes and non-legumes. J. Plant Ecol. 3, 191–199. https://doi.org/10.1093/jpe/rtq014

Tromp-Van Meerveld, H.J., Mcdonnell, J.J., 2006. On the interrelations between topography, soil depth, soil moisture, transpiration rates and species distribution at the hillslope scale. Adv. Water Resour. 29, 293–310. https://doi.org/10.1016/j.advwatres.2005.02.016

UNDESA, 2011. World population prospects, 2011 revision. New York.

Unger, P.W., Stewart, B.A., Parr, J.F., Singh, R.P., 1991. Crop residue management and tillage methods for conserving soil and water in semi-arid regions. Soil Tillage Res. 20, 219–240. https://doi.org/10.1021/ic50213a011

Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C., Nziguheba, G., Schut, M., Van Asten, P., 2014. Sustainable intensification and the African smallholder farmer. Curr. Opin. Environ. Sustain. 8, 15–22. https://doi.org/10.1016/j.cosust.2014.06.001

Wang, X., Wang, N., Xing, Y., BEN El CAID, M., 2018. Synergetic effects of plastic mulching and nitrogen application rates on grain yield, nitrogen uptake and translocation of maize planted in the Loess Plateau of China. Sci. Rep. 8, 14319. https://doi.org/10.1038/s41598-018-32749-9

Webber, H., Gaiser, T., Ewert, F., 2014. What role can crop models play in supporting climate change adaptation decisions to enhance food security in Sub-Saharan Africa? Agric. Syst. 127, 161–177. https://doi.org/10.1016/J.AGSY.2013.12.006

Wilcox, B.P., Wood, M.K., Tromble, J.M., 1988. Factors Influencing Infiltrability of Semiarid Mountain Slopes. J. Range Manag. 41, 197. https://doi.org/10.2307/3899167

Xu, L., Niu, J., Li, C., Zhang, F., 2009. Growth, Nitrogen Uptake and Flow in Maize Plants Affected by Root Growth Restriction. J. Integr. Plant Biol. 51, 689–697. https://doi.org/10.1111/j.1744-7909.2009.00843.x

Young, I.M., Montagu, K., Conroy, J., Bengough, A.G., 1997. Mechanical impedance of root growth directly reduces leaf elongation rates of cereals. New Phytol. 135, 613–619. https://doi.org/10.1046/j.1469-8137.1997.00693.x

Yuan, Y., Meixner, T., Fenn, M.E., Simunek, J., 2011. Impact of transient soil water simulation to estimated nitrogen leaching and emission at high- and low-deposition forest sites in southern California. J. Geophys. Res. 116 G03040 116.

Zhang, J.H., Frielinghaus, M., Tian, G., Lobb, D.A., 2004. Ridge and contour tillage effects on soil erosion from steep hillslopes in the Sichuan Basin, China. J. Soil Water Conserv. 59, 277–284.

Zhang, Yuling, Xu, W., Duan, P., Cong, Y., An, T., Yu, N., Zou, H., Dang, X., An, J., Fan, Q., Zhang, Yulong, 2017. Evaluation and simulation of nitrogen mineralization of paddy soils in Mollisols area of Northeast China under waterlogged incubation. PLoS One 12. https://doi.org/10.1371/journal.pone.0171022

Žurovec, O., Sitaula, B.K., Čustović, H., Žurovec, J., Dörsch, P., 2017. Effects of tillage practice on soil structure, N2O emissions and economics in cereal production under current socio-economic conditions in central Bosnia and Herzegovina. PLoS One 12, e0187681. https://doi.org/10.1371/journal.pone.0187681

Chapter 3

Interactive effects of conservation tillage, residue management, and nitrogen fertilizer application on soil properties under maize-cotton rotation system on highly weathered soils of West Africa

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1. Introduction

Soil degradation is one of the major challenges that significantly hampers global sustainable crop production. This is particularly severe in the Sudan Savanna region of West Africa, that covers the semi-arid portion of tropical Africa. Low productivity of agriculture is predominantly attributed to widespread soil degradation, and a limited capacity to invest in soil improvement, although the majority of the population depends on agriculture for livelihood. Consequently, crop productivity is hampered and economic growth is affected, contributing to poverty and food insecurity (Tully et al., 2015). Causes of on-going soil degradation in West Africa include inappropriate soil management practices leading to poor soil nutrient supply capacity and limiting crop productivity. One of the most widely studied soil management practices is conservation agriculture (CA). CA consists of the combined use of zero or minimum tillage, crop residue incorporation, and crop rotation with legumes, and has been recommended in several previous studies as a potential approach to improve N stock (Martinsen et al., 2019; Naab et al., 2017; Swanepoel et al., 2018), phosphorus (P), potassium (K) (Tolessa et al., 2014), soil moisture (TerAvest et al., 2015) and minimize soil loss through reducing runoff and erosion processes (Araya et al., 2011; Ghosh et al., 2015). Additionally, incorporation of crop residue is imperative to maintain soil health as it offers positive impacts on SOC, N, P, and K (Alam et al., 2018; Huang et al., 2012; Singh et al., 2018). Crop residue retention has also been demonstrated as an effective way to control soil loss by erosion (Cong et al., 2016), and improve soil water holding capacity and infiltration rate (Desrochers et al., 2019). In spite of the fact that CA has the potential to mitigate the severity of soil nutrient loss caused by conventional cultivation methods, numerous studies hold an opposite view. In particular cases, CA can lead to detrimental effects on soil nutrient stock and reduce crop yield (Jan et al., 2016; Okeyo et al., 2016). Studies conducted in steep-slope regions suggest that the use of contour and/or tied ridge tillage is more effective than CA at limiting soil loss by erosion, thereby maintaining more SOC in topsoil layers and improving crop yields (Gathagu et al., 2018; Mohamoud, 2012). Contour ridge tillage was initially promoted to smallholder farmers in SSA to combat soil degradation in areas with high rainfall intensity (Nyamadzawo et al., 2013). In Northern Ethiopia, Araya and Stroosnijder (2010) reported that crop residues retention with contour/tied ridges increased soil water in the root zone by 13%. On the other hand, Karuma et al. (2014) report potentially noxious effects of tied/contour ridge tillage in a maize-bean cultivation system in Eastern Kenya.

Despite the breadth of previous research, much of it has focused on evaluating the effects of tillage, crop residue incorporation or nitrogen fertilizer application on soil properties in mono-cropping systems at single locations (Dossou-Yovo et al., 2016; Kihara et al., 2011; Masvaya et al., 2017). Such studies were often short-term and conducted over 2-3 growing seasons. Accordingly, comprehensive multi-location and multi-factor studies over more than 2 growing seasons on the interactive effects of tillage, crop residue management and N fertilizer application on soil properties are still scarce in the Sudan Savanna Zone of West-Africa. Therefore, the aim of this study was to evaluate the effects of tillage, crop residue management and N fertilizer application on soil nutrient stocks at four representative sites in the Sudan Savanna of West Africa after five years. It was hypothesized that over a 5-years period of continuous cropping i) application of reduced tillage as well as the incorporation of crop residues in a maize-cotton rotation has beneficial effects on topsoil (0-20 cm) properties, SOC, total nitrogen (TN), soil exchangeable phosphorus (P_{CAL}) and potassium (K_{CAL}), and pH compared to current management practices (contour ridge tillage, residue removal, and no mineral N application) irrespective of site, ii) SOC and TN are expected to be higher under combined reduced tillage and crop residue retention at all sites; and iii) amounts of less mobile components, P_{CAL} and K_{CAL}, are increased with crop residue retention across all sites.

2. Materials and methods

2.1. Experimental sites

On-farm trials were carried out (Figure 1) on farmers' fields in Dassari village (10˚49´N, 1˚04´E) in Atakora Province of the Republic of Benin, and in Dano village (11˚10´N, 2˚38´W) in the Loba province of Burkina-Faso for five consecutive years (2012-2016). At each location (Figure 2), two sites were defined based on topographical positions along the slope (footslope and upslope), such that a total of four similar trials were conducted on four different soil types (differed mainly by topography). An average of 3% slope existed between footslope and upslope sites.

Thus, our study consisted of a total of four different sites, where each site shares common weather conditions within the same location but different soil types. The sites were designated as St1 (Dano on Ferric Lixisol at footslope position), St2 (Dano on Eutric Plinthosol at upslope position), St3 (Dassari on Haplic Lixisol at footslope position), and St4 (Dassari on Plinthic Lixisol at upslope position).

2.1.1. Seasonal and spatial variations in temperature and precipitation

The study sites are located in the Sudan Savanna agro-ecological zone, characterized by a semi-humid climate. The mean rainfall ranges between 900 mm to 1000 mm from May to October, while the mean temperature is 15 ˚C during the night and 40 ˚C during the day in the rainy season (Danso et al., 2018a; Kpongor, 2007). The amount of monthly total rainfall during the cotton growing seasons of 2013 and 2015 in Dano was 766 mm and 874 mm, respectively (Figure. 3b). In contrast, Dassari received 777 mm and 973 mm of monthly total rainfall during the cotton growing seasons of 2013 and 2015. Mean monthly cumulative rainfall in Dano and Dassari during the maize growing seasons (2012, 2014 and 2016) were 780 mm and 850 mm, respectively. During the cotton growing seasons at both Dano and Dassari, the average monthly air temperature was 27 ˚C and 28 ˚C, respectively (Figure. 3a). Conversely, monthly mean air temperature during the maize growing seasons at both Dano and Dassari was 27 ˚C. Also, the monthly mean air temperature tended to increase from 2012 to 2016 in Dassari, while in Dano, no such increase was recorded.

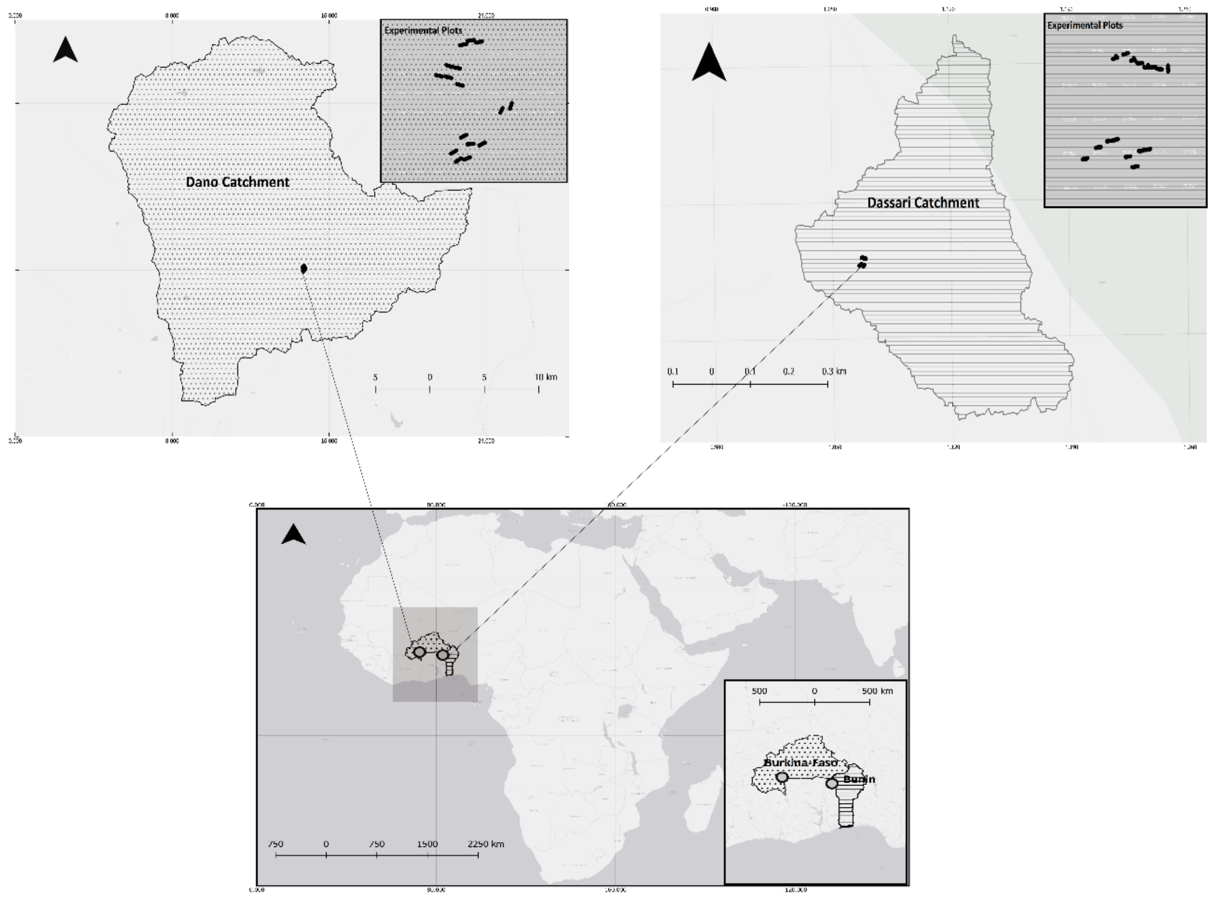

Figure 1. Locations of study and the corresponding experiment plots

2.1.2. Spatial variations in soil properties

According to FAO soil classification system, the major soil types in Dano are Ferric Lixisol (footslope), and Eutric Plinthosol (upslope) with a bedrock type of Andesite; while the soils in Dassari were formed on a parent material of massive Sandstone and classified as Haplic Lixisol (footslope), and Plinthic Lixisol (upslope) (Danso et al., 2018a). These soils differed in many characteristics. Soils in Dano, Ferric Lixisol (FL) and Eutric Plinthosol (EP) had a maximum rooting depth of 75 cm and 65 cm, respectively (Table 1). On the other hand, soils of Dassari, Haplic Lixisol (HL), and Plinthic Lixisol (PL) exhibited a maximum rooting depth of 90 cm and 65 cm, respectively. The total available water capacity (AWC with field capacity at 33 kPa) across the soil profile (up to maximum rooting depth) of HL, EP, PL, and FL was 52.5 mm, 50.6 mm, 42.6 mm, and 29.2 mm, respectively. In addition, these four soil types also varied according to gravel content by mass, exhibiting the following rank: FL (47%) > EP (26%) > PL (24%) > HL (13%) in the topsoil (Table 1).

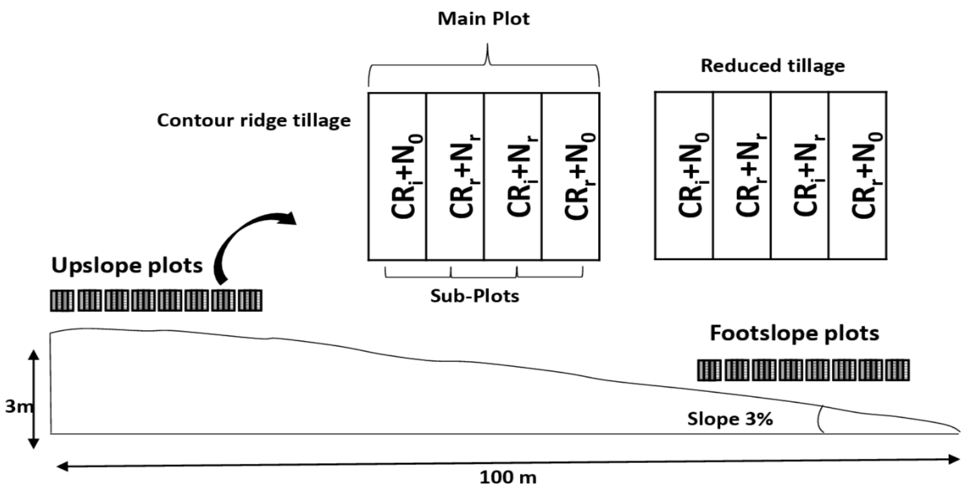

Figure 2: Experimental design and slope layout (Nr = Recommended rate of nitrogen, N0=No nitrogen, CRi = residue incorporated, CRr = residue removed)

2.2. Experimental layout and management practices

The experiments started in 2012 at each site and were conducted for five consecutive growing seasons (2012-2016) under a maize-cotton rotation. A strip-split plot design with four replications was used for statistical analysis. The main plots consisted of two levels of tillage treatment (contour ridge tillage, Ct and reduced tillage, Rt); and the size of each main plot was 30 m long by 10 m wide. Each main plot had sub-plots of 10 m by 5 m, containing random combinations of the two sub-plot treatments. Sub-plot treatments were crop residue management, *i.e.* with incorporation of crop residues from previous crop (CRi) or without crop residues (CRr), and N fertilizer amount, i.e. no fertilizer (N0) or recommended dose of N fertilizer (Nr) at 45 kg N ha^{-1} for cotton and 60 kg N ha^{-1} for maize. In total, there were 32 plots (8 treatments × 4 replications) at each experimental site (Danso et al., 2018b).

Our study used a short cycle maize variety (*Zea mays L.* cv. Dorke SR) that was generally sown in late June and harvested in mid-October of the same year (every even year, 2012, 2014, and 2016). Cotton (*Gossypium hirsutum* L. cv.FK 97) was sown in mid-June and harvested in mid-October to mid-November of the same year (every odd year, 2013 and 2015) at all sites. Animal drawn moldboard ploughing was used to establish contour ridges in mid-June. Commercial mineral fertilizers, urea (46% N), single superphosphate (12% P_2O_5), and potassium chloride (60% K_2O) were used to provide 60 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1} during the maize-growing seasons, and 45 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1} during the cotton-growing season. All P_2O_5 and K_2O and 50% of N fertilizer was broadcast 25 days after planting and the remaining 50% of N fertilizer was used 45 days after planting. In the control plots, P and K, but no N was applied. At harvest of the previous crop, residues were removed, chopped into pieces and stored until the subsequent growing season. At planting, the previous year's residues were distributed evenly in the sub-plots receiving crop residue retention treatments. Thus, the application rate of residues varied across the tillage and N fertilizer treatments. The C:N ratio of the applied cotton and maize residues were 30 and 70, respectively. Maize and cotton were planted at the recommended density and row spacing (Table 1). Weeds were cleared before implementing tillage operations by applying 2.1-liter ha^{-1} glyphosate. Cotton balls were protected from pests by spraying 5-6 times throughout the growing season the pesticide "Super Lambda".

Table 1: Major soil characteristics of all four sites in the topsoil (0-20 cm)

Properties	Units (methods)	Location/Topography/Soil types			
		Dano		Dassari	
		Footslope	Upslope	Footslope	Upslope
		Ferric Lixisol	Eutric Plinthosol	Haplic Lixisol	Plinthic Lixisol
pH	(0.01 M $CaCl_2$)	6.4	6.3	6.6	6.5
Organic C	Mg ha^{-1}	12.5	13.4	16.2	12.3
	(%)	0.5	0.6	0.7	0.5
Total N	Mg ha^{-1}	1.1	1.6	1.9	1.4
	(%)	0.06	0.07	0.07	0.06
CAL P	Mg ha^{-1}	0.03	0.03	0.06	0.06
	(mg kg^{-1})	10	10	20	20
CAL K	Mg ha^{-1}	1.0	1.5	1.8	1.4
	(mg kg^{-1})	60	60	70	60
Sand	%	52.9	32.8	66.4	56.9
Silt	%	43.1	17.1	32.5	40.1
Clay	%	3.0	50.0	1.1	2.0
Texture		Sandy	Sandy clay loam	Sandy Loam	Sandy Loam
Gravel	%	47	26	13	24
Permeability Class		Rapid	Moderately Slow	Moderately Rapid	Moderately Rapid

2.3. Soil sampling and analytical methods

To determine soil fertility related properties (pH, OC, TN, P_{CAL}, and K_{CAL}), soils were sampled systematically from five different points using a gouge auger at five different depths, 0-20 cm, 20-40 cm, 40-70 cm, and >70 cm (depending on the maximum rootable depth) from each sub-plot in August-September, 2016. Collected soil samples were mixed and composited to form a representative sample per sub-plot for each depth. Visible plant residues and other debris were removed from the samples. Soils were then dried at 40 ˚C, clods were broken by hand, passed through a 2 mm sieve for uniformity, and transferred to the laboratory for chemical analysis.

The residual samples (particle diameter > 2mm) after sieving were used to measure and calculate soil gravel content following a mass approach suggested by Gardner (1986). SOC and TN was determined using the dry combustion method in a CHN elemental analyser (Fisons NA 2000, Fisons Instruments, Rodano, Milan, Italy), where about 5 mg soils were weighed, settled in silver capsules, combusted in a furnace at a temperature of 1800 ˚C under a stream of oxygen (Santi et al., 2006). Soil pH was measured using a pH meter after mixing soil with 0.01 M $CaCl_2$ solution in a 1:5 ratio. In order to measure P_{CAL} and K_{CAL}, soils were extracted using calcium acetate lactate (CAL) solution (Schüller, 1969). P_{CAL} was then measured with a photometer, and K_{CAL} determined using atomic absorption spectrophotometry.

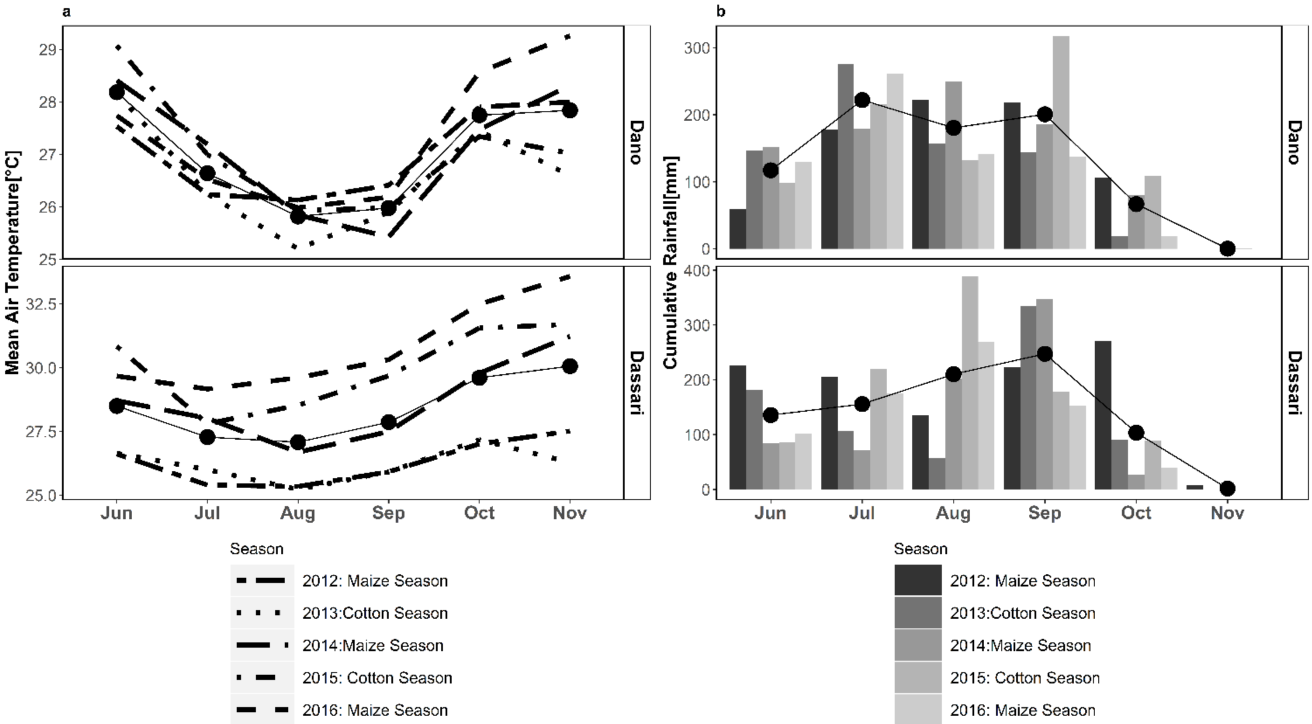

Figure 3: Climatic conditions during growing seasons of cotton and maize (2012-2016) in experimental sites of Dano and Dassari [a] Mean monthly air temperature (˚C), [b] Total monthly rainfall (mm). The black round point indicates the monthly average value over five cropping seasons.

Table 2: Crop characteristics and management practices

Crop characteristics/ Management Practices	Descriptions Maize	Cotton
Variety	Dorke SR	FK 37
Sowing	mid-June	mid-June
Harvesting	mid-October	mid-October - mid-November
Planting density (plants ha^{-1})	62,500 plants ha^{-1}	83,333 plants ha^{-1}
Inter-row spacing (m)	0.8 m	0.8 m
Intra-row spacing (m)	0.4 m	0.3 m
Physiological Maturity (days)	94-108	124-150
N Fertilizer (kg ha^{-1})	60 kg ha^{-1}	45 kg ha^{-1}
P Fertilizer (kg ha^{-1})	60 kg ha^{-1}	60 kg ha^{-1}
K Fertilizer (kg ha^{-1})	60 kg ha^{-1}	60 kg ha^{-1}
Tillage	Contour ridges were developed by using animal drawn moldboard ploughs	
Fertilizer Application	All the P and K and 50 % nitrogen was broadcasted 25 days after planting and the rest 50 % of nitrogen was applied 45 days after planting	
Weeding	2.1liter ha^{-1} glyphosate was applied prior to tillage operations and manual hoe weeding as needed during the growing season	
Pest Management	"Super Lambda" was sprayed 5-6 times to protect the cotton bolls	

2.3.1. Computation of soil nutrient stock

Similarly, soil organic carbon stock/density (SOC_d) was calculated for each layer of the soil, for fine earth particles only, thereby allowing for correction of gravel content. Equation (3) was followed to calculate soil organic carbon stock (SOC_d, Mg ha^{-1}) using values of % of organic carbon (OC), the mass of fine earth materials ($Mass_{fine}$, kg m^{-2}), and % gravel content of the *i* soil layer (cm). Mass of fine earth materials was derived from total soil mass (equation 1) and % gravel content as:

$$Mass_{total}\ (kg\ m^{-2}) = [soil\ layer\ thickness\ (cm) \times BD_{total} \times 10] \quad (1)$$

$$Mass_{fine}\ (kg\ m^{-2}) = \frac{(100\ -\ \%gravel\ content)}{100} \times Mass_{\ total} \quad (2)$$

$$SOC_{di}\ (Mg\ ha^{-1}) = \frac{(\ Mass_{finei} \times \%\ OC_i)}{100} \times 10 \quad (3)$$

SOC_d from each soil layer per sub-plot was aggregated to quantify the total SOC_d within the soil profile (up to rooting depth) for each sub-plot.

Similar steps were followed to calculate nitrogen stock (STN_d), available phosphorus stock (SP_d), and available potassium stock (SK_d) by substituting SOC_d value with the concentration of nutrients ($TN/P_{CAL}/K_{CAL}$) in the respective soil layer.

2.4. Statistical Analysis

R v 3.5.1 (R Core Team 2018) in RStudio was used to perform all the statistical analyses. The arithmetic means, standard error (se), and standard deviation (sd) were calculated independently for all the measured soil attributes using the "summarise" function under the "dplyr" packages (Wickham et al., 2019) and the values were presented as the mean and standard error. To analyse the effects of site, tillage, crop residue management, N fertilizer rates and their interactions on measured soil properties, OC, TN, P_{CAL}, K_{CAL}, a mixed linear model for strip-split plot layout was generated according to Gomez et al. (1984) using the "lme" function in the "nlme" package in R (Gałecki and Burzykowski, 2013). Site, tillage, crop residue management, and N fertilizer rate were considered as fixed factors, while the random factors included replication and replication × tillage interactions. We excluded the effects of crops as the soils were sampled only once after completion of five continuous annual maize-cotton rotation cycles. The site was a fixed factor in our analysis as the sites represent specific soils among which comparisons were to be made (Piepho et al., 2003). Differences in measured soil attributes among the implemented treatments were examined by Tukey test at $p \leq 0.05$

level using the “lsmeans” function (Lenth, 2016). All the figures were produced using the “ggplot2” package (Wickham, 2016).

3. Results

After five years of maize-cotton rotational cropping, all the measured soil attributes (SOC_d, STN_d, SP_d, and SK_d) at 0-20 cm soil depth showed large variation under the influence of different tillage systems, crop residue management measures, and N fertilizer application rates across different experimental sites (Table 3). We conducted an analysis of variance (ANOVA) in order to identify factors significantly affecting the topsoil properties. Topsoil SOC_d significantly varied according to the individual effects of tillage and crop residue, while topsoil STN_d was affected by the single effects of tillage and N fertilizer application. On the other hand, topsoil SP_d and SK_d varied significantly according to only crop residue. Interestingly, we found no treatment effects on topsoil pH. We also observed site-specific effects of the factors (site × factor) on the measured soil traits. A significant effect of site × tillage and site × residue interactions were also observed for topsoil SOC_d, whereas site × tillage and site × N fertilizer interactions were significant for topsoil STN_d. Interestingly, only site × residue interaction effect was recorded for topsoil SP_d and SK_d. No three-way or four-way interactions were observed.

3.1. Changes in topsoil properties

3.1.1 Soil organic carbon stock (SOC_d)

Relative to Rt, Ct increased SOC_d at the surface layer by 8.1% when averaged across sites and treatments (residue and N fertilizer). SOC_d under the Ct system was 31.7% and 15.8% higher than under the Rt system on St2 and St4, respectively, both sites being located on upslope positions (Figure 4). A significantly higher SOC_d (+28.9%) in the surface soil of St3, which was located footslope, was recorded under the Rt system compared to Ct. Interestingly, no difference in SOC_d between the tillage operations was found on St1 (footslope position). The addition of crop residues to the surface soil significantly increased SOC_d only on sites at the upslope positions, St2 and St4 by 14.1% and 15.8%, respectively (Figure 5). CRi had no significant beneficial effects on SOC_d at the footslope sites (St1 and St3). CRi led to a 6.8% increase in SOC_d in the surface soil layer when averaged across sites and treatments (tillage and N fertilizer). Our results suggested that SOC_d on sites in the upslope position benefited from CRi and Ct. On the other hand, implementation of Rt together with CRi improved SOC_d in the topsoil layer only on St3.

Table 3: Mean effects (single main effects) and summary of ANOVA output of the generalized linear mixed model for the effect of sites, tillage, crop residue, and N fertilizer on soil nutrient stocks on topsoil layer (0-20 cm).

