Zentrum fürEntwicklungsforschung (ZEF)

Dynamics of nitrogen and phosphorus under the impact of climate change and agricultural land use in the West African Sudan Savannah

Dissertation

zur

Erlangung des Grades

Doktor der Agrarwissenschaften (Dr. agr.)

der

Landwirtschaftlichen Fakultät

der

Rheinischen Friedrich-Wilhelms-Universität Bonn

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Bonn 2018

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Tag der mündlichen: 15.12.2017

Angefertigt mit Genehmigung der Landwirtschaftlichen Fakultät der Universität Bonn

DEDICATION

To my sweet mother, kind father, and lovely wife

ABSTRACT

Changing climate and agricultural land-use dynamics seriously challenge the future of cropping in the West African Dry Savannah, and, in turn, the livelihoods and food security of rural populations. Current production systems, already vulnerable to soil fertility depletion, are increasingly exposed to rainfall variability and generally to climate change, which, reportedly is expected to increase. Although consent exist that under the "business-as-usual-scenarios" these challenges will exacerbate resource use efficiency and jeopardize the sustainability of the agro-ecosystems, little is predicted about the magnitude of the adverse effects of changing climate on crop responses and hence land use. This obviously hampers the essential development and implementation of both appropriate adaptation measures and policies to increase the resilience of production systems. This study therefore aimed at quantifying and assessing the impact of predicted climate change on growth, yields, and water- and nutrient- use efficiencies of maize-, sorghum-, and cotton-based production systems in the dry savannah of northern Benin. Through a series of farmer- and researcher-managed on-farm trials, data were collected on crop responses to an un-amended soil (no fertilizer application), an integrated soil-crop management practice (recommended fertilizer rates and crop residues retention), a low use of external inputs (i.e. farmers determined the mineral fertilizer rate), and a high rate of mineral fertilizer use. The datasets, collected in 2014 and 2015 at Ouri Yori village in northern Benin, were used to investigate productivity and nutrient use efficiency of three target crops, and to parameterize and evaluate the CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton Cropping System Models. The three crop models were subsequently applied to assess the impact of climate change on responses of maize, sorghum, and cotton to the different soil fertility management practices tested, considering the historical climate (1986-2005) and the ensemble mean of bias-corrected projected climate (2080-2099) from three Global Climate Models for three Representative Concentration Pathways (RCPs 2.6, 4.5, and 8.5). Biomass and economic yields of all three crops responded to both the high use of mineral fertilizer and the integrated soil-crop management practice, but the extent of this response was crop-specific. The highest agronomic efficiencies of nitrogen (N) and phosphorus (P), their apparent recovery as well as the positive partial N and P balances were recorded with the integrated soil-crop management practice, irrespective of the crops. The CERES-Maize model satisfactorily simulated in-season soil moisture and nitrate dynamics, N and P uptake, biomass accumulation, and grain yield. CERES-Maize predicted furthermore a more vigorous crop growth in the projected than in the historical runs, albeit only during the vegetative growth phase. Under the projected climate change, CERES-Maize predicted decreases in water- and N-use efficiencies, N and P uptake, and grain yield, irrespective of the soil fertility management strategies assumed. Similarly, CERES-Sorghum adequately simulated the observed soil water and N dynamics, biomass accumulation, N and P uptake, and the yield of sorghum. It predicted reductions in water- and N- use efficiencies, N and P uptake, and yield across all climate change scenarios and soil fertility management options. CROPGRO-Cotton simulated well soil water dynamics and N uptake during cotton growth, and seed cotton yield. Under the projected climate scenarios, CROPGRO-Cotton predicted increases in water- and N- use efficiencies and yield with the high use of mineral fertilizer or the integrated soil-crop management practice. Cotton responded more efficiently to N applied with integrated soil-crop management practice under future climate scenarios. The increases in productivity will occur, however, at the expense of soil fertility, unless targeted fertilizer management practices are introduced. The overall increase in understanding water- and nutrient- use efficiencies and yields of maize, sorghum, and cotton under both historical and future climate conditions can contribute to updating soil fertility management recommendations for reaching sustainable agricultural production in the Dry Savannah region of West Africa.

DYNAMIQUE DE L'AZOTE ET DU PHOSPHORE SOUS L'IMPACT DU CHANGEMENT CLIMATIQUE ET DE L'UTILISATION DES TERRES AGRICOLES DANS LA SAVANE SOUDANIENNE DE L’AFRIQUE DE L’OUEST

RESUME

Le changement climatique et la dynamique de l'utilisation des terres agricoles remettent sérieusement en question l'avenir des cultures dans la Savane sèche de l'Afrique de l'Ouest et, en conséquence, les moyens de subsistance et la sécurité alimentaire des populations rurales. Les systèmes de production actuels, déjà vulnérables à l'appauvrissement de la fertilité des sols, sont de plus en plus exposés à la variabilité des pluies et, en général, au changement climatique qui devraient augmenter. Bien que le consensus existe que dans les «scénarios de *statu quo*», ces défis exacerberont l'efficacité de l'utilisation des ressources et mettront en péril la durabilité des agroécosystèmes, peu de projections sont faites sur l'ampleur des effets néfastes du changement climatique et de l’utilisation des terres agricoles sur les réponses des cultures. Ceci entrave évidemment le développement et la mise en œuvre de mesures et de politiques appropriées d'adaptation pour accroître la résilience des systèmes de production. Cette étude visait donc à quantifier et évaluer l'impact du changement climatique prévu sur la croissance, les rendements et l'efficacité de l'utilisation de l'eau et des nutriments des cultures de maïs, sorgho et coton dans la savane sèche au Nord du Bénin. Grâce à une série d'essais menés au champ par des chercheurs et agriculteurs, des données ont été collectées sur les réponses des cultures à un sol non amendé (aucune application d'engrais), une pratique de gestion intégrée du système sol-plante (doses recommandées d’engrais minéraux et recyclage des résidus de récolte), une pratique de faible utilisation d'intrants externes (c.-à-d. doses d'engrais minéraux utilisées par les agriculteurs) et un taux élevé d'utilisation d'engrais minéraux. Les données ont été collectées en 2014 et 2015 au village d’Ouri Yori au Nord du Bénin et ont été utilisées pour étudier la productivité et l'efficacité de l'utilisation des nutriments des trois cultures cibles, et pour paramétrer et évaluer les modèles de cultures, CERES-Maize, CERES-Sorghum et CROPGRO-Cotton. Ensuite, les trois modèles ont été appliqués pour évaluer l'impact du changement climatique sur les réponses du maïs, sorgho et coton sous différentes pratiques de gestion de la fertilité des sols, en considérant le climat historique de 1986-2005 et la moyenne des projections à biais corrigés du changement climatique (2080-2099) à partir de trois modèles climatiques pour trois profils représentatifs d’évolution de concentration (RCPs 2.6, 4.5 et 8.5). Les rendements économique et de la biomasse aérienne des trois cultures ont répondu à la fois au taux élevé d'utilisation d'engrais minéraux et à la pratique de gestion intégrée du système sol-plante, mais l'ampleur de la réponse a été spécifique à chaque culture. Les plus élevées efficacités agronomiques de l'azote (N) et du phosphore (P), leur taux de recouvrement ainsi que les bilans partiels positifs de N et P ont été enregistrés sous la pratique de gestion intégrée du système sol-plante, quelle que soit la culture. Le modèle CERES-Maize a simulé de manière satisfaisante la dynamique de l'humidité du sol et du nitrate au cours de la saison, l'exportation de N et P, la croissance de la biomasse et le rendement du maïs. CERES-Maize a en outre prédit une croissance plus vigoureuse de la biomasse aérienne sous le changement climatique que dans les conditions du climat historique, mais seulement pendant la phase de croissance végétative. Dans le cadre du changement climatique, CERES-Maize a prédit des réductions de l'efficacité de l'utilisation de l'eau et de N, de l'exportation de N et P, et du rendement du maïs indépendamment des stratégies de gestion de la fertilité des sols. De même, CERES-Sorghum a simulé de manière adéquate la dynamique de l’humidité du sol et du nitrate, la croissance de la biomasse, l'exportation de N et P, et le rendement du sorgho. Il a prédit des réductions des efficacités d'utilisation de l'eau et de N, de l'exportation de N et P, et du rendement du sorgho sous tous les scénarios du changement climatique et de gestion de la fertilité des sols. CROPGRO-Cotton a bien simulé la dynamique de l'humidité du sol et l'exportation de N pendant la croissance du coton et le rendement en coton graine. Avec le changement climatique, CROPGRO-Cotton a prédit une augmentation des efficacités d'utilisation de l'eau et de N ainsi qu'une amélioration du rendement en coton graine sous le régime du taux élevé d'utilisation d'engrais minéraux et de la pratique de gestion intégrée du système sol-plante. La réponse du coton a été plus efficace avec la fertilisation azotée sous la pratique de gestion intégrée du système sol-plante dans les scénarios du changement climatique. Ces augmentations de la productivité du coton se réaliseront toutefois au détriment de la fertilité du sol, à moins que des mesures adéquates d'utilisation des engrais ne soient introduites. En somme, l'amélioration de la compréhension de l'efficacité de l'utilisation de l'eau et des nutriments et des rendements du maïs, sorgho et coton dans les conditions du climat historique et futur peut contribuer à la mise à jour des recommandations de gestion de la fertilité des sols pour atteindre une production agricole durable dans la région de la Savane sèche de l'Afrique de l'Ouest.

Einfluss von Klimawandel und Landnutzungsänderungen auf die Stickstoff und Phosphor Dynamik in Anbausystemen der westafrikanischen Trockensavanne

KURZFASSUNG

Klimawandel und Änderungen der Nutzungsdynamik in landwirtschaftlichen Systemen gefährden die Zukunft des Nutzpflanzenanbaus in der Westafrikanischen Trockensavanne. Dies beeinträchtigt den Lebensunterhalt und die Sicherheit der Nahrungsmittelversorgung der ländlichen Bevölkerung. Gerade die vulnerablen Produktionssysteme welche bereits durch den Rückgang der Bodenfruchtbarkeit beeinträchtigt sind- werden, Berichten zufolge, in Zukunft vermehrt Niederschlagsschwankungen und den Auswirkungen des Klimawandels ausgesetzt sein. Unter dem ”business-as-usual“ Szenarien werden die Effizienz der Ressourcennutzung sowie die Nachhaltigkeit der Agrarökosysteme zunehmend beinträchtigen werden. Das künftige Ausmaß möglicher negative Effekte des Klimawandel auf den ertrag von Nutzpflanzen und die agrarische Landnutzung sind ungewiss. Dies hemmt die Entwicklung von notwendigen Anpassungsmaßnahmen und die Implementierung entsprechender politischer Entscheidungen um die Resilienz der Produktionssysteme zu erhöhen. Die vorliegende Studie hatte zum Ziel, den Einfluss des zu erwartenden Klimawandels auf das Wachstum, den Ertrag und die Wasser-Nährstoff-Effizienz von Mais-, Sorghum- und Baumwoll-basierender Produktionssysteme in der Trockensavanne Nord-Benins zu quantifizieren und bewerten. Mehrere Feldversuche wurden in Zusammenarbeit mit Landwirten zwischen 2014 und 2015 im Dorf Ouri Yori in Nord-Benin durchgeführt. Die Untersuchungen lieferten Daten zur Produktivität und der Nährstoffeffizienz von Mais, Sorghum und Baumwolle auf unbehandelten Anbauflächen (ohne Düngemitteleinsatz), auf integrierten Anbauflächen (empfohlene Menge an Düngemittel und Rückfuhr von Ernterückständen), auf Anbauflächen mit minimalem Einsatz externer Betriebsmittel (z.B. Landwirt bestimmte die Höhe der den mineralischen Düngung), sowie auf Anbauflächen mit hohen Applikationsraten mineralischer Dünger. Ferner dienten die Daten der Parametrisierung der wachstumsmodelle CERES-Maize-, CERES-Sorghum-, und CROPGRO-Cotton. Mit den kalibrierten Modelle wurde im Anschluss der Einfluss des Klimawandels auf das Verhalten von Mais, Sorghum und Baumwolle unter verschiedenen Szenarien des Bodenfruchtbarkeitsmanagement abgeschätzt. Dies erfolgte auf der Basis historischer Klimadaten (1986-2005), sowie unter Einbeziehung von prognostizierten zukünftigen Klimaszenarien (2080-2099) und auf Basis des globalen Klimamodells für drei repräsentative Konzentratios-Entwicklungen - Representative Concentration Pathways (RCPs 2.6, 4.5, und 8.5). Der Biomasse- und Kornertrag wurde in allen untersuchten Nutzpflanzen durch Mineraldüngereinsatz gesteigert. Das Ausmaß der Ertragswirksamkeit war jedoch Nutzpflanzen-spezifisch. Die höchste Effizienz von Stickstoff (N) und Phosphor (P), und positive partielle N- und P-Bilanzen wurden im Fall des integrierten Managementansatzes unabhängig von der Nutzpflanze ermittelt. CERES-Maize war in der Lage, die Bodenfeuchtigkeit- und Stickstoff-Dynamiken, N- und P-Aufnahmen, die Biomasseakkumulation und den Kornertrag zufriedenstellend zu simulieren. Verglichen mit historischen Daten, prognostiziert CERES-Maize ein verbessertes Wachtum, allerdings nur in der vegetativen Phase. Andererseits prognostiziert CERES-Maize unter den zu erwartenden Bedingungen des Klimawandels und unabhängig vom Manaagment der Bodenfruchtbarkeit eine verminderte Wasser- und N-Nutzungseffizienz und Aufnahme sowie einen verminderten kornertrag. Mit CERES-Sorghum wurden ähnlich gute Schätzungen des Boden-Wassers- der N-Dynamik, der Biomasseakkumulation, der N- und P-Aufnahme und des Kornertrags von Sorghum erzielt. Demnach ist zukünftig und unabhängig vom

Klimaszenario und dem Management der Bodenfruchtbarkeit mit einer geringeren der Wasser- und N-Nutzungseffizienz und N- und P-Aufnahme sowie eines abnehmenden Kornertrags zu rechnen. CROPGRO-Cotton erzielte gute Ergebnisse in Bezug auf Boden-Wasser-Dynamiken und die N-Aufnahme. Im Gegensatz zu den beiden CERES Modellen prognostizierte CROPGRO-Cotton eine verbesserte Nutzungseffizienz von Wasser und N und steigende Baumwoll-Ertäge bei hohem Mineraldünger-Einsatz und unabhängig vom verwendeten Klimamodell. Während Baumwolle stärker auf N-Applikation reagiert als Mais und Sorghum, so muss allerdings mit einer Abnahme der Bodenfruchtbarkeit gerechnet werden, sofern keine geeigneten Düngungsmaßnahmen ergriffen werden. Die in der vorliegenden Studie gewonnenen Erkenntnisse können zur Entwicklung verbesserter Strategien des Düngungsmanagements von Mais, Sorghum und Baumwolle und somit zu einer Verbesserung der Nachhaltigkeit der künftigen Erzeugung in den Trockensavannen West Afrikas beitragen.

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1 GENERAL INTRODUCTION

1.1 Problem statement

Sustainable agricultural practices are acknowledged means to ease food insecurity and support livelihoods in West Africa, where soil nutrient deficiencies widely prevail. Agriculture in the West African Dry Savannah agro-ecological zone, including northern Benin, is dominated by rainfed cropping systems (Wani et al. 2009) that include crop rotations, intercropping, mono-cropping, and mixed cropping (Callo-Concha et al. 2013). Extensive agricultural practices such as fallow rotations with slash-and-burn practices, have previously been common for restoring soil fertility and improving crop productivity (Grinblat et al. 2015; Jayne et al. 2014), albeit with partial success only (Bationo et al. 2007). Also driven by rapid population growth and the corresponding increase in anthropic pressure on land resources, land is increasingly being converted to agricultural production to meet the growing demand (Forkuor 2014; Liniger et al. 2011). This land use change resulted in wide-spread consequences for landscapes and the provision of ecosystem services. Thus, forests, protected areas, and woodlands have largely disappeared with intense deforestation for agricultural production in Benin (Adomou 2005; Ouorou Barre 2014).

The conversion of forest areas into agricultural land was able to ease production deficits only temporarily. Currently, the agricultural croplands in West Africa are typified by low soil fertility, subject to overexploitation, and managed by unsustainable crop and soil fertility practices (Bationo et al. 2012; Christianson and Vlek 1991; Vanlauwe et al. 2014). Various studies pinpointed the continuous macronutrient-mining and consequent soil fertility depletion, not only in West Africa (e.g. Henao and Baanante 1999), but in fact throughout the entire continent (Stoorvogel and Smaling 1990). West African countries such as Benin, Niger, and Togo lose between 30 and 60 kg ha^{-1} of NPK annually (Henao and Baanante 1999); in Burkina Faso, Gambia, Ghana, Ivory Coast, Mali, Nigeria, and Senegal such losses are estimated at more than 60 kg ha^{-1} (Bationo et al. 2012). In addition, while fertilizer use worldwide reached on average about 122 kg ha^{-1} (Druilhe and Barreiro-Hurlé 2012), only a fraction of that, between 7 and 11 kg ha^{-1}, is applied in Sub-Saharan Africa (Honfoga 2013). Other sources of nutrient inputs such atmospheric dust and wet depositions are hardly significant (Kugbe 2013; Stoorvogel et al. 1997). The nutrient mining practiced over longer periods have thus reduced crop productivity and biological processes gradually, and hence the farming population in West Africa must embrace more sustainable cropping systems to maintain and even improve soil fertility, resource use efficiency, and crop productivity as the means to sustain food availability and their livelihoods.

The threat of soil fertility depletion of the rainfed agricultural production systems in West Africa has been recognized since long (Christianson and Vlek 1991; Gemenet et al. 2015; Schlecht et al. 2007), but an additional threat to agriculture is the forecasted change in key climatic parameters that are reportedly to worsen the resources basis. For example, the predicted changes in rainfall (Cooper et al. 2008; Gbobaniyi et al. 2014; Sylla et al. 2013), increase in temperature (IPCC 2007 2013; Paeth et al. 2009; Riede et al. 2016), and enriched CO_2 environments (IPCC 2013) may alter the soil nutrient pools (Delgado-Baquerizo et al. 2013). This in turn will jeopardize the sustainability of soil fertility management and crop productivity. Furthermore, each nutrient has a specific pathway in the soil-plant systems, however the cycling of carbon (C), nitrogen (N), and (P) in terrestrial ecosystems, including agricultural systems, are interlinked by primary production, respiration, and decomposition (Robertson and Rosswall 1986; Vitousek et al. 2010), although to unknown dimensions. The uncertainties about the magnitude of the effects of weather variability and climate change on nutrient and water use of crops render the development of sustainable measures challenging and hence hamper the implementation of highly needed adaptation measures. To this end, in particular sustainable intensification measures are heralded as potential strategies for the region to cope with the adverse impact of climate change and variability on crop productivity and resource use efficiency (Montpellier Panel 2013; Vanlauwe et al. 2014).

Despite abundant research on the impact of climate change on crop yields and food security worldwide (Rosenzweig et al. 2014; Wheeler and von Braun 2013), research on climate change effects on the resource use efficiency of the main staple and cash crops in West Africa, including the Dry Savannah region of northern Benin, is limited. The development of sustainable intensification practices in this region would benefit not only from long-term data, e.g. on soil-plant-climate systems, but also from increased knowledge and understanding about long-term responses of major staple (e.g. maize (*Zea mays L.)*, sorghum *(Sorghum bicolor* L.)) or cash (e.g. cotton (*Gossypium hirsutum* L.)) crops to soil water and nutrient management practices. This would help defining options to increase the resilience to future climate change e.g. with regards to rainfall, temperature, and CO_2 variability. The absence of key information not only hampers the development of appropriate adaptation measures, but also the elaboration of suitable policies to assist the farming and rural population. Essential for determining suitable site- and crop-specific adaptation options are both *ex-post* and *ex-ante* assessments of crop responses to known and recommended soil management practices while considering different climate change scenarios. To bridge such gaps for the complex soil-plant-climate systems prevailing in the region, empirical research can be complemented with cropping system modeling to support the projection of climate change impact on crop responses and thus aid decision-making.

Although several Cropping System Models (CSM) exist, e.g. CSM of DSSAT (Hoogenboom et al. 2015; Jones et al. 2003), APSIM (Keating et al. 2003) or EPIC (Williams et al. 1989), such crop models need first to be parameterized and evaluated for the target region (Hoogenboom et al. 2012; Hunt and Boote 1998). Furthermore, when envisaging localized climate change impact assessment and in turn the development of adaptation or mitigation options, outputs of Global Circulation Models (GCM) must be bias-corrected (Gudmundsson et al. 2012; Hawkins et al. 2013) with station observations to significantly minimize systematic errors and improve crop models projections of climate change impact on crop responses (Challinor et al. 2017; Glotter et al. 2014).

1.2 Research hypothesis and objectives

In constantly changing agro-ecological environments typified by high intra- and inter-annual variations such as those prevailing in the West African Dry Savannah, it is hypothesized that CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton CSM, once parameterized and validated for the region with empirical research data, can (i) capture accurately crop growth, development, yields, and in-season soil moisture and nutrient uptake, and (ii) subsequently be used in exploring *ex-post* and *ex-ante* responses of crop resource use efficiency to known and recommended soil nutrient management practices, and thus improve decision-making for sustainable nutrient management. The overall objective, therefore, was to assess the impact of predicted climate change on growth, yields, and water- and nutrient- use efficiencies of maize-, sorghum-, and cotton-based production systems in the Dry Savannah agro-ecological zone of northern Benin. The specific working objectives were:

(1) Determine the productivity and N- and P- use efficiencies of maize, sorghum, and cotton under different soil management strategies (Chapter 3);

(2) Evaluate the ability of the CERES-Maize and CERES-Sorghum models for predicting yields, N and P uptake, as well as in-season soil water and N dynamics during maize and sorghum growth, and use hence the models to assess the effects of different nutrient management strategies on soil C and N, and crop water- and N- use efficiencies, considering 30 years of historical weather variability (Chapter 4);

(3) Assess the impact of predicted climate change for the study region on water- and N- use efficiencies, as well as on yields of maize and sorghum (Chapter 5); and

(4) Parameterize the CROPGRO-Cotton model to simulate growth, yield, and in-season soil water dynamics and N uptake, and to apply the model to determine optimum planting dates and potential climate change impact on cotton growth, yields, and water- and N- productivity under different soil fertility management practices (Chapter 6).

1.3 Outline of the thesis

This thesis is structured in seven chapters. The first chapter, the General Introduction, sets the problem, the research hypothesis and the objectives, and provides the outline of this thesis. In the second chapter, the general setting of the study region is briefly described with a focus on the geographical location, climate, vegetation, geology, soils, and dominating socio-economic activities generally relevant for all chapters of this thesis. The Material and Methods used (e.g. field experiments, crop management, and data collection) are described in detail in chapter 2 and subsequent chapters (e.g. 3, 4, 5, and 6). In chapter 3, the current productivity and N- and P- use efficiencies of maize, sorghum, and cotton are highlighted, as a result of experimental trials. These findings formed the bases for estimating N and P partial balances and the dynamics of soil residual nitrate-nitrogen (NO_3-N) and available P dynamics. Working-objective 2 was specifically addressed to show the suitability of CERES-Maize and CERES-Sorghum for modeling growth, N and P uptake, and soil moisture dynamics (Chapter 4). This allowed consequently for describing the effects of known and recommended soil fertility management options on soil organic C, inorganic N, and crop water- and N- use efficiencies and yields assuming 30 years of historical weather variability. The next chapter 5, entirely dedicated to dealing with specific objective 3, highlights the climate change impact on water- and N-use efficiencies, N and P uptake, and yields of maize and sorghum. Chapter 6, addressing working objective 4, provides a description of the evaluation of CROPGRO-Cotton and the impact of climate change on cotton responses. The thesis is completed by chapter 7 in which the overarching findings are discussed and the final conclusions are drawn.

2 GENERAL MATERIAL AND METHODS

2.1 Study region

2.1.1 Geographical location and demography

Field experiments were conducted during the 2014 and 2015 cropping seasons in the village of Ouri Yori (10°49’16’’N, 1°4’7’’E) in the Dassari catchment (10°44'0.15''-10°56'0.6'' N, 01°01'37''-01°11’33’’ E) (Fig. 2.1).

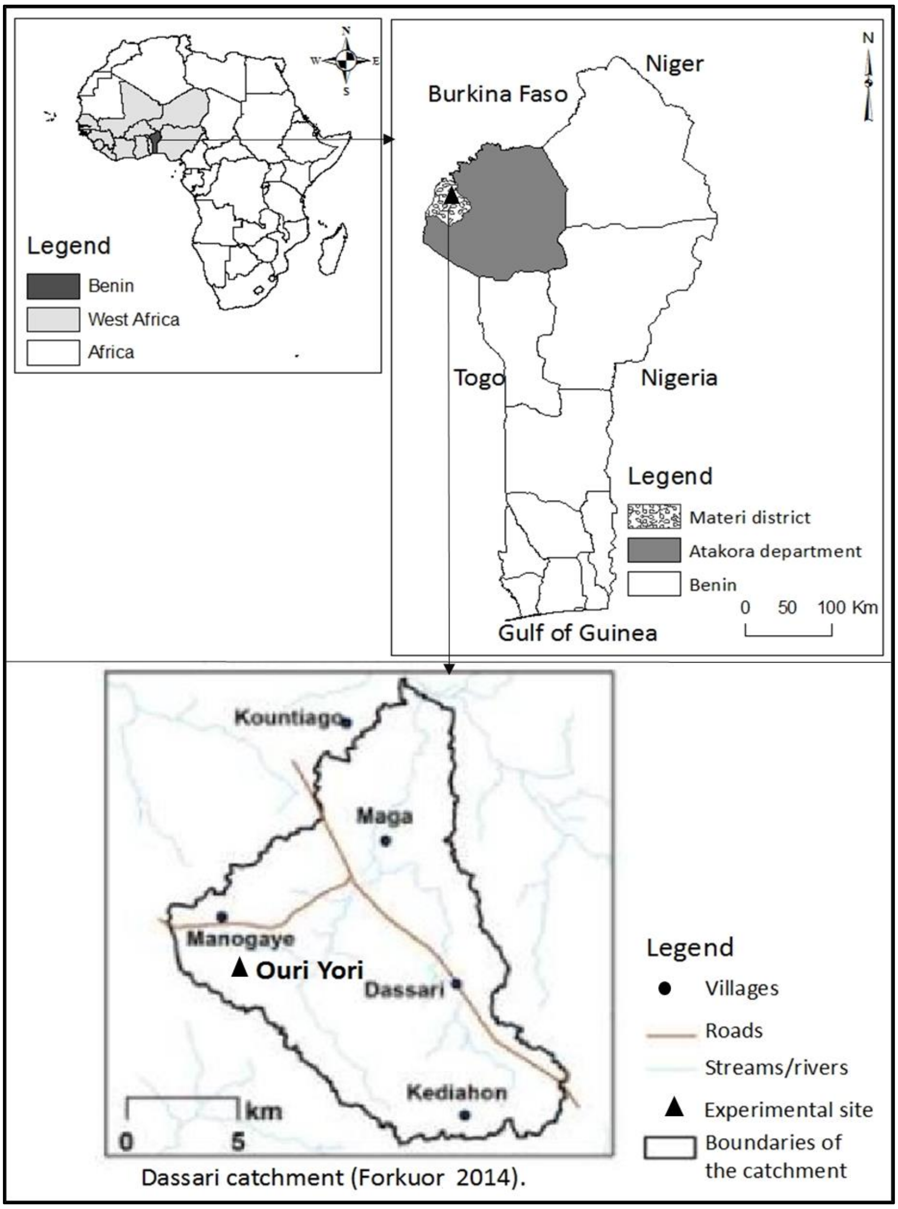

Figure 2.1 Location of Ouri Yori, Dassari catchment in Atakora department of Benin, West Africa.

The catchment belongs to the department of Atakora located in North-west of Benin. Benin is located between the latitudes 6°10'N and 12°25'N and longitudes 0°45'E and 3°55'E in West Africa. It has an area of 112,622 km^2 and borders Niger to the North, Burkina Faso to the North-west, Nigeria to the East, Togo to the West, and the Gulf of Guinea to the South (Fig. 2.1).

2.1.2 Climate

The experimental site of Ouri Yori, representative of the West African Dry Savannah agro-ecological conditions, experiences wet and dry periods usually from May to October and November to April, respectively. West African Sudan Savannah (Dry Savannah) is a continuous belt from Senegal in the West to Nigeria in the East. It limits the Guinean Savannah in the South and the Sahel Savannah in the North (Fund and Hogan 2014; White 1983). The dry savannah climate is under regular influence of circulation of Inter-tropical convergence zone (ITCZ) and West African Monsoon systems (Nicholson 2006).

In the study area, the total annual rainfall amounted to 1099.5±195.8 mm over 1986-2015. The annual mean for minimum temperature, maximum temperature, and solar radiation was 21.4±0.6 °C, 33.7±0.7 °C, and 19.5±0.5 MJ m^{-2} d^{-1}, respectively over the same period. However, the total annual rainfall amounted to 937 mm in 2014 and 1096 mm in 2015 (Fig. 2.2).

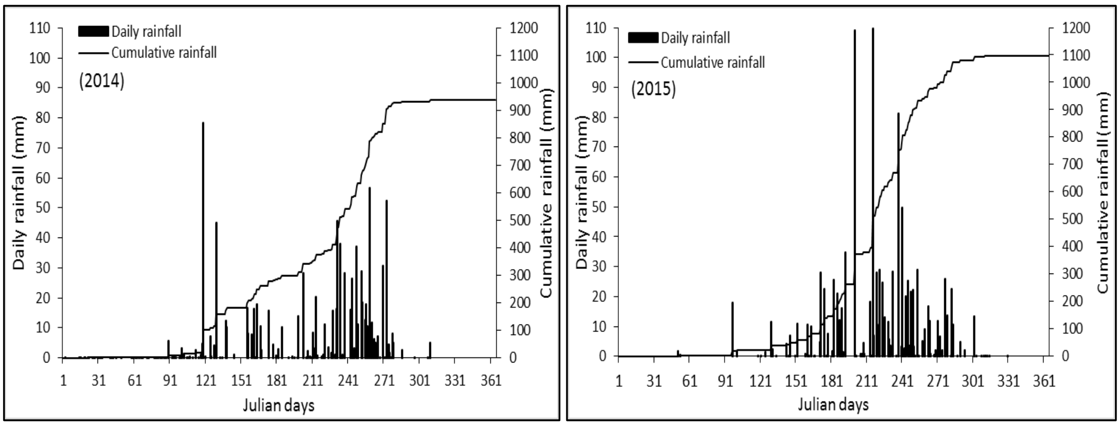

Figure 2.2 Daily and cumulative rainfall distribution during the 2014 and 2015 cropping seasons at the Ouri Yori village in North Benin.

Rainfall in 2014 peaked in September (347 mm), but in 2015 already in August (429 mm). The mean annual air temperature was 29.3 °C in 2014 and 28.9 °C in 2015. The hottest month in 2014 was March (38 °C), and April in 2015 (40 °C), whilst the coldest month was December in both 2014 (18 °C) and 2015 (16 °C).

2.1.3 Geology and soils

In the department of Atakora, the major soils laid out on geological formation of the Precambrian Volta basin. This basin is composed of the structural units of Atakora, Buem and Oti. The parent rocks of Atakora unit are micaschists and quartzites, while Buem and Oti units are formed with quarto-micaschists and schists, respectively (Faure and Volkoff 1998). Trials were established on the three dominant soil types of the study area, which are Plinthosols and Luvisols on the crests and upper slopes of the inland valleys and Alisols on lower slopes and valley bottom lands (IUSS Working Group WRB 2014; Steup 2016). The Alisols and Plinthosols have a loamy sand texture, whilst Luvisols have a sandy loam texture. The initial characteristics of the three soil types are presented in Table 2.1.

Table 2.1 Initial soil physical and chemical properties at the experimental sites in 2014.