Sites/Factors/Levels	SOC_d (Mg ha^{-1})	STN_d (Mg ha^{-1})	SP_d (Mg ha^{-1})	SK_d (Mg ha^{-1})	pH
		Sites			
St1: Ferric Lixisol (FL)	12.5±0.1 c	1.1±0.01 d	0.03±3 b	1.0±0.01 d	6.4±0.03 b
St2: Eutric Plinthosol (EP)	13.4±0.1 b	1.6±0.01 b	0.03±3 b	1.5±0.01 b	6.3±0.03 b
St3: Haplic Lixisol (HL)	16.2±0.1 a	1.9±0.01 a	0.06±3 a	1.8±0.01 a	6.6±0.03 a
St4: Plinthic Lixisol (PL)	12.3±0.1 c	1.4±0.01 c	0.06±3 a	1.4±0.01 c	6.5±0.03 a
		Tillage			
Reduced Tillage (Rt)	13.1±0.1 b	1.5±0.09 b	0.04±3 a	1.4±0.01 a	6.4±0.02 a
Contour Ridges (Ct)	14.2±0.1 a	1.5±0.07 a	0.04±3 a	1.4±0.01 a	6.5±0.02 a
		Crop Residue			
Residues Removed (CRi)	13.2±0.1 b	1.5±0.08 a	0.04±3 b	1.4±0.01 b	6.4±0.02 a
Residues Incorporated (CRr)	14.1±0.1 a	1.5±0.08 a	0.05±3 a	1.5±0.01 a	6.4±0.02 a
		N Fertilizer			
Control (N0)	13.6±0.1 a	1.5±0.08 b	0.04±3 a	1.4±0.01 a	6.5±0.02 a
Recommended N (Nr)	13.6±0.1 a	1.6±0.08 a	0.04±3 a	1.4±0.01 a	6.4±0.02 a

Analysis of Variance					
Site (St)	**<.0001** ***	**<.0001** ***	**<.0001** ***	**<.0001** ***	**<.0001** ***
Tillage (T)	**<.0001** ***	**<.0001** ***	ns	ns	Ns
Residue (R)	**<.0001** ***	ns	**<.0001** ***	**<.0001** ***	Ns
Nitrogen (N)	ns	**<.0001** ***	ns	ns	Ns
St:T	**<.0001** ***	**<.0001** ***	ns	ns	Ns
St:R	**<.0001** ***	ns	**0.0351** *	**0.0249** *	Ns
T:R	ns	ns	ns	ns	Ns
St:N	ns	**<.0001** ***	ns	ns	Ns
T:N	ns	**0.0022** **	ns	ns	Ns
R:N	ns	ns	ns	ns	Ns
St:T:R	ns	ns	ns	ns	Ns
St:T:N	ns	**0.0003** ***	ns	ns	Ns
St:R:N	ns	ns	ns	ns	Ns
T:R:N	ns	ns	ns	ns	Ns
St:T:R:N	ns	ns	ns	ns	Ns

The values are presented as lsmean±standard error. For each main treatment effect, values within a column followed by the same letters are not significantly different at $P \leq 0.05$. The amount of nitrogen fertilizer for cotton was 45 kg ha^{-1} and for maize was 60 kg ha^{-1}.

*, **, and *** denote the significance of the factor at $P \leq 0.05$, 0.01, and 0.001, respectively; ns, not significant at $P \leq 0.05$

SOC_d= soil organic carbon stock, STN_d = soil nitrogen stock, SP_d = soil phosphorus stock, SK_d = soil potassium stock

3.1.2 Soil nitrogen stock (STN_d)

In comparison to Rt, the implementation of Ct increased STN_d in the topsoil layer of St2 and St4 by 10.3% and 19.4%, respectively (Figure 4). Although there was a small variation in STN_d between Ct and Rt on St1, this difference was not significant ($P > 0.05$). Contrarily, the application of Rt instead of Ct increased topsoil STN_d of St3 by 12.7%. The average STN_d in the topsoil layer over all sites was 14% greater under Ct than under Rt (Table 3). After the application of the recommended rate of N fertilizer, the average STN_d in the topsoil layer increased by 6% (1.6 Mg ha^{-1} vs 1.54 Mg ha^{-1}) compared to the control (Table 3). STN_d increase in the topsoil layer was 7%, 5.8%, and 19.4% with the recommended rate of N fertilizer at St2, St3, and St4, respectively (Figure 6).

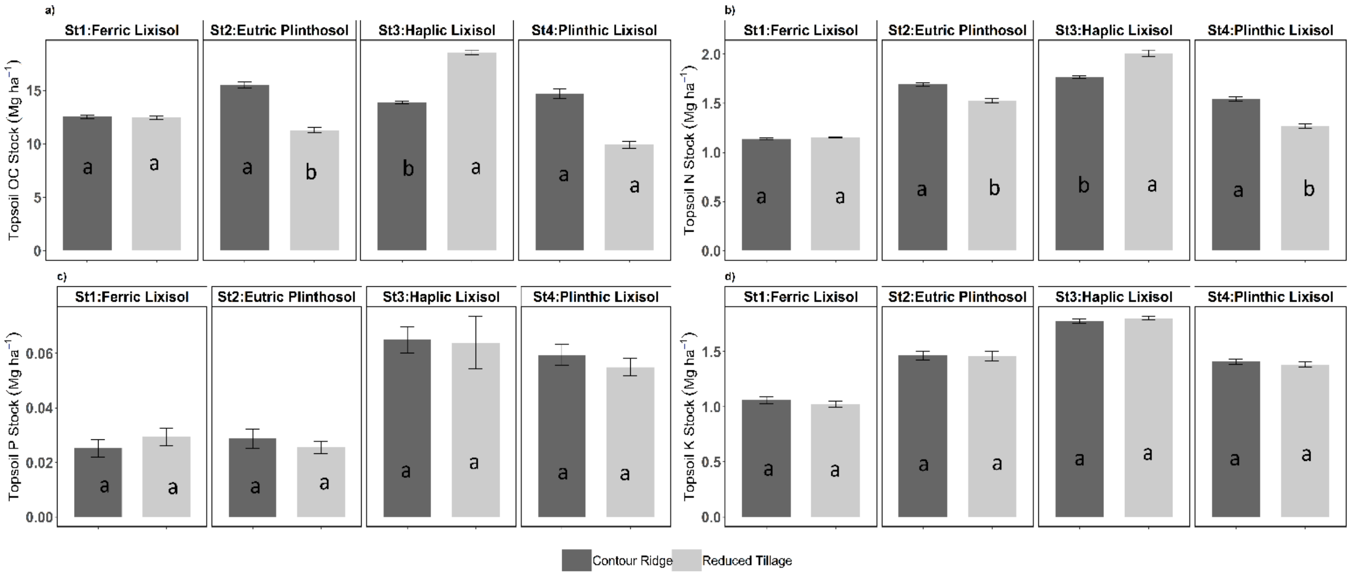

Figure 4: Topsoil soil organic carbon stock (Mg ha^{-1}) [a], topsoil soil nitrogen stock (Mg ha^{-1}) [b], topsoil soil phosphorus stock (Mg ha^{-1}) [c], and topsoil potassium stock (Mg ha^{-1}) [d] as affected by contour ridge tillage and reduced tillage in four sites. Each bar is a mean of 16 values (1 tillage×2 crop residue×2 N fertilizer×4 replications). Vertical bars indicate the mean standard error (±). Bars belonging to the same variable within a soil group followed by the same letter (s) are not significantly different at P≤0.05 level according to Tukey test.

Topsoil STN_d was also significantly affected by soil × tillage × N fertilizer interactions. For example, the application of the recommended dose of N fertilizer under the Ct system sharply increased STN_d in the topsoil layer of St2 and St4 (Figure 7). Rt together with the recommended dose of N fertilizer increased topsoil STN_d on St3. We did not find any difference in topsoil STN_d between tillage and N fertilizer combinations on St1. These results indicated that sites located in upslope positions increased STN_d in the topsoil layer under Ct and judicial application of N fertilizer. Similar to SOC_d, Rt combined with the recommended rate of N fertilizer was beneficial to STN_d only on one of the sites (St3) in footslope position.

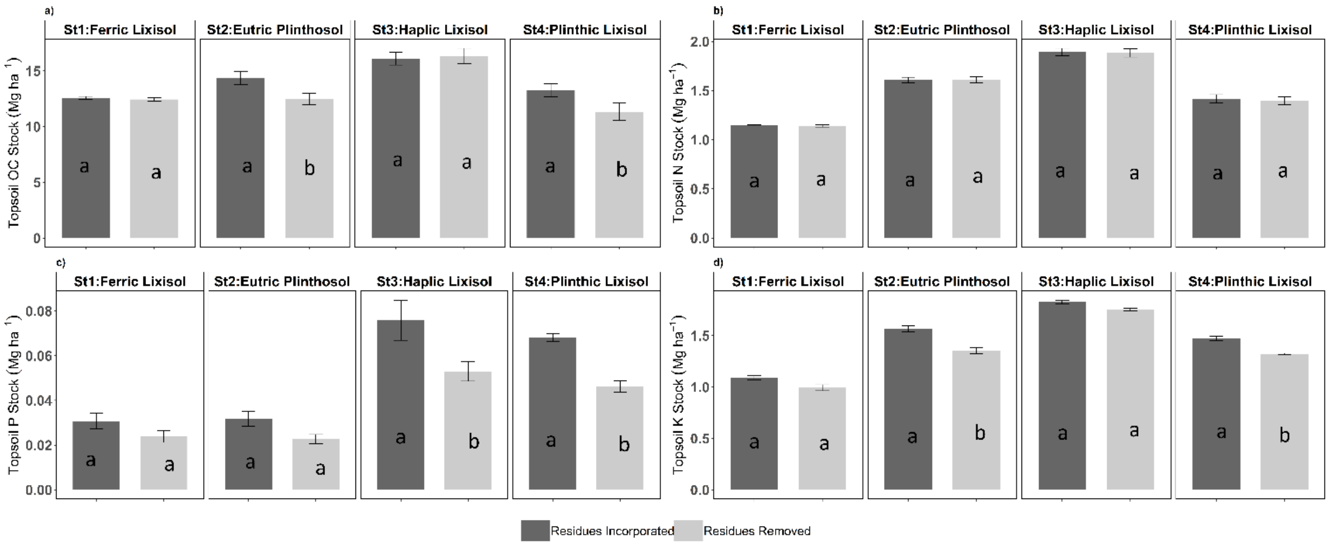

Figure 5: Topsoil soil organic carbon stock (Mg ha^{-1}) [a], topsoil soil nitrogen stock (Mg ha^{-1}) [b], topsoil soil phosphorus stock (Mg ha^{-1}) [c], and topsoil potassium stock (Mg ha^{-1}) [d] as affected by crop residue retention in four sites. Each bar is a mean of 16 values (1 crop residue×2 tillage×2 N fertilizer×4 replications). Vertical bars indicate the mean standard error (±). Bars belonging to the same variable within a soil group followed by the same letter (s) are not significantly different at P≤0.05 level according to Tukey test.

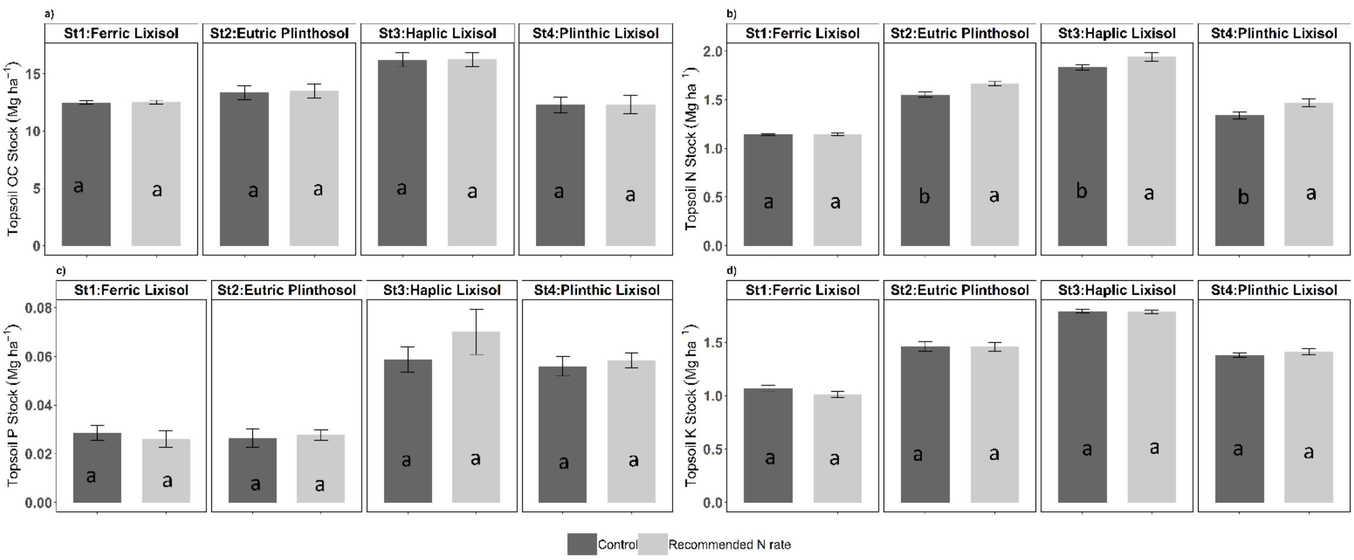

Figure 6: Topsoil soil organic carbon stock (Mg ha^{-1}) [a], topsoil soil nitrogen stock (Mg ha^{-1}) [b], topsoil soil phosphorus stock (Mg ha^{-1}) [c], and topsoil potassium stock (Mg ha^{-1}) [d] as affected by N fertilizer applications in four sites. Each bar is a mean of 16 values (2 crop residue×2 tillage×1 N fertilizer×4 replications). Vertical bars indicate the mean standard error (±). Bars belonging to the same variable within a soil group followed by the same letter (s) are not significantly different at P≤0.05 level according to Tukey test.

3.1.3 Soil phosphorus stock (SP_d)

CRi increased SP_d in the topsoil layer at all sites except St1 (Figure 5). The order of the topsoil SP_d increase over the sites due to CRi was St1 (+25%) < St2 (+33%) < St3 (+35%) < St4 (+38%). When averaged across sites and treatments, CRi resulted in a 34.8% increase in SP_d in the topsoil layer (Table 3). These results illustrated that CRi improved SP_d in the topsoil layer across all sites.

3.1.4 Soil potassium stock (SK_d)

Due to the incorporation of crop residues into the surface soil layer (Table 3), SK_d in the topsoil increased by almost 9.4% when averaged over sites and treatments (tillage and N fertilizer). However, only sites located in upslope positions had significantly higher SK_d with CRi. CRi resulted in an increase of 14.3% and 10.8% in SK_d in the topsoil layer of St2 and St4, respectively (Figure 5). However, such an effect was not significant when crop residues were applied to sites located at the footslope position. These results indicate that incorporation of crop residues into soils of upslope sites showed marked positive effects on topsoil SK_d, while such effects were smaller and not significant on sites in footslope positions.

3.1.5 Soil pH

The pH of the topsoil layer varied from 6.3 to 6.6. Sites at Dassari had the highest average topsoil pH of 6.6 (St3) and 6.5 (St4), while sites at Dano, St2 and St1 had an average topsoil pH of 6.3 and 6.4, respectively.

4. Discussion

This study adds to the understanding of the combined effects of tillage, crop residues, and N fertilizer application on major soil chemical properties under maize-cotton rotations in highly weathered soils of West Africa. The evidence gathered aids in addressing the questions, i) how the observed topsoil attributes (0-20 cm) respond to different management practices and how they vary across locations differing by climatic and soil conditions; and ii) how the combined effects of these management practices contribute to the conservation of soil fertility.

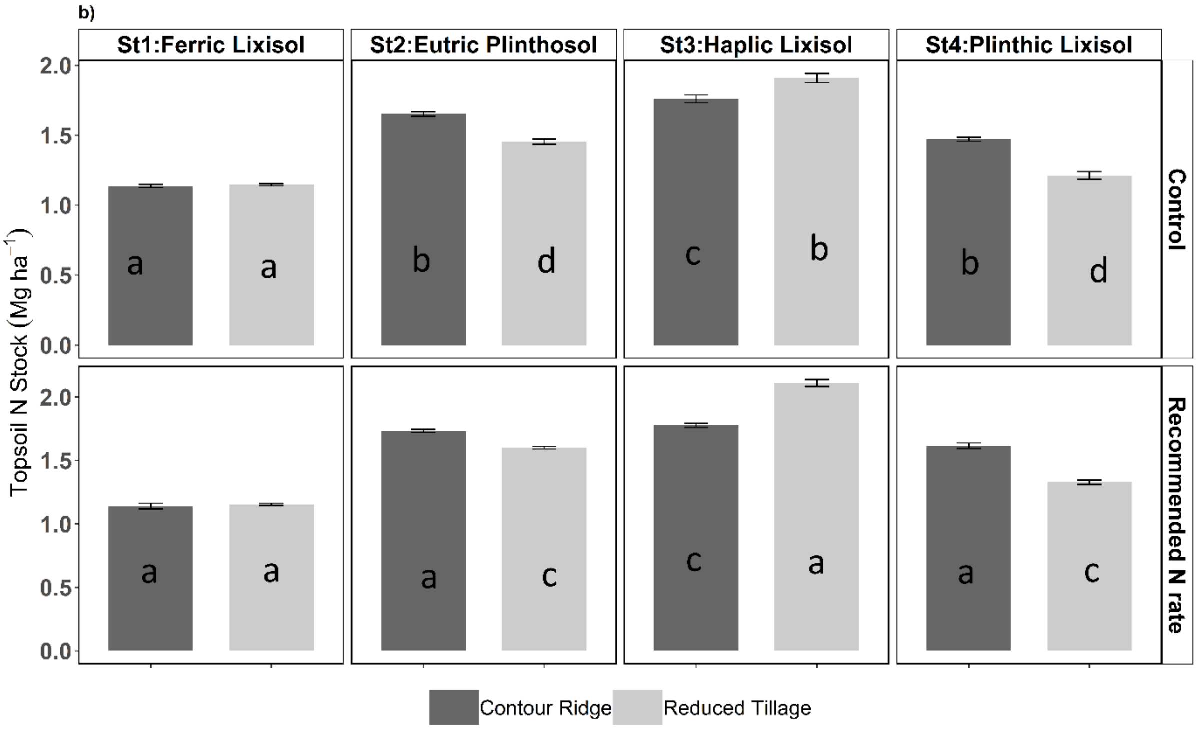

Figure 7: Topsoil soil nitrogen stock (Mg ha^{-1}) as affected by N fertilizer (control and recommended rate) and tillage interactions (N×T) in four sites. Each bar is a mean of 8 values (2 crop residue×1 tillage×1 N fertilizer×4 replications). Vertical bars indicate the mean standard error (±). Bars within a soil group followed by the same letter (s) are not significantly different at P≤0.05 level according to Tukey test.

4.1. Effects of tillage operations

or the soils considered in our study, Ct over 5 years improved SOC_d in both the topsoil and over the entire soil profile compared to Rt when averaged across soil types and treatments. This is consistent with the findings from a study conducted in Luvisols with a gentle slope (1-3%) in Southern Mali under semi-arid climate by Traoré et al. (2004) who found a significant positive impact of Ct implementation on crop yield, SOC_d, and soil water content. Ct prevents the rainwater from moving footslope which in turn provides the rainwater with more time to infiltrate and increases soil water storage (Traore et al., 2017). An increase in soil water storage can be expected to stimulate crop biomass production and consequently root biomass when water is otherwise limiting (Nunes et al., 2018; Thierfelder et al., 2013; Wolka et al., 2018). Higher above and below-ground biomass is one possible explanation of the greater SOC_d in both topsoil and the entire soil profile (Berhongaray et al., 2019). Additionally, it is well documented that the adoption of Ct could be an effective measure to control the loss of topsoil through erosion (Hatfield et al., 1998; Lal, 1990; Wolka et al., 2018).

In our study, about 14% higher topsoil STN_d under Ct was observed compared to Rt when averaged across soil types and treatments. This is explained by the fact discussed above that Ct increased on average SOC_d and the close relationship between SOC_d and STN_d in all arable soils. According to Dai et al. (2018), the implementation of Ct in red clay soils with 5° to 25° slope under subtropical monsoon climatic conditions resulted in an approximately 97% reduction in total N loss. Generally, the underlying mechanism is that Ct across the slope increases surface roughness and acts as a barrier that reduces run-off velocity, traps sediments, and increases soil water infiltration, thereby controlling sediment loss during the period of intensive rainfall (Lal, 1990; Liu and Huang, 2013; Liu et al., 2014, 2011; Quinton and Catt, 2006).

Moreover, the present study has shown significant interactions between tillage and site with respect to the effect on SOC_d and STN_d. Ct significantly improved SOC_d and STN_d on two out of four sites, St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol, upslope in Dassari). At the same time, Rt contributed to significantly higher SOC_d and STN_d on St3 (Haplic Lixisol, footslope in Dassari) compared to Ct. As mentioned earlier, soil erosion risk was probably lower on the footslope site St3, and the site might even benefit from eroded sediments from upslope. On the same experimental site (St3), Danso et al. (2018b) stated that the average biomass production was greatest under Rt compared to Ct. Another possible contribution of Rt to higher SOC_d compared to Ct could be related to reduced disruption of soil aggregates. Minimum soil mechanical disturbance due to Rt likely results in restricted SOC oxidation, which is the primary source of SOC loss from tropical soils (Nandan et al., 2019). Therefore, increased biomass production, as well as improved soil aggregate stability resulting from minimum soil disturbance, could have contributed to increased SOC input under the Rt system in St3. Implementation of Rt also markedly improved STN_d only on St3, which is consistent with the higher SOC_d that occurred only on this site.

4.2. Effects of crop residue retention

Consistent with our expectations and other studies (Ghimire et al., 2017; Han et al., 2018; J. Xu et al., 2019; X. Xu et al., 2019), greater SOC_d in the topsoil was detected with crop residues returned to the field when averaged over all sites (Table 3). Application of crop residue as a surface mulch is one of the most prominent measures to rebuild SOC stock in dryland soils of West Africa, although our results showed that this effect was site-dependent.

The decomposition of added high-quality cotton residue (C:N ratio 30) might have promoted microbial growth (Srinivasan et al., 2012; West and Post, 2002), whereas returning low-quality maize residues (C:N ratio 70) might have added more recalcitrant SOC. This is consistent with the findings from Ghosh et al. (2016) who observed an increased stable SOC pool by adding cereal residues with a high content of less decomposable lignin. However, our results contradict findings by Wang et al. (2015) who reported a rapid decomposition rate of maize residues that had smaller C:N ratio and lower lignin content.

In agreement with previous studies, SP_d was also improved with CRi in our experiments. On a Vertisol in India, the application of wheat residue markedly reduced soil P adsorption and increased both bicarbonate-extractable inorganic and organic P (Reddy et al., 2014). Moreover, soil phosphatase is the most common enzyme in soil that accelerates the transformation of organic P into the available form (Nannipieri et al., 2011). CRi can increase phosphatase activity in the topsoil layer (Akhtar et al., 2018; Yang et al., 2016) causing greater soil P availability. Another probable explanation could be that the rapid decomposition of previously added cotton residues released a considerable amount of organic acids, thereby solubilizing inorganic P (Laboski and Lamb, 2003). Oxidation of added residues releases some organic ligands that physically block the adsorption sites by forming complex compounds (Agbenin and Igbokwe, 2006). CRi also increased SK_d in the topsoil, although interaction with the sites was observed. As demonstrated by Wei et al. (2015) and Yang et al. (2018), soil available K in the topsoil increases as a result of CRi. Findings from China by Zhao et al. (2014) demonstrated that CRi could be an ideal measure for increasing the level of both soil available and slowly available K.

Our study also demonstrated a significant interaction of sites and crop residue management on soil chemical properties. It appeared that improved SOC_d, SK_d, and SP_d were recorded under CRi in all sites (soil types) except St1 (Ferric Lixisol, footslope in Dano). The addition of crop residues to the soil is an effective measure to limit soil erosion, sediment concentration in the runoff, and runoff discharge (Abrantes et al., 2018; Keesstra et al., 2019). During the period of intensive rainfall, crop residues act as a barrier that protects soil particles from detachment by raindrop impact and loss by water erosion (Brant et al., 2017; Edwards et al., 2000). Accordingly, we assume that crop residue retention exerts strong control over surface run-off that could result in improved soil nutrient stock at St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol, upslope in Dassari), as these sites are located in upslope positions and are more prone to erosion. In addition, increased physical protection of soil organic matter through improved soil aggregate stability triggered by CRi could have increased SOC_d on St2, St3 and St4. In contrast to St3 (Haplic Lixisol, footslope in Dassari), St1 (the footslope site in Dano) had much higher gravel content in the topsoil and contributed to much lower crop biomass production. Scant soil cover and rapid oxidation of existing soil organic matter, as well as lower quantity of fine earth to stabilize SOC due to high gravel content, could be a possible explanation of poor SOC_d with CRi on St1. Lower crop residue production in St1 compared to St2 and St4 resulted in the lower release of mobile P and K and therefore CRi did not improve SK_d and SP_d compared to CRr on this site. In addition, P and K could have been subjected to more rapid leaching losses on St1 due to higher hydraulic conductivity with greater gravel content (47%).

4.3. Effects of N fertilizer application

The average total aboveground biomass with the recommended rate of N fertilizer was approximately 27% higher compared to no N fertilizer application as evidenced by Danso et al. (2018a). Improved crop biomass production contributes to increased organic matter input to the soils by aboveground litter and root exudates. Steady decomposition of large amounts of maize litter with high C:N ratios causes immobilization of mineral N added through synthetic fertilizer (Chen et al., 2014; Gentile et al., 2009; Kaleeem Abbasi et al., 2015). Few studies confirmed that N fertilizer application stabilizes soil organic matter, preserves native and stable organic matter, and immobilizes N, which in turn increase soil TN content (Hagedorn et al., 2003; Ren et al., 2014). Collectively, these assumptions can explain why, averaged over all sites, higher STN_d was recorded with the application of recommended rates of mineral N fertilizer. However, our study revealed a significant interaction of mineral N fertilizer with site and tillage on STN_d. Ct with N fertilizer application had significant effects on STN_d in St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol, upslope in Dassari) while higher STN_d was recorded under Rt combined with N fertilizer application in St3 (Haplic Lixisol, footslope in Dassari). As shown before implementation of Ct might have acted as a barrier to surface runoff in upslope soils, reducing soil erosion and mitigating mineral N loss added as synthetic fertilizer. However, on footslope sites and in particular, on St3, N fertilizer application combined with Rt was related to increased residue production, higher SOC_d and consequently higher N immobilization of the added N fertilizer.

The lack of a significant increase in SOC_d under N fertilizer application in this study is in agreement with many other studies (Chen et al., 2014; Mahal et al., 2019; Poffenbarger et al., 2017). This might be due to the fact that inorganic N inputs can accelerate soil organic matter decomposition by increasing soil microbial biomass and enzymatic activities. Further, no significant changes in SP_d and SK_d content were observed with the application of N fertilizer. The addition of N fertilizer stimulates crop growth, increases biotic P and K demand, and concurrently promotes P and K uptake by the crops which decrease SP_d and SK_d (Apthorp et al., 1987; Káš et al., 2016; Yang et al., 2015).

Collectively, with respect to our hypothesis that implementation of Rt along with CRi increases SOC_d and STN_d across sites, we found only partial support. Rt combined with CRi was effectively increasing SOC_d and STN_d only on one out of four sites (St3, Haplic Lixisol, footslope in Dassari) while Ct along with CRi was beneficial for conservation of SOC_d and STN_d on St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol, upslope in Dassari). Regarding the second hypothesis that CRi increases SP_d and SK_d across sites, we found that SP_d and SK_d were higher with CRi on all sites except St1 (Ferric Lixisol, footslope in Dano). However, soil pH was unaffected by the implemented management practices. Overall, the findings of our study suggest the potential of Ct along with CRi in building-up of soil nutrient stocks in upslope soils (St2 and St4), while Rt combined with CRi could be more effective on footslope soils like St3

5. Conclusions

Our study helps to understand alternative management effects on soil fertility and crop production in different soils of West Africa and may be used in the development of site-specific agronomic practices aiming to reduce negative impacts of soil degradation on soil properties and agronomic productivity. Our experiment demonstrated that in a gently undulated region subject to soil degradation through runoff and erosion, implementation of contour ridge tillage along with crop residue retention in upslope areas maintained soil fertility and sustained crop productivity. On the other hand, in footslope areas, the adoption of reduced tillage with crop residue retention could be more beneficial. We emphasized that water retention capacity of the soils, which strongly affects water supply to the crops, is one of the most prominent factors influencing the conservation of SOC_d, STN_d, and SK_d across sites. We recommend additional simulation-based studies in order to predict the long-term effect of the management practices tested in this paper as well as the effect of future climate change.

6. References

Abrantes, J.R.C.B., Prats, S.A., Keizer, J.J., de Lima, J.L.M.P., 2018. Effectiveness of the application of rice straw mulching strips in reducing runoff and soil loss: Laboratory soil flume experiments under simulated rainfall. Soil Tillage Res. 180, 238–249. https://doi.org/10.1016/J.STILL.2018.03.015

Abrol, V., Sharm, P., 2012. An Appraisal of Conservation Tillage on the Soil Properties and C Sequestration, in: Resource Management for Sustainable Agriculture. InTech. https://doi.org/10.5772/51304

Agbenin, J.O., Igbokwe, S.O., 2006. Effect of soil–dung manure incubation on the solubility and retention of applied phosphate by a weathered tropical semi-arid soil. Geoderma 133, 191–203. https://doi.org/10.1016/J.GEODERMA.2005.07.006

Akhtar, K., Wang, W., Ren, G., Khan, A., Feng, Y., Yang, G., 2018. Changes in soil enzymes, soil properties, and maize crop productivity under wheat straw mulching in Guanzhong, China. Soil Tillage Res. 182, 94–102. https://doi.org/10.1016/J.STILL.2018.05.007

Alam, M.K., Bell, R.W., Haque, M.E., Kader, M.A., 2018. Minimal soil disturbance and increased residue retention increase soil carbon in rice-based cropping systems on the Eastern Gangetic Plain. Soil Tillage Res. 183, 28–41. https://doi.org/10.1016/J.STILL.2018.05.009

Al-Qinna, M., Scott, H.D., Brye, K.R., Van Brahana, J., Sauer, T.J., Sharpley, A., 2014. Coarse Fragments Affect Soil Properties in a Mantled-Karst Landscape of the Ozark Highlands. Soil Sci. 179, 42–50. https://doi.org/10.1097/SS.0000000000000034

Apthorp, J.N., Hedley, M.J., Tillman, R.W., 1987. The effects of nitrogen fertilizer form on the plant availability of phosphate from soil, phosphate rock and mono-calcium phosphate. Fertil. Res. 12, 269–283. https://doi.org/10.1007/BF01315111

Araya, T., Cornelis, W.M., Nyssen, J., Govaerts, B., Bauer, H., Gebreegziabher, T., Oicha, T., Raes, D., Sayre, K.D., Haile, M., Deckers, J., 2011. Effects of conservation agriculture on runoff, soil loss and crop yield under rainfed conditions in Tigray, Northern Ethiopia. Soil Use Manag. 27, no-no. https://doi.org/10.1111/j.1475-2743.2011.00347.x

Barber, S.A., 1995. Soil nutrient bioavailability : a mechanistic approach. Wiley.

Bationo, A., Mokwunye, A.U., 1991. Alleviating soil fertility constraints to increased crop production in West Africa: The experience in the Sahel. Fertil. Res. 29, 95–115. https://doi.org/10.1007/BF01048992

Beibei, Z., Ming'an, S., Hongbo, S., 2009. Effects of rock fragments on water movement and solute transport in a Loess Plateau soil. Comptes Rendus Geosci. 341, 462–472. https://doi.org/10.1016/J.CRTE.2009.03.009

Berhongaray, G., Cotrufo, F.M., Janssens, I.A., Ceulemans, R., 2019. Below-ground carbon inputs contribute more than above-ground inputs to soil carbon accrual in a bioenergy poplar plantation. Plant Soil 434, 363–378. https://doi.org/10.1007/s11104-018-3850-z

Bescansa, P., Imaz, M.J., Virto, I., Enrique, A., Hoogmoed, W.B., 2006. Soil water retention as affected by tillage and residue management in semiarid Spain. Soil Tillage Res. 87, 19–27. https://doi.org/10.1016/J.STILL.2005.02.028

Brant, V., Kroulík, M., Pivec, J., Zábranský, P., Hakl, J., Holec, J., Kvíz, Z., Procházka, l., 2017. Splash erosion in maize crops under conservation management in combination with shallow strip-tillage before sowing. Soil Water Res. 12, 106–116. https://doi.org/10.17221/147/2015-SWR

Brhane, G., Wortmann, C.S., Mamo, M., Gebrekidan, H., Belay, A., 2006. Micro-Basin Tillage for Grain Sorghum Production in Semiarid Areas of Northern Ethiopia. Agron. J. 98, 124. https://doi.org/10.2134/agronj2005-0148

Chaves, B., De Neve, S., Hofman, G., Boeckx, P., Van Cleemput, O., 2004. Nitrogen mineralization of vegetable root residues and green manures as related to their (bio)chemical composition. Eur. J. Agron. 21, 161–170. https://doi.org/10.1016/J.EJA.2003.07.001

Chen, B., Liu, E., Tian, Q., Yan, C., Zhang, Y., 2014. Soil nitrogen dynamics and crop residues. A review. Agron. Sustain. Dev. 34, 429–442. https://doi.org/10.1007/s13593-014-0207-8ï

Chen, R., Senbayram, M., Blagodatsky, S., Myachina, O., Dittert, K., Lin, X., Blagodatskaya, E., Kuzyakov, Y., 2014. Soil C and N availability determine the priming effect: microbial N mining and stoichiometric decomposition theories. Glob. Chang. Biol. 20, 2356–2367. https://doi.org/10.1111/gcb.12475

Cong, P., Yin, G., Gu, J., 2016. Effects of stubble and mulching on soil erosion by wind in semi-arid China. Sci. Rep. 6, 29966. https://doi.org/10.1038/srep29966

Dai, C., Liu, Y., Wang, T., Li, Z., Zhou, Y., 2018. Exploring optimal measures to reduce soil erosion and nutrient losses in southern China. Agric. Water Manag. 210, 41–48. https://doi.org/10.1016/J.AGWAT.2018.07.032

Danso, I., Gaiser, T., Webber, H., Naab, J., Ewert, F., 2018. Response of Maize to Different Nitrogen Application Rates and Tillage Practices Under Two Slope Positions in the Face of Current Climate Variability in the Sudan Savanna of West Africa. Springer, Singapore, pp. 41–58. https://doi.org/10.1007/978-981-10-4796-1_3

Danso, I., Webber, H., Bourgault, M., Ewert, F., Naab, J.B., Gaiser, T., 2018. Crop management adaptations to improve and stabilize crop yields under low-yielding conditions in the Sudan Savanna of West Africa. Eur. J. Agron. 101, 1–9. https://doi.org/10.1016/J.EJA.2018.08.001

de Cárcer, P.S., Sinaj, S., Santonja, M., Fossati, D., Jeangros, B., 2019. Long-term effects of crop succession, soil tillage and climate on wheat yield and soil properties. Soil Tillage Res. 190, 209–219. https://doi.org/10.1016/J.STILL.2019.01.012

Desrochers, J., Brye, K.R., Gbur, E., Mason, R.E., 2019. Infiltration as affected by long-term residue and water management on a loess-derived soil in eastern Arkansas, USA. Geoderma Reg. 16, e00203. https://doi.org/10.1016/J.GEODRS.2019.E00203

Dick, R.P., 1992. A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. Biot. Divers. Agroecosystems 25–36. https://doi.org/10.1016/B978-0-444-89390-1.50005-6

Dikgwatlhe, S.B., Chen, Z.-D., Lal, R., Zhang, H.-L., Chen, F., 2014. Changes in soil organic carbon and nitrogen as affected by tillage and residue management under wheat–maize cropping system in the North China Plain. Soil Tillage Res. 144, 110–118. https://doi.org/10.1016/J.STILL.2014.07.014

Dossou-Yovo, E.R., Ampofo, E., Igue, A.M., Sintondji, L.O., Agbossou, E.K., 2016. Tillage , Rice Straw Mulch and Nitrogen Fertilization Effects on Upland Rice Yield in Northern Benin 6, 107–117.

Edwards, L.M., Volk, A., Burney, J.R., 2000. Mulching potatoes: Aspects of mulch management systems and soil erosion. Am. J. Potato Res. 77, 225–232. https://doi.org/10.1007/BF02855790

Erkossa, T., Stahr, K., Gaiser, T., 2006. Effect of different methods of land preparation on runoff, soil and nutrient losses from a Vertisol in the Ethiopian highlands. Soil Use Manag. 21, 253–259. https://doi.org/10.1111/j.1475-2743.2005.tb00132.x

FAO, ITPS, 2015. Status of the World's Soil Resources. Chapter 9: Regional Assessment of Soil Changes in Africa South of the Sahara. Rome, Italy.

Frank, D.A., Pontes, A.W., Maine, E.M., Caruana, J., Raina, R., Raina, S., Fridley, J.D., 2010. Grassland root communities: species distributions and how they are linked to aboveground abundance. Ecology 91, 3201–3209. https://doi.org/10.1890/09-1831.1

Gaiser, T., Graef, F., Cordeiro, J.C., 2000. Water retention characteristics of soils with contrasting clay mineral composition in semi-arid tropical regions. Aust. J. Soil Res. 38, 523. https://doi.org/10.1071/SR99001

Gałecki, A., Burzykowski, T., 2013. Linear Mixed-Effects Models Using R. Springer, Verlag New York. https://doi.org/10.1007/978-1-4614-3900-4_1

Gao, J., Feng, J., Zhang, X., Yu, F.-H., Xu, X., Kuzyakov, Y., 2016. Drying-rewetting cycles alter carbon and nitrogen mineralization in litter-amended alpine wetland soil. CATENA 145, 285–290. https://doi.org/10.1016/J.CATENA.2016.06.026

Gardner, W.H., 1986. Water Content, in: Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods. American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 493–544. https://doi.org/10.2136/sssabookser5.1.2ed.c21

Gathagu, J.N. ang a., Mourad, K.A., Sang, J., 2018. Effectiveness of contour farming and filter strips on ecosystem services. Water (Switzerland) 10. https://doi.org/10.3390/w10101312

Gentile, R., Vanlauwe, B., van Kessel, C., Six, J., 2009. Managing N availability and losses by combining fertilizer-N with different quality residues in Kenya. Agric. Ecosyst. Environ. 131, 308–314. https://doi.org/10.1016/J.AGEE.2009.02.003

Ghadiri, H., Rose, C.W., Hogarth, W.L., 2001. The influence of grass and porous barrier strips on runoff hydrology and sediment transport. Trans. Am. Soc. Agric. Eng. 44, 259–268. https://doi.org/10.13031/2013.4687

Ghimire, R., Lamichhane, S., Acharya, B.S., Bista, P., Sainju, U.M., 2017. ScienceDirect Tillage, crop residue, and nutrient management effects on soil organic carbon in rice-based cropping systems: A review. J. Integr. Agric. 16, 1–15. https://doi.org/10.1016/S2095-3119(16)61337-0

Ghosh, B.N., Dogra, P., Sharma, N.K., Bhattacharyya, R., Mishra, P.K., 2015. Conservation agriculture impact for soil conservation in maize–wheat cropping system in the Indian sub-Himalayas. Int. Soil Water Conserv. Res. 3, 112–118. https://doi.org/10.1016/J.ISWCR.2015.05.001

Ghosh, P.K., Hazra, K.K., Venkatesh, M.S., Singh, K.K., Kumar, N., Mathur, R.S., 2016. Potential of Crop Residue and Fertilizer on Enrichment of Carbon Pools in Upland Soils of Subtropical India. Agric. Res. 5, 261–268. https://doi.org/10.1007/s40003-016-0215-9

Gomez, K.A., Gomez, A.A., Gomez, K.A., 1984. Statistical procedures for agricultural research. Wiley.

Grunes, D.L., 1959. Effect of Nitrogen on the Availability of Soil and Fertilizer Phosphorus to Plants. Adv. Agron. 11, 369–396. https://doi.org/10.1016/S0065-2113(08)60127-3

Hagedorn, F., Spinnler, D., Siegwolf, R., 2003. Increased N deposition retards mineralization of old soil organic matter. Soil Biol. Biochem. 35, 1683–1692. https://doi.org/10.1016/J.SOILBIO.2003.08.015

Han, X., Xu, C., Dungait, J.A.J., Bol, R., Wang, X., Wu, W., Meng, F., 2018. Straw incorporation increases crop yield and soil organic carbon sequestration but varies under different natural conditions and farming practices in China: a system analysis. Biogeosciences 15, 1933–1946. https://doi.org/10.5194/bg-15-1933-2018

Hatfield, J.L., Allmaras, R.R., Rehm, G.W., Lowery, B., 1998. Ridge tillage for corn and soybean production: environmental quality impacts. Soil Tillage Res. 48, 145–154. https://doi.org/10.1016/S0167-1987(98)00141-X

He, Y., Xu, X., Kueffer, C., Zhang, X., Shi, P., 2014. Leaf litter of a dominant cushion plant shifts nitrogen mineralization to immobilization at high but not low temperature in an alpine meadow. Plant Soil 383, 415–426. https://doi.org/10.1007/s11104-014-2216-4

Hossner, L.R., Juo, A.S.R., 1999. Soil nutrient management for sustained food crop production in upland farming systems in the tropics, Extension Bulletin - ASPAC, Food &

Fertilizer Technology Center. Food and Fertilizer Technology Center for the Asian and Pacific Region, Taipei, Taiwan.

Hu, W., Tian, S., Di, Q., Liu, J., Zhang, S., 2018. Nitrogen mineralization simulation dynamic in tobacco soil, Journal of Soil Science and Plant Nutrition.

Huang, G.B., Luo, Z.Z., Li, L.L., Zhang, R.Z., Li, G.D., Cai, L.Q., Xie, J.H., 2012. Effects of Stubble Management on Soil Fertility and Crop Yield of Rainfed Area in Western Loess Plateau, China. Appl. Environ. Soil Sci. 2012, 1–9. https://doi.org/10.1155/2012/256312

Hunink, J.E., Droogers, P., Kauffman, S., Mwaniki, B.M., Bouma, J., 2012. Quantitative simulation tools to analyze up- and downstream interactions of soil and water conservation measures: Supporting policy making in the Green Water Credits program of Kenya. J. Environ. Manage. 111, 187–194. https://doi.org/10.1016/j.jenvman.2012.07.022

Hurni, H., W.A., B., P., C., D., D., Zeleke, G., M., G., G., K., 2016. Soil and Water Conservation in Ethiopia: Guidelines for Development Agents, 2nd revise. ed. Centre for Development and Environment (CDE); Bern Open Publishing (BOP), Bern, Switzerland. https://doi.org/10.7892/boris.80013

Jan, A., Hussain, N., Ostergaard, L., 2016. Spring wheat response to nitrogen, tillage and cropping system under rainfed condition. Cogent Biol. 2, 1167653. https://doi.org/10.1080/23312025.2016.1167653

Jiang, X.-J., Xie, D.-T., 2009. Combining Ridge with No-Tillage in Lowland Rice-Based Cropping System: Long-Term Effect on Soil and Rice Yield. Pedosphere 19, 515–522. https://doi.org/10.1016/S1002-0160(09)60144-2

Jonasson, S., Castro, J., Michelsen, A., 2006. Interactions between plants, litter and microbes in cycling of nitrogen and phosphorus in the arctic. Soil Biol. Biochem. 38, 526–532. https://doi.org/10.1016/J.SOILBIO.2005.05.024

Jungk, A., Claassen, N., 1997. Ion diffusion in the soil-root system, 61st ed, Advances in agronomy. Academic Press.

Kaleeem Abbasi, M., Mahmood Tahir, M., Sabir, N., Khurshid, M., 2015. Impact of the addition of different plant residues on nitrogen mineralization–immobilization turnover and carbon content of a soil incubated under laboratory conditions. Solid Earth 6, 197–205. https://doi.org/10.5194/se-6-197-2015

Kaneda, S., Kaneko, N., 2011. Influence of Collembola on nitrogen mineralization varies with soil moisture content. Soil Sci. Plant Nutr. 57, 40–49. https://doi.org/10.1080/00380768.2010.551107

Karuma, A., Mtakwa, P., Amuri, N., Gachene, C.K., Gicheru, P., 2014. Tillage Effects on Selected Soil Physical Properties in a Maize-Bean Intercropping System in Mwala District, Kenya. Int. Sch. Res. Not. 2014, 497205. https://doi.org/10.1155/2014/497205

Káš, M., Mühlbachová, G., Kusá, H., Pechová, M., 2016. Soil phosphorus and potassium availability in long-term field experiments with organic and mineral fertilization. Plant, Soil Environ. 62, 558–565. https://doi.org/10.17221/534/2016-PSE

Kassambara, A., Mundt, F., 2017. factoextra: Extract and Visualize the Results of Multivariate Data Analyses. R package version 1.0.5.

Keesstra, S.D., Rodrigo-Comino, J., Novara, A., Giménez-Morera, A., Pulido, M., Di Prima, S., Cerdà, A., 2019. Straw mulch as a sustainable solution to decrease runoff and erosion in glyphosate-treated clementine plantations in Eastern Spain. An assessment using rainfall simulation experiments. CATENA 174, 95–103. https://doi.org/10.1016/J.CATENA.2018.11.007

Khorami, S.S., Kazemeini, S.A., Afzalinia, S., Gathala, M.K., 2018. Changes in Soil Properties and Productivity under Different Tillage Practices and Wheat Genotypes: A Short-Term Study in Iran. Sustainability 10, 1–17.

Kihara, J., Bationo, A., Mugendi, D.N., Martius, C., Vlek, P.L.G., 2011. Conservation Tillage, Local Organic Resources, and Nitrogen Fertilizer Combinations Affect Maize Productivity, Soil Structure and Nutrient Balances in Semi-arid Kenya, in: Innovations as Key to the Green Revolution in Africa. Springer Netherlands, Dordrecht, pp. 155–167. https://doi.org/10.1007/978-90-481-2543-2_14

Kpongor, D.S., 2007. Spatially explicit modeling of sorghum (Sorghum bicolor (L.) Moench) production on complex terrain of a semi-arid region in Ghana using APSIM. University of Bonn, Germany.

Kuchenbuch, R., Claassen, N., Jungk, A., 1986. Potassium availability in relation to soil moisture. Plant Soil 95, 221–231. https://doi.org/10.1007/BF02375074

Laboski, C.A.M., Lamb, J.A., 2003. Changes in Soil Test Phosphorus Concentration After Application of Manure or Fertilizer. Soil Sci. Soc. Am. J. 67, 544. https://doi.org/10.2136/sssaj2003.5440

Lal, R., 1987. Managing the Soils of Sub-Saharan Africa. Science (80-.). 236, 1069–1076. https://doi.org/10.1126/science.236.4805.1069

Lal, R., 1976. No-tillage Effects on Soil Properties under Different Crops in Western Nigeria. Soil Sci. Soc. Am. J. 40, 762. https://doi.org/10.2136/sssaj1976.03615995004000050039x

Lal, R., 1990. Ridge-tillage. Soil Tillage Res. 18, 107–111. https://doi.org/10.1016/0167-1987(90)90053-G

Lenth, R. V., 2016. Least-Squares Means: The R Package lsmeans. J. Stat. Softw. 69, 1–33. https://doi.org/10.18637/jss.v069.i01

Li, J., Lu, J., Li, X., Ren, T., Cong, R., 2014. Dynamics of Potassium Release and Adsorption on Rice Straw Residue. PLoS One 9, 90440. https://doi.org/10.1371/journal.pone.0090440

Liu, H., Huang, Q., 2013. Adoption and continued use of contour cultivation in the highlands of southwest China. Ecol. Econ. 91, 28–37. https://doi.org/10.1016/J.ECOLECON.2013.03.015

Liu, Q.J., An, J., Wang, L.Z., Wu, Y.Z., Zhang, H.Y., 2015. Influence of ridge height, row grade, and field slope on soil erosion in contour ridging systems under seepage conditions. Soil Tillage Res. 147, 50–59. https://doi.org/10.1016/J.STILL.2014.11.008

Liu, Q.J., An, J., Zhang, G.H., Wu, X.Y., 2016. The effect of row grade and length on soil erosion from concentrated flow in furrows of contouring ridge systems. Soil Tillage Res. 160, 92–100. https://doi.org/10.1016/J.STILL.2016.02.012

Liu, Q.J., Zhang, H.Y., An, J., Wu, Y.Z., 2014. Soil erosion processes on row sideslopes within contour ridging systems. CATENA 115, 11–18. https://doi.org/10.1016/J.CATENA.2013.11.013

Liu, X., Zhang, S., Zhang, X., Ding, G., Cruse, R.M., 2011. Soil erosion control practices in Northeast China: A mini-review. Soil Tillage Res. 117, 44–48. https://doi.org/10.1016/J.STILL.2011.08.005

Lupwayi, N.Z., Clayton, G.W., O'Donovan, J.T., Harker, K.N., Turkington, T.K., Soon, Y.K., 2006. Potassium release during decomposition of crop residues under conventional and zero tillage. Can. J. Soil Sci. 86, 473–481. https://doi.org/10.4141/S05-049

Mahal, N.K., Osterholz, W.R., Miguez, F.E., Poffenbarger, H.J., Sawyer, J.E., Olk, D.C., Archontoulis, S. V., Castellano, M.J., 2019. Nitrogen Fertilizer Suppresses Mineralization of Soil Organic Matter in Maize Agroecosystems. Front. Ecol. Evol. 7, 59. https://doi.org/10.3389/fevo.2019.00059

Martinsen, V., Munera-Echeverri, J.L., Obia, A., Cornelissen, G., Mulder, J., 2019. Significant build-up of soil organic carbon under climate-smart conservation farming in Sub-Saharan Acrisols. Sci. Total Environ. 660, 97–104. https://doi.org/10.1016/J.SCITOTENV.2018.12.452

Masvaya, E.N., Nyamangara, J., Descheemaeker, K., Giller, K.E., 2017. Tillage, mulch and fertiliser impacts on soil nitrogen availability and maize production in semi-arid Zimbabwe. Soil Tillage Res. 168, 125–132. https://doi.org/10.1016/J.STILL.2016.12.007

Mati, M.B., 2007. 100 ways to manage Water for smallholder agriculture in Eastern and Southern Africa, A Compendium Technologies Practices.SWMnet Working Pap.

Matula, S., 2003. The influence of tillage treatments on water infiltration into soil profile. Plant, Soil Environ. 49, 298–306.

McDaniel, M.D., Tiemann, L.K., Grandy, A.S., 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24, 560–570. https://doi.org/10.1890/13-0616.1

Merante, P., Dibari, C., Ferrise, R., Sánchez, B., Iglesias, A., Lesschen, J.P., Kuikman, P., Yeluripati, J., Smith, P., Bindi, M., 2017. Adopting soil organic carbon management practices in soils of varying quality: Implications and perspectives in Europe. Soil Tillage Res. 165, 95–106. https://doi.org/10.1016/J.STILL.2016.08.001

Mhazo, N., Chivenge, P., Chaplot, V., 2016. Tillage impact on soil erosion by water: Discrepancies due to climate and soil characteristics. Agric. Ecosyst. Environ. 230, 231–241. https://doi.org/10.1016/J.AGEE.2016.04.033

Miriti, J.M., Kironchi, G., Esilaba, A.O., Heng, L.K., Gachene, C.K.K., Mwangi, D.M., 2012. Yield and water use efficiencies of maize and cowpea as affected by tillage and cropping systems in semi-arid Eastern Kenya. Agric. Water Manag. 115, 148–155. https://doi.org/10.1016/J.AGWAT.2012.09.002

Mishra, B., Sharma, P.K., Bronson, K.F., 2001. Decomposition of Rice Straw and Mineralization of Carbon, Nitrogen, Phosphorus and Potassium in Wheat Field Soil in Western Uttar Pradesh. J. Indian Soc. Soil Sci. 49, 419–424.

Mohamoud, Y.M., 2012. Effect of contour ridging on runoff and soil loss. African J. Agric. Res. 7, 6115–6124. https://doi.org/10.5897/AJAR11.2307

Mrabet, R., Ibno-Namr, K., Bessam, F., Saber, N., 2001. Soil chemical quality changes and implications for fertilizer management after 11 years of no-tillage wheat production systems in semiarid Morocco. L. Degrad. Dev. 12, 505–517. https://doi.org/10.1002/ldr.464

Mupangwa, W., Twomlow, S., Walker, S., 2012. Dead level contours and infiltration pits for risk mitigation in smallholder cropping systems of southern Zimbabwe. Phys. Chem. Earth, Parts A/B/C 47–48, 166–172. https://doi.org/10.1016/J.PCE.2011.06.011

Naab, J.B., Mahama, G.Y., Yahaya, I., Prasad, P.V. V, 2017. Conservation Agriculture Improves Soil Quality, Crop Yield, and Incomes of Smallholder Farmers in North Western Ghana. Front. Plant Sci. 8, 996. https://doi.org/10.3389/fpls.2017.00996

Nandan, R., Singh, V., Singh, S.S., Kumar, V., Hazra, K.K., Nath, C.P., Poonia, S., Malik, R.K., Bhattacharyya, R., McDonald, A., 2019. Impact of conservation tillage in rice–based cropping systems on soil aggregation, carbon pools and nutrients. Geoderma 340, 104–114. https://doi.org/10.1016/J.GEODERMA.2019.01.001

Nannipieri, P., Giagnoni, L., Landi, L., Renella, G., 2011. Role of Phosphatase Enzymes in Soil, in: Bünemann, E., Oberson, A., Frossard, E. (Eds.), Phosphorus in Action. Springer, Berlin, Heidelberg, pp. 215–243. https://doi.org/10.1007/978-3-642-15271-9_9

Nunes, M.R., van Es, H.M., Schindelbeck, R., Ristow, A.J., Ryan, M., 2018. No-till and cropping system diversification improve soil health and crop yield. Geoderma 328, 30–43. https://doi.org/10.1016/J.GEODERMA.2018.04.031

Nyamadzawo, G., Wuta, M., Nyamangara, J., Gumbo, D., 2013. Opportunities for optimization of in-field water harvesting to cope with changing climate in semi-arid smallholder farming areas of Zimbabwe. Springerplus 2, 100. https://doi.org/10.1186/2193-1801-2-100

Nyamangara, J., Nyagumbo, I., 2010. Interactive effects of selected nutrient resources and tied-ridging on plant growth performance in a semi-arid smallholder farming environment in central Zimbabwe. Nutr. Cycl. Agroecosystems 88, 103–109. https://doi.org/10.1007/s10705-009-9282-7

Nyamekye, C., Thiel, M., Schönbrodt-Stitt, S., Zoungrana, B., Amekudzi, L., Nyamekye, C., Thiel, M., Schönbrodt-Stitt, S., Zoungrana, B.J.-B., Amekudzi, L.K., 2018. Soil and Water Conservation in Burkina Faso, West Africa. Sustainability 10, 3182. https://doi.org/10.3390/su10093182

Obalum, S.E., Buri, M.M., Nwite, J.C., Hermansah, Watanabe, Y., Igwe, C.A., Wakatsuki, T., 2012. Soil Degradation-Induced Decline in Productivity of Sub-Saharan African Soils: The Prospects of Looking Downwards the Lowlands with the *Sawah* Ecotechnology. Appl. Environ. Soil Sci. 2012, 1–10. https://doi.org/10.1155/2012/673926

Okeyo, J.M., Norton, J., Koala, S., Waswa, B., Kihara, J., Bationo, A., 2016. Impact of reduced tillage and crop residue management on soil properties and crop yields in a long-term trial in western Kenya. Soil Res. 54, 719. https://doi.org/10.1071/SR15074

Ouédraogo, E., Mando, A., Stroosnijder, L., 2006. Effects of tillage, organic resources and nitrogen fertiliser on soil carbon dynamics and crop nitrogen uptake in semi-arid West Africa. Soil Tillage Res. 91, 57–67. https://doi.org/10.1016/J.STILL.2005.11.004

Owusu, G., 2012. A GIS-Based Estimation of Soil Loss in the Densu Basin in Ghana. West African J. Appl. Ecol. 20, 41–51.

Oyedele, D.J., Aina, P.O., 2006. Response of soil properties and maize yield to simulated erosion by artificial topsoil removal. Plant Soil 284, 375–384. https://doi.org/10.1007/s11104-006-0041-0

Piepho, H.P., Buchse, A., Emrich, K., 2003. A Hitchhiker's Guide to Mixed Models for Randomized Experiments. J. Agron. Crop Sci. 189, 310–322. https://doi.org/10.1046/j.1439-037X.2003.00049.x

Poesen, J., Lavee, H., 1994. Rock fragments in top soils: significance and processes. CATENA 23, 1–28. https://doi.org/10.1016/0341-8162(94)90050-7

Poffenbarger, H.J., Barker, D.W., Helmers, M.J., Miguez, F.E., Olk, D.C., Sawyer, J.E., Six, J., Castellano, M.J., 2017. Maximum soil organic carbon storage in Midwest U.S. cropping systems when crops are optimally nitrogen-fertilized. PLoS One 12, e0172293. https://doi.org/10.1371/journal.pone.0172293

Prasad, J.V.N.S., Rao, C.S., Srinivas, K., Jyothi, C.N., Venkateswarlu, B., Ramachandrappa, B.K., Dhanapal, G.N., Ravichandra, K., Mishra, P.K., 2016. Effect of ten years of reduced tillage and recycling of organic matter on crop yields, soil organic carbon and its fractions in Alfisols of semi arid tropics of southern India. Soil Tillage Res. 156, 131–139. https://doi.org/10.1016/J.STILL.2015.10.013

Prosdocimi, M., Jordán, A., Tarolli, P., Keesstra, S., Novara, A., Cerdà, A., 2016. The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. Sci. Total Environ. 547, 323–330. https://doi.org/10.1016/J.SCITOTENV.2015.12.076

Quinton, J.N., Catt, J.A., 2006. The effects of minimal tillage and contour cultivation on surface runoff, soil loss and crop yield in the long-term Woburn Erosion Reference Experiment on sandy soil at Woburn, England. Soil Use Manag. 20, 343–349. https://doi.org/10.1111/j.1475-2743.2004.tb00379.x

R Development Core Team, 2011. R: a language and environment for statistical computing. https://doi.org/ISBN: 3-900051-07-0

Reddy, D.D., Kushwaha, S., Srivastava, S., Khamparia, R.S., 2014. Long-Term Wheat Residue Management and Supplementary Nutrient Input Effects on Phosphorus Fractions and Adsorption Behavior in a Vertisol. Commun. Soil Sci. Plant Anal. 45, 541–554. https://doi.org/10.1080/00103624.2013.867043

Reddy, P.P., 2016. Micro-Catchment Rainwater Harvesting, in: Sustainable Intensification of Crop Production. Springer Singapore, Singapore, pp. 209–222. https://doi.org/10.1007/978-981-10-2702-4_14

Ren, T., Wang, J., Chen, Q., Zhang, F., Lu, S., 2014. The effects of manure and nitrogen fertilizer applications on soil organic carbon and nitrogen in a high-input cropping system. PLoS One 9, e97732. https://doi.org/10.1371/journal.pone.0097732

Santi, C., Certini, G., D'Acqui, L.P., 2006. Direct Determination of Organic Carbon by Dry Combustion in Soils with Carbonates. Commun. Soil Sci. Plant Anal. 37, 155–162. https://doi.org/10.1080/00103620500403531

Schüller, H., 1969. Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphates in Böden. Zeitschrift für Pflanzenernährung und Bodenkd. 123, 48–63. https://doi.org/10.1002/jpln.19691230106

Seiffert, S., Kaselowsky, J., Jungk, A., Claassen, N., 1995. Observed and Calculated Potassium Uptake by Maize as Affected by Soil Water Content and Bulk Density. Agron. J. 87, 1070. https://doi.org/10.2134/agronj1995.00021962008700060007x

Shah, F., Wu, W., Shah, F., Wu, W., 2019. Soil and Crop Management Strategies to Ensure Higher Crop Productivity within Sustainable Environments. Sustainability 11, 1485. https://doi.org/10.3390/su11051485

Shao, W., Zhu, J., Teng, Z., Zhang, K., Liu, S., Li, M., 2019. Distribution of inorganic phosphorus and its response to the physicochemical characteristics of soil in Yeyahu Wetland, China. Process Saf. Environ. Prot. 125, 1–8. https://doi.org/10.1016/J.PSEP.2019.02.025

Singh, G., Bhattacharyya, R., Das, T.K., Sharma, A.R., Ghosh, A., Das, S., Jha, P., 2018. Crop rotation and residue management effects on soil enzyme activities, glomalin and aggregate stability under zero tillage in the Indo-Gangetic Plains. Soil Tillage Res. 184, 291–300. https://doi.org/10.1016/J.STILL.2018.08.006

Somasundaram, J., Chaudhary, R.S., Awanish Kumar, D., Biswas, A.K., Sinha, N.K., Mohanty, M., Hati, K.M., Jha, P., Sankar, M., Patra, A.K., Dalal, R., Chaudhari, S.K., 2018. Effect of contrasting tillage and cropping systems on soil aggregation, carbon pools and aggregate-associated carbon in rainfed Vertisols. Eur. J. Soil Sci. 69, 879–891. https://doi.org/10.1111/ejss.12692

Srinivasan, V., Maheswarappa, H.P., Lal, R., 2012. Long term effects of topsoil depth and amendments on particulate and non particulate carbon fractions in a Miamian soil of Central Ohio. Soil Tillage Res. 121, 10–17. https://doi.org/10.1016/J.STILL.2012.01.014

Sui, N., Yu, C., Song, G., Zhang, F., Liu, R., Yang, C., Meng, Y., Zhou, Z., 2017. Comparative effects of crop residue incorporation and inorganic potassium fertilisation on apparent potassium balance and soil potassium pools under a wheat–cotton system. Soil Res. 55, 723. https://doi.org/10.1071/SR16200

Sun, B., Roberts, D.M., Dennis, P.G., Caul, S., Daniell, T.J., Hallett, P.D., Hopkins, D.W., 2014. Microbial properties and nitrogen contents of arable soils under different tillage regimes. Soil Use Manag. 30, 152–159. https://doi.org/10.1111/sum.12089

Swanepoel, C.M., Rötter, R.P., van der Laan, M., Annandale, J.G., Beukes, D.J., du Preez, C.C., Swanepoel, L.H., van der Merwe, A., Hoffmann, M.P., 2018. The benefits of conservation agriculture on soil organic carbon and yield in southern Africa are site-specific. Soil Tillage Res. 183, 72–82. https://doi.org/10.1016/J.STILL.2018.05.016

TerAvest, D., Carpenter-Boggs, L., Thierfelder, C., Reganold, J.P., 2015. Crop production and soil water management in conservation agriculture, no-till, and conventional tillage systems in Malawi. Agric. Ecosyst. Environ. 212, 285–296. https://doi.org/10.1016/J.AGEE.2015.07.011

Thierfelder, C., Chisui, J.L., Gama, M., Cheesman, S., Jere, Z.D., Trent Bunderson, W., Eash, N.S., Rusinamhodzi, L., 2013. Maize-based conservation agriculture systems in Malawi: Long-term trends in productivity. F. Crop. Res. 142, 47–57. https://doi.org/10.1016/J.FCR.2012.11.010

Thierfelder, C., Chisui, J.L., Gama, M., Cheesman, S., Jere, Z.D., Trent Bunderson, W., Eash, N.S., Rusinamhodzi, L., 2013. Maize-based conservation agriculture systems in Malawi: Long-term trends in productivity. F. Crop. Res. 142, 47–57. https://doi.org/10.1016/J.FCR.2012.11.010

Tolessa, D., Du Preez, C.C., Ceronio, G.M., 2014. Effect of tillage system and nitrogen fertilization on the pH, extractable phosphorus and exchangeable potassium of Nitisols in Western Ethiopia. African J. Agric. Res. 9, 2669–2680. https://doi.org/10.5897/AJAR2013.7779

Traoré, K.B., Gigou, J., Coulibaly, H., Doumbia, M.D., 2004. Contoured ridge-tillage increases cereal yields and carbon sequestration. 13th Int. Soil Conserv. Organ. Conf. Brisbane, 4-8 July 2004.