Parameters	Unit	Gleyic Alisols			Dystric Plinthosols			Ferric Luvisols		
		Depths (cm)			Depths (cm)			Depths (cm)		
		0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60
pH H_20 (1:2.5)		5.9	6.1	5.9	6.5	6.8	7.0	6.6	6.4	6.5
C_{org}	g kg^{-1}	2.8	1.4	1.3	7.0	1.8	1.7	6.8	3.1	2.3
N_{tot}	g kg^{-1}	0.5	0.4	0.6	0.9	0.6	0.5	0.8	0.6	0.6
Bray1-P	(mg kg^{-1})	1.0	1.0	1.0	3.0	1.0	2.0	4.0	3.0	1.0
CEC	cmol$_c$ kg^{-1}	6.2	7.8	5.8	6.4	8.6	7.2	8.5	4.6	8.7
Sand	%	82.4	82.1	79.4	75	77.2	63.9	68.7	63.1	27.9
Silt	%	15.2	12.8	10.7	19.9	19.4	26.4	21.1	29.3	32.9
Clay	%	2.5	5	10.9	4	4.5	10.8	4.8	9.3	31.2
Bulk density	(g cm^{-3})	1.4	1.4	1.4	1.5	1.5	1.4	1.5	1.5	1.5

Source: Datasets from Steup (2016)

2.1.4 Vegetation

The study area is covered by southern and northern Sudanian vegetation zones (Wezel et al. 1999). Major vegetation type of these zones encompasses woodlands, woody shrubs, grasses, and gallery forests (White 1983). The past and present zonation of vegetation indicate changes in the vegetation cover, e.g. former tree savannah into shrub or grass savannah, even bare landscapes (Adomou 2005).

Rainfall patterns determine the vegetation gradient in the region (Scheiter and Higgins 2009). East-west and South-north decreasing patterns of rainfall have a correlation with the downwards shifting of the vegetation zones. Yet, the shift in vegetation zones moving from the North towards the South, is associated with micro- and meso-scale climatic changes, which may alter C, N, and P cycles on one, and primary productivity in the other hand.

2.1.5 Demography and socio-economic activity

The population of Benin reached 10 million inhabitants in 2013. The share of females was >51% of the total population, which increased at the rate of 3.5% between 2002 and 2013. The department of the Atakora had a population of 772,000, with about 51% being female. The demographic growth rate was as high as 3.1% and the average household size comprised 7.2 members (INSAE 2015).

The livelihoods of the population are based on the production of staple and cash crops in combination with livestock rearing, forestry, and few off-farm income-generating activities (Callo-Concha et al. 2013; Heubach et al. 2011). Farmers in the case study region often migrate to southern and central Benin or Nigeria in search of fertile lands and casual labor to improve their livelihoods (Sow et al. 2014).

2.2 Field experiments

Three field experiments were conducted to assess the responses of an improved variety of maize (cv. EVDT-97 STR), cotton (cv. H-279-1), and a local variety of sorghum (cv. local) to four soil fertility management systems. The experimental factors and design as well as crop and soil management are summarized in Table 2.2.

In experiment-1 (on-farm researcher-managed trial), maize, sorghum, and cotton were grown under a high use of mineral fertilizer (HMF). Existing fertilizer recommendation rates for the tested crops are 44 kg N ha^{-1}, 15 kg P ha^{-1}, and 17.5 kg K ha^{-1} (Igue et al. 2015; Saidou et al. 2012). In the high mineral fertilizer use treatment, the recommended fertilization rates were almost doubled to test crop responses under nutrient-stress-free and reduced water-stress conditions, and to assess the effectiveness of increased fertilizer use. To minimize water-stress, supplementary irrigation was applied (1.5-8 mm per event of watering) during dry spells. In total 7 and 9 applications occurred over a period of 30 days after planting in 2014 and 38 days after planting in 2015.

In experiment-2 (on-farm researcher-managed trial), treatments comprised an un-amended soil as control (CONT) and an integrated soil-crop management practice (ISC) combining the recommended mineral fertilizer use and return of crop residues. The integration of crop residues and inorganic fertilizer use is reportedly a potential option for sustainable soil fertility restoration in the region (Lal 2006; Schlecht et al. 2007).

Experiment-3 (farmer-managed trial) comprised the three crops with a low use of external inputs (LEI), i.e. the farmers determined the mineral fertilizer rate. Three farmers intercropped maize with local cowpea (*Vigna anguiculata* L), three other farmers intercropped sorghum with local cowpea whilst three other also grown sole cotton. The cultivation practices were monitored throughout both cropping seasons. The three farmers for each cropping system were considered as replications. The objective of experiment-3 was to record in details farmers' practices with respect to their crop and soil management and compare these to the practices under the researcher-managed fields. Farmers decided on all management practices while researchers documented them. The density of cowpea in the "intercropping" system amounted to less than 1 plant m^{-2}, reflecting more a situation of a "pure" maize and sorghum stand than that of a purposely designed intercropping stand. Therefore, the "intercropping" systems were analyzed as sole production systems.

Table 2.2 Description of experimental treatments, design, and management practices in the three field experiments carried out during the 2014 and 2015 cropping seasons.

Designations	Experiment-1	Experiment-2	Experiment-3
Treatments	High use of mineral fertilizer (HMF)	Un-amended soil as control (CONT), and integrated soil-crop (ISC)	Low external input (LEI)
Exp. design	Randomized complete block design (RCBD)	RCBD	RCBD
Replications	3	3	3 farmers per cropping system
Plots size	6 m X 5 m	7 m X 4.2 m	0.5-1.5 ha
Test crops	Maize, sorghum, cotton	Maize, sorghum, cotton	Maize, sorghum, cotton
Soil type	Gleyic Alisols	Gleyic Alisols	Alisols, Plinthosols, Luvisols
Planting dates	2014: July 19th 2015: June 23th	2014: July 4th 2015: June 25th	2014: July 18th -31st 2015: June 23rd -July25th
Planting scheme	For maize and sorghum: - 80 cm x 40 cm For cotton: - 80 cm x 30 cm	For maize and sorghum: - 80 cm x 40 cm For cotton: - 80 cm x 30 cm	For each main crop 70-80 cm x 40-50 cm
Density at seeding	For maize and sorghum: - 6 plants m^{-2} For cotton: - 8 plants m^{-2}	For maize and sorghum: 6 plants m^{-2} For cotton: 8 plants m^{-2}	5-7 plants m^{-2}
Fertilizer rates	80 kg N ha^{-1} , 26 kg P ha^{-1} , and 30 kg K ha^{-1}	CONT: no fertilizers; ISC: 44 kg N ha^{-1} , 15 kg P ha^{-1} , and 17.5 kg K ha^{-1} + residues retention	Different rates according to farmers (Table 3)
Weeding	Regularly weeded manually	Regularly weeded manually	Weeded twice in each season
Net plot	4 m X 2 m	4 m X 2 m	4 m X 2 m, 3 replications per plot

Experiment-1: On-farm researcher-managed trial with high mineral fertilizer use (HMF)
Experiment-2: On-farm researcher-managed trial with an un-amended soil as control (CONT) and integrated soil-crop management (ISC)
Experiment-3: On-farm farmer-managed trial with low use of external inputs (LEI)

2.3 Soil and crop management

In both seasons before planting, all experimental plots were tilled to 15-cm depth using an animal-drawn plow. The previous crop residues were removed from the control (experiment-2) and high mineral fertilizer use (experiment-1) plots, but the remaining surface residues were incorporated into the soil during the tillage. For the integrated soil-crop management treatment plots (experiment-2), all crop residues were incorporated into the soil. In the farmer-managed trial (experiment-3), plots were sprayed with glyphosate (300-600 g a.i. ha^{-1}) following tillage to clear any remaining weeds.

During both seasons, crops were planted at the first suitable occasions (Table 2.2). Planting densities of all crops as well as fertilization timing in experiments-1 and 2 (Table 2.2) followed local recommendations by the national agricultural extension services (Igue et al. 2015; Saidou et al. 2012). In experiment-3, farmers planted all crops according to their own scheme (Table 2.2). Thinning of seedlings was done during the first weeding (≈ 15 days after planting) leaving 2 plants per stand in experiments-1 and 2. Farmers did not thin seedlings in experiment-3.

In experiment-1 for maize and sorghum, N fertilizer (80 kg N ha^{-1}) was split-applied as urea (46%), 50% of the total amount at 20 days after planting, and the remaining 50% at 45 days after planting. During the first N application, P as triple superphosphate (46% P_2O_5) and K as potassium chloride (60% K_2O) were applied at rates of 26 and 30 kg ha^{-1}, respectively. For cotton, a compound fertilizer containing NPK as well as sulfur (S) and boron (B) was applied at the rates of 21, 15, 17.5, 7.5, and 0.25 kg ha^{-1}, respectively. During this application, the quantity of N, P, and K was topped up with 19, 11, and 12.5 kg ha^{-1} using urea, triple superphosphate, and potassium chloride, respectively. Nitrogen was top-dressed at a rate of 40 kg N ha^{-1} using urea bringing the total N applied to cotton to also 80 kg ha^{-1} (Table 2.2).

In experiment-2, maize and sorghum received N, P, and K for the first fertilization (21 days after planting) at the rates of 21, 15, and 17.5 kg ha^{-1} as urea, triple superphosphate, and potassium chloride, respectively. The same amounts of N, P, and K were applied to cotton but using the compound fertilizer NPKSB thus applying 7.5 kg S ha^{-1} and 0.25 kg B ha^{-1}. Each crop received 23 kg N ha^{-1} as urea for the second fertilization (40 days after planting in 2014 and 42 in 2015) bringing the total N applied to all crops to 44 kg ha^{-1} (Table 2.2).

In experiment-3, only maize and cotton were fertilized by the farmers with a combination of compound fertilizer and urea as is typically done, leading to different rates of application (Table 2.3).

Table 2.3 Rates of N, P, and K applied by farmers (n=3) participating in experiment-3 to maize and cotton in 2014 and 2015 cropping seasons.

Seasons	Nutrients	Units	Maize/Cowpea intercropping*			Sole cotton		
			Farmer 1	Farmer 2	Farmer 3	Farmer 1	Farmer 2	Farmer 3
2014	N	kg ha^{-1}	35	47	28	18	50	27
	P	kg ha^{-1}	25	33	20	13	10	9
	K	kg ha^{-1}	29	39	23	15	12	11
2015	N	kg ha^{-1}	12	23	23	18	47	23
	P	kg ha^{-1}	8	4	6	3	10	6
	K	kg ha^{-1}	10	5	7	3	14	7

* Although farmers included cowpea as an intercrop, the density was less than 1 plant m^{-2}. Therefore, this crop arrangement was considered as a sole crop during further analyses

Cotton was sprayed against pests in all experiments between first flowering (35-40 days after planting) and physiological maturity (≈120 days after planting). In the experiments-1 and 2, cotton was sprayed six times. The first and second sprays involved Emamectin benzoate (24 g a.i. ha^{-1}) and Acetamiprid (32 g a.i. ha^{-1}), the third and fourth Lambda-Cyhalothrin (7.5 g a.i. ha^{-1}) and Profenofos (100 g a.i. ha^{-1}), and the fifth and sixth Lambda-Cyhalothrin (20 g a.i. ha^{-1}) and Acetamiprid (15 g a.i. ha^{-1}). The farmers in experiment-3 conducted 4-6 phytosanitary sprays always with the same pesticides.

2.4 Data collection

2.4.1 Assessment of aboveground biomass and economic yields

From 20 days after planting till harvest, aboveground biomass was assessed fortnightly in experiments-1 and 2 during the 2015 season, resulting in 7 measurements for maize and 9 for both sorghum and cotton. At each aboveground biomass assessment, whole plants were cut from three randomly selected plant stands in the outer bordered rows. The fresh aboveground biomass was chopped, mixed, and weighed with a portable scale and subsampled. The subsamples were weighed and oven-dried at 70°C till constant weight. The oven-dried samples were weighed again and dry matter (DM) content extrapolated to kg DM ha^{-1}.

At final harvest in 2014 and 2015, economic yields (grain of maize and sorghum and seed + lint of cotton) and stover yields were determined by harvesting the net plots in each experiment (Table 2.2). The fresh weight of all harvested fractions was weighed with a portable scale in the field, subsampled, and oven-dried at 70°C till constant weight to determine the moisture content and dry matter (kg DM ha^{-1}). The total aboveground biomass from the net plot was weighed fresh and subsamples were taken, and oven-dried to determine total aboveground biomass DM.

2.4.2 Soil and plant sampling and analysis, and weather data recording

In experiment-2, soils were sampled twice in 2014 (before planting and at final harvest) and 3 times in 2015 (3 weeks before planting, at planting, and at final harvest) for determination of NO_3-N and available P. At each sampling event, the soil was sampled at 3 random spots in each plot over 3 soil depths (0-20, 20-40, and 40-60 cm). The samples from each depth were bulked per plot and thoroughly mixed. The composite subsamples were analyzed for NO_3-N according to IITA (1982) and available P following the Bray1 procedure (Bray and Kurtz 1945).

The dried subsamples of maize and sorghum grain and seed cotton as well as the stover of all crops from the net plot at final harvest were ground with a Wiley mill to pass a 2 mm sieve and subsampled. The subsamples were analyzed for N and P contents. A fraction of each ground sample (0.5 g) was digested in a mixture of sulfuric acid, selenium oxychloride, and salicylic acid by heating gradually until complete mineralization. Contents of N and P in each digest were determined with an auto-analyzer (SKALAR) using Nessler's reagent as indicator for N and ammonium molybdate solution as an indicator for P (Anderson and Ingram 1993). The N and P uptake in grain or seed cotton were estimated by multiplying the yields with the N and P concentrations. The N and P uptake of stover was calculated accordingly, albeit by using the stover yield and corresponding N and P contents. The total N and P uptake was extrapolated to kg

ha^{-1} by adding the results of the N and P uptake of all fractions (economic product and stover components).

During the two growing seasons, daily rainfall (mm), minimum and maximum air temperatures (°C), and solar radiation ($MJ\ m^{-2}d^{-1}$) were measured at the experimental site with a Campbell Advanced Weather Station (CR1000). All the sites of the three experiments were located within a 0.5-2 km radius around the weather station.

3 PRODUCTIVITY AND NUTRIENT USE EFFICIENCY OF MAIZE, SORGHUM, AND COTTON

3.1 Introduction

Sustainable production systems are key for achieving food security in West Africa. However, widespread land degradation and soil fertility depletion in the region, often mirrored in macronutrient deficiencies (Bationo et al. 2012; Schlecht et al. 2007), are threatening crop growth and productivity. The prevailing agricultural land-use practices in rainfed cropping systems enhance soil fertility depletion in West Africa (Christianson and Vlek 1991) with negative effects on yields (Lal 2006), productivity (Wu and Ma 2015), and nutrient use efficiency (Dobermann 2007; Murrell 2009). Faced with declining productivity and concurrent growing food demands, West Africa has become a net food importer (FAO 2012), exerting a massive strain on the foreign exchange expenditures.

Agricultural land-use practices in the West African Dry Savannah agro-ecological zone are characterized by diverse cropping systems including crop rotations, intercropping, mono-cropping, mixed cropping, and fallow rotations or combinations thereof (Callo-Concha et al. 2013). Current cropping systems, are predominantly based on the staple crops such as maize*,* sorghum, millet (*Pennisetum glaucum* L.), and yam (*Dioscorea sp*). The cropping systems also include the industrial cash crop cotton and legumes such as groundnut (*Arachis hypogaea* L.) and cowpea. Legumes are typically intercropped with the staple crops, however, their direct contribution to soil fertility enhancement is limited owing to low planting densities (Naab et al. 2008) and low rates of biological N_2-fixation (Sanginga 2003). Furthermore, existing soil fertility management recommendations are insufficiently adjusted to soil, crop or even cropping system (Bationo et al. 2012), and are rarely financially viable (Lamers et al. 2015a, b).

Given the ongoing increase in pressure on land resources, the predicted climate change and variability, and the diversity of crops and cropping environments, the existing “blanket” -type of fertilizer recommendations (Igue et al. 2015; Saidou et al. 2012) are unsuitable to sustain food production now and in the future. To counterbalance the existing nutrient deficiencies, they need to be revised by taking into account site- and system-specific requirements, whilst considering and assessing the feasibility of sustainable cropping strategies such as integrated soil fertility management (Bationo et al. 2007; Vanlauwe et al. 2010) or integrated nutrient management (Wu and Ma 2015). However, identifying sustainable soil fertility management practices necessitates knowledge and understanding of crop-specific response patterns, plant nutrient uptake and use efficiency, which have until today rarely been assessed for the Dry Savannah agro-ecological zone in West Africa, including northern Benin. To support a better-informed decision making on site- and crop-specific soil fertility management, the objective of this study was to determine the productivity and N- and P- use efficiencies of maize, sorghum, and cotton under different soil management strategies in the dry savannah of northern Benin.