Traore, K., Sidibe, D.K., Coulibaly, H., Bayala, J., 2017. Optimizing yield of improved varieties of millet and sorghum under highly variable rainfall conditions using contour ridges in Cinzana, Mali. Agric. Food Secur. 6, 11. https://doi.org/10.1186/s40066-016-0086-0

Tully, K., Sullivan, C., Weil, R., Sanchez, P., Tully, K., Sullivan, C., Weil, R., Sanchez, P., 2015. The State of Soil Degradation in Sub-Saharan Africa: Baselines, Trajectories, and Solutions. Sustainability 7, 6523–6552. https://doi.org/10.3390/su7066523

Turner, B.L., Haygarth, P.M., 2005. Phosphatase activity in temperate pasture soils: Potential regulation of labile organic phosphorus turnover by phosphodiesterase activity. Sci. Total Environ. 344, 27–36. https://doi.org/10.1016/J.SCITOTENV.2005.02.003

Wang, J., Wang, X., Xu, M., Feng, G., Zhang, W., Yang, X., Huang, S., 2015. Contributions of wheat and maize residues to soil organic carbon under long-term rotation in north China. Sci. Rep. 5, 11409. https://doi.org/10.1038/srep11409

Wegehenkel, M., Wagner, A., Amoriello, T., Fleck, S., Meesenburg, H., Raspe, S., 2017. Impact of stoniness correction of soil hydraulic parameters on water balance simulations of forest plots. J. Plant Nutr. Soil Sci. 180, 71–86. https://doi.org/10.1002/jpln.201600244

Wei, T., Zhang, P., Wang, K., Ding, R., Yang, B., Nie, J., Jia, Z., Han, Q., 2015. Effects of wheat straw incorporation on the availability of soil nutrients and enzyme activities in semiarid areas. PLoS One 10, e0120994. https://doi.org/10.1371/journal.pone.0120994

Wells, T., Hancock, G.R., Martinez, C., Dever, C., Kunkel, V., Gibson, A., 2019. Differences in soil organic carbon and soil erosion for native pasture and minimum till agricultural management systems. Sci. Total Environ. 666, 618–630. https://doi.org/10.1016/J.SCITOTENV.2019.02.097

West, T.O., Post, W.M., 2002. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation. Soil Sci. Soc. Am. J. 66, 1930. https://doi.org/10.2136/sssaj2002.1930

Whitbread, A.M., Blair, G.J., Lefroy, R.D.B., 2000. Managing legume leys, residues and fertilisers to enhance the sustainability of wheat cropping systems in Australia: 2. Soil physical fertility and carbon. Soil Tillage Res. 54, 77–89. https://doi.org/10.1016/S0167-1987(99)00113-0

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer New York, New York, NY. https://doi.org/10.1007/978-0-387-98141-3_1

Wickham, H., Francois, R., Henry, L., Müller, K., 2019. Package ‘dplyr’. A Grammar of Data Manipulation. R Packag. version 0.8.0.1 1–88.

Wolka, K., Mulder, J., Biazin, B., 2018. Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: A review. Agric. Water Manag. 207, 67–79. https://doi.org/10.1016/J.AGWAT.2018.05.016

Woyessa, Y.E., Bennie, A.T.P., 2007. Tillage-crop residue management and rainfall-runoff relationships for the Alemaya catchment in Eastern Ethiopia. South African J. Plant Soil 24, 8–15. https://doi.org/10.1080/02571862.2007.10634774

Xu, J., Han, H., Ning, T., Li, Z., Lal, R., 2019. Long-term effects of tillage and straw management on soil organic carbon, crop yield, and yield stability in a wheat-maize system. F. Crop. Res. 233, 33–40. https://doi.org/10.1016/J.FCR.2018.12.016

Xu, X., An, T., Zhang, J., Sun, Z., Schaeffer, S., Wang, J., 2019. Transformation and stabilization of straw residue carbon in soil affected by soil types, maize straw addition and fertilized levels of soil. Geoderma 337, 622–629. https://doi.org/10.1016/J.GEODERMA.2018.08.018

Yamoah, C.F., Bationo, A., Shapiro, B., Koala, S., 2002. Trend and stability analyses of millet yields treated with fertilizer and crop residues in the Sahel. F. Crop. Res. 75, 53–62. https://doi.org/10.1016/S0378-4290(02)00008-4

Yang, K., Zhu, J., Gu, J., Yu, L., Wang, Z., 2015. Changes in soil phosphorus fractions after 9 years of continuous nitrogen addition in a Larix gmelinii plantation. Ann. For. Sci. 72, 435–442. https://doi.org/10.1007/s13595-014-0444-7

Yang, S., Wang, Y., Liu, R., Xing, L., Yang, Z., 2018. Improved crop yield and reduced nitrate nitrogen leaching with straw return in a rice-wheat rotation of Ningxia irrigation district. Sci. Rep. 8, 9458. https://doi.org/10.1038/s41598-018-27776-5

Yang, X., Li, Z., Cheng, C., 2016. Effect of Conservation Tillage Practices on Soil Phosphorus Nutrition in an Apple Orchard. Hortic. Plant J. 2, 331–337. https://doi.org/10.1016/J.HPJ.2016.11.005

Young, A., 1999. Is there Really Spare Land? A Critique of Estimates of Available Cultivable Land in Developing Countries. Environ. Dev. Sustain. 1, 3–18. https://doi.org/10.1023/A:1010055012699

Zeng, Q., Brown, P.H., 2000. Soil potassium mobility and uptake by corn under differential soil moisture regimes. Plant Soil 221, 121–134. https://doi.org/10.1023/A:1004738414847

Zhang, J.H., Frielinghaus, M., Tian, G., Lobb, D.A., 2004. Ridge and contour tillage effects on soil erosion from steep hillslopes in the Sichuan Basin, China. J. Soil Water Conserv. 59, 277–284.

Zhang, X., Zhu, A., Xin, X., Yang, W., Zhang, J., Ding, S., 2018. Tillage and residue management for long-term wheat-maize cropping in the North China Plain: I. Crop yield and integrated soil fertility index. F. Crop. Res. 221, 157–165. https://doi.org/10.1016/J.FCR.2018.02.025

Zhao, S., He, P., Qiu, S., Jia, L., Liu, M., Jin, J., Johnston, A.M., 2014. Long-term effects of potassium fertilization and straw return on soil potassium levels and crop yields in north-central China. F. Crop. Res. 169, 116–122. https://doi.org/10.1016/J.FCR.2014.09.017

Zheng, H., Liu, W., Zheng, J., Luo, Y., Li, R., Wang, H., Qi, H., 2018. Effect of long-term tillage on soil aggregates and aggregate-associated carbon in black soil of Northeast China. PLoS One 13, e0199523. https://doi.org/10.1371/journal.pone.0199523

Zuber, S.M., Behnke, G.D., Nafziger, E.D., Villamil, M.B., 2015. Crop Rotation and Tillage Effects on Soil Physical and Chemical Properties in Illinois. Agron. J. 107, 971. https://doi.org/10.2134/agronj14.0465

Zuber, S.M., Behnke, G.D., Nafziger, E.D., Villamil, M.B., Zuber, S.M., Behnke, G.D., Nafziger, E.D., Villamil, M.B., 2018. Carbon and Nitrogen Content of Soil Organic Matter and Microbial Biomass under Long-Term Crop Rotation and Tillage in Illinois, USA. Agriculture 8, 37. https://doi.org/10.3390/agriculture8030037

Chapter 4

Effect of tillage practices and return of crop residues on maize yield under 2-degree-warming scenarios in different weathered soils of West Africa

This chapter is ready to be submitted for publication

1. Introduction

Decline in agricultural production is predominantly attributed to soil degradation, a serious widespread issue, that hits sorely the people of West Africa, where the majority of the population depends on the soil to reap their livelihood. Consequently, crop productivity is hampered and economic growth is affected, leading to poverty and hunger (Tully et al., 2015). A wealth of information has documented the underlying causes of the on-going soil degradation in West Africa including, for instance, the (i) inherently poor soil fertility (Bationo and Mokwunye, 1991; Raimi et al., 2017), (ii) existence of highly erodible soils, (iii) loss of fertile topsoil due to improper management practices and soil erosion (Nyamekye et al., 2018; Obalum et al., 2012; Oyedele and Aina, 2006), (iv) expansion of arable lands to steep slope areas (Young, 1999), (v) increased population pressure on lands and intensive cultivation by smallholder farmers (FAO and ITPS, 2015). Displacement of topsoil particles by erosion is believed to be expanding at an alarming rate in different parts of West Africa. Damage to agricultural productivity is not only caused by the above stated natural phenomena but also by human-induced factors aggravating soil degradation in West Africa such as over-cultivation, overgrazing, deforestation and unskilled irrigation practices (Henao and Baanante, 2006).

Appropriate soil management practices need to be adopted in order to restore soil fertility and sustain crop production and avoid poor soil nutrient supply capacity limiting crop productivity. Also, poor soil management practices in steep areas cause considerable soil loss through erosion (Panagos et al., 2015). Hitherto, numerous studies have suggested a wide range of soil management practices to restore soil fertility in West Africa. Some soil-water conservation approaches, popular among the local farmers in Sub-Saharan Africa, were well documented in review studies by Lal (1987) and Wolka et al. (2018). Common soil management practices like stone bunds (Reddy, 2016), graded soil bunds (Mupangwa et al., 2012), graded Fanya juu (Hurni et al., 2016), grass strips (Ghadiri et al., 2001), bench terraces (Mati, 2007), tied/contour ridge (Brhane et al., 2006), retention of crop residues (Yamoah et al., 2002) were tested in several parts of Sub-Saharan Africa contrasting in edaphic, climatic, topographic, and crop conditions.

Conservation agriculture (CA) is one of the most popular and widely recognized adaptive soil management practices, consisting of minimum or no-tillage, crop residue incorporation, and crop rotation. It has been recommended by several previous studies as a potential approach to improve maize yield (Nyagumbo et al., 2015; Sithole et al., 2016), soil carbon and nitrogen stock (Kiboi et al., 2019; Martinsen et al., 2019; Naab et al., 2017), phosphorus, potassium (Tolessa et al., 2014), and soil moisture (Gicheru et al., 2004) in Sub-Saharan region. While CA is believed to improve soil quality by altering its major properties, the growing interest in conservation tillage has also emerged in response to its demand for mitigating soil loss through runoff and erosion (Araya et al., 2011; Vach et al., 2018; Williams et al., 2009). Meanwhile, an increasing number of studies evidenced the retention of crop residues combined with conservation tillage, as a viable option to alleviate soil degradation and restore soil fertility (Merante et al., 2017; Mhazo et al., 2016; Thierfelder et al., 2013). Returning crop residues have been demonstrated as an effective way to control soil loss by erosion (Cong et al., 2016) and improve soil water holding capacity and infiltration rate (Desrochers et al., 2019).

Another widely adopted technology towards improving soil quality, and controlling the severity of soil loss through surface runoff, would include contour/tied ridge tillage. Greater crop yield has been recorded under contour/tied ridge tillage system, and the major underlying mechanism is that contour/tied ridges reduce sediment loss by controlling surface runoff (Gathagu et al., 2018; Mohamoud, 2012; Zhang et al., 2004). In addition, the application of contour/tied ridge can actually improve soil water retention and infiltration (Hunink et al., 2012), thus favoring crop nutrient uptake and yield (Miriti et al., 2012; Nyamangara and Nyagumbo, 2010).

Furthermore, West Africa's ecosystems and arable lands are susceptible to climate change (Challinor et al., 2007; Sylla et al., 2018) due to widespread warming and an increase in the occurrence of climate extremes (Sultan and Gaetani, 2016). Agricultural production is particularly susceptible to climate change because of its dependence on narrow and predominantly rain-fed production systems (Boko et al., 2007). Climate-induced yield loss in West Africa is mainly driven by increased mean temperature along with potential wetter or drier conditions (Sultan and Gaetani, 2016). Also, future climate projections based on Global Circular Models (GCM) and Regional Climate Models (RCM) predict an increase in more frequent and longer heatwaves and dry spells, but slight to no-change in heavy rainfall events (Belle et al., 2016). Despite the wide range of predictions, consent exists that soil degradation together with climate change will very likely severely limit agriculture production in West Africa and ultimately put the food and livelihood security under insurmountable stress.

Long-term impacts of climatic conditions and tillage are difficult to assess through experimental approaches; thus, to strengthen the understanding of tillage and crop residue management effects on crop yield and their potential to offset future warming effects on crop yield, crop models based on field trial are required (Jones et al., 2003). Several previous studies concentrated on climate change adaptation options and their uncertainties using various crop models in this region (Akinseye et al., 2017; Egbebiyi et al., 2019; Oettli et al., 2011). Sultan et al. (2019) revealed yield reductions of 10–20% for millet and 5–15% for sorghum under historical (2000-2009) frequent heat and rainfall extremes in West Africa using two process-based crop models, SARRA-H and CYGMA. Another study by Parkes et al. (2018) assessed the change in maize, millet, and sorghum yield in West Africa using GLAM, ORCHIDEE-CROP, SARRA-H models during the recent historic period (1986–2005) and a near-term future when global temperatures are 1.5 K above pre-industrial levels. Faye et al. (2018) assessed impacts of 1.5 °C versus 2.0 °C (above pre-industrial levels) on yields of maize, pearl millet and sorghum in the West African Sudan Savanna using two crop models, SIMPLACE and DSSAT. Unlike climate change effects, only a few studies have so far attempted to model crop response to different tillage practices, especially in Africa. Mkoga et al. (2010) used the APSIM model in order to assess conservation tillage effects on maize yield in Tanzania. A study by Gerardeaux et al. (2012) in Madagascar illustrated the effects of tillage and N fertilizer on rice yield using CERES-Rice in DSSAT. In Malawi, the effects of conservation tillage on maize yield was modelled using DSSAT model (Ngwira et al., 2014). Long-term effects of conservation tillage on maize yield in Zambia was assessed using DSSAT by Corbeels et al. (2016). However, none of the studies actually demonstrated the potential of different tillage and crop residue management options to buffer climate change effects on crop yield in West Africa. Thus, we lack knowledge on the crop production losses induced by climate change that can be offset by introducing optimized management practices consisting of tillage and crop residue management. To this end, the objectives of this paper were two-fold: firstly, we calibrated and validated the tillage module in DSSAT in order to test its capacity to simulate contour ridge and reduced tillage along with crop residue application effects on maize yield in four soil types in the Sudan Savanna of West Africa. For this purpose, we used an experimental dataset from the year 2014 for model calibration and 2016 data for model validation. As a next step, we applied the validated model to compare the effects of contour ridge and reduced tillage on maize yields under a 2°C warming scenario on two sites and four and four soil types. Within this context, we used 200 years (10 years and 20 runs) of climate data output from an ensemble of three global circulation models (GCMs) ECHAM6, MIROC5, and NorESM1.

2. Materials and methods

2.1. Site description

The field experiments to calibrate and validate the DSSAT model for tillage effects were conducted from 2012 to 2016 on farmers' fields in Dassari village (10˚49´N, 1˚04´E) in Atakora Province of the Republic of Benin, and in Dano village (11˚10´N, 2˚38´W) in the Loba province of Burkina-

Faso. Each of the sites consists of two different soil types based on topographical posture (footslope and upslope), such that a total of four parallel trials were set up on four different soil types. According to FAO classification system (Nafi et al., 2019), the four soil types studied in this research were: St1 (Ferric Lixisol at footslope position in Dano), St2 (Eutric Plinthosol at upslope position in Dano), St3 (Haplic Lixisol at footslope position in Dassari), and St4 (Plinthic Lixisol at upslope position in Dassari). These soils differed in many characteristics and have been discussed in detail in the model input data section (section 2.4.3, Table 1). The study sites belong to the Sudan Savanna agro-ecological zone, characterized by a semi-humid climate. The mean rainfall ranges between 900 mm to 1000 mm from May to October, while the mean temperature is 15 ˚C during the night and 40 ˚C during the day in the rainy season (Danso et al., 2018a; Kpongor, 2007). Mean monthly cumulative rainfall in Dano and Dassari during the maize growing seasons (, 2014 and 2016) were 780 mm and 850 mm, respectively (Nafi et al., 2019). Monthly mean air temperature over the maize growing season in both Dano and Dassari was 27 ˚C. Also, the monthly mean air temperature during the maize growing season tended to increase from 2012 to 2016 in Dassari, while in Dano, no such increase was recorded

2.2. Experimental design and crop management

The on-farm trials were performed for five consecutive growing seasons from 2012 to 2016 under the maize-cotton rotation system and observations from the maize growing cycles in 2014 and 2016 were used for model evaluation. The trial was laid out as strip-split plot design with four replications. Two levels of tillage operations (contour ridge tillage, Cr and reduced tillage, Rt) were included as the main plot factor, while the sub-plot factors consisted of two levels of crop residue treatment (with crop residue and without crop residue) and three levels of nitrogen fertilizer treatment (no N, recommended N rate: 60 kg N ha^{-1} and double recommended N rate: 120 kg N ha^{-1}. The subplot factors were randomized within the main plot. Thus, a total of 32 experimental plots were allocated at each study site. An explicit illustration of the study fields and management practices has been presented in the model input data section (Section 2.4.5, Table 2).

2.3. Model description

CERES-maize model (Jones et al., 1986) within DSSAT version 4.7.5. platform (Hoogenboom et al., 2019) which is a cultivar and site-specific model, was used in this study in order to dynamically simulate crop growth and development on a daily time step as a function of soil, weather conditions, crop management practices, and cultivar characteristics. An explicit description of the CERES-maize model can be found in Jones et al. (2003). CERES-maize model simulates the rate of maize crop development governed by thermal time or growing degree days (GDD) which is calculated based on daily maximum and minimum temperature. It calculates the daily maize crop growth through transforming daily photosynthetically active radiation (PAR) intercepted by the maize canopy into maize dry matter using radiation use efficiency (RUE). Light interception is mainly determined as a function of leaf area index (LAI), plant population, and row spacing. The development of daily plant tissue is largely dominated by water and nitrogen stress, temperature and atmospheric CO_2 concentration. Photoassimilate, mainly in the form of carbohydrate is predominantly loaded into the above-ground biomass (AGB). The leftover carbohydrate at the end of each day is translocated into plant roots. Kernel numbers per crop are calculated during the flowering stage depending on the cultivar’s genetic potential, canopy weight, the average rate of carbohydrate accumulation during flowering, and temperature, water, and nitrogen stress. The daily growth rate of kernels is dominated by temperature and photoassimilate availability.

The tillage module in DSSAT was first developed following the procedures introduced by Dadoun (1994) as the CERES-Till model for maize and later modified for CROPGRO-Soybean model by Andales et al. (2000). The major soil properties that undergo a radical change due to tillage effects in DSSAT are (Corbeels et al., 2016): (1) soil bulk density; (2) saturated soil hydraulic conductivity; (3) the soil runoff curve number, and (4) soil water content at saturation. Input parameters included within the tillage module of DSSAT are divided into two levels (White et al., 2010). The first set of parameters deals with tillage effects on the soil surface and includes percent change in SCS curve number immediately after the tillage operation (CN2T), percent of residue incorporated (RINP), percent soil surface that is disturbed by the tillage operation (SSDT), mixing efficiency of tillage event (MIXT). The second set of parameters mainly concerns tillage effects with soil depth and includes maximum potential (soil depth, cm) of tillage operation (SLB), the percent change in bulk density just after tillage event (SBDT), the percent change in saturated hydraulic conductivity (cm/day) just after tillage operation (SKST). Initially, tillage sub-routine compares the specified depth of the user input tillage event (Y_T) with the cumulative soil depth of the particular soil type in order to decide the layer that requires mixing (White et al., 2010). Based on mixing efficiency (M%) of the input tillage event, a given soil component $X_O(L)$ (e.g. soil moisture or nitrate) at each soil layer is allocated into fractions to mixed, $X_M(L)$, or left unmixed $X_U(L)$. The mixed fraction of the given soil component can be calculated as:

$$X_M(L)\ (\nu) = \frac{X_0(L) \times M\%}{100} \tag{1}$$

$X_U(L)$ is calculated as the remaining portion of $X_0(L)$, ν.

Cumulative $X_M(L)$ over all the soil layers affected by the specified tillage event is denoted as ΣX_M. Thus, the amount of the given soil component, $X_T(L)$ followed by a tillage event is calculated as:

$$X_T(L)\ (\nu) = \frac{\Sigma X_M \times Z(L)}{Y_T + X_U(L)} \tag{2}$$

Here, Z(L) is the depth of the layer L and is reduced if only a portion of a layer is tilled.

A discrete crop residue sub-routine consisting of different compartments for carbon, nitrogen, and phosphorous is used to reflect the effects of surface crop residue incorporation (White et al., 2010). Thus, incorporated crop residue, R_T, is calculated as:

$$R_T\ (\text{kg ha}^{-1}) = \frac{R_0 \times R\%}{100} \tag{3}$$

Here, R% is the portion of total crop residue mass, R_0 (kg ha^{-1}) incorporated. R_T is then allocated uniformly through the soil layers up to Y_T (cm).

Tillage effects on soil bulk density vary with soil depth and consequently alter saturated water content, $\theta_S(L)$. Three soil depth indices, M (depths for the effect of an implement), N (depths in the field soil), and L (combined index for depths of tillage and soil layers) are included in order to simulate tillage effects on soil bulk density.

Initial soil bulk density $B_C(N)$ in g cm^{-3} at each soil layer read from user input soil file (s) is altered by the implemented tillage event, B%(M) and such change are calculated as:

$$B_T(L\ ) = \frac{(1.0+B\%(M)}{100} \times BC(N) \tag{4}$$

B%(M) can be negative when the implemented tillage operation reduces soil bulk density.

Water content at saturation, $\theta_S(L)$ for a given soil layer L (mm3 mm^{-3}), is computed using a bulk density value of 2.66 g cm^{-3}. Thus,

$$\theta_S(L) = 0.95 \times [1- \frac{B_T(L\ )}{2.66}] \tag{5}$$

It is assumed that 95% of the air space can be occupied by water

Similarly, saturated hydraulic conductivity, $K_T(L)$ in cm h^{-1} at a given soil layer is calculated as follows by considering percent change K%(M) of initial saturated hydraulic conductivity, $K_0(N)$ in cm h^{-1} due to implemented tillage operation.

2.4. Model input data

2.4.1. Crop data

The **.**CUL-file contains a set of genetic coefficients that are used for cultivar calibration. Definition of the genetic parameters listed in .CUL file and their calibrated values are given in Table 3. Maize ecotype coefficients are listed into MZCER047.ECO file. Ecotype parameters include base temperature below which no development occurs (TBASE in °C), temperature at which maximum development rate occurs during vegetative stages (TOPT in °C), temperature at which maximum development rate occurs for reproductive stages (ROPT in °C), daylength below which daylength does not affect development rate, hours (P2O), minimum days from end of juvenile stage to tassel initiation if the cultivar is not photoperiod sensitive, days (DJTI), growing degree days per cm seed depth required for emergence, GDD/cm (GDDE), GDD from silking to effective grain filling period, ˚C (DSGFT), radiation use efficiency, g plant dry matter/MJ PAR (RUE), canopy light extinction coefficient for daily PAR (KCAN), critical temperature below which leaf damage occurs (TSEN) with a default value of 6°C, number of cold days parameter (CDAY), default 15.0. Maize species coefficients, such as temperature effects, photosynthesis parameters, stress response, seed and root growth parameters, N and P content in plants, etc are listed in MZCER047.SPE file. It is recommended that ecotype and species parameters should remain unchanged unless reliable data are available for calibration (Jing et al., 2017).

2.4.2. Weather data

Minimum weather data required to run CERES-maize model include daily average incoming solar radiation, SRAD (MJ/m2.day); daily minimum, TMINA, and maximum air temperature, TMAXA (°C), and daily cumulative precipitation, PREC (mm). Weather files (.WTH) for 2014 and 2016 were created by including the above-mentioned parameters using the WeatherMan program of DSSAT.

2.4.3. Soil data

SBuild utility was used to create four soil profile databases used in our study. Soil properties including soil organic carbon, total nitrogen, pH, soil texture, and stone percentage were obtained from soil analysis as mentioned by Nafi et. al., 2019. CEC at a given soil layer was estimated using pedotransfer function proposed by Liao et al. (2015) that calculate CEC based on the information of soil clay, sand, pH, and organic carbon content. Each soil layer has a specified drainage upper limit (LL), drainage upper limit (DUL), water content at saturation (SAT), and saturated hydraulic conductivity (KS) that is read from the soil file by the model in order to simulate the soil water flow throughout the soil profile. These parameters including soil bulk density were estimated using PTFs proposed by Saxton et al. (1986) depending on soil clay and sand content. Run-off curve number, a surface soil hydrological property, is also a crucial input parameter for the soil file and was estimated based on methods suggested by Hawkins et al. (2009). A summary description of the four studies soil profiles is presented in Table 1. Besides the soil data in the soil file, some additional information on initial soil conditions such as water, nitrate, and ammonium content is also required by the model.

2.4.4. Experimental data

FILE A (.MZA) and FILET (.MZT) files are the experimental data files used by DSSAT in order to compare the observed data with the simulated data. FILE A includes average values of the observed crop data such as anthesis and maturity date, yield and biomass at harvest. On the other hand, FILET consists of time-series crop biomass data. Maize crop development was observed by recording the days it took to attain each phenological phase. The physiological maturity date was recorded when a kernel black layer was formed at the base of the kernel. The dry weight of maize biomass was estimated at different growth stages: 4, 6, and 8 weeks after planting and at physiological maturity. Collected maize samples were separated into leaves and stem and oven-dried at 70°C for 36–48 hours until the sample obtained constant weight. Maize yield was measured by harvesting all plants from an area of 9 m^2 at maturity.

2.4.5. Management file

Management routine allows the user to input different field operations performed during the experiment by calling other related sub-routines and input data files (Jones et al., 2003). Eight management files (.MZX), four for calibration (2014) and four for evaluation (2016) were developed for four soil types based on the input data described above. However, these files can be distinguished based on experiment name, fields (soil profile and weather dataset), initial conditions, and crop residue applications (organic amendments). At the same time, these files share a common set of management settings e.g., cultivar, planting (date, method, distribution, population at seeding, row spacing and direction, and planting depth) and harvesting (date, stage, and component), tillage and fertilizer applications, simulation options (simulation date, crop module, output options, photosynthesis, evapotranspiration, infiltration, soil organic matter methods, etc), and treatment combinations. An overview of different management settings used for model calibration and evaluation is given in Table 2.