3.2 Material and methods

3.2.1 Experimental site

Field experiments were conducted in northern Benin dry savannah during the 2014 and 2015 growing seasons. The experimental area is described in detail in section 2.1.

3.2.2 Crop and soil management

The three field experiments and the rationale of the soil fertility management treatments tested as well as crop and soil management practices are previously reported (Sections 2.2, 2.3).

3.2.3 Data collection

Datasets for aboveground biomass accumulation, economic yields, total N and P uptake of each crop, and times series soil NO_3-N and available P were collected as described in section 2.4.

3.2.4 Evaluation of nutrient use efficiency

N- and P- use efficiencies were evaluated using the agronomic efficiency (AE) as an indicator for the improvement of productivity per unit of nutrient applied and the apparent recovery efficiency (RE) as a proxy for assessing nutrient uptake by crops relative to the amount of nutrient applied (Dobermann 2007; Murrell 2009). The indicator ratios were computed as:

(1) $AE = (Y-Y_0)/F$ and

(2) $RE = (U-U_0)/F$

where Y is the yield of the harvested portion of the respective crops (maize, sorghum, and cotton) with nutrients applied (kg ha^{-1}); Y_0 is the yield without nutrients applied (kg ha^{-1}); F is the amount of nutrients (N and P) applied (kg ha^{-1}); U is the total nutrient (N and P) uptake in aboveground biomass with nutrients applied (kg ha^{-1}); and U_0 is the nutrient uptake in aboveground biomass without nutrients applied (kg ha^{-1}).

3.2.5 Evaluation of N and P partial balances

The N and P partial balances were estimated for the maize-, sorghum-, and cotton-based production systems during the 2014 and 2015 growing seasons. The N and P input pathways comprised the application of fertilizers and the crop residues retention. The output pathways included the removal of the harvested products and crop residues. All crop residues under the integrated soil-crop management practice were left as surface mulch and incorporated into the soil during land preparation. The residues were removed from the other three fertility management treatments (un-amended soil, low use of external inputs, and high use of mineral fertilizer). Additional N-input pathways such as through biological N_2-fixation, wet and dry deposition, and sedimentation or N losses through, for example, erosion, leaching, denitrification, and ammonia volatilization, were not considered. Similarly, P input through atmospheric deposition or losses through, for example, leaching and erosion were not considered in the analyses. The partial balances for N and P were computed as the difference between the estimated inputs and outputs (Adamtey et al. 2016; Buerkert et al. 2005).

3.2.6 Statistical analysis

The effects of the four soil fertility management systems on the economic yields (grain and seed cotton), aboveground biomass, N and P uptake, and N- and P-agronomic efficiency and apparent recovery of each crop were analyzed within seasons while comparing the inter-seasonal changes. A linear robust mixed effects model (Milliken and Johnson 2009; Mitchell 2015) was used under Stata 14.0 to account for repeated measurements, to correct for putative heteroscedasticity, and to analyze the margins with a pairwise comparison between and within factors. Hereby soil fertility management systems and seasons were considered as fixed effects and replications as a random factor. The least significant difference (LSD), multi-comparisons method was used to separate the mean values at 5% level. The effects of soil fertility management systems and monitoring time on aboveground biomass accumulation of each crop during the 2015 cropping season in the experiments-1 and 2 were analyzed also with the linear robust mixed effects model. The same method was used to analyze soil NO_3-N and available P in each production system of experiment-2. Hereby soil fertility management systems, soil depths, and monitoring time were considered fixed effects and replications as a random factor. The correlation between economic yield, aboveground biomass, and N and P uptake was assessed for each production system with Stata 14.0. The N and P partial balances were analyzed graphically using a bar chart.

3.3 Results

3.3.1 Aboveground biomass accumulation

In experiments-1 and 2, there were no significant differences in maize aboveground biomass accumulation between the treatments (un-amended soil, integrated soil-crop management practice, and high use of mineral fertilizer) during the first 30 days after planting (Fig. 3.1a). Thereafter, aboveground biomass values were significantly higher with high use of mineral fertilizer and integrated soil-crop management practice compared to un-amended soil. Similarly, early-season sorghum aboveground biomass accumulation did not differ significantly between the three soil fertility management systems up to 60 days after planting (Fig. 3.1b). Between 60 days after planting and final harvest (128 days after planting), differences became substantial: sorghum biomass growth was the highest with high use of mineral fertilizer and lowest with un-amended soil. No significant differences were observed in cotton aboveground biomass accrual in response to soil fertility management systems between 20 and 50 days after planting (Fig. 3.1c). Thereafter, cotton aboveground biomass increased faster with high use of mineral fertilizer and integrated soil-crop management practice relative to un-amended soil.

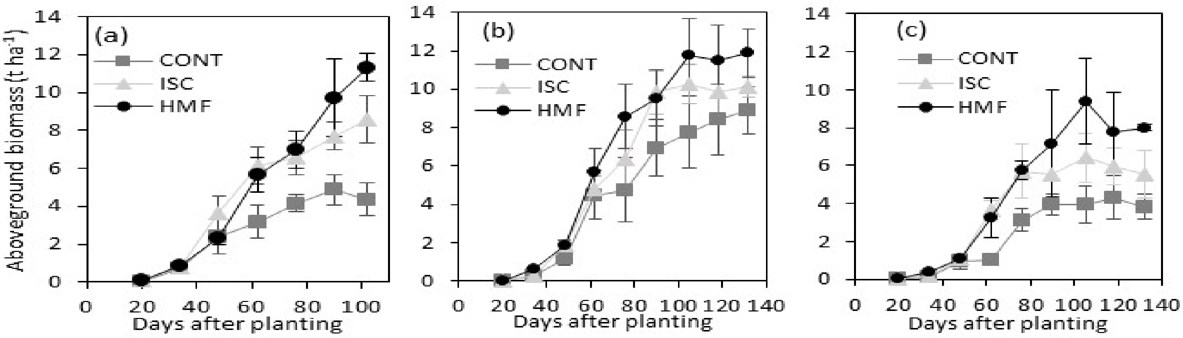

Figure 3.1 Aboveground biomass response to un-amended soil (CONT), integrated soil-crop management practice (ISC), and high use of mineral fertilizer (HMF) of maize (a), sorghum (b), and cotton (c) during the 2015 cropping season in experiments 1 and 2.

Source of variation: SMS ($p< 0.001$), time ($P < 0.001$), and SMS x time ($P < 0.001$), irrespective of the crop.

3.3.2 Economic and biomass yields

Maize grain and biomass yields were significantly impacted by soil fertility management systems and seasons (Table 3.1A). In 2014, maize grain yield with high use of mineral fertilizer was significantly higher than that of integrated soil-crop management practice (by 21%), low use of external inputs (by 53%), and un-amended soil (by 107%). In 2015, maize grain yields with high use of mineral fertilizer and integrated soil-crop management practice were similar, but significantly higher than that of un-amended soil (by 118%) and low use of external inputs (by 208%). Grain yield in 2015 was 21% higher with un-amended soil and about 29% higher with both high use of mineral fertilizer and integrated soil-crop management practice compared to 2014, but 37% lower with low use of external inputs.

Table 3.1 Economic yield and aboveground biomass, and nitrogen and phosphorus uptake (N-UPT, P-UPT) under four soil fertility management systems (SMS) in maize (A), sorghum (B), and cotton (C) production systems at the final harvest of 2014 and 2015.

Seasons	SMS	Economic yield (t ha^{-1})	AGB (t ha^{-1})	N- UPT (kg N ha^{-1})	P- UPT (kg N ha^{-1})
(A) ***Maize-based production systems***					
2014	CONT	1.4c	4.9b	40.6b	15.2b
	ISC	2.4b	7.8a	79.6a	29.8a
	HMF	2.9a	9.1a	93.5a	35.2a
	LEI	1.9c	5.4b	48.9b	17.3b
2015	CONT	1.7b	3.5c	39.5c	13.7b
	ISC	3.1a	7.6b	80.1b	36.1a
	HMF	3.7a	9.4a	97.9a	43.9a
	LEI	1.2b	2.9c	27.0c	9.0b
P-values SMS		< 0.001	< 0.001	< 0.001	< 0.001
P-values Seasons		0.024	0.029	0.162	0.326
P-values SMS x Seasons		< 0.001	0.059	0.015	< 0.001
(B) ***Sorghum-based production systems***					
2014	CONT	1.5b	6.1b	55.9b	18.9b
	ISC	1.7a	8.5a	82.5a	27.1a
	HMF	1.8a	8.3a	78.9a	26.4a
	LEI	0.7c	2.8c	33.3c	10.1c
2015	CONT	1.8b	7.5b	69.4b	19.7b
	ISC	2.6a	10.8a	109.6a	30.5a
	HMF	2.5a	11.6a	111.3a	32.1a
	LEI	0.8c	3.7c	42.5c	12.5c
P-values SMS		< 0.001	< 0.001	< 0.001	< 0.001
P-values Seasons		< 0.001	< 0.001	< 0.001	0.049
P-values SMS x Seasons		0.002	0.087	0.007	0.502
(C) ***Cotton-based production systems***					
2014	CONT	1.2c	3.2b	35.3bc	11.2c
	ISC	1.8a	4.3a	55.8a	20.8a
	HMF	1.4b	3.4b	45.5b	16.8b
	LEI	0.9d	1.8c	28.2c	9.9c
2015	CONT	1.6b	4.2b	39.8b	13.8c
	ISC	2.2a	5.6ab	70.5a	23.6b
	HMF	2.4a	6.1a	79.2a	29.0a
	LEI	0.8c	2.5c	32.6b	11.2c
P-values SMS		< 0.001	< 0.001	< 0.001	< 0.001
P-values Seasons		< 0.001	< 0.001	< 0.001	< 0.001
P-values SMS x Seasons		< 0.001	< 0.001	< 0.001	< 0.001

Means in a column within a season and crop production system with similar letters are not significantly different at the 5% level according to the LSD test. CONT: un-amended soil as control, ISC: integrated soil-crop management practice, LEI: low use of external inputs, and HMF: high use of mineral fertilizer.

Maize biomass yield under high use of mineral fertilizer was statistically as high as that of integrated soil-crop management practice in 2014, but was the highest in 2015

(Table 3.1A). The biomass yields were lowest with un-amended soil and low use of external inputs in both seasons. Relative to 2014, maize biomass yield in 2015 increased by 3% with high use of mineral fertilizer, but decreased by 3% with integrated soil-crop management practice, 29% with un-amended soil, and 46% with low use of external inputs.

In the sorghum-based production systems, soil fertility management systems and seasons significantly impacted grain and biomass yields (Table 3.1B). Sorghum grain yields with high use of mineral fertilizer and integrated soil-crop management practice were similar, but significantly higher than with un-amended soil and low use of external inputs in both seasons. Grain yields under high use of mineral fertilizer and integrated soil-crop management practice were consistently higher than with un-amended soil (20% in 2014 and 39% in 2015) and low use of external inputs (157% in 2014 and 225% in 2015). The sorghum grain yields in 2015 increased by 14% with low use of external inputs, 20% with un-amended soil, 39% with high use of mineral fertilizer, and 59% with integrated soil-crop management practice relative to 2014. Sorghum biomass yields with high use of mineral fertilizer and integrated soil-crop management practice were similar in both seasons. The biomass yield was significantly higher with integrated soil-crop management practice compared to un-amended soil (39% in 2014 and 44% in 2015) and low use of external inputs (204% in 2014 and 192% in 2015). The sorghum biomass yield significantly increased in 2015 compared to 2014 with un-amended soil by 23%, integrated soil-crop management practice by 27%, low use of external inputs by 32%, and high use of mineral fertilizer by 40%.

The soil fertility management systems and seasons, as well as their interaction, significantly impacted both seed cotton and biomass yields (Table 3.1C). In 2014, seed cotton yield with integrated soil-crop management practice was significantly higher than that of high use of mineral fertilizer (by 29%), un-amended soil (by 50%), and low use of external inputs (by 100%). In 2015, seed cotton yield with integrated soil-crop management practice did not differ from high use of mineral fertilizer, but was higher than that of un-amended soil (by 50%) and low use of external inputs (by 175%). Seed cotton yield increased in 2015 compared to 2014 with integrated soil-crop management practice (by 22%), un-amended soil (by 33%), and high use of mineral fertilizer (by 71%), but decreased with low use of external inputs (by 11%). In 2014, cotton biomass yield with integrated soil-crop management practice was higher than that of un-amended soil and high use of mineral fertilizer (both by 26%) and low use of external inputs (by 139%). In 2015, with high use of mineral fertilizer cotton biomass yield was the highest of all soil fertility management systems, albeit statistically similar to that of integrated soil-crop management practice. Cotton biomass yield under high use of mineral fertilizer in 2015 was 45% higher compared to un-amended soil and 144% higher than that of low use of external inputs in the same season. Cotton biomass yield increased in 2015 compared to 2014 with all soil fertility management systems, i.e. by 24% with un-amended soil, 30% with integrated soil-crop management practice, 39% with low use of external inputs, and 79% with high use of mineral fertilizer.

3.3.3 Nitrogen and phosphorus uptake

Maize N and P uptake (N-UPT, P-UPT) were significantly affected by soil fertility management systems although this effect differed between seasons (Table 3.1A). The highest N-UPT occurred with high use of mineral fertilizer in both seasons. In 2014, N-UPT followed the order high use of mineral fertilizer > integrated soil-crop management practice (17%) > low use of external inputs (91%) > un-amended soil (130%), but in 2015 the trend was high use of mineral fertilizer > integrated soil-crop management practice (22%) > un-amended soil (148%) > low use of external inputs (263%). Compared to 2014, the N-UPT of maize decreased in 2015 by 45% with low use of external inputs, but was similar for all other soil fertility management systems. Maize P-UPT with high use of mineral fertilizer and integrated soil-crop management practice were statistically similar in 2014 and 2015, but were significantly higher than that of un-amended soil by 132% in 2014 and 220% in 2015. Compared to low use of external inputs, the P-UPT with high use of mineral fertilizer was 103% higher in 2014 and 388% in 2015. The P-UPT in 2015 decreased by 48% with low use of external inputs and 10% with un-amended soil compared to 2014, but increased by 21% for integrated soil-crop management practice and 25% for high use of mineral fertilizer over the same period.

Sorghum N- and P-UPT were substantially affected by soil fertility management systems although this effect differed by seasons (Table 3.1B). The N- as well as P-UPT with high use of mineral fertilizer in both cropping seasons did not differ from integrated soil-crop management practice. In 2014, the N-UPT with un-amended soil was 48% and with low use of external inputs 148% lower compared to integrated soil-crop management practice. In 2015, the N-UPT with high use of mineral fertilizer was 60% higher than with un-amended soil and 162% greater compared to low use of external inputs. From 2014 to 2015, the N-UPT increased irrespective of the soil fertility management systems, i.e. with un-amended soil by 24%, low use of external inputs by 28%, integrated soil-crop management practice by 33%, and high use of mineral fertilizer by 41%. The P-UPT with integrated soil-crop management practice in 2014 was 43% higher than that of un-amended soil and even 168% greater than with low use of external inputs, whilst with high use of mineral fertilizer in 2015, it exceeded that of un-amended soil by 63% and that of low use of external inputs by 157%. From 2014 to 2015, sorghum P-UPT increased by 4% with un-amended soil, 13% with integrated soil-crop management practice, 22% with high use of mineral fertilizer, and 24% with low use of external inputs.

There were significant effects of soil fertility management systems and season and their interaction on cotton N- and P-UPT (Table 3.1C). In 2014, cotton N-UPT with integrated soil-crop management practice was significantly higher than that of high use of mineral fertilizer (by 23%), un-amended soil (by 58%) or with low use of external inputs (by 98%). In 2015, N-UPT by cotton with high use of mineral fertilizer and integrated soil-crop management practice were similar, but both were higher than that of un-amended soil (by 99%) and with low use of external inputs (by 143%). Cotton N-UPT increased in 2015 compared to 2014 with all soil fertility management systems, i.e. with un-amended soil by 13%, low use of external inputs by 16%, integrated soil-crop management practice by 26%, and high use of mineral fertilizer by 74%. Clear differences emerged between the soil fertility management systems in cotton P-UPT in 2014 and 2015. The P-UPT with integrated soil-crop management practice in 2014 exceeded that of high use of mineral fertilizer, un-amended soil, and low use of external inputs by 24%, 86%, and 110%, respectively. In 2015, cotton P-UPT with high use of mineral fertilizer was higher than that of integrated soil-crop management practice by 23%, un-amended soil by 110%, and low use of external inputs by 159%. Cotton P-UPT over time increased by 23% with un-amended soil, 13% with integrated soil-crop management practice, 73% with high use of mineral fertilizer, and 13% with low use of external inputs.

Irrespective of the three crops tested, strong relations existed between economic yield, biomass yield, and N and P uptake (Table 3.2A, B, C).

Table 3.2 Relationship (Pearson's correlation matrix) between economic yield (Econ. yield), and aboveground biomass yield (AGB), nitrogen (N-UPT) and phosphorus uptake (P-UPT) within the maize, sorghum, and cotton production systems in 2014 and 2015 cropping seasons.

		Econ. yield	AGB	N- UPT	P-UPT
(A) ***Maize production systems***					
Econ. yield		1			
AGB	Coefficients	0.86*	1		
	P values	< 0.001			
N- UPT	Coefficients	0.92*	0.96*	1	
	P values	< 0.001	< 0.001		
P-UPT	Coefficients	0.89*	0.93*	0.94*	1
	P values	< 0.001	< 0.001	< 0.001	
(A) ***Sorghum production systems***					
Econ. yield		1			
AGB	Coefficients	0.95*	1		
	P values	< 0.001			
N- UPT	Coefficients	0.93*	0.93*	1	
	P values	< 0.001	< 0.001		
P-UPT	Coefficients	0.91*	0.96*	0.91*	1
	P values	< 0.001	< 0.001	< 0.001	
(A) ***Cotton production systems***					
Econ. yield		1			
AGB	Coefficients	0.87*	1		
	P values	< 0.001			
N- UPT	Coefficients	0.93*	0.85*	1	
	P values	< 0.001	< 0.001		
P-UPT	Coefficients	0.92*	0.81*	0.97*	1
	P values	< 0.001	< 0.001	< 0.001	

* = significant at 0.05 level
ns = non-significant at 5% level

3.3.4 Nitrogen and phosphorus use efficiencies

In the maize-based production systems, N agronomic efficiency was significantly higher with integrated soil-crop management practice than with high use of mineral fertilizer (Table 3.3A). The N agronomic efficiency in 2015 increased by 37% with integrated soil-crop management practice and 34% with high use of mineral fertilizer compared to 2014. No significant differences existed between integrated soil-crop management practice and high use of mineral fertilizer in N apparent recovery of maize in both seasons (Table 3.3A). From 2014 to 2015, the N apparent recovery of maize increased by 5% with integrated soil-crop management practice and 11% with high use of mineral fertilizer. Similarly, no differences were found between integrated soil-crop management practice and high use of mineral fertilizer in P agronomic efficiency as well as P apparent recovery of maize within the seasons (Table 3.3A). The inter-seasonal changes in P agronomic efficiency were greater for high use of mineral fertilizer (34%) compared to integrated soil-crop management practice (20%), but the increases for P apparent recovery amounted to 53% with integrated soil-crop management practice and 51% with high use of mineral fertilizer.

In the sorghum-based production systems, N agronomic efficiency with integrated soil-crop management practice was significantly higher than with high use of mineral fertilizer in all seasons (Table 3.3B). From 2014 to 2015, the N agronomic efficiency of sorghum increased by 128% with integrated soil-crop management practice and 20% with high use of mineral fertilizer. In contrast to maize, there were differences in sorghum N apparent recovery between integrated soil-crop management practice and high use of mineral fertilizer with the latter being significantly lower (Table 3.3B). Relative to 2014, N apparent recovery in 2015 increased by 98% with integrated soil-crop management practice and by 134% with high use of mineral fertilizer. Sorghum P agronomic efficiency did not differ between integrated soil-crop management practice and high use of mineral fertilizer in the 2014 season, but was higher with integrated soil-crop management practice than with high use of mineral fertilizer in the 2015 (Table 3.3B). The inter-seasonal increases of P agronomic efficiency amounted to 128% with integrated soil-crop management practice and 21% with high use of mineral fertilizer.

No significant effect of soil fertility management systems was found for P apparent recovery within both seasons (Table 3.3B). However, inter-seasonal increases in P apparent recovery were observed for integrated soil-crop management practice (21%) and high use of mineral fertilizer (71%).

Table 3.3 Nitrogen and phosphorus agronomic efficiency (AE) and apparent recovery (RE) of maize, sorghum, and cotton-based production systems under high use of mineral fertilizer (HMF) and integrated soil-crop management practice (ISC) in 2014 and 2015.

Seasons	SMS	Nitrogen use efficiencies ratios		Phosphorus use efficiencies ratios	
		AE	RE	AE	RE
(A) ***Maize-based production systems***					
2014	ISC	24.7a	0.88a	62.1a	0.83a
	HMF	19.3b	0.66a	59.2a	0.77a
2015	ISC	33.8a	0.92a	74.6a	1.27a
	HMF	25.8b	0.73a	79.4a	1.16a
P-values SMS		< 0.001	0.130	0.935	0.699
P-values Seasons		0.003	0.482	0.182	< 0.001
P-values SMS x Seasons		0.636	0.811	0.751	0.702
(B) ***Sorghum-based production systems***					
2014	ISC	7.5a	0.60a	18.8a	0.47a
	HMF	6.4b	0.29b	19.7a	0.28a
2015	ISC	17.1a	1.19a	42.9a	0.62a
	HMF	7.7b	0.68b	23.8b	0.48a
P-values SMS		0.002	0.010	0.010	0.273
P-values Seasons		0.004	< 0.001	0.004	0.221
P-values SMS x Seasons		0.073	0.238	0.013	0.882
(C) ***Cotton-based production systems***					
2014	ISC	11.9a	0.47a	29.8a	0.49a
	HMF	3.1b	0.16b	7.5b	0.21b
2015	ISC	14.4a	0.49a	36.1a	0.54a
	HMF	10.1a	0.45a	30.9a	0.59a
P-values SMS		0.042	0.006	0.017	0.049
P-values Seasons		< 0.001	0.007	0.002	< 0.001
P-values SMS x Seasons		0.032	0.024	0.073	< 0.001

Means in a column within a season and crop production system with similar letters are not significantly different at the 5% level according to the LSD test. SMS: Soil management systems

In the cotton-based production systems, N and P agronomic efficiencies as well as their apparent recovery were higher with integrated soil-crop management practice than with high use of mineral fertilizer in the 2014 season. However, in 2015, no differences emerged between integrated soil-crop management practice and high use of mineral fertilizer in all indicators (Table 3.3C). From 2014 to 2015, N agronomic efficiency increased by 21% with integrated soil-crop management practice and 226% with high use of mineral fertilizer. The inter-seasonal increases in N apparent recovery amounted to 4% with integrated soil-crop management practice and 181% with high use of mineral fertilizer. In 2015, the P agronomic efficiency was 21% higher for integrated soil-crop management practice compared to 2014, but 312% higher with high use of mineral fertilizer over the same period. From 2014 to 2015, a great increase occurred in P apparent recovery of cotton with high use of mineral fertilizer (181%) compared to integrated soil-crop management practice (10%).

3.3.5 Nitrogen and phosphorus partial balances

In the maize-based production systems, N and P partial balances were consistently negative for un-amended soil and high use of mineral fertilizer, but positive with integrated soil-crop management practice in both seasons. Whilst the N partial balance for low use of external inputs was negative with maize in both seasons, the P partial balance was positive in 2014 and closer to the equilibrium in 2015 (Fig. 3.2a, b).

With sorghum in 2014, high use of mineral fertilizer resulted in almost balanced N and P input and output flows, but negative balances in 2015. The N and P partial balances for sorghum were largely negative with low use of external inputs and un-amended soil, but positive with integrated soil-crop management practice in both seasons (Fig. 3.2a, b).

The N and P partial balances for cotton were positive with high use of mineral fertilizer in 2014, but in 2015 nearly zero for N and even negative for P. With low use of external inputs, the N partial balance was nearly zero in both seasons, while the P partial balance was near to zero in 2014 and negative in 2015. The N and P balances for cotton were positive with integrated soil-crop management practice, but negative under un-amended soil in both 2014 and 2015 (Fig. 3.2a, b).

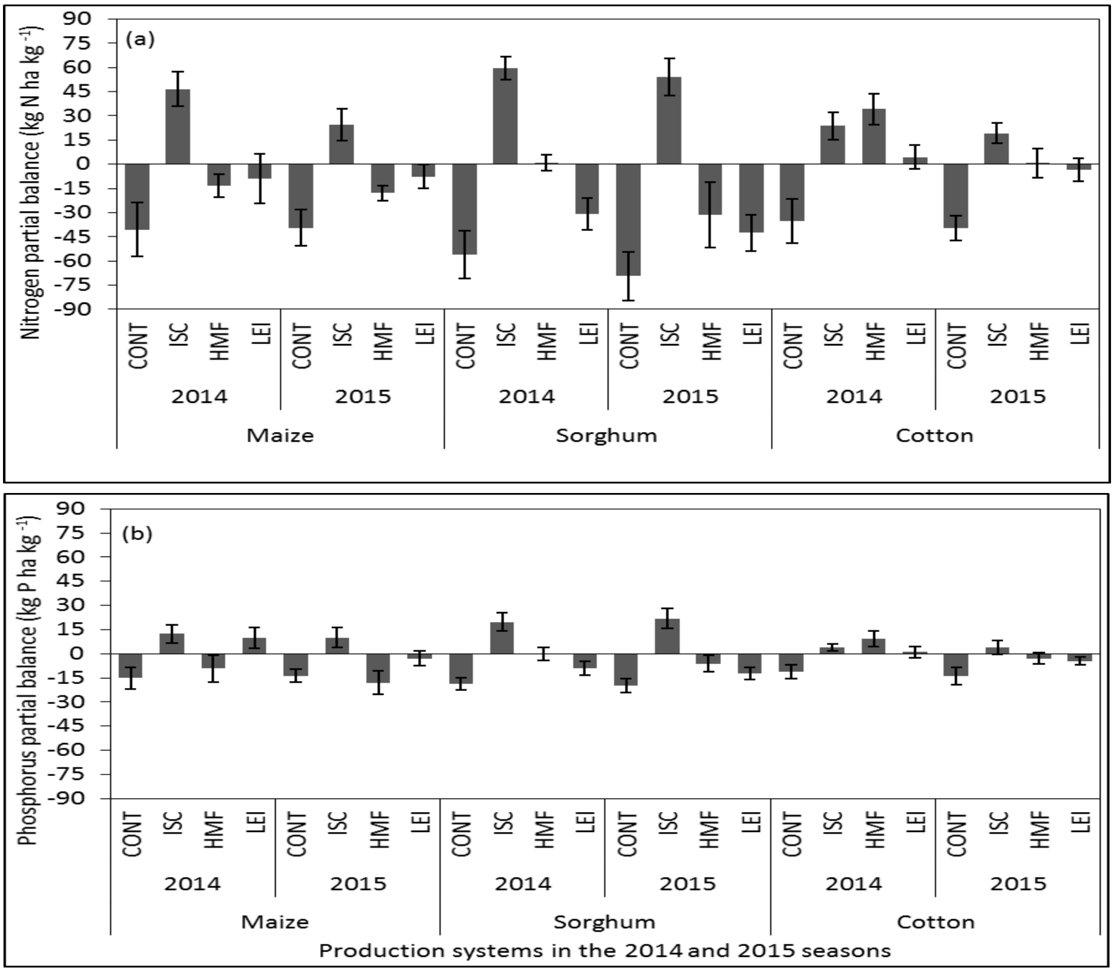

Figure 3.2 N and P balances for the un-amended soil (CONT), integrated soil-crop management practice (ISC), high use of mineral fertilizer (HMF), and low use of external inputs (LEI) under maize (A1, A2), sorghum (B1, B2), and cotton (C1, C2) during the 2014 and 2015 cropping seasons.

3.3.6 Soil residual nitrogen and phosphorus dynamics

The soil management systems and time of sampling significantly impacted NO_3-N, irrespective of the crops. Soil layers impacted significantly NO_3-N in both sorghum and cotton-based production systems, but not with maize (Table 3. 4; Fig 3.3A1, B1, C1).

Prior to planting in 2014 (166 day of year (DOY)), no differences existed between soil layers and neither between the un-amended soil and integrated soil-crop management practice treatments in NO_3-N for all crops (Fig 3.3A1, B1, C1). At final harvest of each crop, NO_3-N with integrated soil-crop management practice was higher than with un-amended soil. Nitrate-N tended to be higher in the 0-20 cm layer than in deeper layers under sorghum and cotton cultivation. In the 2015 cropping season, no differences were monitored in NO_3-N between un-amended soil and integrated soil-crop management practice or between soil layers at the first sampling (153 DOY). However, around the planting period (176 DOY), NO_3-N tended to be higher under maize and sorghum than under cotton. Under maize, NO_3-N was significantly higher with integrated soil-crop management practice than with un-amended soil. Nitrate-N was more variable under sorghum. At final harvest of each crop, differences in NO_3-N between un-amended soil and integrated soil-crop management practice had diminished.

Available P varied substantially with soil layers and time of sampling, but was not significantly affected by soil fertility management systems for all crops (Table 3.4; Fig. 3.3A2, B2, C2). In the 2014 season, available P prior to planting (166 DOY) was significantly higher in the top 0-20 cm soil layer than that in deeper layers, irrespective of the soil fertility management systems. The pattern was similar at final harvest, being generally higher in the top than in the bottom layers. In the 2015 cropping season, available P was also higher in the 0-20 cm soil layer compared to the bottom layers at 153 DOY and 176. However at final harvest, clear patterns between soil layers did not exist and neither between the un-amended soil and integrated soil-crop management practice treatments.

Table 3.4 P-values of the analysis of the effects of soil management systems (SMS), soil layers, and monitoring time on soil nitrogen-nitrate and available phosphorus.

Main source of variation	P-values	
	Soil nitrogen-nitrate	Available phosphorus
(A) ***Maize-based production systems***		
SMS	< 0.001	0.085
Soil layers	0.971	< 0.001
Time of sampling	< 0.001	< 0.001
(B) ***Sorghum-based production systems***		
SMS	< 0.001	0.092
Soil layers	0.013	< 0.001
Time of sampling	< 0.001	< 0.001
(C) ***Cotton-based production systems***		
SMS	< 0.001	0.889
Soil layers	< 0.001	< 0.001
Time of sampling	< 0.001	< 0.001

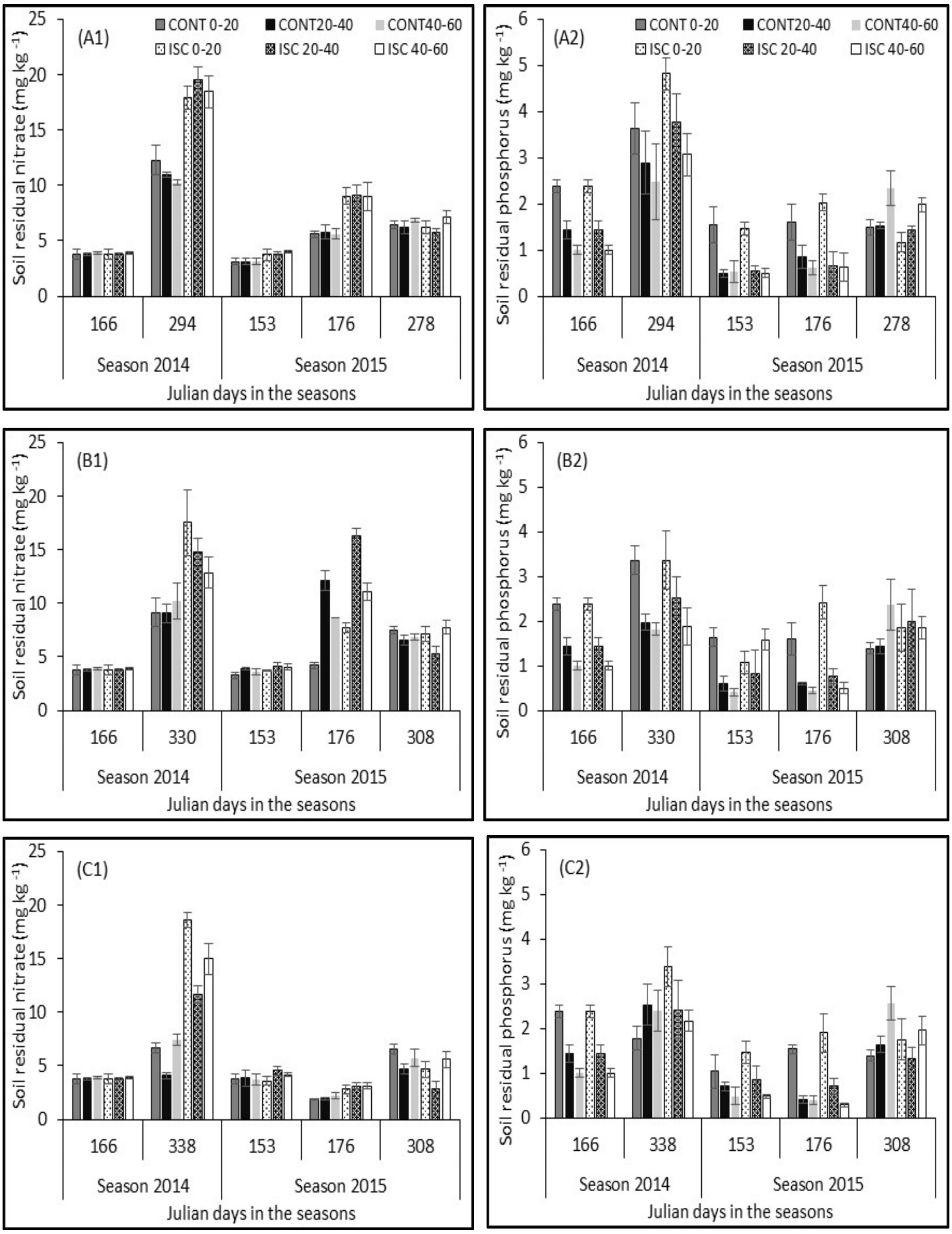

Figure 3.3 Soil residual nitrate and available phosphorus dynamics in soil without any amendment (CONT) and with integrated soil-crop management practice (ISC) under maize (A1, A2), sorghum (B1, B2), and cotton (C1, C2) production systems in 2014 and 2015.