Table 2: Crop management file description for calibration and validation in four soil types

Options	**Calibration**				**Validation**			
	Soil types							
	St1:FL	**St2:EP**	**St3:HL**	**St4:PL**	**St1:FL**	**St2:EP**	**St3:HL**	**St4:PL**
General								
Village code	DN	DN	DS	DS	DN	DN	DS	DS
Site code	FL	EP	HL	PL	FL	EP	HL	PL
Year	2014	2014	2014	2014	2016	2016	2016	2016
Experiment No.	1	1	1	1	2	2	2	2
Gross plot area, m2	300	300	300	300	300	300	300	300
Rows per plot	6	6	6	6	6	6	6	6
Harvest area, m2	9	9	9	9	9	9	9	9
Harvest No.	4	4	4	4	4	4	4	4
Harvest row length, m	3	3	3	3	3	3	3	3
Fields								
Weather	DANO 2014	DANO 2014	DASSARI 2014	DASSARI 2014	DANO 2016	DANO 2016	DASSARI 2016	DASSARI 2016
Soil	FL	EP	HL	PL	FL	EP	HL	PL

Soil surface texture	Sandy loam	Silty clay	Sandy loam	Sandy loam	Sandy loam	Silty clay	Sandy loam	Sandy loam
Soil depth, cm	20	20	20	20	20	20	20	20
Soil surface stone, %	47	26	13	24	47	26	13	24
Cultivar								
	Dorke SReal	Dorke SReal	Dorke SReal	Dorke SReal	Dorke SReal	Dorke SReal	Dorke SReal	Dorke SReal
Planting								
Date	06.24.2014	06.24.2014	06.24.2014	06.24.2014	07.11.2016	07.11.2016	07.11.2016	07.11.2016
Method	Dry seed	Dry seed	Dry seed	Dry seed	Dry seed	Dry seed	Dry seed	Dry seed
Distribution	Rows	Rows	Rows	Rows	Rows	Rows	Rows	Rows
Population at seedling, plant/m2	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25
Row spacing	80	80	80	80	80	80	80	80
Row distribution	0	0	0	0	0	0	0	0
Planting depth, cm	5	5	5	5	5	5	5	5
Fertilizer								
1st N application (25 DAP), kg/ha	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8
2nd N application (45 DAP), kg/ha	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8
P application (25 DAP), kg/ha	26.4	26.4	26.4	26.4	26.4	26.4	26.4	26.4
K application (25 DAP), kg/ha	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8
Application method	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated
Application depth, cm	0	0	0	0	0	0	0	0

				Organic Amendments				
Date	06.22.2014	06.22.2014	06.22.2014	06.22.2014	07.09.2016	07.09.2016	07.09.2016	07.09.2016
Residue material	User cotton residue	User cotton residue	User cotton residue	User cotton residue	User cotton residue	User cotton residue	User cotton residue	User cotton residue
Amount, kg/ha	5893	5723	9104	8004	6174	6492	1007	8472
%N in residue	0.75	0.85	0.97	0.88	0.75	0.85	0.97	0.88
Incorporation %	0	0	0	0	0	0	0	0
Depth, cm	0	0	0	0	0	0	0	0
Method	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated	Broadcast, not incorporated
				Tillage				
Date	06.22.2014	06.22.2014	06.22.2014	06.22.2014	07.09.2016	07.09.2016	07.09.2016	07.09.2016
Types	1)Contour ridge, 2)Reduced	1)Contour ridge, 2)Reduced	1)Contour ridge, 2)Reduced	1)Contour ridge, 2)Reduced	1)Contour ridge, 2)Reduced	1)Contour ridge, 2)Reduced	1)Contour ridge, 2)Reduced	1)Contour ridge, 2)Reduced
Depth, cm	1) 25, 2)3	1) 25, 2)3	1) 25, 2)3	1) 25, 2)3	1) 25, 2)3	1) 25, 2)3	1) 25, 2)3	1) 25, 2)3
				Harvest				
Date	10.14.2014	10.14.2014	10.14.2014	10.14.2014	11.10.2016	11.10.2016	11.10.2016	11.10.2016
stage	GS006	GS006	GS006	GS006	GS006	GS006	GS006	GS006
Component	Harvest product	Harvest product	Harvest product	Harvest product	Harvest product	Harvest product	Harvest product	Harvest product
Group size	All	All	All	All	All	All	All	All
				Simulation Options				
Simulation date	06.20.2014	06.20.2014	06.20.2014	06.20.2014	11.08.2016	11.08.2016	11.08.2016	11.08.2016
Crop module	CERES-Maize	CERES-Maize	CERES-Maize	CERES-Maize	CERES-Maize	CERES-Maize	CERES-Maize	CERES-Maize

Weather	Measured data	Measured data	Measured data	Measured data	Measured data	Measured data	Measured data	Measured data
Evaporation	Ritchie-ceres	Ritchie-ceres	Ritchie-ceres	Ritchie-ceres	Ritchie-ceres	Ritchie-ceres	Ritchie-ceres	Ritchie-ceres
Evapotranspiration	FAO-56	FAO-56	FAO-56	FAO-56	FAO-56	FAO-56	FAO-56	FAO-56
Infiltration	Soil conservation service	Soil conservation service	Soil conservation service	Soil conservation service	Soil conservation service	Soil conservation service	Soil conservation service	Soil conservation service
Soil organic matter	Century (parton)	Century (parton)	Century (parton)	Century (parton)	Century (parton)	Century (parton)	Century (parton)	Century (parton)
Hydrology	Ritchie water balance	Ritchie water balance	Ritchie water balance	Ritchie water balance	Ritchie water balance	Ritchie water balance	Ritchie water balance	Ritchie water balance
Photosynthesis	Radiation efficiency	Radiation efficiency	Radiation efficiency	Radiation efficiency	Radiation efficiency	Radiation efficiency	Radiation efficiency	Radiation efficiency
Soil layer distribution	Modified soil profile	Modified soil profile	Modified soil profile	Modified soil profile	Modified soil profile	Modified soil profile	Modified soil profile	Modified soil profile

St1:FL = Ferric Lixisol ,St2:EP = Eutric Plinthosol, St3:HL = Haplic Lixisol, and St4:PL = Plinthic Lixisol

2.5. Cultivar calibration

In order to simulate climate change impact on crop growth with CERES-Maize model, cultivar coefficients that control the development and growth of maize have to be calibrated and validated under specific environmental conditions (Hunt and Boote, 1998). For model calibration, we used growth and development data recorded during 2014. Initially, 8 data points (2 tillage × with crop residue × double N fertilizer × 4 replications) out of 48 data points (2 tillage × 2 crop residue × 3 N fertilizer × 4 replications) for St3 (Haplic Lixisol, footslope in Dassari, highest yield in 2014 while assuming no stress) was considered to estimate the genetic coefficients. Later, 48 data points were sub-divided into 12 groups (2 tillage × 2 crop residue × 3 N fertilizer) by treatments (average of 4 replications) in order to simulate the tillage effects. Additionally, we calibrated soil fertility factor (SLPF) in order to highlight tillage effects on different soil types. The cultivar (Dorke SReal) used in our study was previously calibrated by Danso, 2015. However, we modified some parameters to attain the minimum root mean square error (RMSE) between simulated and upgraded observed data (mainly biomass and harvested yield). We started with the phenological parameters (P1, P2, P5, and PHINT; Table) that were adjusted to get a close match for anthesis and physiological maturity dates, and leaf number. Similarly, the other two coefficients, G2 and G3 that defines growth and yield characteristics have also been modified and the values were set as 700 and 10, respectively. Required crop genetic inputs and their calibrated values for CERES Maize are given in Table 3.

Table 1: Soil properties of four soil types used for the DSSAT calibration and validation.

Soil Types	Tillage	Parameters																		
		SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHB	SCEC
St1:FL	**Cr**	0.13	6	0.2	76	1	0.6	0.04	0.13	0.42	1	4.5	1.38	0.75	3	43.1	47	0.07	6.4	11.5
	Rt	0.13	6	0.2	76	1	0.6	0.04	0.13	0.42	1	4.5	1.38	0.75	3	43.1	47	0.08	6.4	11.5
St2:EP	**Cr**	0.13	6	0.2	81	1	0.73	0.08	0.51	0.80	1	5.0	1.40	0.85	50	17.1	26	0.08	6.3	23
	Rt	0.13	6	0.2	81	1	0.73	0.08	0.51	0.80	1	5.0	1.40	0.76	50	17.1	26	0.06	6.3	23
St3:HL	**Cr**	0.13	6	0.4	73	1	1	0.02	0.3	0.60	1	6.7	1.33	0.85	4	32.5	13	0.07	6.5	10.5
	Rt	0.13	6	0.4	73	1	1	0.02	0.3	0.60	1	6.7	1.33	0.93	4	32.5	13	0.09	6.5	10.5
St4:PL	**Cr**	0.13	6	0.4	73	1	0.90	0.06	0.2	0.35	1	4.0	1.35	0.85	6	51.6	24	0.08	6.5	10.2
	Rt	0.13	6	0.4	73	1	0.90	0.06	0.2	0.35	1	4.0	1.35	0.74	6	51.6	24	0.06	6.5	10.2

St1:FL = Ferric Lixisol ,St2:EP = Eutric Plinthosol, St3:HL = Haplic Lixisol, and St4:PL = Plinthic Lixisol, Cr = contour ridge tillage, Rt = reduced tillage, SALB = Albedo, SLU1 = Evaporation limit, SLDR = Drainage rate, SLRO = Runoff curve number, SLNF = Mineralization factor, SLPF = Soil fertility factor, SLLL = Lower limit of plant extractable soil water, SDUL = Drained upper limit, SSAT = Saturated upper limit, SRGF = Root growth factor,
SSKS = Saturated hydraulic conductivity, SBDM = Bulk density, SLOC = Soil organic carbon concentration, SLCL = Clay, SLSI = Silt, SLCF = Coarse fraction,
SLNI = Total nitrogen concentration, SLHB = pH in buffer, SCEC = Soil cation exchange capacity

Table 3: Genetic coefficients modified for the cultivar DORKE

coefficients	Definitions	Calibrated values
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8 ˚C) during which the plant is not responsive to changes in photoperiod.	330
P2	Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours).	0.5
P5	Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 ˚C).	680
G2	Maximum possible number of kernels per plant.	700
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day).	10
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	60

2.6. Tillage module parameterization

TILOP047.SDA is an input file for the tillage module in DSSAT under the Standard Data folder that contains all the tillage parameters (Table 4). This file allows the user to parametrize the tillage parameters based on the implemented tillage event and corresponding field data from the experiment. Eight tillage parameters (Table 4) were estimated based on our experiment in order to simulate the difference between the contour ridge tillage and reduced tillage system. After defining the user tillage event, one has to include the new tillage event into the DETAIL.CDE file in order to make them appear in the dropdown list of tillage operations within the graphical user interface of DSSAT.

Table 4: Tillage parameters calibrated for contour ridge tillage and reduced tillage

Parameters	Soil Types							
	St1:FL		St2:EP		St3:HL		St4:PL	
	Cr	Rt	Cr	Rt	Cr	Rt	Cr	Rt
CN2T	-75	0	-75	0	-75	0	-75	0
RINP	60	10	60	10	60	10	60	10
SSDT	90	10	90	10	90	10	90	10
MIXT	50	0	50	0	50	0	50	0
HPAN	0	0	0	0	0	0	0	0
SLB	25	3	25	3	25	3	25	3
SBDT	-10	0	-10	0	-10	0	-10	0
SKST	5	0	5	0	5	0	5	0

St1: FL = Ferric Lixisol, St2: EP = Eutric Plinthosol, St3: HL = Haplic Lixisol, and St4: PL = Plinthic Lixisol, Cr = contour ride tillage, Rt = reduced tillage, CN2T = Percent change in SCS curve number immediately after ith field operation, RINP = Percent of residue incorporated, SSDT = Percent soil surface that is disturbed by the field operation, MIXT = Mixing efficiency of tillage event, HPAN = Percent reduction in hardpan, SLB = Soil layer depth, cm -- maximum potential of operation, SBDT = Percent change in bulk density just after field operation, SKST = Percent change in saturated hydraulic conductivity just after field operation (cm/day).

Parameterization of tillage components was performed based on literature review and expert opinions. The value of percent change in curve number (CN2T) was set to -75 and 0 for contour ridge tillage and reduced tillage, respectively. This decision was made based on the concept that contour ridge tillage reduces curve number by cutting off surface run-off. Other parameters like mixing efficiency (MIXT), change in bulk density (SBDT), and change in saturated hydraulic conductivity (SKST) were set to 0 for reduced tillage as topsoil layer remains unaltered under the reduced tillage system. A value of 10 was set for both percent of residue incorporation (RINP) and percent of disturbed soil surface (SSDT) under reduced tillage since harrowing was performed to remove weeds. Similarly, the maximum potential depth for tillage operation under reduced tillage system was set to 3 cm. In contrast, higher values of RINP(=60), SSDT (=90), MIXT (=50) and SKST (=5%) was proposed for contour ridge tillage such that it disturbs and mixes most of the topsoil layer, incorporates greater amount of applied crop residues, and increase soil water movement throughout the soil profile. An animal-drawn moldboard plough was used to create the ridges which generally extended 25 cm deep into the soil. Since contour ridge tillage loosens the topsoil layer, it is assumed that topsoil bulk density is reduced under the contour ridge tillage system by 10% (SBDT=-10). In order to produce the effects of the crop residues from our study, we tuned two more parameters, N content of initial surface (shoots) residue (%, SCN) from crop residue file (RESCH047.SDA) and C:N ratio of newly added structural material [ratio, CESTR(1)] from soil organic matter file (SOMFX047.SDA).

We also parametrized soil fertility factor (SLPF) to simulate the effects of different tillage operations implemented in our study on crop yield and biomass for four soil types. SLPF factor was manually adjusted and the value was set to 0.74, 0.81, 0.90, and 0.85 for St1 (Ferric Lixisol, footslope in Dano), St2 (Eutric Plinthosol, upslope in Dano), St3 (Haplic Lixisol, footslope in Dassari), and St4 (Plinthic Lixisol, upslope in Dassari), respectively.

2.7. Model validation

Following calibration, the model was validated using field observations of maize growth and yield in response to different treatments (12 treatments used for calibration) collected over the 2016 maize growing season. For this purpose, we used the calibrated cultivars (Table 3) and similar soil data (Table 1) used during the calibration of CERES-Maize. Weather dataset (.WTH) used for model validation was created using the 2016 weather data for two study locations in weatherman utility. Management files (.MZX) also differed from those used for calibration in terms of planting and harvest date, initial conditions, and crop residue application. For the initial conditions of the soil water content and available nitrogen, the calibrated model was run for the years 2014 and 2015, and the simulated outputs for these parameters were used as the soil initial conditions for 2016. The amount of crop residue used for model evaluation was taken from the biomass yield data for 2015 (Table 2). Model evaluation was performed on two sets of data: single observed data including biomass and yield at physiological maturity, and time-series data consisting of biomass data recorded at the different growth stages. In order to test the agreement between the observed and the simulated values, we used 4 statistical indicators: (1) coefficient of determination (R^2,) (2) the normalized root mean square error (nRMSE), a measure of how much average individual observation deviate from the model simulated value, (3) d-statistics, which provides a single index of model performance by including both bias and variability, and (4) mean relative absolute error (MRAE), which is the average of absolute difference between observed and simulated value. These indicators were calculated based on the following equations:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (M_i - S_i)^2}{\sum_{i=1}^{n} (M_i - \underline{M})^2} \quad (6)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (M_i - S_i)^2}{n}} \quad (7)$$

$$nRMSE = \frac{RMSE}{\underline{M}} \times 100 \quad (8)$$

$$MRAE = \frac{\sum_{i=1}^{n} \left(\frac{|M_i - S_i|}{M_i}\right)}{n} \quad (9)$$

$$d = 1 - \frac{\sum_{i=1}^{n} (M_i - S_i)^2}{\sum_{i=1}^{n} (|M| + |S|)^2} \quad (10)$$

where M is the observed value, S is the simulated value, $\underline{M}$ is the mean observed data, n is the number of total samples, and i represents a given sample.

A model having a perfect fit should fulfil the following conditions (Jing et al., 2017): R^2 close to zero, nRMSE and MRAE close to 0, and d close to 1. A 1:1 regression plot was also created

(Figure 3 and 4) using 12 data points for each soil type in order to compare observed and simulated data. We performed a t-test to identify the difference between the contour ridge tillage and reduced tillage system for measured and simulated data.

2.8. Scenario simulation setup

Following calibration and evaluation, the model was used as a tool to test the capacity of the implemented tillage practices along with crop residue and recommended rate of N fertilizer to buffer the future climate change impact. For this purpose, we used the seasonal analysis option in DSSAT to simulate the effects of contour ridge tillage and reduced tillage on maize yield over a period of 10 years using the calibrated model. All historic (2006-2015) and future simulations were run using similar cultivar and soil files but with different weather datasets and management practices.

HAPPI, which stands for Half a degree additional warming, prognosis and projected impacts daily climate data introduced by Mitchell et al. (2017) consisting of three GCMs (ECHAM6, MIROC5, NorESM1), and two climate scenarios: current baseline (2006–2015), and 2°C warmer than pre-industrial levels, were used for weather dataset. The future 10 years time period varied between the GCMs. In some GCMs a future increase in average annual air temperature was reached earlier or later. Additionally, we used 20 runs of 10-year time series for each of the GCMs and climate scenarios such that the model produced outputs for 200 years that allows getting a more robust evaluation of changes in yield and biomass production.

A factorial combination of 2 tillage operations (contour ridge and reduced tillage), 1 crop residue treatment (with crop residue), and 1 N fertilizer rate (recommended N fertilizer: 60 kg ha^{-1}) was implemented as treatments for seasonal analysis. A common planting date, 7^{th} July was set for all simulations depending on the number of consecutive rainfall days. The cultivar, soil profiles, tillage operation, and N fertilizer application method, and simulation options were the same as in the validated model. We set the harvest date as 110 days after planting assuming that most of the plants have reached physiological maturity. Initially, we ran the model without applying any crop residue for 10 year under each GCMs and 2-degree-warming scenarios. The average above-ground biomass (TAGB) produced for each GCMs and 2-degree-warming scenario over the 10 years (10 years × 20 runs) were used as the amount of crop residue incorporated during the seasonal analysis. 24 seasonal analysis files (.SNX) for a combination of 3 GCMs, 2 climate scenarios, and 4 soil types were created using the above-mentioned information. Each of these files contains 40 runs which were generated by combining 2 treatments (2 tillage × 1 residue × 1 N fertilizer rate) and 20 runs. We analysed the time series output of yield and biomass by taking ensemble mean yield (e-mean) of all the GCMs and runs over 10 years of each 2-degree-warming scenario and implemented tillage practices. Additionally, the ensemble means of all GCMs, runs and years for each 2-degree-warming scenario were used to produce cumulative probability distribution (CPD) plots. We used CPD as a future risk assessment tool for implemented management practices. CPD also reveals options to reduce the risk associated with future weather (Ngwira et al., 2014). CPD presents mean yield and biomass, and variance at 0.5 cumulative probabilities. In general, the treatment with the highest cumulative probability is considered riskier (Ngwira et al., 2014). We calculated the relative changes in yield between baseline and future warming scenarios as a result of implementing tillage practices. The following equation was used to calculate relative yield change:

$$\Delta Y\ \% = \frac{\underline{Y}_f - \underline{Y}_b}{\underline{Y}_b} \times 100 \qquad (11)$$

Here, ΔY is the change in yield (%), $\underline{Y}f$ is the mean ensemble yield (kg ha^{-1}) for future scenario (mean of 10 years, 20 runs, 3 GCMs), and $\underline{Y}b$ is the mean ensemble yield for the baseline scenario.

3. Results

This part of the paper deals with the calibration and validation of CERES-Maize model, especially the capacity of the tillage module to depict the effects and or trend of contour ridge and reduced tillage on maize yield. Additionally, we deployed the validated model as a tool to forecast the implemented tillage effects on maize yield and biomass production under 2-degree-warming- scenarios using the ensemble mean yield (e-mean) over the GCMs and years, and an overview of yield change between baseline and future climate scenario (equation 11) under each tillage operation.

3.1. Projected climate change under 2-degree-warming scenarios

The corresponding changes in average temperature and cumulative daily rainfall over the maize growing seasons (July to November) under the future 2-degree-warming scenarios compared to the baseline is shown in Figure 1. Compared to the baseline, the average temperature for all the GCMs, ECHAM6, MIROC5, NorESM1 were projected to increase in both locations, Dano and Dassari. At the same time, cumulative rainfall increased only for MIROC5 (2%) in Dano and for MIROC5 (1%) and NorESM1 (3%) in Dassari. In both sites, cumulative rainfall is expected to decrease by 2% for ECHAM6. The greatest average temperature increase was projected for MIROC5 in Dano by 6% and for ECHAM6 in Dassari by 5%. The difference in absolute mean cumulative rainfall during the maize growing seasons under each GCM has been presented in Table 5. Higher Ensemble mean of rainfall during the maize growing season under the future climate scenario was found compared to the baseline.

3.2. Model calibration

Six genetic coefficients of CERES-Maize cultivar file were adjusted for the cultivar “Dorke” based on the field observations and presented in Table 3. The range of these parameters are close to the variety calibrated by Danso (2015). Initially, we compared the simulated with the observed mean phenology and maize growth data, averaged across all the treatments for each soil type (Table 6). The calibrated model predicted the maturity day quite well. CERES-Maize simulated the maturity day as (107±3 days after planting) for St1 (Ferric Lixisol, footslope in Dano) and St2 (Eutric Plinthosol, upslope in Dano) with a RMSE of 4 days. At the same time, the simulated maturity day for St3 (Haplic Lixisol, footslope in Dassari) and St4 (Plinthic Lixiosol, upslope in Dassari) was (103±2 days after planting) with a nRMSE of 3 days. Subsequently, we also found a close match between the observed and simulated values of yield and TAGB at physiological maturity which expressed the fairly good simulation capacity of the model.

Table 5: Absolute mean cumulative rainfall (mm) over the maize growing seasons for 200 years (10 years and 20 runs) under each GCMs

Site	GCM	Rainfall, baseline, mm	Rainfall, future, mm	Change in rainfall, %
Dano	ECHAM6	997	935	-6.2
	MIROC5	947	960	+1.4
	NorESM1	933	918	-1.6
Dassari	ECHAM6	1200	1112	-7.3
	MIROC5	1149	1186	+3.2
	NorESM1	1112	1196	+7.5

Calibration of biomass at maturity using observed data resulted in d-index value of 0.9, 0.9, 0.8, and 0.8 for St1, St2, St3, and St4, respectively. At the same time, the MRAE value between the simulated and observed aboveground biomass ranged from 6% to 10%, independent of soil type. Similarly, the MRAE value for maize yield in St1, St2, St3, and St4 was 15%, 13%, 10%, and 14%, respectively. Interestingly, we recorded a d-index value of 0.8 for maize yield in all soil types.

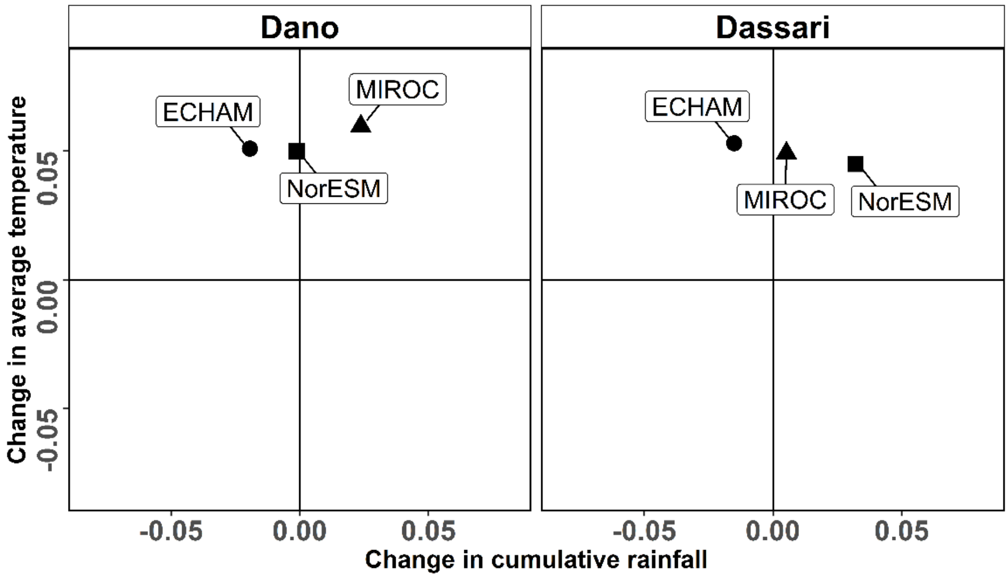

Figure 1: Relative change in the projected average growing season mean temperature (Dec-%) and cumulative growing season rainfall (Dec-%) during the maize growing seasons for GCMs, ECHAM6, MIROC5, and NorESM1 under a 2°C warming scenario compared to the baseline (2006-2015) in Dano and Dassari.

For the calibration of the tillage module in DSSAT, we compared the maize biomass production at four-time steps (4, 6, 8 weeks after planting and at harvest) under two different tillage practices, contour ridge tillage, and reduced tillage. The model simulated maize biomass production well under the contour ridge tillage system, as indicated by good d-index and considerable low MRAE and nRMSE. The d-index of contour ridge tillage for St1, St2, St3, and St4 were 0.93, 0.91, 0.79, and 0.78, respectively (Figure 2). While the RMSE and MRAE in St3 and St4 under contour ridge tillage was between 10 and 10-13, respectively, the model had a better performance (MRAE between 8-9%, and nRMSE between 5-6%) in St1 and St2 (Figure 2).

Table 6: Difference between means of simulated and observed maize yield and total aboveground biomass (kg ha^{-1}) for all treatments in each soil type in 2014 during calibration

Soil Types	Yield (kg ha^{-1})(N=12)					Total aboveground biomass (kg ha^{-1}) (N=12)				
	Simulated	**Observed**	**RMSE**	**MRAE**	**d**	**Simulated**	**Observed**	**nRMSE**	**MRAE**	**d**
St1:FL	2177	2270	17	15	0.8	4723	4783	11	8	0.9
St2:EP	2763	3030	15	13	0.8	5935	6216	7	6	0.9
St3:HL	4527	4481	10	10	0.8	10365	10510	11	9	0.8
St4:PL	2754	2649	16	14	0.8	6667	6814	12	10	0.8

St1:FL = Ferric Lixisol ,St2:EP = Eutric Plinthosol, St3:HL = Haplic Lixisol, and St4:PL = Plinthic Lixisol

Concurrently, the simulation of maize biomass production at different growth stages under reduced tillage was good as shown by the high d-index value of 0.87, 0.75, 0.74, and 0.78 for St1, St2, St3, and St4, respectively (Figure 2). The nRMSE and MRAE value for simulated biomass production under reduced tillage irrespective of soil type ranged between 10% to 16% and 10% to 14%, respectively. However, while considering the N fertilizer effects together with tillage practices, the model slightly overestimates the tillage effects in control plots (N0) and slightly underestimates in double N fertilizer plots (N120) at all soil types. Thus, the calibrated model differentiated maize biomass production under the two tillage practices quite well. when a recommended rate of N fertilizer was applied along with crop residue incorporation.

3.3. Model validation

The observations in 2016 were used to validate the model for the four study sites. Likewise, calibration, we performed model validation in two steps. Firstly, we conducted a comparative analysis between the simulated and observed yield and biomass at physiological maturity by considering 12 data points (a combination of 2 tillage, 2 crop residue treatments, and 3 N fertilizer rates) for each soil type. The result is presented as 1:1 regression plot by including additional statistical indicators like, R^2, nRMSE, MRAE, and d-index (Figure 3). Simulated yield matched very well with the observed yield during the validation year. The performance statistics (Figure 3) indicated that R^2 for harvested maize yield was very high for the footslope soils, St1 (0.95) and St3 (0.91), while it was 0.89 and 0.82 for upslope soils, St2 and St4, respectively. In addition, low nRMSE and MRAE for harvested maize yield (Figure 3) were also observed. nRMSE was 14% and 18% for footslope soils and upslope soils, respectively. Similarly, MRAE for footslope and upslope soils was 12% and 14%, respectively. The model evaluation also revealed a good d-index between the simulated and observed yield, ranging from 0.71-0.81. Regarding TAGB of maize, the model showed higher accuracy during the validation process (Figure 4). Most data points of TAGB were concentrated around the 1:1 line with higher R^2 value raging between 0.85 and 0.95 depending on soil types. nRMSE and MRAE values ranged from 12% to 14%, and from 10% to 13%, respectively, indicating good agreement between the simulated and observed TAGB (Figure 4). A high d-index (0.75-0.85) at different soil types was also recorded between simulated and observed TAGB. Regarding yield and TAGB at harvest, the model performed well in simulating the response to the combined application of tillage, crop residue management, and N fertilizer application at four soil types in 2016.

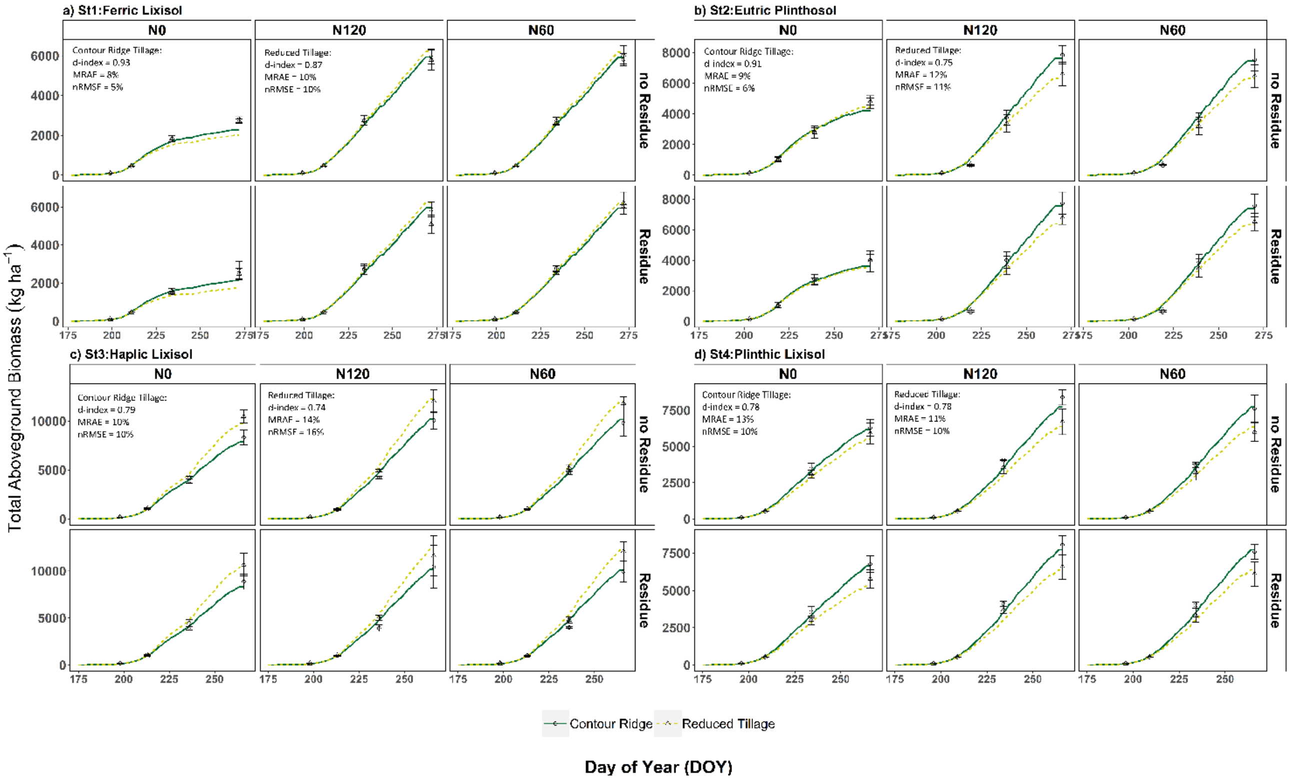

Figure 2: Comparison between observed and simulated time-series of maize total above-ground biomass (TAGB) during model calibration in 2014 at four soil types, St1: Ferric Lixisol (a), St2: Eutric Plinthosol (b), St3: Haplic Lixisol (c), and St4: Plinthic Lixisol (d). Line types indicate the simulated TAGB for two tillage levels, the points with error bars (n=4) indicate the observed TAGB. nRMSE = normalized root-mean-square error, MRAE = mean relative absolute error, d = index of agreement. N0 = no N fertilizer, N60 = 60 kg ha^{-1} N fertilizer, N120 = 120 kg ha^{-1} N fertilizer.