3.4 Discussion

To support a better-informed decision making on site- and crop-specific soil fertility management practices in the Dry Savannah agro-ecological zone, productivity and N- and P- use efficiencies of maize, sorghum, and cotton under different soil fertility management systems were assessed in northern Benin. The findings gained with the four soil fertility management systems reinforced the urgency for updating the current soil fertility recommendations in the region for the three crops while considering crop-specific responses and improvement of soil organic matter.

3.4.1 Soil fertility management effects on biomass accrual and yields

The monitored magnitude of the initial aboveground biomass growth is likely due to a favorable soil moisture induced by good rainfall and its distribution at the onset of the 2015 season (Fig. 2.2), resulting in pulse of nitrate-N around planting period (Fig. 3.3). The release of soil nutrients, mainly N immediately after early-season rainfall (Lançon et al. 2007), counterbalanced the initial fertility differences caused by the different soil fertility management systems. The significant effects of N and P fertilization on biomass accumulation was previously reported (e.g. for maize, Dzotsi et al. 2010).

The positive response of the economic and biomass yields of all three crops to fertilizers amendments, confirms previous findings for maize in the savannah region of Benin (Igue et al. 2015), sorghum in the semi-arid regions of Ghana (McCarthy et al. 2010), and cotton in the savannah zone in Mali (Ripoche et al. 2015). The responses to the soil fertility management systems tested on economic yields and aboveground biomass were, however, crop-specific and caused by a crop-specific resources use (Table 3.3). For instance, the lower level of seed cotton yield and aboveground biomass with high use of mineral fertilizer relative to integrated soil-crop management practice in 2014 resulted probably from the delayed planting. Lançon et al. (1989) already reported the depressive effects of delayed planting on seed cotton yield and recommended planting dates before 30 June in the West African Dry Savannah, including northern Benin. In addition, the significantly lower seed cotton and biomass yields under low use of external inputs compared to those of un-amended soil were not only caused by the soil fertility management systems and the resulting differences in soils properties but were also due to management practices (e.g. delayed planting, lower planting density, inappropriate fertilizer management, and weed competition). Similarly, the low productivity of sorghum under low use of external inputs in the farmer-managed trial was due to the lack of fertilizer applications during cultivation, since sorghum grain yields increased with integrated soil-crop management practice and high use of mineral fertilizer, which confirm previous findings (McCarthy et al. 2010). Furthermore, the effect of integrated soil-crop management practice on economic and biomass yields of all three crops suggests a further improved plant nutrition with integrated soil-crop management practice compared to high use of mineral fertilizer and probably even a luxury consumption when applying the high rates of mineral fertilizer. The current findings together with an archive of worldwide information (Kumar and Goh 1999), but more specifically for various regions in West Africa (Bationo et al. 2007; Lal 2006), demonstrate a significant contribution of crop residues to soil fertility enhancement and crop productivity (Buerkert and Hiernaux 1998; Schlecht et al. 2007), thus underlining the benefit of an approach that integrates inorganic and organic fertilizers (Vanlauwe et al. 2014; Wu and Ma 2015).

Notable was that the inter-seasonal differences resulting in increased economic yields for all three crops in 2015 occurred also with the un-amended soil treatment. Given that all factors in 2014 and 2015 had been kept equal, the seasonal-related differences are thus likely a result of rainfall, which in 2015 in terms of quantity and distribution was more advantageous compared to 2014 (Fig. 2.2). In contrast, the marked inter-seasonal decreases in final maize grain and seed cotton yields with low use of external inputs under the farmer-managed experiment is a result of the inaccessibility of fertilizers combined with inadequate soil management practices. The lack of consistency in fertilization rates on the farmer-managed fields (Table 2.3) implies also tradeoffs made by farmers as previously reported (Theriault and Tschirley 2014). For instance, since fertilizers are hardly affordable by farmers, fertilizers provided through the input-credit system established for cotton production are (partly) diverted to boost in particular maize production for reaching food security. It, therefore, has recurrently been underlined that improving access of smallholder farmers to affordable input markets is greatly needed and could boost sustainable production of all crops (Ripoche et al. 2015; Theriault and Tschirley 2014).

3.4.2 Soil fertility management effects on N- and P- use efficiencies and balances

The known extent of seasonal N- (35.3 - 69.4 kg N ha^{-1}) and P- (11.2 - 19.7 kg P ha^{-1}) uptake in un-amended soil under maize, sorghum, and cotton cultivation (Table 3.1) implies an alarming ongoing nutrient mining, which cannot be countered unless targeted amendments are ensured (Schlecht et al. 2007). Hence, the N and P uptake, which were highest with integrated soil-crop management practice and high use of mineral fertilizer, confirm previous postulations that fertilization can enhance and sustain plant nutrition not only in the region (Vanlauwe et al. 2014) but also worldwide (Godwin and Singh 1998). Despite the differences in applied amounts of chemical fertilizers (Table 2.2), the similar levels of N and P uptake under integrated soil-crop management practice and high use of mineral fertilizer are supported by the impact of crop residue recycling and its consequent nutrient release as substantiated by the agronomic efficiencies of N and P, and their apparent recovery. Units of N- and P-fertilizers applied as part of the integrated soil-crop management practice resulted in higher economic yields and lower nutrient losses compared to the use of chemical fertilizers alone (high rates of mineral fertilizer). Moreover, the current estimates of N apparent recovery under integrated soil-crop management practice were even within the range recognized in general as “best management options” (Fixen et al. 2015; Snyder and Bruulsema 2007).

The lack of a targeted application of external input results in unbalanced N and P input and output flows. This is true not only when assuming the un-amended soil for all three crops, but also with regards to sorghum under the low use of external inputs in the farmer-managed trial. Hence, under such conditions crop production depends largely on the N and P supplied by the soils alone (Bowen and Baethgen 1998). However, the soils have been mined for decades at an alarming rate under the maize, sorghum, and cotton production practices common in Sub-Saharan Africa countries, including

Benin, and this process is still ongoing (Stoorvogel and Smaling 1990). These general trends contrasts thus with the positive N and P balances estimated for all three crops with the integrated soil-crop management practice, i.e. integrating inorganic fertilizers with crop residues recycling. The other trends of the N and P balances (i.e. negative or near to zero) were estimated under high use of mineral fertilizer and low use of external inputs (Fig. 3.2) that did not experience a targeted input of organic matter but only of chemical fertilizers (Table 2.2, 2.3). A comprehensive review on partial and full nutrient balances for several countries in Africa (e.g. Mali, Ethiopia, Kenya, Uganda) pointed at evident N losses, but less remarkable losses for P (Cobo et al. 2010). Recently in Kenya, Adamtey et al. (2016) estimated positive P partial balances under both low and high inputs compared to conventional and organic production systems. They underlined also the negative trends for N in conventional systems and positive trends for organic high input systems. Overall, it should be noted that the current N and P partial balances, however, did not account for all potential inputs and outputs of N and P and should therefore be treated with caution because, for instance, nutrient depletion by leaching and wind erosion (Schlecht et al. 2007), and gaseous losses (Godwin and Singh 1998) could be non-negligible.

3.4.3 Effects of onset season rainfall and crop residues on nutrient pulse

The levels of NO_3-N and available P at the harvest with integrated soil-crop management practice relative to un-amended soil are driven mainly by the N and P fertilization, return of residues, and seasonal nutrient uptake. The increased accessibility of NO_3-N at the onset of the rainy season 2015 (Fig. 3.3) is attributed to a mineralization of soil organic matter under un-amended soil or the mineralization of both organic matter and N-based fertilizers applied under integrated soil-crop management practice. This phenomenon, known as the N “Birch effect” (Unger et al. 2010) for N release mainly, eased in part the recurrently mentioned key biophysical constraints for crop growth and productivity in the Dry Savannah region (Lançon et al. 2007). However, crop residues with relatively high lignin contents (e.g. here cotton stems) could reduce the extent of soil-N peaks as observed between the cotton harvest in 2014 and the planting time of 2015 due to N immobilization by soil microorganisms (Kumar and Goh 1999; Muhammad et al. 2011). The similarities noted for soil NO_3-N and P between soil fertility management systems and soil layers at 166 DOY in 2014 and 153 DOY in 2015 could be explained by the drier conditions (Unger et al. 2010).

Irrespective of the soil fertility management systems tested, all three crops had benefitted from the sudden flow of nutrients that occurred at the onset of the rainy season. However, to exploit these flows, a careful synchronization of peaks in N release and crop demands is compulsory, which in turn demands good management, e.g. timely planting. Whilst such a synchronization was previously handled and managed by the farmers, the growing increase in erratic rainfall at the onset of the season, as reported for the region (Cooper et al. 2008; Ouorou Barre 2014), renders an effective management more and more challenging. Options to counterbalance the growing insecurity and risks at the onset of the growing season include the application of supplementary water to cope, for instance, with in-season dry spells (Fox and Rockström 2003; Reddy 2016). The synergetic effect of crop residues retention and fertilizer applications on crop production and nutrient use efficiency must be of interest not only to the farmers, but also to decision makers since the affordability of inorganic fertilizers and financial viability of fertilization strategies are still of major concern in the region (Lamers et al. 2015a, b).

3.5 Conclusions

Two out of the four tested soil fertility management options, i.e. the high use of mineral fertilizer and the integrated soil-crop management practice, improved growth and productivity of maize, sorghum, and cotton, albeit with differences depending on crop type. Only when using integrated soil-crop management practice were higher yield responses sustained as substantiated by the N- and P-use efficiencies and partial balances. The levels reached in the region are usually monitored with “best management and sustainable practices”, at least with reference to maize, sorghum, and cotton cultivation. The findings overall indicate that the current soil fertility recommendations for the three crops tested need to be updated while considering crop-specific responses and accounting for the different sources of external inputs. This is true in particular when considering the use and retention of crop residues, since this could lead to a further competition between the use of crop residues as soil amendment, livestock feed, and/or domestic fuel, which must be avoided. It furthermore becomes clear that the improved soil fertility management practices should be flanked with soil and water conservation options to cope successfully with the weather vagaries at the onset of the season such as dry spells, since crops will otherwise no longer be able to rely on the contribution of early-season organic matter mineralization. The integrated soil-crop management practice improved yields and nutrient use and balances most efficiently, and can thus sustain better the responses of the crop under the ongoing climate variability.

4 CERES-MAIZE AND CERES-SORGHUM FOR MODELING GROWTH, NITROGEN AND PHOSPHORUS UPTAKE, AND SOIL MOISTURE DYNAMICS

4.1 Introduction

Declining agricultural productivity, demographic growth, urbanization, and changing consumption habits are major drivers of the increase in the demand for food and feed in West Africa (Garrity et al. 2010; Schlecht et al. 2007; Wheeler and von Braun 2013). The trends for more demand are further challenged by dwindling resources as manifested by widespread soil fertility depletion and evidenced by low soil organic matter (Schlecht et al. 2007) and chronic N and P deficiencies (Bationo et al. 2012). Furthermore, consent exists that the predicted changes in climate and agricultural land use will adversely alter nutrient dynamics (Whitehead and Crossman 2012), and likely exacerbate the impact of soil fertility depletion on crop productivity and resource use efficiency (Wu and Ma 2015). This, in turn, threatens the diversity of the prevailing cropping systems (Callo-Concha et al. 2013), which usually are dominated by staple crops. Therefore, unless action is taken, agricultural land degradation and increasing climate variability will jeopardize food security in West Africa (Wheeler and von Braun 2013), particularly the availability of maize and sorghum, which are major local staple crops (Garrity et al. 2010). Under the current conditions of food insecurity and limited access to and affordability of production factors (Wheeler and von Braun 2013), there is an urgent need to improve resource use efficiency and yields in smallholder production systems (Wu and Ma 2015). Hence, sustainable intensification practices are required in the region (Drechsel et al. 2015; Vanlauwe et al. 2014) to ensure production of sufficient, affordable, and nutritious food without compromising the environment.

Field experimentation has been pivotal in assessing the effects of single or multiple factors on crop productivity. However, given the growing costs of conducting multi-level, multifactorial, and long-term field experiments to respond to the existing complexities in soil-plant-climate interactions, complementary approaches are needed. Process-based models are recognized to complement empirical data collection to support decision-making (Tsuji et al. 2013) concerning not only crop responses to soil fertility management, but also the framing of alternative measures to increase the resilience of production systems. While a wide array of simulation models have been assessed for their use in West Africa (Akinseye et al. 2017; Webber et al. 2014), the Decision Support System for Agrotechnology Transfer (DSSAT) - Cropping System Models (Jones et al. 2003) appear promising to simulate soil-plant-climate interactions in this region. Reportedly, the CERES-Maize and CERES-Sorghum models of DSSAT can simulate growth, development, and yield in response to weather conditions and soil/crop management (Hoogenboom et al. 2015). They are also recognized to simulate soil water (Ritchie 1998) and N-balance (Godwin and Singh 1998) in cropping systems and the impact of climate change on crop production (White et al. 2011). Both CERES-Maize and CERES-Sorghum have been extensively tested in terms of crop growth and yield predictions and N fertilizer management in India (Liu et al. 2013; Yang et al. 2011), Togo (Dzotsi et al. 2003), Ghana (Fosu et al. 2012; McCarthy et al. 2012), Mali (Akinseye et al. 2017), Nigeria (Adnan et al. 2017; Jagtap et al. 1993; Jibrin et al. 2012), and Benin (Igue et al. 2013). However, these models have hardly been screened in terms of soil water and nutrient dynamics under typical environment of the Dry Savannah region of West Africa. While it has been postulated that seasonal soil moisture dynamics potentially affect the soil supply of N and P (Bationo et al. 2012) and crop nutrient uptake (Buerkert and Hiernaux 1998), neither processes have been modeled by CERES-Maize and CERES-Sorghum and therefore do not yet support the framing of better soil-crop and water management options in this region.

Recent improvements enable CERES-Maize and CERES-Sorghum to respond to conditions of low N and P (Dzotsi et al. 2010; Gijsman et al. 2002; Porter et al. 2009), which are typical for the production environment in the Dry Savannah zone of West Africa, including northern Benin. However, before exploiting the potential of these models to predict the consequences of climate change on crop growth, development, soil water dynamics, and nutrient balances, they must be parameterized and evaluated for these agro-ecological conditions and must prove to be sufficiently robust to respond to these typically N- and P-poor environments. The twofold objectives were: (i) Evaluate the ability of the CERES-Maize and CERES-Sorghum models for predicting yields, N and

P uptake, as well as in-season soil water and N dynamics during maize and sorghum growth, and (ii) use hence the models to assess the effects of different nutrient management strategies on soil C and N, and crop water- and N- use efficiencies, considering 30 years of historical weather variability in the dry savannah agro-ecological zone of northern Benin, West Africa.

4.2 Material and methods

4.2.1 Description of the CERES-Maize and CERES-Sorghum models

Cropping System Models, CERES-Maize and CERES-Sorghum within the DSSAT Version 4.6 (Hoogenboom et al. 2015) are process-level, comprehensive models to simulate crop growth, development, and final grain yield of maize and sorghum. The models simulate growth and development using a daily time-step routine from sowing to maturity or a specified harvest time based on physiological processes that describe crop responses to soil and weather conditions. Phenological development and growth are specified by cultivar-specific genetic coefficients depending on the photoperiod, thermal time, temperature response, and dry matter partitioning. Both models account for temperature effects on crop growth and grain filling rate based on cardinal temperatures, assuming trapezoidal responses and an optimum temperature of 34°C (Kumudini et al. 2014; White et al. 2015). Potential dry matter production is assumed to be proportional to the photosynthetically active solar radiation absorbed by a crop canopy. The actual dry matter production on a given day is constrained by suboptimal air temperature, soil water deficits, or N and P deficit factors for crops. The dry matter simulated is partitioned into different parts of the plant on the basis of temperature and phenological stage of the crop (Hoogenboom et al. 2010; Ritchie et al. 1998). Soil water, N, P, and organic C dynamics and their interactions with crop management are determined in subroutines that are shared by all crops in Cropping System Models. More detailed descriptions of the soil water, N, and C balance dynamics are found in Ritchie (1998) and Godwin and Singh (1998), but elements key to the present study are briefly described hereafter.

The soil-water balance component simulates the daily water balance processes, i.e. infiltration (rainfall and irrigation), surface runoff, drainage, evaporation from the soil surface, and water extraction by the plant. The downward flow of soil water to lower soil layers occurs according to a cascading approach based on the water content between saturation (SAT) and drained upper limit (field capacity, DUL); this flow is a determinant in computing the share of nitrate leaching (Ritchie 1998). The CERES-N balance routine for upland cropping systems simulates the turnover of soil organic matter and the decay of crop residues with the associated mineralization and/or immobilization of N, the major N loss processes (nitrification of ammonium and associated denitrification), and the contribution to the N balance made by mineralization. The model neither simulates losses by ammonium volatilization or ammonium exchange equilibria nor nitrogen dioxide (N_2O) and dinitrogen (N_2) emissions (Bowen and Baethgen 1998; Gijsman et al. 2002; Godwin and Singh 1998). Recent adaptation of CENTURY-based soil organic matter-residues module for DSSAT-Cropping System Models allows better understanding of soil organic nutrient processes (Gijsman et al. 2002; Parton et al. 1988; Porter et al. 2009).

The routine simulates plant N uptake and distribution within crops, the remobilization during grain filling, and the effects of N deficiency on crop growth processes. The N-deficit demand is defined as the difference between a critical N concentration and an actual N concentration in the plant. The potential N uptake is the product of soil inorganic N concentrations, root length density, maximum N uptake per unit root length, and a soil water factor. The actual N uptake is determined as the lesser of either potential crop N demand or potential N uptake. The NFACT submodel calculates N-deficit factors in maize and sorghum.

The soil-plant P-submodule integrates inorganic P pools (labile, active, and stable) and organic P pools (active and stable) with plant P uptake (Dzotsi et al. 2010). The P-submodule computes daily P transformation between the pools in the roots and non-roots zones of the soil. The P uptake is constrained by the minimum of plant demand and soil P supply capacity, and the minimum of daily N:P ratio (Dzotsi et al. 2010). Since the rates of transformation of N and P are very much influenced by soil water status, the simulation of N and P dynamics requires that the soil water content is well simulated.

4.2.2 Field experiments and data

Experiment-1: researcher-managed on-farm trial for calibrating and validating the models

Experiment-1 was set up to collect essential data for calibrating and validating both models in reduced nutrient- and water- stress conditions (Table 2.2; Sections 2.2, 2.3). In addition to aboveground biomass accumulation and yields measurements (Section 2.4), the number of days to 50% anthesis and physiological maturity were also recorded for 15 plants randomly selected from the inner rows of each plot. Biomass accumulation was assessed in 2014 and 2015.

Experiment-2: researcher-managed on-farm trial for evaluating the models

Experiment-2 was conducted in 2014-2015 (Table 2.2; Sections 2.2, 2.3) to collect independent datasets for evaluating the models. In 2014, the treatments comprised the two soil fertility management options, un-amended soil and integrated soil-crop management practice. In 2015, the experiment was re-designed as a factorial combination of the two soil fertility management options and two water management levels (rainfed and rainfed + supplementary irrigation). The objective of the supplementary irrigation practice was to examine the influence of moisture availability, notably at the onset of the rainy season, on N and P dynamics and the uptake of both minerals by crops. Supplementary irrigation occurred during dry spells only and through drip irrigation. The quantities of water applied per irrigation were 1.7, 2.0, 6.7, 3.3, 10.0, 6.7, and 6.7 mm at 2, 4, 14, 20, 22, 23, 30, 35, and 36 days after planting, respectively.

In 2014, no in-season biomass accumulation assessment occurred in experiment-2. In 2015, in-season biomass dynamics were monitored weekly from 13 to 34 days after planting. Thereafter, the measurements were made bi-weekly until final harvest. The aboveground biomass accumulation at each event was determined as described previously (Section 2.4.1).

In-season soil water content was measured from the 0-20, 20-40, and 40-60 cm depths of each plot from 20 days after planting until harvest in synchronization with biomass accrual measurements. Soil water was measured with a HH2 moisture meter connected to a PR2/6 profile probe (Delta-T Devices Ltd) that was calibrated for the experimental site. For the calibration, one access tube of the profile Probe device was installed nearby the site of experiment-2 in 110 cm depth. The probe reading (permittivity in volt) were regularly recorded (11 measurements) over the soil layers 0-10, 10-20, 20-30, 30-40, 40-60, and 60-100 cm during two weeks. In synchrony with the permittivity readings, the soil was sampled around the access tube over the same layers for gravimetric water content measurement. In addition, one meter soil profile was dug at 10 m away from the access tube where three intact cores (100 cm^3) were sampled from each layer. The fresh cores samples were weighed and oven-dried at 100°C for 24 hours to determine the bulk density for each layer. Next, the gravimetric water measurements and bulk density were used to calculate volumetric moisture contents (m^3m^{-3}) for each soil layer. The calibration process of the Profile Probe PR 2/6 was based on the variable intercept approach. The permittivity readings (V) were converted into dielectric property ($\surd\varepsilon$) using the approximate linear relationship ($\surd\varepsilon = 0.37 + 43.43$ V) (Delta-T Devices Ltd 2015). Furthermore, the dielectric property was regressed against volumetric water content and fitted by trend-line to determine the slope and intercept for each profile layer. Therefore, the coefficients of the profile probe were updated over the layers 10, 20, 30, and 40. The gravimetric soil moisture content showed less variability over the layers 60 and 100 cm. Therefore, the default values were kept for these two layers. After calibration, one access tube was installed in each plot to a depth of 1.10 m. Probe reading was taken at 10 cm depth intervals down to 40 cm depth and thereafter at 20 cm intervals to 1.10 m.

Soil samples were taken from the 0-20, 20-40, and 40-60 cm depths at the same time as biomass measurements. Composite subsamples from each depth were analyzed colorimetrically for soil NO_3-N concentrations (IITA 1982).

The in-season aboveground biomass samples were ground using a Wiley mill and sent to laboratory for chemical analyses. Total N and P concentrations were determined colorimetrically in an auto-analyzer as reported by Anderson and Ingram (1993). The resulting concentrations allowed for estimating total N and P in the aboveground biomass. Data for grain and biomass yields, and plant N and P uptake at harvest were measured as previously described (Section 2.4.2).

Experiment-3: farmer-managed on-farm trial for evaluating the models

Experiment-3 was conducted on different farmers' fields selected to cover all three dominant soil types (Table 2.2). This allowed for an evaluation of the robustness of the CERES-Maize and CERES-Sorghum models while assuming farmers' circumstances. In each field of the farmers, researchers delineated three rectangular plots (8.0 m^2) at the beginning of the cropping season to monitor phenological stages and assessing yield at harvest. Additional observations and measurements on each field were kept to a minimum but sufficient to quantify all input parameters/variables as demanded by both Cropping System Models. The monitoring of the output variables permitted the evaluation of model predictions. All management practices including dates of planting, weeding, and fertilizer applications were recorded as well as the type and amount of fertilizer used. Plant population at emergence and final harvest were also recorded. Environmental characteristics such as soils data (Table 2.1) and weather data (Section 2.4.2) were recorded as well.

4.2.3 Model calibration

Calibration of genetic coefficients

The 2014 dataset of experiment-1, involving high rates of mineral fertilizer and supplementary irrigation to minimize nutrient and water-stress, was used for the model calibration. The genetic coefficients of each crop cultivar were manually adjusted to reach an accurate goodness of fit between simulated and measured dataset. The calibration for maize was based on an existing maize cultivar included in DSSAT, namely AB-11-TG. The default coefficients for the thermal time from emergence to the end of juvenile phase (P1) was reduced to match the observed anthesis of the maize cv. EVDT-97 STR used. The thermal time from silking to physiological maturity (P5) was decreased to match the observed physiological maturity, while the maximum number of kernels (G2) and kernel filling rate (G3) were adjusted to match the observed grain yield and biomass (Table 4.1).

Table 4.1 Genetic coefficients of maize cv. EVDT-97 STR after calibration and used during validation of CERES-Maize.

Codes	Definition	Default values AB-11-TG	Calibrated EVDT-97 STR
P1	Thermal time from seedling emergence to the end of the juvenile phase (> 8°C in degree days)	250	210
P2	Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above 12.5 hours	0.1	0.10
P5	Thermal time from silking to physiological maturity (degree days)	620	580
G2	Maximum possible number of kernels per plant	920	900
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)	8.5	9.23
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	55	55

Likewise, for sorghum, the default coefficients of an existing sorghum cultivar in DSSAT, cv. W. African, were used as starting points to calibrate the local sorghum cultivar. The thermal time from seedling emergence to the end of the juvenile phase (P1), the critical photoperiod (P2O), and extent of delay in phasic development leading to panicle initiation (P2R) were adjusted to match the observed anthesis of the local sorghum cultivar. Next, the thermal time from grain filling to physiological maturity (P5) was decreased and finally the scaler for the relative leaf size (G1) and for the partitioning of assimilates to the panicle (G2) were calibrated for grain yield and final biomass (Table 4.2).

After the adjustment for anthesis and physiological maturity, the soil fertility factor for photosynthesis (SLPF) was calibrated so that the simulated top weight matched the initial slope of the observed AGB. The SLPF value needed to be set to 0.98, which is slightly less than the default value of 1. The calibrated models were validated against the 2015 dataset of experiment-1 without a re-calibration of the cultivar specific coefficients.

Table 4.2 Genetic coefficients of sorghum cv. local after calibration and used during validation of CERES-Sorghum.

Codes	Definitions	Default values W. African	Calibrated local
P1	Thermal time from seedling emergence to the end of the juvenile phase	413	650
P2	Thermal time from the end of the juvenile stage to tassel initiation under short days (degree days above TBASE)	102	102
P2O	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate	13.6	13
P2R	Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P2O	40	100
PANTH	Thermal time from the end of tassel initiation to anthesis (degree days above TBASE)	617.5	617.5
P3	Thermal time from to end of flag leaf expansion to anthesis (degree days above TBASE)	152.5	152.5
P4	Thermal time from anthesis to onset of grain filling (degree days above TBASE)	81.5	81.5
P5	Thermal time from beginning of grain filling to physiological maturity (degree days above TBASE)	640	500
PHINT	Phylochron interval; the interval in thermal time between successive leaf tip appearances (degree days)	49	49
G1	Scaler for relative leaf size	3	2
G2	Scaler for partitioning of assimilates to the panicle (head)	6.5	5

To account for differences in soil fertility between sites for experiment-1 (used for model calibration) and experiments-2 and 3 (used for model evaluation), one treatment was selected on the different soil types. Here the default SLPF was manually adjusted such that simulated final grain yields were close to measured values in the two seasons. Therefore, the SLPF value for experiment-2 was reduced from 1 (default value) to 0.75 while for experiment-3 the SLPF were reduced to 0.65 on Gleyic Alisols, 0.55 on Dystric Plinthosols, and 0.50 on Ferric Luvisols. The calibrated SLPF values were used to run the models for all treatments on each site without further modification.

Soil water-holding characteristics

The default soil water-holding characteristics required by the models (e.g. DUL, lower limit (LL), SAT, saturated hydraulic conductivity (SWCN), root weighting factor (WR), runoff curve number (CN2), and drainage coefficient (SWCON)) were initially calculated by inputting soil texture, bulk density, soil organic carbon, and other information (Table 2.1) into the DSSAT soil creation utility program. These estimated soil water-holding characteristics were next modified to make them more specific for the site of experiment-2. The default values of SAT were first optimized for each layer by using total porosity values obtained during bulk density measurements for the calibration of the soil moisture probe for the site. Measured soil water content under rainfed conditions without fertilization enabled to estimate the LL and DUL by adjusting the default values to match the lowest water content during drying cycles or when the soil water content remained constant for 2-3 days after a rainfall event for each soil layer. Finally, SWCN, SWCON, CN2, and WR were defined by adjusting the default values to match the measured soil water contents. Table 4.3 shows the calibrated soil water-holding characteristics used during the runs of the CERES-Maize and CERES-Sorghum under all scenarios: rainfed, supplementary irrigation, with and without fertilizers and combinations thereof.

Table 4.3 Soil hydraulic properties after calibration and used during models simulations in experiment-2.

Hydraulic properties	Starting points per soil depth			Optimized values per soil depth		
	20 cm	40 cm	60 cm	20 cm	40 cm	60 cm
LL ($cm^3\ cm^{-3}$)	0.046	0.055	0.084	0.050	0.085	0.090
DUL ($cm^3\ cm^{-3}$)	0.116	0.118	0.147	0.205	0.254	0.292
SAT ($cm^3\ cm^{-3}$)	0.435	0.461	0.433	0.280	0.310	0.390
SWCN ($cm\ h^{-1}$)	6.110	6.110	2.590	5.500	3.650	2.230
WR	1.000	0.549	0.368	1.000	0.749	0.468
Other inputs	Default values	Adjusted values				
Soil surface albedo (SLAB)	0.13	0.13				
First stage evaporation (U)	6	6				
CN2	73	70				
SWCON	0.6	0.3				

4.2.4 Model input data

The soil input files were created by inputting measured soil properties data, such as soil texture (percent silt, clay, and sand), soil bulk density, pH, organic carbon, total N, available phosphorus, and CEC for each researcher- and farmer-managed fields (Table 2.1) into the soil file creation utility program (SBuild) of the DSSAT software.

Weather files for 2014 and 2015 were created using daily minimum and maximum air temperatures, rainfall, and solar radiation recorded at the experimental site with the Weatherman utility program in DSSAT. Additionally, a weather file was created for 30 years (1986-2015) of observed daily minimum and maximum temperature, solar radiation (collected by the nearest synoptic weather station in Natitingou, 63 km from the research site), and rainfall (collected from a nearby rain gauge station in Tanguieta (27 km)). All the data on crop management, growth, and yields collected for the two seasons were used to create the standard DSSAT file formats (*.MZX, *.SGX, *.MZA, *.SGA, *.MZT, and *.SGT) for each experiment, needed to run the CERES-Maize and CERES-Sorghum models.