Next, we tested the model performance in terms of simulating yield and TAGB at harvest under two different tillage practices, contour ridge tillage and reduced tillage in four soil types using t-test ($P \leq 0.05$). Outputs from t-test presented, i) difference between simulated and observed data (lower case letters, Table 7) and ii) difference between tillage practices (upper case letters, Table 7). Hence, the initial results from t-test indicated that means of simulated yield and TAGB at harvest were not significantly different from the observed data in all soil types except St3 (Haplic Lixisol, footslope in Dassari).

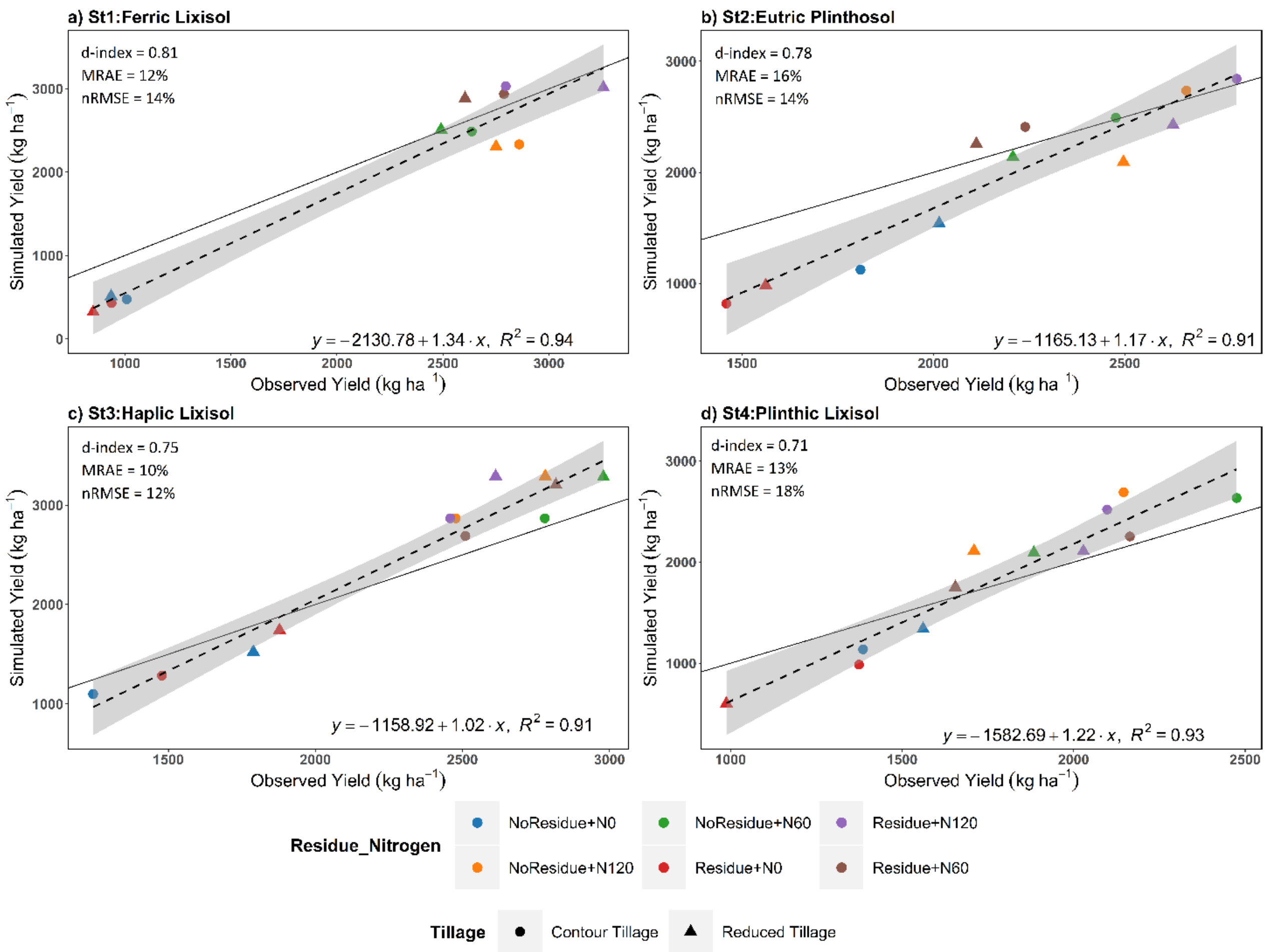

Figure 3: Comparisons between simulated and observed maize yield for four soil types, St1:Ferric Lixisol (a), St2:Eutric Plinthosol (b), St3:Haplic Lixisol (c), and St4:Plinthic Lixisol (d), using12 data points (2 tillage × 2 crop residue × 3 N fertilizer) at each soil type during model validation in 2016. Solid lines = 1:1 lines and dashed lines = regression lines. nRMSE = normalized root mean-square error, MRAE = mean relative absolute error, d = index of agreement. N0 = no N fertilizer, N60 = 60 kg ha^{-1} N fertilizer, N120 = 120 kg ha^{-1} N fertilizer.

In terms of distinguishing between tillage practices, the model did not show any difference between contour ridge tillage and reduced tillage with respect to simulating harvested yield in St1 and St2. Consistently, such a difference was also negligible for observed data. Moreover, the model successfully captured the difference in harvested yield simulation between the implemented tillage operations in St3 and St4, which was also true for observed data. For the simulation of TAGB, the model nicely depicted the difference between the tillage practices as reflected in experimental observations. As with the observed data, the simulated TAGB also showed a significant difference between contour ridge tillage and reduced tillage in all soil types, except St1 (Ferric Lixisol, footslope in Dano). Also, a significant difference between the simulated and observed TAGB was observed at St3. Thus, we concluded that the calibrated model adequately reproduced the yield observations (good agreement between the observed and simulated data), in terms of simulating tillage effects on yield and TAGB at all soil types. Thus, the validated model is suitable for the assessment of tillage effects under 2-degree-warming scenarios.

Table 7: Difference (t- test) between means of simulated and observed maize yield and total aboveground biomass (kg ha^{-1}) per tillage operation during model validation (2016).

Soil Types	**Tillage**	**Yield (kg ha^{-1}) (N=6)**			**Total aboveground biomass (kg ha^{-1}) (N=6)**		
		Simulated	**Observed**	**t-test (P)**	**Simulated**	**Observed**	**t-test (P)**
St1:FL	**Cr**	1948 a A	2171 a A	0.72	5896 a A	6102 a A	0.89
	Rt	1924 a A	2147 a A	0.73	5828 a A	5847 a A	0.98
	t-test (P)	0.3	0.8		0.2	0.4	
St2:EP	**Cr**	2069 a A	2239 a A	0.69	5889 a A	6067 a A	0.83
	Rt	1906 b A	2169 a A	0.35	4870 a B	5109 a B	0.65
	t-test (P)	0.3	0.3		0.02	0.02	
St3:HL	**Cr**	2279 a B	2158 a B	0.78	7029 b B	8468 a B	0.21
	Rt	2722 a A	2476 b A	0.55	8311 b A	9097 a A	0.45
	t-test (P)	9.621e-07	0.002		0.002	0.09	
St4:PL	**Cr**	2036 a A	1940 a A	0.79	6633 a A	6830 a A	0.81
	Rt	1667 a B	1637 a B	0.92	5513 a B	5703 a B	0.78
	t-test (P)	0.02	0.04		0.007	0.002	

t-test (p) = probability, lowercase letters compare simulated vs. observed values, uppercase letter compares the tillage methods, Cr = contour ridge tillage, Rt = reduced tillage, N = total observation number.

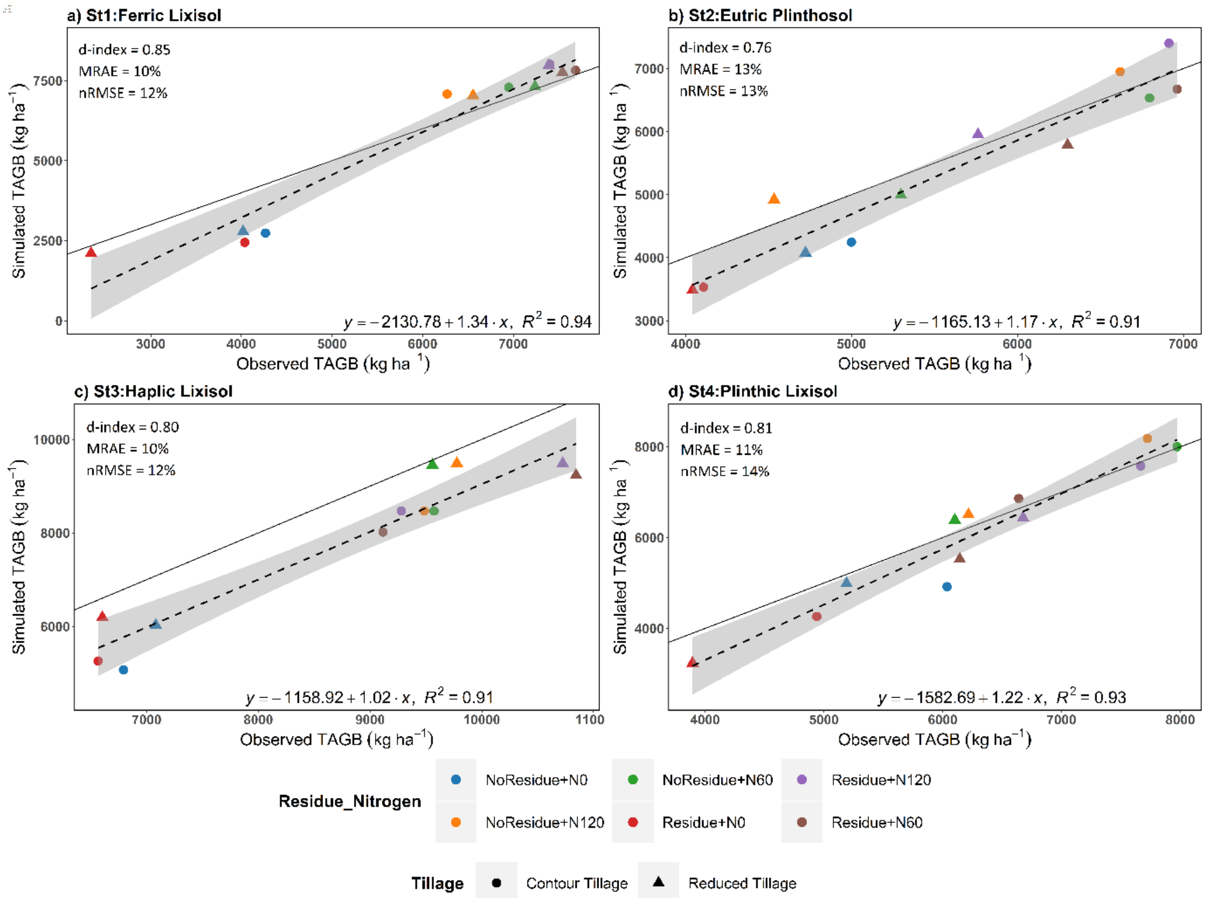

Figure 4: Comparisons between simulated and observed maize total above-ground biomass (TAGB) for four soil types, St1:Ferric Lixisol (a), St2:Eutric Plinthosol (b), St3:Haplic Lixisol (c), and St4:Plinthic Lixisol (d), using 12 data points (2 tillage × 2 crop residue × 3 N fertilizer) at each soil type during model validation in 2016. Solid lines = 1:1 lines and dashed lines = regression lines. nRMSE = normalized root mean-square error, MRAE = mean relative absolute error, d = index of agreement. N0 = no N fertilizer, N60 = 60 kg ha^{-1} N fertilizer, N120 = 120 kg ha^{-1} N fertilizer.

3.4. Long-term scenario analysis

The next step was to simulate the maize yield using the calibrated model for the baseline and the 2-degree-warming scenario and to assess the relative yield change (equation 11) under different tillage practices. This is a prerequisite to select suitable climate change adaptation strategies. For this purpose, the calibrated model was run for two different management options (contour ridge and reduced tillage) under baseline (2006-2015) and future (2˚C warmer than pre-industrial period). An ensemble mean yield of all the GCMs and years (200) for each climate scenario, treatment, and soil type was considered for comparative testing of the second hypothesis of our study.

3.4.1. Interannual yield variability

The seasonal analysis tool successfully simulated the impacts of contour ridge tillage and reduced tillage on maize yield under historical and future 2-degree-warming scenarios. The pattern of simulated yield under these two tillage practices was observed, i.e., excellence of contour ridge tillage over the reduced tillage on St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol, upslope in Dassari), while reduced tillage produced significantly higher yields in St3 (Haplic Lixisol, footslope in Dassari). In St1, maize yield patterns were more or less similar throughout the years, both for baseline and future climate scenarios and under both tillage practices. i.e., no difference in yield between contour ridge tillage and reduced tillage. Under both the baseline and 2-degree-warming scenario, the decreasing yield trend continued with time for both tillage practices in St1. For the baseline maize yield simulation, the highest yield peak was observed as 2879 kg ha^{-1} in 2010 for St2 and as 6745 kg ha^{-1} in 2011 for St3. In St2, the pattern of simulated maize yield under different management practices in the 2-degree warming scenario was similar to that of the baseline simulation, *i.e.*, high interannual variability. On the other hand, a gradual and somewhat unusual increase in maize yield was observed in St3 for both contour ridge and reduced tillage under the baseline and future climate scenario. The trend was rather flat before 2011 (baseline) and year 6 (future), followed by 5 years (both baseline and future) of strongly increasing yield. A gradual yield decline was recorded in St4 for both of the climate scenarios (Figure 5).

3.4.2. Relative changes in maize yield under future climate change scenarios

Relative change of the simulated yield of maize under contour ridge tillage and reduced tillage practice for the 2-degree-warming scenario was estimated using equation 11. The average relative change (mean over the GCMs and years) in simulated maize yield under both contour ridge tillage and reduced tillage was quite similar, at the two downslope sites St1 and St3 (Figure 6). Mostly, the changes were positive in all soils (St3 and St4) in Dassari under both tillage practices. On the other hand, a negative trend of relative yield changes was observed in all soil types in Dano under both tillage practices except contour ridge tillage in St2. Under the contour ridge tillage system, relative changes in simulated maize yield were: -11%, +4%, +14%, +7% in St1, St2, St3, and St4, respectively.

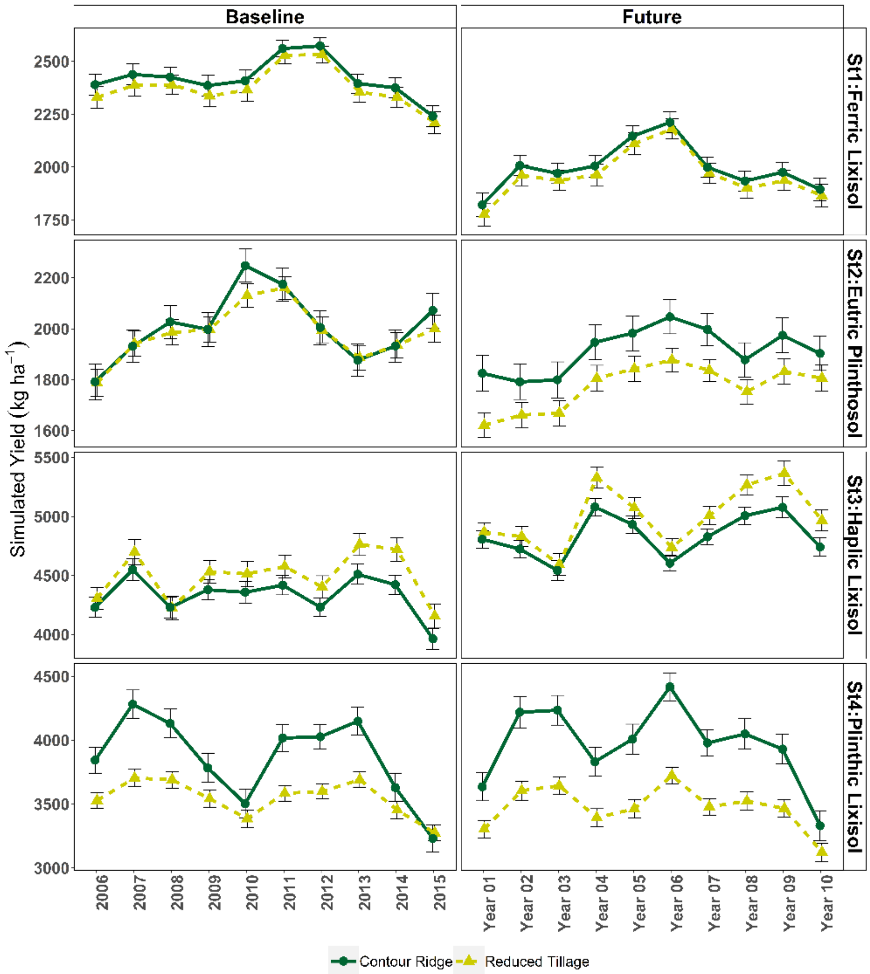

Figure 5: Simulated total above-ground biomass at harvest (a), and maize yield (b) for baseline (2006-2015) and future (2˚C warmer than the pre-industrial period) under contour ridge tillage (dark green solid line) and reduced tillage (light green dashed line) at four soil types. The error bars represent the standard deviation (n=60, 3 GCMs and 20 runs) due to variations in climate models.

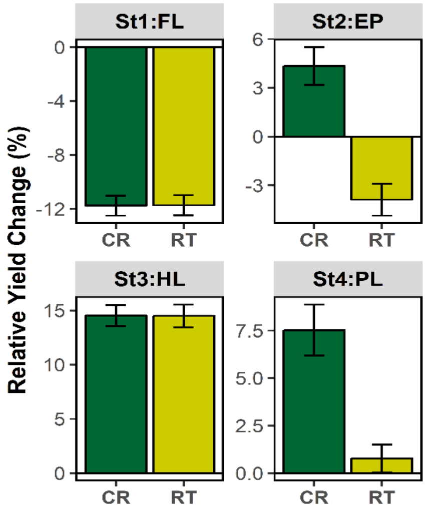

Figure 6: Relative change (%) in simulated maize yield under 2-degree-warming scenarios from 3 GCMs compared to the baseline for both contour ridge tillage and reduced tillage at four soil types (St1=Ferric Lixisol, St2=Eutric Plinthisol, St3=Haplic Lixisol, St4=Plinthic Lixisol). The error bar is the mean error for 600 data points (1 tillage × 20 runs × 10 years × 3 GCMs).

A similar pattern of relative yield changes was also observed under the reduced tillage system, *i.e.* -11% in St1, -3.5% in St2, +14.5% in St3, and +1% in St4 (Figure 6). Figure 5 confirms that the application of contour ridge tillage practice has the potential to increase maize yields under the future warming in soils that are located at upslope positions like St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol, upslope in Dassari) as well as in St3 (Haplic Lixisol at Dassari). At the same time, the implementation of reduced tillage could increase maize yield under the future warming in St3 (Haplic Lixisol, footslope in Dassari). Both of the tillage practices might help to take advantage of the future warming effects on maize yield in St3 (Haplic Lixisol, footslope in Dassari), while none of the tillage operations were able to mitigate the future global warming effects on maize yield in St1 (Ferric Lixisol, footslope in Dano).

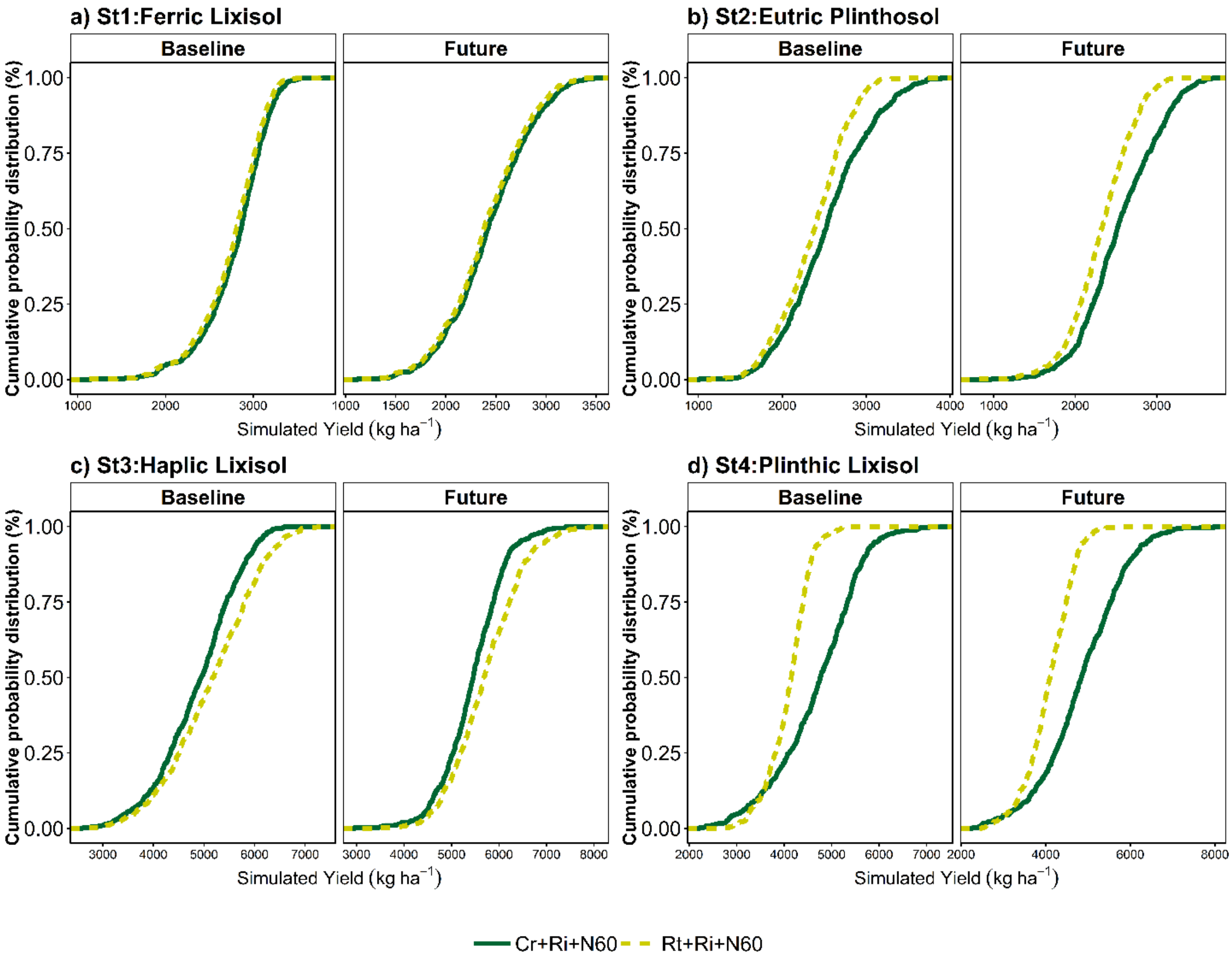

Figure 7: Cumulative probability distribution for simulated mean maize yield (n=600, 1 tillage × 20 runs × 10 years × 3 GSMs) under baseline and 2-degree-warming scenarios for both contour ridge tillage and reduced tillage at four soil types.

3.4.3. Strategic assessment of optimized management option

Cumulative Probability Distributions (CPD) are used to identify sustainable management strategies. In general, a strategy is considered favourable compared to an alternative strategy if the cumulative probability distribution (CPD) line remains in the first position from the right-hand side of the probability plot. The plots of cumulative probability distribution (CPD) at 0.5 (Figure 7) illustrated that the mean simulated maize yield for both baseline and future climate scenarios was higher under contour ridge tillage practice along with crop residue incorporation and recommended N fertilizer rate (60 kg ha^{-1}) in St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol). Simultaneously, the implementation of reduced tillage along with crop residue and recommended N fertilizer rate was advantageous over contour ridge tillage in St3 (Haplic Lixisol, footslope in Dassari) under both baseline and 2-degree-warming scenarios. Again, no difference in yield between contour ridge tillage and reduced tillage was found in St1 (Ferric Lixisol, footslope in Dano).

Thus, we concluded that contour ridge tillage along with crop residue incorporation and recommended N fertilizer rate could be regarded as a better and safe tillage practice in St2 and St4. Conversely, the adoption of reduced tillage together with returning crop residue and recommended N fertilizer rate could be a safer option for the farmers in St3.

4. Discussion

4.1. CERES-Maize and Tillage module performance

In order to validate the models employed we assessed, 1) whether tillage module in DSSAT v. 4.7.5 can reproduce the tillage effects observed during the field trial? and if yes, 2) how contour ridge tillage differs from reduced tillage in terms of the calibrated tillage parameters? To answer the first question, we analysed the statistical indicators presented in Table 6 and Figure 2, in terms of simulating maize yield and biomass (both at harvest and time-series) under these two different tillage practices during the model calibration and validation. The CERES-Maize model in DSSAT has been calibrated for more than 160 cultivars of maize worldwide (Jing et al., 2017). In our study, calibration of the genetic coefficients in CERES-Maize and soil parameters indicated “good” to “excellent” agreement between the simulated and measured maize yields and above-ground biomass for all the soil types. The calibrated parameters of the maize cultivar used in our study were comparable to the reported values used for TZEEY-SRBC5 cultivar in a study by Freduah et al. (2019) in semi-arid zones of Senegal and Ghana, and for OBA-9 cultivar in a study by Adnan et al. (2019) in Nigerian Savanna. Maize yields at harvest were also accurately simulated with nRMSE of 6% and 11%, and d-index of 0.89 and 0.97, respectively in these two studies. Notably, our results were not in agreement with the outputs from the studies by Tovihoudji et al. (2019) in northern Benin, by Saïdou et al. (2018) in Sudano zones of Benin, and by Chisanga et al. (2015) in Zambia, although early maturity maize variety was used in those experiments. Our parametrization of the tillage module led to a reasonably good reproduction of the observed maize biomass and grain yield during the 2014 and 2016 maize growing seasons both for the contour ridge tillage and reduced tillage, as indicated by the nRMSE, MRAE, d-index between observed and simulated data (Figure 2, 3, and 4). We also used paired t-test in order to illustrate the difference between the two tillage practices for both simulated and observed maize yield and biomass (Table 7). Previous studies simulating tillage effects on crop yield and soil properties considered differences between the conventional, CT and conservation agriculture, CA (reduced or no-tillage with crop residue or rotation) under various cropping systems, and typically found moderate to good agreement between the simulated and observed crop yields under both management practices (Joshi et al., 2017; Liu et al., 2013; Nangia et al., 2010; Ngwira et al., 2014; Om et al., 2016; Soldevilla-Martinez et al., 2013). Overall, the performance of the calibrated and validated tillage module in DSSAT v. 4.7.5 was generally acceptable for the purpose of simulating maize yield and biomass for all soil types, but of course with few exceptions. For example, the simulated maize yield and biomass followed the observed values reasonably well, except for St3: Haplic Lixisol, where the model showed a slight discrepancy between the simulated and observed maize biomass. Thus, it was confirmed that the parameterization of the tillage module was adequate, and therefore, this model is a reliable tool for climate change impact studies in such geographic conditions.

4.2. Site-specific yield variation

The 2-degree warming future climate scenario indicated a general tendency towards a relative increase in yield compared to baseline except in St1 (Ferric Lixisol, footslope in Dano). In this region, the most important causative factors for future changes in rainfed maize yield are increasing temperature and decreasing precipitation (Cairns et al., 2013). However, As shown in Figure 1 and Table 5, temperature is expected to increase during the 2-degree warming period in both sites, but the cumulative rainfall during maize growing season is expected to slightly increase in Dassari, at least under MIROC5 and NorESM1, whereas at Dano, one GCM expects an increase and another GCM expects a decrease in the future. An increase in mean air temperature together with lower or constant rainfall during the maize growing season can introduce heat and water stress to maize resulting in yield decline (Li et al., 2019; Ma and Maystadt, 2017). This may be the reason for the maize yield decline in Dano, in particular on St1 which has the lowest water retention capacity. Increasing water stress at St1 is evidenced by a decrease in simulated daily average available soil water during the growing season of Dano (Table 8). Such a low content of soil water can be explained by the presence of high soil gravel content in this site (Nafi et al., 2020). In contrast, the increases in maize yield under the 2-degree future warming scenario in Dassari at both soil types (St3, Haplic Lixisol, footslope in Dassari and St4, Plinthic Lixisol, upslope in Dassari) could be due to the higher baseline rainfall in Dassari plus a modest increase in rainfall under the 2-degree warming scenario, hence higher soil water availability as reflected in higher simulated daily average available soil water during the growing season in the soil profiles of Dassari (St3 and St4) (Table 8). The underlying mechanism could be that maize yield can be increased with a modest increase in total precipitation counteracting the negative effects associated with increased temperature (Kucharik and Serbin, 2008; Xu et al., 2016).

4.3. Effects of tillage practices on maize yield

Next, we investigated the comparative effects of both contour ridge tillage and reduced tillage on maize yield and relative yield change under the future warming climate scenario. While comparing the site-specific tillage effects on maize yield, we found that reduced tillage along with crop residue incorporation resulted in a higher maize yield increase in St3 (Haplic Lixisol, footslope in Dassari) compared to contour ridge tillage. A study by Ngwira et al. (2014) in Malawi also found a similar pattern of maize yield under the CA practice system. In contrast, Soldevilla-Martinez et al. (2013) showed a lower maize yield in semiarid Spain under reduced or no-tillage conditions. The stronger effect of reduced tillage on maize yield at St3 (Haplic Lixisol at footslope) could be explained by the fact that Dassari is rather a sub-humid site, the improved fertility status of the soil (soil organic carbon) and higher simulated daily average available soil water during the growing season compared to St4 at the upslope. We found higher simulated daily average available soil water content under the reduced tillage system in St3, especially in the warming climate scenario (Table 8). In agreement with the results from Fuentes et al. (2003), Wang et al. (2019), and Xu et al. (2019), improved maize yield can be attributed to higher soil nutrient stocks, soil organic carbon and improved NUE of maize crop under the reduced tillage system, which was also observed during the field experiment in this site (Nafi et al., 2020, 2019). Crop production under rain-fed conditions heavily depends on soil water storage (Sang et al., 2016). Enhanced soil water content and soil organic carbon stock under reduced tillage and crop residue incorporation at the footslope in Dassari resulted in improved soil properties that stimulated maize yield (Liu et al., 2012; Wang et al., 2019).

Table 8: Simulated daily average available soil water content, SWXD (mm) over the maize growing seasons for 200 years (10 years and 20 runs) during baseline and future climate scenarios in four soil types.

Soil Types	Baseline, SWXD (mm)		Future, SWXD (mm)	
	Cr	**Rt**	**Cr**	**Rt**
St1:FL	66	65	63	66
St2:EP	71	54	73	59
St3:HL	100	103	113	117
St4:PL	78	66	93	79

SWXD = Simulated daily average available soil water content, SWXD (mm), Cr = contour ridge tillage, Rt = reduced tillage.

In all soil types located in the upslope positions, St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol, upslope in Dassari), implementation of contour ridge tillage together with crop residue application instead of reduced tillage with crop residue application led to a higher maize yield in both baseline and future scenario. One of the greatest benefits of implementing contour ridge tillage instead of reduced tillage at upslope sites is improved infiltration of rainwater and hence higher soil water storage within the profile. Especially the high rainfall site that sees an increase in rainfall in the future (Dassari) seems to benefit more from contour ridging at the upslope to retain the excess water and reduce nutrient loss through surface runoff. Restoration of soil water storage under contour and tied ridge tillage compared to minimum tillage was revealed in a study conducted by Marimi (1978) in Chromic Luvisol. Another study performed by Brhane et al. (2006) in Typic Pellustert, illustrated the importance of contour or tied ridge tillage in improving soil moisture storage as well as crop yield. A study by Hulugalle

(1987) in Oxic Paleustalf of Burkina-Faso suggested the effectiveness of tied/contour ridges in terms of increasing soil profile water content and root growth. Shaxson et al. (2003) reflected the convenience of tied/contour ridge to confine rainfalls where it occurs so that there is more opportunity for infiltration and soil water storage and to prevent runoff i.e. losses of water and nutrients. Thus, enhanced soil water availability under the contour ridge tillage system could lead to increased nutrient availability, fertilizer uptake efficiency, and maize yield.

4.4. Adaptation options evaluation

Our research suggests that the contour ridge tillage along with crop residue incorporation could be a valuable alternative to other management options in soil types located in upslope positions (St2: Eutric Plinthosol, upslope in Dano and St4: Plinthic Lixisol, upslope in Dassari) as higher maize yield was evidenced under contour ridge tillage during both baseline and future climate scenario (Figure 5). On the other hand, in St3, Haplic Lixisol at footslope in Dassari, slightly higher maize yield was recorded during both baseline and future climate scenarios under reduced tillage along with crop residue application. Markedly, the difference in maize yield between two tillage practices was marginal at St3, while in the upslope, St4, such a difference was more prominent and contour ridge tillage showed an obvious advantage over reduced tillage.

Furthermore, Figure 7 illustrated that the cumulative probability curve for contour ridge tillage placed in the far-right side of the plot in St2 and St4, while the opposite is true in St3 where the curve for reduced tillage is located in the far-right side of the plot. This suggests that contour ridge tillage along with crop residue incorporation has a lower probability of low yield than reduced tillage in St2 and St4. In contrast, contour tillage with crop residue application has also a slightly higher probability of low yield than contour ridge tillage in St3. According to Danso et al., (2018), higher maize yield was attributed to the contour ridge tillage system compared to reduced tillage system. Nafi et al. (2020, 2019) also showed a higher crop NUE, SOC, and soil nutrient stocks under contour ridge tillage in St2 and St4, while reduced tillage led to a slightly better performance of maize crop in St3. Unfortunately, no difference in crop yield and soil properties between two tillage systems was observed in St1, neither during experiments nor in the simulation study. Thus, contour ridge tillage and crop residue application could be preferred by risk-averse farmers in this region during future extreme climatic conditions in soil types like St2 and St4. Similarly, reduced tillage along with crop residue application could be a possible alternative to conventional farmers' practice in St3 to take more advantage of future climate change for maize production.

5. Conclusion:

In this study, we proved the ability of the DSSAT CERES-Maize model to accurately simulate maize response to different tillage and crop residue management effects in order to assess the effects of seasonal climate variability on maize yield under future warming periods. Using independent datasets (2014 and 2016) for the calibration and validation, DSSAT exhibited good performance when simulating phenology, total biomass, and grain yield under different implemented tillage practices. However, there is the need for conducting further tests of the tillage module in DSSAT under other soil and climate conditions in order to confirm its robustness to simulate the effect of tillage practices on maize and other crops.

Long term future climate simulations and cumulative probability distribution confirmed that contour ridge tillage along with crop residue application could contribute to higher maize yield at upslope field sites under a future 2-degree warming scenario, where soil erosion and loss of water and nutrients through runoff is a serious risk. Simultaneously, reduced tillage with crop residue application could be a valuable alternative to farmer's practice in fields with deep soils with high water retention capacity at footslope position, as it resulted in a slightly higher increase of maize yield under future 2-degree warming compared to contour tillage. Maize production on gravelly soils with low water retention capacity (St1) may suffer from future 2-degree warming regardless of the tillage practice. Hence, the application of site-specific tillage operations and crop residue application has the potential to buffer future warming effects on maize yield as confirmed by DSSAT simulations.

6. References

Adnan, A.A., Diels, J., Jibrin, J.M., Kamara, A.Y., Craufurd, P., Shaibu, A.S., Mohammed, I.B., Tonnang, Z.E.H., 2019. Options for calibrating CERES-maize genotype specific parameters under data-scarce environments. PLoS One 14, e0200118. https://doi.org/10.1371/journal.pone.0200118

Akinseye, F.., Adam, M., Agele, S.., Hoffmann, M.P., Traore, P.C.., Whitbread, A.M., 2017. Assessing crop model improvements through comparison of sorghum (sorghum bicolor L. moench) simulation models: A case study of West African varieties. F. Crop. Res. 201, 19–31. https://doi.org/10.1016/j.fcr.2016.10.015

Andales, A.A., Batchelor, W.D., Anderson, C.E., Farnham, D.E., Whigham, D.K., 2000. Incorporating tillage effects into a soybean model. Agric. Syst. 66, 69–98. https://doi.org/10.1016/S0308-521X(00)00037-8

Araya, T., Cornelis, W.M., Nyssen, J., Govaerts, B., Bauer, H., Gebreegziabher, T., Oicha, T., Raes, D., Sayre, K.D., Haile, M., Deckers, J., 2011. Effects of conservation agriculture on runoff, soil loss and crop yield under rainfed conditions in Tigray, Northern Ethiopia. Soil Use Manag. 27, no--no. https://doi.org/10.1111/j.1475-2743.2011.00347.x

Bationo, A., Mokwunye, A.U., 1991. Role of manures and crop residue in alleviating soil fertility constraints to crop production: With special reference to the Sahelian and Sudanian zones of West Africa. Fertil. Res. 29, 117–125. https://doi.org/10.1007/BF01048993

Belle, E.M.S., Burgess, N.D., Misrachi, M., Arnell, A., Masumbuko, B., Somda, J., Hartley A., Jones, R., Janes, T., McSweeney, C., Mathison, C., Buontempo, C., Butchart, S., Willis, S.G., Baker, D.J., Carr, J., Hughes, A., Foden, W., Smith, R.J., Smith, J., Stolton, S., Dudley, N., Hockings, M., Mulongoy, J., Kingston, N., 2016. Climate Change Impacts on Biodiversity and Protected Areas in West Africa, Summary of the main outputs of the PARCC project, Protected Areas Resilient to Climate Change in West Africa. UNEP-WCMC, Cambridge, UK.

Brhane, G., Wortmann, C.S., Mamo, M., Gebrekidan, H., Belay, A., 2006. Micro-basin tillage for grain sorghum production in semiarid areas of Northern Ethiopia. Agron. J. 98, 124–128. https://doi.org/10.2134/agronj2005-0148

Brhane, G., Wortmann, C.S., Mamo, M., Gebrekidan, H., Belay, A., 2006. Micro-Basin Tillage for Grain Sorghum Production in Semiarid Areas of Northern Ethiopia. Agron. J. 98, 124. https://doi.org/10.2134/agronj2005-0148

Cairns, J.E., Hellin, J., Sonder, K., Araus, J.L., MacRobert, J.F., Thierfelder, C., Prasanna, B.M., 2013. Adapting maize production to climate change in sub-Saharan Africa. Food Secur. 5, 345–360. https://doi.org/10.1007/s12571-013-0256-x

Challinor, A., Wheeler, T., Garforth, C., Craufurd, P., Kassam, A., 2007. Assessing the vulnerability of food crop systems in Africa to climate change. Clim. Change 83, 381–399. https://doi.org/10.1007/s10584-007-9249-0

Chisanga, C.B., Phiri, E., Shepande, C., Sichingabula, H., 2015. Evaluating CERES-Maize Model Using Planting Dates and Nitrogen Fertilizer in Zambia. J. Agric. Sci. 7. https://doi.org/10.5539/jas.v7n3p79

Cong, P., Yin, G., Gu, J., 2016. Effects of stubble and mulching on soil erosion by wind in semi-arid China. Sci. Rep. 6, 29966. https://doi.org/10.1038/srep29966

Corbeels, M., Chirat, G., Messad, S., Thierfelder, C., 2016. Performance and sensitivity of the DSSAT crop growth model in simulating maize yield under conservation agriculture. Eur. J. Agron. 76, 41–53. https://doi.org/10.1016/J.EJA.2016.02.001

Dadoun, F., 1994. Modelling tillage effects on soil physical properties and maize (Zea mays, L.) development and growth.

Danso, I., Gaiser, T., Webber, H., Naab, J., Ewert, F., 2018. Response of Maize to Different Nitrogen Application Rates and Tillage Practices Under Two Slope Positions in the Face of Current Climate Variability in the Sudan Savanna of West Africa. Springer, Singapore, pp. 41–58. https://doi.org/10.1007/978-981-10-4796-1_3

Desrochers, J., Brye, K.R., Gbur, E., Mason, R.E., 2019. Infiltration as affected by long-term residue and water management on a loess-derived soil in eastern Arkansas, USA. Geoderma Reg. 16, e00203. https://doi.org/10.1016/J.GEODRS.2019.E00203

Egbebiyi, T.S., Crespo, O., Lennard, C., 2019. Defining Crop–climate Departure in West Africa: Improved Understanding of the Timing of Future Changes in Crop Suitability. Climate 7, 101. https://doi.org/10.3390/cli7090101

Faye, B., Webber, H., Naab, J.B., MacCarthy, D.S., Adam, M., Ewert, F., Lamers, J.P.A., Schleussner, C.F., Ruane, A., Gessner, U., Hoogenboom, G., Boote, K., Shelia, V., Saeed, F., Wisser, D., Hadir, S., Laux, P., Gaiser, T., 2018. Impacts of 1.5 versus 2.0 °c on cereal yields in the West African Sudan Savanna. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aaab40

Freduah, B., MacCarthy, D., Adam, M., Ly, M., Ruane, A., Timpong-Jones, E., Traore, P., Boote, K., Porter, C., Adiku, S., 2019. Sensitivity of Maize Yield in Smallholder Systems to Climate Scenarios in Semi-Arid Regions of West Africa: Accounting for Variability in Farm Management Practices. Agronomy 9, 639. https://doi.org/10.3390/agronomy9100639

Fuentes, J.P., Flury, M., Huggins, D.R., Bezdicek, D.F., 2003. Soil water and nitrogen dynamics in dryland cropping systems of Washington State, USA. Soil Tillage Res. 71, 33–47. https://doi.org/10.1016/S0167-1987(02)00161-7

Gathagu, J.N. ang a., Mourad, K.A., Sang, J., 2018. Effectiveness of contour farming and filter strips on ecosystem services. Water (Switzerland) 10. https://doi.org/10.3390/w10101312

Gerardeaux, E., Giner, M., Ramanantsoanirina, A., Dusserre, J., 2012. Positive effects of climate change on rice in Madagascar. Agron. Sustain. Dev. 32, 619–627. https://doi.org/10.1007/s13593-011-0049-6

Ghadiri, H., Rose, C.W., Hogarth, W.L., 2001. The influence of grass and porous barrier strips on runoff hydrology and sediment transport. Trans. Am. Soc. Agric. Eng. 44, 259–268. https://doi.org/10.13031/2013.4687

Gicheru, P., Gachene, C., Mbuvi, J., Mare, E., 2004. Effects of soil management practices and tillage systems on surface soil water conservation and crust formation on a sandy loam in semi-arid Kenya. Soil Tillage Res. 75, 173–184. https://doi.org/10.1016/S0167-1987(03)00161-2

Hawkins, R.H., Ward, T.J., Van Mullem, J.A., Woodward, D.E., 2009. Curve number hydrology : state of the practice. American Society of Civil Engineers.

Henao, J., Baanante, C., 2006. Estimating Rates of Nutrient Depletion in Soils of Agricultural Lands of Africa. Muscle Shoals, Alabama.

Hoogenboom, G., Porter, C.H., Shelia, V., Boote, K.J., Singh, U., White, J.W., Hunt, L.A., Ogoshi, R., Lizaso, J.I., Koo, J., Asseng, S., Singels, A., Moreno, L.P., Jones, J.W., 2019. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7.5 (https://DSSAT.net).

Hulugalle, N.R., 1987. Effect of tied ridges on soil water content, evapotranspiration, root growth and yield of cowpeas in the Sudan Savanna of Burkina Faso. F. Crop. Res. 17, 219–228. https://doi.org/10.1016/0378-4290(87)90036-0

Hunink, J.E., Droogers, P., Kauffman, S., Mwaniki, B.M., Bouma, J., 2012. Quantitative simulation tools to analyze up- and downstream interactions of soil and water conservation measures: Supporting policy making in the Green Water Credits program of Kenya. J. Environ. Manage. 111, 187–194. https://doi.org/10.1016/j.jenvman.2012.07.022

Hunt, L.A., Boote, K.J., 1998. Data for model operation, calibration, and evaluation. Springer, Dordrecht, pp. 9–39. https://doi.org/10.1007/978-94-017-3624-4_2

Hurni, H., W.A., B., P., C., D., D., Zeleke, G., M., G., G., K., 2016. Soil and Water Conservation in Ethiopia: Guidelines for Development Agents, 2nd revise. ed. Centre for Development and Environment (CDE); Bern Open Publishing (BOP), Bern, Switzerland. https://doi.org/10.7892/boris.80013

Jing, Q., Shang, J., Huffman, T., Qian, B., Pattey, E., Liu, J., Dong, T., Drury, C.F., Tremblay, N., 2017. Using the CSM–CERES–Maize model to assess the gap between actual and potential yields of grain maize. J. Agric. Sci. 155, 239–260. https://doi.org/10.1017/S0021859616000290

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model, in: European Journal of Agronomy. pp. 235–265. https://doi.org/10.1016/S1161-0301(02)00107-7

Joshi, N., Singh, A.K., Madramootoo, C.A., 2017. Application of DSSAT Model to Simulate Corn Yield under Long-Term Tillage and Residue Practices. Trans. ASABE 60, 67–83. https://doi.org/10.13031/trans.11545

Kiboi, M.N., Ngetich, K.F., Fliessbach, A., Muriuki, A., Mugendi, D.N., 2019. Soil fertility inputs and tillage influence on maize crop performance and soil water content in the Central Highlands of Kenya. Agric. Water Manag. 217, 316–331. https://doi.org/10.1016/J.AGWAT.2019.03.014

Kpongor, D.S., 2007. Spatially explicit modeling of sorghum (Sorghum bicolor (L.) Moench) production on complex terrain of a semi-arid region in Ghana using APSIM. University of Bonn, Germany.

Kucharik, C.J., Serbin, S.P., 2008. Impacts of recent climate change on Wisconsin corn and soybean yield trends. Environ. Res. Lett. 3, 034003. https://doi.org/10.1088/1748-9326/3/3/034003

Lal, R., 1987. Managing the Soils of Sub-Saharan Africa. Science (80-.). 236, 1069–1076. https://doi.org/10.1126/science.236.4805.1069

Li, Y., Guan, K., Schnitkey, G.D., DeLucia, E., Peng, B., 2019. Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. Glob. Chang. Biol. 25, gcb.14628. https://doi.org/10.1111/gcb.14628

Liu, S., Yang, J.Y., Zhang, X.Y., Drury, C.F., Reynolds, W.D., Hoogenboom, G., 2013. Modelling crop yield, soil water content and soil temperature for a soybean–maize rotation under conventional and conservation tillage systems in Northeast China. Agric. Water Manag. 123, 32–44. https://doi.org/10.1016/J.AGWAT.2013.03.001

Liu, Y., Tao, Y., Wan, K.Y., Zhang, G.S., Liu, D.B., Xiong, G.Y., Chen, F., 2012. Runoff and nutrient losses in citrus orchards on sloping land subjected to different surface mulching practices in the Danjiangkou Reservoir area of China. Agric. Water Manag. 110, 34–40. https://doi.org/10.1016/J.AGWAT.2012.03.011

Ma, J., Maystadt, J.-F., 2017. The impact of weather variations on maize yields and household income: Income diversification as adaptation in rural China. Glob. Environ. Chang. 42, 93–106. https://doi.org/10.1016/J.GLOENVCHA.2016.12.006

Marimi, A.M., 1978. The effects of tillage methods and cropping systems for conserving rainfall in a semiarid area of eastern Kenya, In Soil and WaterConservation in Kenya. Kenya.

Martinsen, V., Munera-Echeverri, J.L., Obia, A., Cornelissen, G., Mulder, J., 2019. Significant build-up of soil organic carbon under climate-smart conservation farming in Sub-Saharan Acrisols. Sci. Total Environ. 660, 97–104. https://doi.org/10.1016/J.SCITOTENV.2018.12.452

Mati, M.B., 2007. 100 ways to manage Water for smallholder agriculture in Eastern and Southern Africa, A Compendium Technologies Practices.SWMnet Working Pap.

Merante, P., Dibari, C., Ferrise, R., Sánchez, B., Iglesias, A., Lesschen, J.P., Kuikman, P., Yeluripati, J., Smith, P., Bindi, M., 2017. Adopting soil organic carbon management practices in soils of varying quality: Implications and perspectives in Europe. Soil Tillage Res. 165, 95–106. https://doi.org/10.1016/J.STILL.2016.08.001

Mhazo, N., Chivenge, P., Chaplot, V., 2016. Tillage impact on soil erosion by water: Discrepancies due to climate and soil characteristics. Agric. Ecosyst. Environ. 230, 231–241. https://doi.org/10.1016/J.AGEE.2016.04.033

Miriti, J.M., Kironchi, G., Esilaba, A.O., Heng, L.K., Gachene, C.K.K., Mwangi, D.M., 2012. Yield and water use efficiencies of maize and cowpea as affected by tillage and cropping systems in semi-arid Eastern Kenya. Agric. Water Manag. 115, 148–155. https://doi.org/10.1016/J.AGWAT.2012.09.002

Mitchell, D., AchutaRao, K., Allen, M., Bethke, I., Beyerle, U., Ciavarella, A., Forster, P.M., Fuglestvedt, J., Gillett, N., Haustein, K., Ingram, W., Iversen, T., Kharin, V., Klingaman, N., Massey, N., Fischer, E., Schleussner, C.F., Scinocca, J., Seland, Ø., Shiogama, H., Shuckburgh, E., Sparrow, S., Stone, D., Uhe, P., Wallom, D., Wehner, M., Zaaboul, R., 2017. Half a degree additional warming, prognosis and projected impacts (HAPPI): Background and experimental design. Geosci. Model Dev. 10, 571–583. https://doi.org/10.5194/gmd-10-571-2017

Mkoga, Z.J., Tumbo, S.D., Kihupi, N., Semoka, J., 2010. Extrapolating effects of conservation tillage on yield, soil moisture and dry spell mitigation using simulation modelling. Phys. Chem. Earth 35, 686–698. https://doi.org/10.1016/j.pce.2010.07.036

Mohamoud, Y.M., 2012. Effect of contour ridging on runoff and soil loss. African J. Agric. Res. 7, 6115–6124. https://doi.org/10.5897/AJAR11.2307

Mupangwa, W., Twomlow, S., Walker, S., 2012. Dead level contours and infiltration pits for risk mitigation in smallholder cropping systems of southern Zimbabwe. Phys. Chem. Earth, Parts A/B/C 47–48, 166–172. https://doi.org/10.1016/J.PCE.2011.06.011

Naab, J.B., Mahama, G.Y., Yahaya, I., Prasad, P.V. V, 2017. Conservation Agriculture Improves Soil Quality, Crop Yield, and Incomes of Smallholder Farmers in North Western Ghana. Front. Plant Sci. 8, 996. https://doi.org/10.3389/fpls.2017.00996

Nafi, E., Webber, H., Danso, I., Naab, J.B., Frei, M., Gaiser, T., 2020. Interactive effects of conservation tillage, residue management, and nitrogen fertilizer application on soil properties under maize-cotton rotation system on highly weathered soils of West Africa. Soil Tillage Res. 196, 104473. https://doi.org/10.1016/J.STILL.2019.104473

Nafi, E., Webber, H., Danso, I., Naab, J.B., Frei, M., Gaiser, T., 2019. Soil tillage, residue management and site interactions affecting nitrogen use efficiency in maize and cotton in the Sudan Savanna of Africa. F. Crop. Res. 244, 107629. https://doi.org/10.1016/J.FCR.2019.107629

Nangia, V., Ahmad, M.-D., Jiantao, D., Changrong, Y., hoogenboom, G., Xurong, M., Wenqing, H., Shuang, L., Qin, L., 2010. Effects of Conservation Agriculture on Land and Water Productivity in Yellow River Basin, China. Int. J. Agric. Biol. Eng. 3, 5–17. https://doi.org/10.25165/IJABE.V3I2.212

Ngwira, A.R., Aune, J.B., Thierfelder, C., 2014. DSSAT modelling of conservation agriculture maize response to climate change in Malawi. Soil Tillage Res. 143, 85–94. https://doi.org/10.1016/J.STILL.2014.05.003

Nyagumbo, I., Munamati, M., Mutsamba, E.F., Thierfelder, C., Cumbane, A., Dias, D., 2015. The effects of tillage, mulching and termite control strategies on termite activity and maize yield under conservation agriculture in Mozambique. Crop Prot. 78, 54–62. https://doi.org/10.1016/J.CROPRO.2015.08.017

Nyamangara, J., Nyagumbo, I., 2010. Interactive effects of selected nutrient resources and tied-ridging on plant growth performance in a semi-arid smallholder farming environment in central Zimbabwe. Nutr. Cycl. Agroecosystems 88, 103–109. https://doi.org/10.1007/s10705-009-9282-7

Nyamekye, C., Thiel, M., Schönbrodt-Stitt, S., Zoungrana, B., Amekudzi, L., 2018. Soil and Water Conservation in Burkina Faso, West Africa. Sustainability 10, 3182. https://doi.org/10.3390/su10093182

Obalum, S.E., Buri, M.M., Nwite, J.C., Hermansah, Watanabe, Y., Igwe, C.A., Wakatsuki, T., 2012. Soil degradation-induced decline in productivity of sub-saharan african soils: The prospects of looking downwards the lowlands with the sawah ecotechnology. Appl. Environ. Soil Sci. https://doi.org/10.1155/2012/673926

Oettli, P., Sultan, B., Baron, C., Vrac, M., 2011. Are regional climate models relevant for crop yield prediction in West Africa? Environ. Res. Lett. 6, 014008. https://doi.org/10.1088/1748-9326/6/1/014008

Om, H., Gh, A.E.-H., Ma, H., Mm, A.E.-E., 2016. Calibration and Validation of DSSAT V.4.6.1, CERES and CROPGROModels for Simulating No-Tillage in Central Delta, Egypt. Agrotechnology 05. https://doi.org/10.4172/2168-9881.1000143

Oyedele, D.J., Aina, P.O., 2006. Response of soil properties and maize yield to simulated erosion by artificial topsoil removal. Plant Soil 284, 375–384. https://doi.org/10.1007/s11104-006-0041-0

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C., 2015. The new assessment of soil loss by water erosion in Europe. Environ. Sci. Policy 54, 438–447. https://doi.org/10.1016/j.envsci.2015.08.012

Parkes, B., Defrance, D., Sultan, B., Ciais, P., Wang, X., 2018. Projected changes in crop yield mean and variability over West Africa in a world 1.5 K warmer than the pre-industrial era. Earth Syst. Dyn. 9, 119–134. https://doi.org/10.5194/esd-9-119-2018

Reddy, P.P., 2016. Micro-Catchment Rainwater Harvesting, in: Sustainable Intensification of Crop Production. Springer Singapore, Singapore, pp. 209–222. https://doi.org/10.1007/978-981-10-2702-4_14

Saïdou, A., Balogoun, I., Ahoton, E.L., Igué, A.M., Youl, S., Ezui, G., Mando, A., 2018. Fertilizer recommendations for maize production in the South Sudan and Sudano-Guinean zones of Benin. Nutr. Cycl. Agroecosystems 110, 361–373. https://doi.org/10.1007/s10705-017-9902-6

Sang, X., Wang, D., Lin, X., 2016. Effects of tillage practices on water consumption characteristics and grain yield of winter wheat under different soil moisture conditions. Soil Tillage Res. 163, 185–194. https://doi.org/10.1016/J.STILL.2016.06.003

Saxton, K.E., Rawls, W.J., Romberger, J.S., Papendick, R.I., 1986. Estimating Generalized Soil-water Characteristics from Texture. Soil Sci. Soc. Am. J. 50, 1031. https://doi.org/10.2136/sssaj1986.03615995005000040039x

Shaxson, T.F., Barber, R.G., Food and Agriculture Organization of the United Nations., 2003. Optimizing soil moisture for plant production : the significance of soil porosity. Food and Agriculture Organization of the United Nations.

Sithole, N.J., Magwaza, L.S., Mafongoya, P.L., 2016. Conservation agriculture and its impact on soil quality and maize yield: A South African perspective. Soil Tillage Res. 162, 55–67. https://doi.org/10.1016/J.STILL.2016.04.014

Soldevilla-Martinez, M., Martin-Lammerding, D., Tenorio, J.L., Walter, I., Quemada, M., Lizaso, J.I., 2013. Simulating improved combinations tillage-rotation under dryland conditions. Spanish J. Agric. Res. 11, 820. https://doi.org/10.5424/sjar/2013113-3747

Sultan, B., Defrance, D., Iizumi, T., 2019. Evidence of crop production losses in West Africa due to historical global warming in two crop models. Sci. Rep. 9. https://doi.org/10.1038/s41598-019-49167-0

Sultan, B., Gaetani, M., 2016. Agriculture in West Africa in the twenty-first century: Climate change and impacts scenarios, and potential for adaptation. Front. Plant Sci. https://doi.org/10.3389/fpls.2016.01262

Sylla, M.B., Pal, J.S., Faye, A., Dimobe, K., Kunstmann, H., 2018. Climate change to severely impact West African basin scale irrigation in 2 °C and 1.5 °C global warming scenarios. Sci. Rep. 8. https://doi.org/10.1038/s41598-018-32736-0

Thierfelder, C., Chisui, J.L., Gama, M., Cheesman, S., Jere, Z.D., Trent Bunderson, W., Eash, N.S., Rusinamhodzi, L., 2013. Maize-based conservation agriculture systems in Malawi: Long-term trends in productivity. F. Crop. Res. 142, 47–57. https://doi.org/10.1016/J.FCR.2012.11.010

Tolessa, D., Du Preez, C.C., Ceronio, G.M., 2014. Effect of tillage system and nitrogen fertilization on the pH, extractable phosphorus and exchangeable potassium of Nitisols in Western Ethiopia. African J. Agric. Res. 9, 2669–2680. https://doi.org/10.5897/AJAR2013.7779

Tovihoudji, P.G., Akponikpè, P.B.I., Agbossou, E.K., Bielders, C.L., 2019. Using the DSSAT Model to Support Decision Making Regarding Fertilizer Microdosing for Maize Production in the Sub-humid Region of Benin. Front. Environ. Sci. 7. https://doi.org/10.3389/fenvs.2019.00013

Vach, M., Hlisnikovský, L., Javůrek, M., 2018. The Effect of Different Tillage Methods on Erosion. Agric. 64, 28–34. https://doi.org/https://doi.org/10.2478/agri-2018-0003

Wang, L., Yuan, X., Liu, C., Li, Z., Chen, F., Li, S., Wu, L., Liu, Y., 2019. Soil C and N dynamics and hydrological processes in a maize-wheat rotation field subjected to different tillage and straw management practices. Agric. Ecosyst. Environ. 285, 106616. https://doi.org/10.1016/J.AGEE.2019.106616

White, J.W., Jones, J.W., Porter, C., McMaster, G.S., Sommer, R., 2010. Issues of spatial and temporal scale in modeling the effects of field operations on soil properties. Oper. Res. 10, 279–299. https://doi.org/10.1007/s12351-009-0067-1

Williams, J.D., Gollany, H.T., Siemens, M.C., Wuest, S.B., Long, D.S., 2009. Comparison of runoff, soil erosion, and winter wheat yields from no-till and inversion tillage production systems in northeastern Oregon. J. Soil Water Conserv. 64, 43–52. https://doi.org/10.2489/jswc.64.1.43

Wolka, K., Mulder, J., Biazin, B., 2018. Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: A review. Agric. Water Manag. 207, 67–79. https://doi.org/10.1016/J.AGWAT.2018.05.016

Xu, H., Twine, T.E., Girvetz, E., 2016. Climate Change and Maize Yield in Iowa. PLoS One 11, e0156083. https://doi.org/10.1371/journal.pone.0156083

Xu, X., An, T., Zhang, J., Sun, Z., Schaeffer, S., Wang, J., 2019. Transformation and stabilization of straw residue carbon in soil affected by soil types, maize straw addition and fertilized levels of soil. Geoderma 337, 622–629. https://doi.org/10.1016/J.GEODERMA.2018.08.018

Yamoah, C.F., Bationo, A., Shapiro, B., Koala, S., 2002. Trend and stability analyses of millet yields treated with fertilizer and crop residues in the Sahel. F. Crop. Res. 75, 53–62. https://doi.org/10.1016/S0378-4290(02)00008-4

Zhang, J.H., Frielinghaus, M., Tian, G., Lobb, D.A., 2004. Ridge and contour tillage effects on soil erosion from steep hillslopes in the Sichuan Basin, China. J. Soil Water Conserv. 59, 277–284.

Chapter 5

General Discussion, Conclusions and Recommendations

1. General Discussion

The goal of this research was twofold.

Firstly, we aimed in identifying management options to improve crop productivity and livelihood among the farming population in the Sudan Savanna of West Africa under the current climate conditions by using monitoring data from long-term field experiments on several sites. We further divided the main objective into the following specific objectives in order to validate it:

1. To assess the single and interactive effects of tillage and crop residue management on crop nitrogen uptake and nitrogen use efficiency (Chapter 2),
2. To assess the single and interactive effects of tillage and crop residue management on soil nutrient stocks and soil organic carbon in four different soil types of West Africa (Chapter 3).

Secondly, we tried to identify which of the management practices show robust performance under future climate conditions. For this purpose, we setup the working objectives as:

1. To calibrate and validate CERES-Maize model using the dataset of 2014 and 2016 (chapter 4)
2. To use the validated model under future climate scenario, identify management practices which offsets or take advantage of the future extreme climate effects on crop productivity based on different soil types (Chapter 4).

Moreover, throughout the entire thesis, we tried to answer the following questions by dividing the thesis into different sections (chapters and published papers)

Q1: How do management practices affect soil quality and crop nutrient uptake and do they behave differently in different soil types?

In agreement with our hypothesis (chapter 2), shifting to contour ridge tillage from reduced tillage might improve crop yield, nitrogen use efficiency, and nitrogen uptake. It is indisputable that, adopting contour ridge tillage instead of reduced tillage, particularly in upslope areas (St2:Eutric Plinthosol and St4:Plinthic Lixisol) could entail benefits like improved crop nitrogen use efficiency (NUE). We suggested that increased NUE of crops under contour tillage is probably linked to higher infiltration of rainwater and higher soil available water content. Other potential soil properties which affect nitrogen uptake and NUE are, for instance soil gravel content, soil organic carbon, total nitrogen, and soil texture. Our study supports other research findings that NUE of crops is strongly attributable to soil available water content which again is influenced by soil gravel content, organic carbon, and textural class. We argued that contour ridge tillage could have acted as a barrier to runoff and erosion loss of soil nutrients, and increased soil water holding capacity, soil nutrient release and uptake by plant roots, thus improving crop NUE. However, in terms of improving crop NUE, crop residue incorporation might not be that efficient compared to tillage effect for both cotton and maize. We are also aware that mineralization of added crop residue might take time. We further stated that the effectiveness of tillage operations and crop residue retention closely related to soil types. These findings indicated that better soil management consisting of contour ridge tillage and crop residue retention (in particular cases) could be a potential solution for maintaining high crop yield through improving nitrogen uptake and its efficient use, particularly in upslope areas.

The findings from the second paper (chapter 3) provide insights into alternative management practices effects on soil fertility in different soils of West Africa and may be used in the development of novel agronomic practices aiming to reduce negative impacts of soil degradation on soil properties and agronomic productivity. Our long-term experiment demonstrated that in an undulated region subject to soil degradation through erosion and runoff, implementation of contour ridge tillage along with crop residue retention displayed the best comprehensive performances in terms of improving soil fertility status. At the same time, in footslope areas (St1:Ferric Lixisol and St3:Haplic Lixisol), adoption of reduced tillage with crop residue retention preserved more nutrients in the surface soil layer, which would eventually restore soil fertility. Here, we emphasized that soil moisture is one of the most prominent factors that alters soil organic carbon density (SOC_{d}), soil organic nitrogen density (SON_d), and soil available potassium density (SK_d) across sites. In fact, both contour ridge tillage and crop residue act as a barrier to the steep slope soils (St2:Eutric Plinthosol and St4:Plinthic Lixisol) that could cutoff sediment loss though runoff and increase soil moisture content by favoring soil water infiltration. Similarly, reduced tillage offers less soil mass disturbance which in turn improves soil aggregate stability and soil moisture content. Strong positive correlation among SOC_d, STN_d, SK_d, and crop yield were also observed. This highlights the fact that crop yield could be stabilized by improving SOC_d, STN_d, and SK_d, especially in the topsoil layer under particular site-specific management practices as stated in this research. Thus, embracing resource conserving tillage–based crop establishment practices combined with residue incorporation are crucial for sustainable soil fertility management and crop productivity under maize-cotton rotation in smallholder production systems in West Africa.

Q2: Can DSSAT reproduce the effects of contour ridge tillage and reduced tillage along with crop residue on crop yield?

Our parametrization of the tillage module led to a reasonably good reproduction of the observed maize biomass and grain yield during the 2012 and 2014 maize growing seasons both for the contour ridge tillage and reduced tillage, as indicated by the nRMSE, MRAE, d-index between observed and simulated data. For model calibration under CA (reduced tillage with crop residues), a considerably lower nRMSE and MRAE, and a higher d-index (Chapter 4, Figure 2) indicated good agreement between simulated and observed maize yield and biomass for all soil types. Furthermore, the calibrated model exemplified a similar or even slightly better agreement between the simulated and observed maize yield under the CA system for all soil types during model validation (Chapter 4, Figure 3) as evidenced by low nRMSE and MRAE, and higher R^2 and d-index. Besides the CA system, we also introduced another tillage option, contour ridge tillage, in order to simulate maize yield and biomass under this tillage practice. Relative to CA, calibration of contour ridge tillage along with crop residue showed better accuracy in terms of simulating maize biomass production As evidenced by Figure 3 and 4 (Chapter 4), good agreement (low nRMSE and MRAE, and higher R^2 and d-index) between the simulated and observed maize yield and biomass under the contour ridge tillage system was recorded for all soil types. In addition, we performed paired t-test to verify any significant mean difference between tillage practices, and the simulated and observed maize yield and biomass (Chapter 4, Table 7). Overall, the performance of the calibrated and validated tillage module in DSSAT v. 4.7.5 was generally acceptable for the purpose of simulating maize yield and biomass for all soil types, but of course with few exceptions. For example, the simulated maize yield and biomass followed the observed values reasonably well, expect for St3, where the model showed slight discrepancy between the simulated and observed maize biomass. A further examination through t-test (Chapter 4, Table 6) illustrated that significant differences in simulated maize yield and biomass between the two tillage systems for St3 and St4, while no such difference was recorded for St1 and St2. A similar trend was also recorded for the observed data. Thus, it was confirmed that parameterization of the tillage module was adequate, and therefore, this model is a reliable tool for climate change impact studies in such geographic conditions.

Q3: Can different tillage practices along with residue management buffer the future extreme climate effects on crop yield in different soil types?

This research suggests that contour ridge tillage along with crop residue incorporation could be a valuable alternative to other management options in soil types (St3: Eutric Plinthosol, upslope in Dano and St4: Plinthic Lixisol, upslope in Dassari) located in upslope positions as higher maize yield was evidenced under contour ridge tillage during both baseline and future climate scenario (Chapter 4, Figure 5). On the other hand, in St3, Haplic Lixisol, footslope in Dassari, higher maize yield was recorded during both baseline and future climate scenario upon switching into reduced tillage along with crop residue application. The plots of cumulative probability distribution (CPD) at 0.5 illustrated that (Chapter 4, Figure 7) the mean simulated maize yield for both baseline and future climate scenarios was higher under contour ridge tillage practice along with crop residue incorporation and recommended N fertilizer rate (60 kg ha^{-1}) in St2 and St4. We argued that enhanced soil water availability under contour ridge tillage system could lead to increased nutrient availability and maize yield.

Simultaneously, implementation of reduced tillage along with crop residue and recommended N fertilizer rate was advantageous over contour ridge tillage in St1 (Ferric Lixisol, footslope in Dano) and St3 (Haplic Lixisol, footslope in Dassari) under both climate scenarios (baseline and future). Enhanced soil water content and soil organic carbon stock under reduced tillage and crop residue incorporation at the footslope in Dassari resulted in improved soil properties that stimulated maize yield.

Furthermore, Figure 7 (Chapter 4) illustrated that the cumulative probability curve for contour ridge tillage placed in the far-right side of the plot in St2 and St4, while the it is opposite is true in St3 where the curve for reduced tillage located in the far-right side of the plot. This suggests that contour ridge tillage along with crop residue incorporation has lower probability of low yield than reduce tillage in St2 and St4. Additionally, reduced tillage with crop residue application has also lower probability of low yield than contour ridge tillage in St3. According to Danso et al., (2018), a higher crop (maize) yield was also attributed to contour ridge tillage system compared to reduced tillage system. Our results (Chapter 2 and 3) also showed a higher crop NUE, SOC, and soil nutrient stocks under contour ridge tillage in St2 and St4, while a better condition was observed under the reduced tillage system in St3. No difference in crop yield and soil properties between two tillage systems was observed, neither during experiments nor in the simulation study. Thus, contour ridge tillage and crop residue application could be preferred by risk-averse farmers in this region during future extreme climatic conditions in soil types like St2 and St4. Similarly, reduced tillage along with crop residue application could be a possible alternative to conventional farmers' practice in St3 to combat future climate change effects on maize yield.

2. Conclusion

Taken together, our results suggest that contour ridge tillage with crop residue retention generally resulted in improved NUE of both maize and cotton in upslope areas by improving soil N availability and soil available water content. On footslope areas, the effects of the two tillage practices was less pronounced. Our experiment further demonstrated that in a gently undulated region subject to soil degradation through runoff and erosion, implementation of contour ridge tillage along with crop residue retention in upslope areas maintained soil fertility and sustained crop productivity. On the other hand, in footslope areas, adoption of reduced tillage with crop residue retention could be more beneficial. Finally, long term future climate simulations and cumulative probability distribution confirmed that contour ridge tillage along with crop residue application could lead positive changes in maize yield at upslope field sites under a future 2-degree warming scenario, where soil erosion and loss of water and nutrients through runoff is a serious risk. Simultaneously, reduced tillage with crop residue application could be a valuable alternative to farmer's practice in fields with deep soils at footslope position, as it resulted in higher increase of maize yield under future 2-degree warming compared to the baseline and could be preferred by risk-averse farmers. Maize production on gravelly soils with low water retention capacity (St1) may suffer from future 2-degree warming regardless of the tillage practice. Hence, application of site-specific tillage operations and crop residue application has the potential to buffer future warming effects on maize yield as confirmed by DSSAT simulations. Also, we feel the importance of sharing this information to the local smallholders, policy makers, and scientific communities to adjust their decisions accordingly, and redirect their steps towards improving crop nitrogen use efficiency and soil fertility which in turn can sustain crop productivity.

3. Recommendations

Recommendations for further studies include:

1. DSSAT simulations were operated at field scale in our study. However, in order to assess the future climate change under varying agronomic management practices on regional crop productivity, an upscaling is necessary by e.g. using gridded soil and climate input data at high resolution.
2. Another approach would be to deploy a multi-model ensemble approach using member models that can simulate tillage effects on crop productivity. Such an ensemble method has the potential to improve predictions by reducing uncertainties related to individual crop models.

4. General References

Adejuwon, J., 2005. Assessing the suitability of the EPIC crop model for use in the study of impacts of climate variability and climate change in West Africa.Singap. J. Trop. Geogr. 26, 44–60. https://doi.org/10.1111/j.0129-7619.2005.00203.x

Alvarez, R., 2006. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. Soil Use Manag. 21, 38–52. https://doi.org/10.1111/j.1475-2743.2005.tb00105.x

Angima, S.., Stott, D.., O'Neill, M.., Ong, C.., Weesies, G.., 2003. Soil erosion prediction using RUSLE for central Kenyan highland conditions. Agric. Ecosyst. Environ. 97, 295–308. https://doi.org/10.1016/S0167-8809(03)00011-2

Asiamah, R.D., Quansah, C., Dedzoe, C.D., 2000. Soil degradation: management and rehabilitation in Ghana- an overview report, in: Proceedings of the FAO/ISCW Expert Consultation On: Management of Degraded Soils in Southern and East Africa (MADS-SEA), 2nd Network Meeting, 18-22 September, 2000. Pretoria South Africa, pp. 89–101.

Babalola, O., Opara-Nadi, O.A., 1993. Tillage systems and soil properties in West Africa. Soil Tillage Res. 27, 149–174. https://doi.org/10.1016/0167-1987(93)90066-X

Baptista, I., Ritsema, C., Geissen, V., 2015. Effect of Integrated Water-Nutrient Management Strategies on Soil Erosion Mediated Nutrient Loss and Crop Productivity in Cabo Verde Drylands. PLoS One 10, e0134244. https://doi.org/10.1371/journal.pone.0134244

Basso, B., Ritchie, J.T., 2015. Simulating Crop Growth and Biogeochemical Fluxes in Response to Land Management Using the SALUS Model. Environ. Sci.

Basso, B., Ritchie, J.T., Grace, P.R., Sartori, L., 2006. Simulation of Tillage Systems Impact on Soil Biophysical Properties Using the SALUS Model. Ital. J. Agron. 1, 677. https://doi.org/10.4081/ija.2006.677

Blanco-Canqui, H., Lal, R., 2009. Crop residue removal impacts on soil productivity and environmental quality. CRC. Crit. Rev. Plant Sci. 28, 139–163. https://doi.org/10.1080/07352680902776507

Blanco-Canqui, H., Lal, R., 2007. Regional assessment of soil compaction and structural properties under no-tillage farming. Soil Sci. Soc. Am. J. 71, 1770–1778. https://doi.org/10.2136/sssaj2007.0048

Bodner, G., Scholl, P., Kaul, H.P., 2013. Field quantification of wetting-drying cycles to predict temporal changes of soil pore size distribution. Soil Tillage Res. 133, 1–9. https://doi.org/10.1016/j.still.2013.05.006

Boko, M., Niang, I., Nyong, A., Vogel, A., Githeko, A., 2018. Africa Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel.

Busari, M.A., Kukal, S.S., Kaur, A., Bhatt, R., Dulazi, A.A., 2015. Conservation tillage impacts on soil, crop and the environment. Int. Soil Water Conserv. Res. https://doi.org/10.1016/j.iswcr.2015.05.002

Butterly, C.R., Baldock, J.A., Tang, C., 2013. The contribution of crop residues to changes in soil pH under field conditions. Plant Soil 366, 185–198. https://doi.org/10.1007/s11104-012-1422-1

Callo-Concha, D., Gaiser, T., Ewert, F., 2012. Farming and cropping systems in the West African Sudanian Savanna. WASCAL research area: Northern Ghana, Southwest Burkina Faso and Northern Benin, ZEF Working Paper Series 100. Bonn: University of Bonn, Center for Development Research (ZEF).

Carrizo, M.E., Alesso, C.A., Cosentino, D., Imhoff, S., 2015. Aggregation agents and structural stability in soils with different texture and organic carbon contents. Sci. Agric. 72, 75–82. https://doi.org/10.1590/0103-9016-2014-0026

CDKN, C. and D.K.N., 2012. Managing climate extremes and disasters in Africa: Lessons from the SREX report.

Challinor, A., Wheeler, T., Garforth, C., Craufurd, P., Kassam, A., 2007. Assessing the vulnerability of food crop systems in Africa to climate change. Clim. Change 83, 381–399. https://doi.org/10.1007/s10584-007-9249-0

Cillis, D., Maestrini, B., Pezzuolo, A., Marinello, F., Sartori, L., 2018. Modeling soil organic carbon and carbon dioxide emissions in different tillage systems supported by precision agriculture technologies under current climatic conditions. Soil Tillage Res. 183, 51–59. https://doi.org/10.1016/J.STILL.2018.06.001

Corbeels, M., Chirat, G., Messad, S., Thierfelder, C., 2016. Performance and sensitivity of the DSSAT crop growth model in simulating maize yield under conservation agriculture. Eur. J. Agron. 76, 41–53. https://doi.org/10.1016/J.EJA.2016.02.001

Du Preez, C.C., Steyn, J.T., Kotze, E., 2001. Long-term effects of wheat residue management on some fertility indicators of a semi-arid plinthosol. Soil Tillage Res. 63, 25–33. https://doi.org/10.1016/S0167-1987(01)00227-6

Gaiser, T., de Barros, I., Sereke, F., Lange, F.M., 2010. Validation and reliability of the EPIC model to simulate maize production in small-holder farming systems in tropical sub-humid West Africa and semi-arid Brazil. Agric. Ecosyst. Environ. 135, 318–327. https://doi.org/10.1016/j.agee.2009.10.014

Gaiser, T., Stahr, K., Billen, N., Mohammad, M.A.-R., 2008. Modeling carbon sequestration under zero tillage at the regional scale. I. The effect of soil erosion. Ecol. Modell. 218, 110–120. https://doi.org/10.1016/J.ECOLMODEL.2008.06.025

Gerardeaux, E., Giner, M., Ramanantsoanirina, A., Dusserre, J., 2012. Positive effects of climate change on rice in Madagascar. Agron. Sustain. Dev. 32, 619–627. https://doi.org/10.1007/s13593-011-0049-6

Ghimire, R., Norton, J.B., Stahl, P.D., Norton, U., 2014. Soil Microbial Substrate Properties and Microbial Community Responses under Irrigated Organic and Reduced-Tillage Crop and Forage Production Systems. PLoS One 9, e103901. https://doi.org/10.1371/journal.pone.0103901

Gupta, S.C., Lowery, B., Moncrief, J.F., Larson, W.E., 1991. Modeling tillage effects on soil physical properties. Soil Tillage Res. 20, 293–318. https://doi.org/10.1016/0167-1987(91)90045-Y

Hagmann, J., 1996. Mechanical soil conservation with contour ridges: Cure for, or cause of, rill erosion? L. Degrad. Dev. 7, 145–160. https://doi.org/10.1002/(SICI)1099-145X(199606)7:2<145::AID-LDR224>3.0.CO;2-Z

Houghton, D.M., 1986. Handbook of Applied Meteorology. Edited by David D. Houghton, John Wiley & Sons. 1985. Pp 1461. £98.25. Q. J. R. Meteorol. Soc. 112, 561–562. https://doi.org/10.1002/qj.49711247217

Hulugalle, N.R., 1987. Effect of tied ridges on soil water content, evapotranspiration, root growth and yield of cowpeas in the Sudan Savanna of Burkina Faso. F. Crop. Res. 17, 219–228. https://doi.org/10.1016/0378-4290(87)90036-0

Hulugalle, N.R., 1990. Alleviation of soil constraints to crop growth in the upland Alfisols and associated soil groups of the West African Sudan savannah by tied ridges. Soil Tillage Res. 18, 231–247. https://doi.org/10.1016/0167-1987(90)90063-J

Ismail, I., Blevins, R.L., Frye, W.W., 1994. Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci. Soc. Am. J. 58, 193–198. https://doi.org/10.2136/sssaj1994.03615995005800010028x

Jacobs, A., Rauber, R., Ludwig, B., 2009. Impact of reduced tillage on carbon and nitrogen storage of two Haplic Luvisols after 40 years. Soil Tillage Res. 102, 158–164. https://doi.org/10.1016/j.still.2008.08.012

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model, in: European Journal of Agronomy. pp. 235–265. https://doi.org/10.1016/S1161-0301(02)00107-7

Joshi, N., Singh, A.K., Madramootoo, C.A., 2017. Application of DSSAT Model to Simulate Corn Yield under Long-Term Tillage and Residue Practices. Trans. ASABE 60, 67–83. https://doi.org/10.13031/trans.11545

Kalipeni, E., 1996. Demographic response to environmental pressure in Malawi. Popul. Environ. 17, 285–308. https://doi.org/10.1007/BF02208230

Ker, A., 1995. Farming systems of the African savanna: a continent in crisis.

Khaledian, M.R., Mailhol, J.C., Ruelle, P., Rosique, P., 2009. Adapting PILOTE model for water and yield management under direct seeding system: The case of corn and durum wheat in a Mediterranean context. Agric. Water Manag. 96, 757–770. https://doi.org/10.1016/J.AGWAT.2008.10.011

Kiage, L.M., 2013. Perspectives on the assumed causes of land degradation in the rangelands of Sub-Saharan Africa. Prog. Phys. Geogr. Earth Environ. 37, 664–684. https://doi.org/10.1177/0309133313492543

Kumar, K., Goh, K.M., 1999. Crop Residues and Management Practices: Effects on Soil Quality, Soil Nitrogen Dynamics, Crop Yield, and Nitrogen Recovery. Adv. Agron. 68, 197–319. https://doi.org/10.1016/S0065-2113(08)60846-9

Lahmar, R., Bationo, B.A., Dan Lamso, N., Guéro, Y., Tittonell, P., 2012. Tailoring conservation agriculture technologies to West Africa semi-arid zones: Building on traditional local practices for soil restoration. F. Crop. Res. 132, 158–167. https://doi.org/10.1016/j.fcr.2011.09.013

Lal, R., 2005. World crop residues production and implications of its use as a biofuel. Environ. Int. 31, 575–584. https://doi.org/10.1016/j.envint.2004.09.005

Liu, J., Williams, J.R., Zehnder, A.J.B., Yang, H., 2007. GEPIC - modelling wheat yield and crop water productivity with high resolution on a global scale. Agric. Syst. 94, 478–493. https://doi.org/10.1016/j.agsy.2006.11.019

MacCarthy, D.S., Vlek, P.L.G., Fosu-Mensah, B.Y., 2012. The Response of Maize to N Fertilization in a Sub-humid Region of Ghana: Understanding the Processes Using a Crop Simulation Model, in: Improving Soil Fertility Recommendations in Africa Using the Decision Support System for Agrotechnology Transfer (DSSAT). Springer Netherlands, pp. 61–75. https://doi.org/10.1007/978-94-007-2960-5_5

Mitchell, D., AchutaRao, K., Allen, M., Bethke, I., Beyerle, U., Ciavarella, A., Forster, P.M., Fuglestvedt, J., Gillett, N., Haustein, K., Ingram, W., Iversen, T., Kharin, V., Klingaman, N., Massey, N., Fischer, E., Schleussner, C.F., Scinocca, J., Seland, Ø., Shiogama, H., Shuckburgh, E., Sparrow, S., Stone, D., Uhe, P., Wallom, D., Wehner, M., Zaaboul, R., 2017. Half a degree additional warming, prognosis and projected impacts (HAPPI): Background and experimental design. Geosci. Model Dev. 10, 571–583. https://doi.org/10.5194/gmd-10-571-2017

Mkoga, Z.J., Tumbo, S.D., Kihupi, N., Semoka, J., 2010. Extrapolating effects of conservation tillage on yield, soil moisture and dry spell mitigation using simulation modelling. Phys. Chem. Earth 35, 686–698. https://doi.org/10.1016/j.pce.2010.07.036

Morgan, R.P.C. (Royston P.C., 2005. Soil erosion and conservation. Blackwell Pub.

Mrabet, R., 2002. Stratification of soil aggregation and organic matter under conservation tillage systems in Africa. Soil Tillage Res. 66, 119–128. https://doi.org/10.1016/S0167-1987(02)00020-X

Mwansa, B.F., 2016. Assessing the potential of conservation agriculture to off-set the effects of climate change on crop productivity using crop simulations model (APSIM).

Nelson, G.C., Rosegrant, M.W., Koo, J., Robertson, R.D., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., Magalhaes, M., Rowena, V.-S., Ewing, M., Lee, D., Nelson, G., Rosegrant, M., Koo, J., Robertson, R., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., Magalhaes, M., Rowena, V.-S., Ewing, M., Lee, D., 2009. Climate change: Impact on agriculture and costs of adaptation.

Ngwira, A.R., Aune, J.B., Thierfelder, C., 2014. DSSAT modelling of conservation agriculture maize response to climate change in Malawi. Soil Tillage Res. 143, 85–94. https://doi.org/10.1016/J.STILL.2014.05.003

Ogbodo, E.N., 2011. Effect of Crop Residue on Soil Chemical Properties and Rice Yield on an Ultisol at Abakaliki, Southeastern Nigeria. World J. Agric. Sci. 7, 13–18.

Osunbitan, J.A., Oyedele, D.J., Adekalu, K.O., 2005. Tillage effects on bulk density, hydraulic conductivity and strength of a loamy sand soil in southwestern Nigeria. Soil Tillage Res. 82, 57–64. https://doi.org/10.1016/j.still.2004.05.007

Paul, B.K., Vanlauwe, B., Ayuke, F., Gassner, A., Hoogmoed, M., Hurisso, T.T., Koala, S., Lelei, D., Ndabamenye, T., Six, J., Pulleman, M.M., 2013. Medium-term impact of tillage and residue management on soil aggregate stability, soil carbon and crop productivity. Agric. Ecosyst. Environ. 164, 14–22. https://doi.org/10.1016/j.agee.2012.10.003

Rahman, M.H., Okubo, A., Sugiyama, S., Mayland, H.F., 2008. Physical, chemical and microbiological properties of an Andisol as related to land use and tillage practice. Soil Tillage Res. 101, 10–19. https://doi.org/10.1016/j.still.2008.05.006

Rauff, K.O., Bello, R., 2015. A Review of Crop Growth Simulation Models as Tools for Agricultural Meteorology. Agric. Sci. 06, 1098–1105. https://doi.org/10.4236/as.2015.69105

Salinas-Garcia, J.R., Báez-González, A.D., Tiscareño-López, M., Rosales-Robles, E., 2001. Residue removal and tillage interaction effects on soil properties under rain-fed corn production in Central Mexico. Soil Tillage Res. 59, 67–79. https://doi.org/10.1016/S0167-1987(00)00187-2

Samaké, O., Smaling, E.M.A., Kropff, M.J., Stomph, T.J., Kodio, A., 2005. Effects of cultivation practices on spatial variation of soil fertility and millet yields in the Sahel of Mali. Agric. Ecosyst. Environ. 109, 335–345.

Sanchez, P.A., 2002. ECOLOGY: Soil Fertility and Hunger in Africa. Science (80-.). 295, 2019–2020. https://doi.org/10.1126/science.1065256

Senayah, J., Kufogbe, S., Dedzoe, C., 2009. Land degradation in the Sudan Savanna of Ghana: A case study in the Bawku Area. West African J. Appl. Ecol. 8. https://doi.org/10.4314/wajae.v8i1.45805

Shaver, T.M., Petersona, G.A., Ahujab, L.R., Westfalla, D.G., Sherrodb, L.A., Dunnb, G., 2002. Surface soil physical properties after twelve years of dryland no-till management. Soil Sci. Soc. Am. J. 66, 1296–1303. https://doi.org/10.2136/sssaj2002.1296

Soldevilla-Martinez, M., Martin-Lammerding, D., Tenorio, J.L., Walter, I., Quemada, M., Lizaso, J.I., 2013. Simulating improved combinations tillage-rotation under dryland conditions. Spanish J. Agric. Res. 11, 820. https://doi.org/10.5424/sjar/2013113-3747

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., Ciais, P., Guimberteau, M., Traore, S., Baron, C., 2013. Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. Environ. Res. Lett. 8. https://doi.org/10.1088/1748-9326/8/1/014040

Tavares, U.E., Rolim, M.M., de Oliveira, V.S., Pedrosa, E.M.R., Siqueira, G.M., Magalhães, A.G., 2015. Spatial Dependence of Physical Attributes and Mechanical Properties of Ultisol in a Sugarcane Field. Sci. World J. 2015, 531231. https://doi.org/10.1155/2015/531231

Tingem, M., Rivington, M., Bellocchi, G., Colls, J., 2009. Crop yield model validation for Cameroon. Theor. Appl. Climatol. 96, 275–280. https://doi.org/10.1007/s00704-008-0030-8

Traoré, S.B., Alhassane, A., Muller, B., Kouressy, M., Somé, L., Sultan, B., Oettli, P., Siéné Laopé, A.C., Sangaré, S., Vaksmann, M., Diop, M., Dingkhun, M., Baron, C., 2011. Characterizing and modeling the diversity of cropping situations under climatic constraints in West Africa. Atmos. Sci. Lett. 12, 89–95. https://doi.org/10.1002/asl.295

Valbuena, D., Tui, S.H.-K., Teufel, N., Duncan, A., Abdoulaye, T., Swain, B., Mekonnen, K., Germaine, I., 2015. Identifying determinants, pressures and trade-offs of crop residue use in mixed smallholder farms in Sub-Saharan Africa and South Asia. Agric. Syst. 134, 107–118. https://doi.org/10.1016/J.AGSY.2014.05.013

Wang, X., Gassman, P.W., Williams, J.R., Potter, S., Kemanian, A.R., 2008. Modeling the impacts of soil management practices on runoff, sediment yield, maize productivity, and soil organic carbon using APEX. Soil Tillage Res. 101, 78–88. https://doi.org/10.1016/J.STILL.2008.07.014

Waongo, M., Laux, P., Kunstmann, H., 2015. Adaptation to climate change: The impacts of optimized planting dates on attainable maize yields under rainfed conditions in Burkina Faso. Agric. For. Meteorol. 205, 23–39. https://doi.org/10.1016/j.agrformet.2015.02.006

Whitbread, A., Blair, G., Konboon, Y., Lefroy, R., Naklang, K., 2003. Managing crop residues, fertilizers and leaf litters to improve soil C, nutrient balances, and the grain yield of rice and wheat cropping systems in Thailand and Australia, in: Agriculture, Ecosystems and Environment. Elsevier, pp. 251–263. https://doi.org/10.1016/S0167-8809(03)00189-0

Williams, J.R., 1990. The Erosion-Productivity Impact Calculator (EPIC) Model: A Case History. Philos. Trans. Biol. Sci. 329, 421–428. https://doi.org/10.2307/76847

Yang, X., Zheng, L., Yang, Q., Wang, Z., Cui, S., Shen, Y., 2018. Modelling the effects of conservation tillage on crop water productivity, soil water dynamics and evapotranspiration of a maize-winter wheat-soybean rotation system on the Loess

Plateau of China using APSIM. Agric. Syst. 166, 111–123. https://doi.org/10.1016/J.AGSY.2018.08.005

Young, A., 1999. Is there Really Spare Land? A Critique of Estimates of Available Cultivable Land in Developing Countries. Environ. Dev. Sustain. 1, 3–18. https://doi.org/10.1023/A:1010055012699

Zeleke, T.B., Grevers, M.C.J., Si, B.C., Mermut, A.R., Beyene, S., 2004. Effect of residue incorporation on physical properties of the surface soil in the South Central Rift Valley of Ethiopia. Soil Tillage Res. 77, 35–46. https://doi.org/10.1016/j.still.2003.10.005