4.2.5 Assessment of models performance

The performance of CERES-Maize and CERES-Sorghum were evaluated graphically by comparing the time series of aboveground biomass, soil water and NO_3-N dynamics, N and P uptake, and final grain and biomass yields from the experiments with predicted values. Statistical assessments to judge the accuracy of model outputs included the root mean square error (RMSE) (Willmott 1981), normalized-RMSE (nRMSE), and Index of agreements (d) (Yang et al. 2014). These indicators were computed as:

$$(1) \quad \mathrm{RMSE} = \left[\sum_{i=1}^{N} \frac{(Yi - Xi)^2}{N}\right]^{1/2}$$

$$(2) \quad \mathrm{nRMSE} = \frac{\mathrm{RMSE}}{\bar{X}} * 100$$

$$(3) \qquad \mathrm{d} = 1 - \frac{\sum_{i=1}^{N}(Yi - Xi)^2}{\sum_{i=1}^{N}(|(Yi - \bar{X})| + |Xi - \bar{Y}|)^2}$$

where N is number of observations, Yi is the predicted value for the ith measurement, Xi is the observed value for the ith measurement, $\bar{Y}$ is the mean of the predicted values, and $\bar{X}$ is the mean of the observed values. When predicted values exactly fitted the observed values, RMSE and nRMSE are 0 and the corresponding d-value is 1. The criteria of agreement between observed and predicted values were set according to Yang et al. (2014): the predictions of the models were considered accurate when evidenced by the lowest RMSE and nRMSE and with d ≥ 0.75 for the outputs of the yield components. The minimum criterion d ≥ 0.60 was set as threshold for the acceptance of the accuracy of predictions in soil-plant N and P and water dynamics.

4.2.6 Simulations of effects of different soil fertility management strategies

The validated CERES-Maize and CERES-Sorghum models were finally used to assess the effects of three soil fertility management strategies on soil C and N, water- and N- use efficiencies, and grain yields of maize and sorghum on the Alisols, assuming 30 years of weather variability (1986-2015). The three tested options during simulations were (i) the un-amended soil as control, (ii) integrated soil-crop management practice, and (iii) high use of mineral fertilizer (Table 2.2; Section 2.2).

The simulations were conducted using the seasonal analysis option in DSSAT for rainfed conditions. The outputs of the models were evaluated graphically with the cumulative probability function. The outputs for water use efficiency, N-partial productivity, and N-internal utilization efficiency were expressed as grain yield per unit of evapotranspiration [kg grain (mm ET)$^{-1}$], grain yield per N fertilizer applied [kg grain (kg N fertilizer)$^{-1}$], and grain yield per N uptake [kg grain (kg N uptake)$^{-1}$], respectively.

4.3 Results

4.3.1 Weather during the crop growing cycle

From planting to harvest, rainfall was about 619 mm in 2014 during the growing cycle of maize and sorghum, but in 2015 it amounted to 912 mm for maize and 948 mm for sorghum. The mean annual minimum temperature was 23.4 °C in 2014 and 22.7 °C in 2015. However, the average minimum temperature over the growing cycle of both crops was approximately 24.0 °C in 2014 and 23.0 °C in 2015. The mean annual maximum temperature was 35.1 °C in 2014 and 2015. The average maximum temperature from planting to harvest of maize was 32.4 °C while it was 33.0 °C for sorghum in 2014. In 2015, the average maximum temperature was 31.3°C during the growth cycle of both crops. The average solar radiation was about 18.6 (MJ m^{-2} d^{-1}) over the growing cycle of both crops in both growing seasons.

4.3.2 Calibration of models: phenology, biomass, and grain yields

Phenology

CERES-Maize and CERES-Sorghum predicted accurately phenology of maize and sorghum as monitored in experiment-1 during the 2014 season. CERES-Maize predicted observed anthesis (52±4 days after planting) and physiological maturity (80±5 days after planting) with RMSE (nRMSE) of 0 day (0%). In 2015, CERES-Maize satisfactorily predicted observed anthesis of maize (53±3 days after planting) with RMSE of 1 day and nRMSE of 2%, and physiological maturity (86±4 days after planting) with RMSE of 1 day and nRMSE of 1%.

In the 2014 season, CERES-Sorghum simulated the observed anthesis (78±8 days after planting) with RMSE (nRMSE) of 2 days (3%), and physiological maturity (103±6 days after planting) with RMSE (nRMSE) of 0 day (0%). In 2015, CERES-Sorghum predicted fairly well the observed anthesis of sorghum (92±7 days after planting) with RMSE (nRMSE) of 14 days (15%), and physiological maturity (123± 5 days after planting) with RMSE (nRMSE) of 14 days (11%) also.

Biomass accumulation

In the 2014 season, the models predicted accurately the observed aboveground biomass accumulation of both maize and sorghum (Fig. 4.1A1, B1). CERES-Maize simulated the changes in aboveground biomass over time with nRMSE of 13% and d-value of 0.99 (Fig. 4.1A1).

Likewise, CERES-Sorghum showed a satisfactory fit between predicted and observed aboveground biomass accumulation, as evidenced by nRMSE of 14% and d-value of 0.99 (Fig. 4.1B1). Both parameterized models simulated fairly well the changes in aboveground biomass during the 2015 season (Figure 4.1A2, B2).

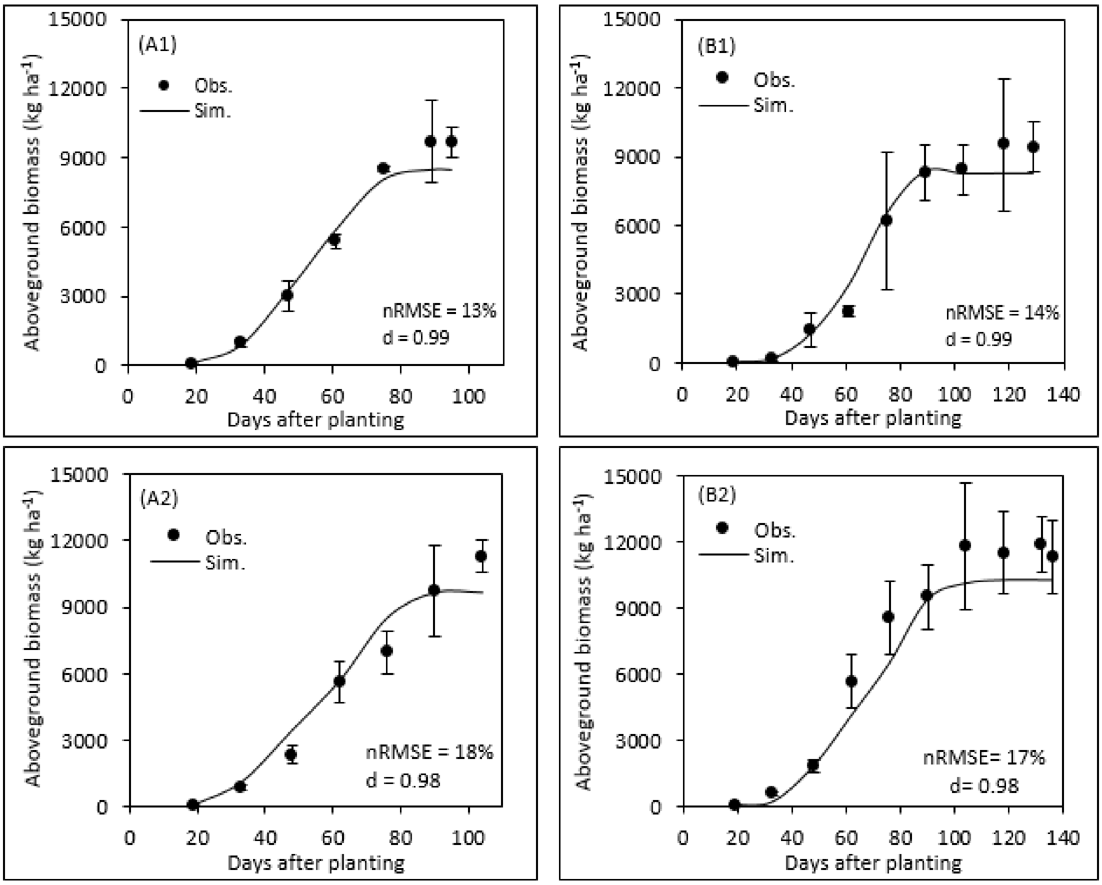

Figure 4.1 Observed (symbols) and simulated (lines) aboveground biomass changes with time of maize (A1, 2) and sorghum (B1, 2) in experiment-1 during the 2014 (A1, B1) and 2015 (A2, B2) cropping seasons.

Yields at final harvest

In experiment-1, CERES-Maize predicted the measured biomass (9110±578 kg ha^{-1}) and grain yields (2889±159 kg ha^{-1}) at harvest in 2014 with RMSE (nRMSE) of 621 kg ha^{-1} (7%) and 47 kg ha^{-1} (2%), respectively. In 2015, CERES-Maize predicted maize biomass yield (9416±567 kg ha^{-1}) with RMSE of 253 kg ha^{-1} and nRMSE of 3%, and maize grain yield (3718±363 kg ha^{-1}) with RMSE of 252 kg ha^{-1} and nRMSE of 7%.

At final harvest in 2014, sorghum biomass and grain yields were 8265±705 kg ha^{-1} and 1778±157 kg ha^{-1}, respectively. The RMSE (nRMSE) between observed and simulated values with CERES-Sorghum was 15 kg ha^{-1} (0.2%) for biomass and 44 kg ha^{-1} (2%) for grain yields. In the 2015 season, CERES-Sorghum simulated observed biomass yield (11623±1780 kg ha^{-1}) with RMSE of 1342 kg ha^{-1} and nRMSE of 25%, and grain yield (2456±168 kg ha^{-1}) with RMSE of 510 kg ha^{-1} and nRMSE of 21%.

4.3.3 Evaluation of models

In-season soil water content dynamics

Measured and simulated soil water contents in various layers of the soil profile are shown for experiment-2 in the 2015 season (Fig. 4.2 and 4.3). Under rainfed and supplementary irrigation conditions with fertilizer application, CERES-Maize predicted accurately in-season soil water dynamics in all layers (Fig. 4.2).

CERES-Sorghum predicted reasonably well changes in soil water content in the top 0-20 and 20-40-cm of the soil profile under rainfed conditions, but tended to under-predict soil water from 70 days after planting onwards in the 40-60-cm layer under rainfed conditions and in all layers with supplementary irrigation (Fig. 4.3).

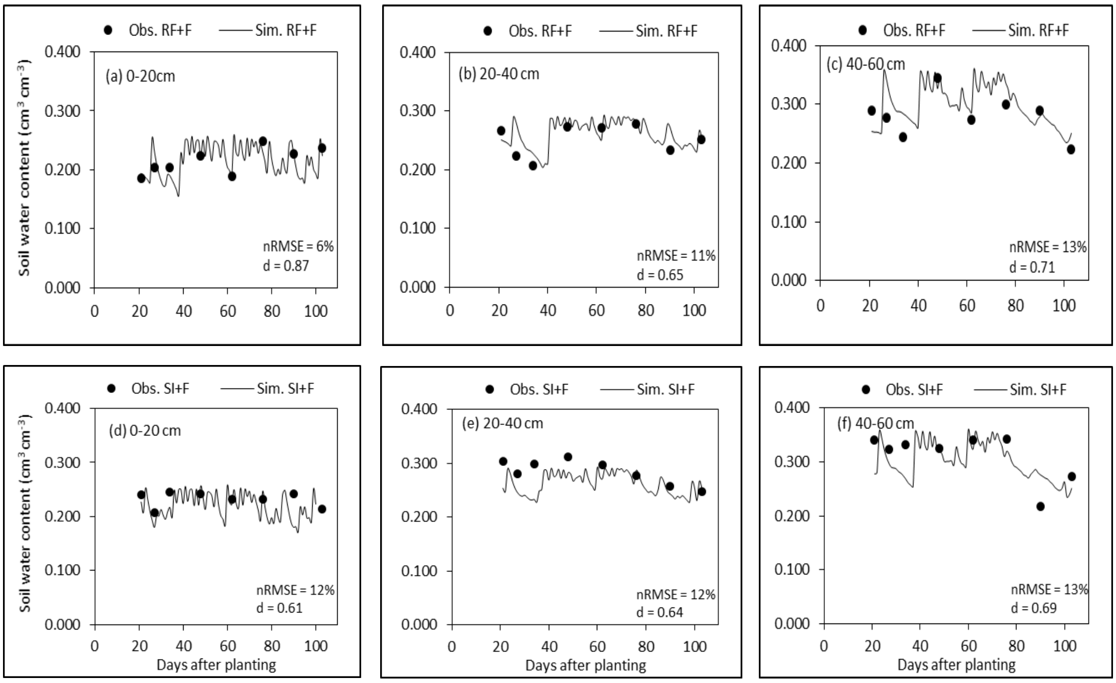

Figure 4.2 Measured (symbols) and simulated (lines) soil water content under maize rainfed with fertilization (a, b, c) and supplementary irrigation with fertilization (d, e, f) in the 0-20 cm, 20-40 cm, and 40-60 cm soil depths in experiment-2 during the 2015 cropping season.

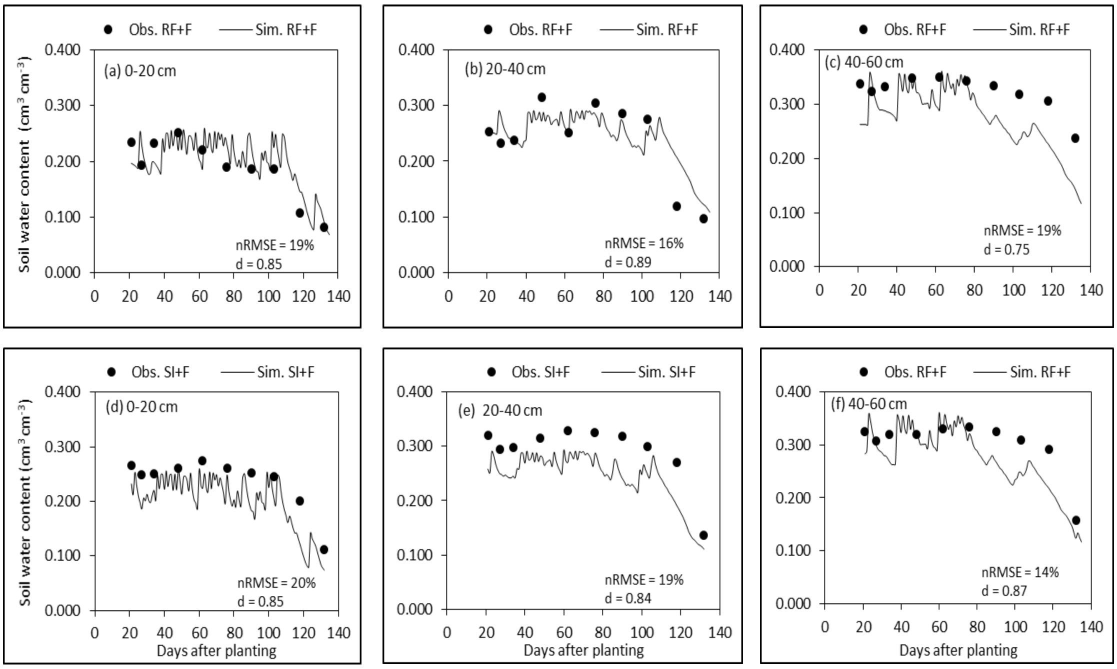

Figure 4.3 Measured (symbols) and simulated (lines) soil water content under sorghum rainfed with fertilization (a, b, c) and supplementary irrigation with fertilization (d, e, f) in the 0-20 cm, 20-40 cm, and 40-60 cm soil depths in experiment-2 during the 2015 cropping season.

In-season soil nitrate-nitrogen dynamics

Both CERES-Maize and CERES-Sorghum captured fairly well the pattern of soil NO_3-N dynamics under rainfed and supplementary irrigation conditions with fertilization in experiment-2 (Fig. 4.4 and 4.5), but both models differed in accuracy. CERES-Maize predicted early season dynamics (up to 30 days after planting) fairly well, but tended to under-predict the dynamics from mid-to the end of the season (Fig. 4.4). CERES-Maize mimicked in-season NO_3-N dynamics under rainfed with fertilization conditions with nRMSE of 56 to 59% and d-values between 0.61 and 0.69 (Fig. 4.4a, b, c). CERES-Maize predictions were slightly better with supplementary irrigation as shown by lower nRMSE and (d values) ranging from 46 and 56% (0.74 and 0.76) (Fig. 4.4d, e, f).

Under rainfed conditions, CERES-Sorghum predicted in-season NO_3-N dynamics with nRMSE of 44-56% and d-values of 0.62-0.76 (Fig. 4.5a, b, c). Predictions of CERES-Sorghum were relatively better under supplementary irrigation conditions (nRMSE = 35-49%; d = 0.76-0.82) (Fig. 4.5d, e, f).

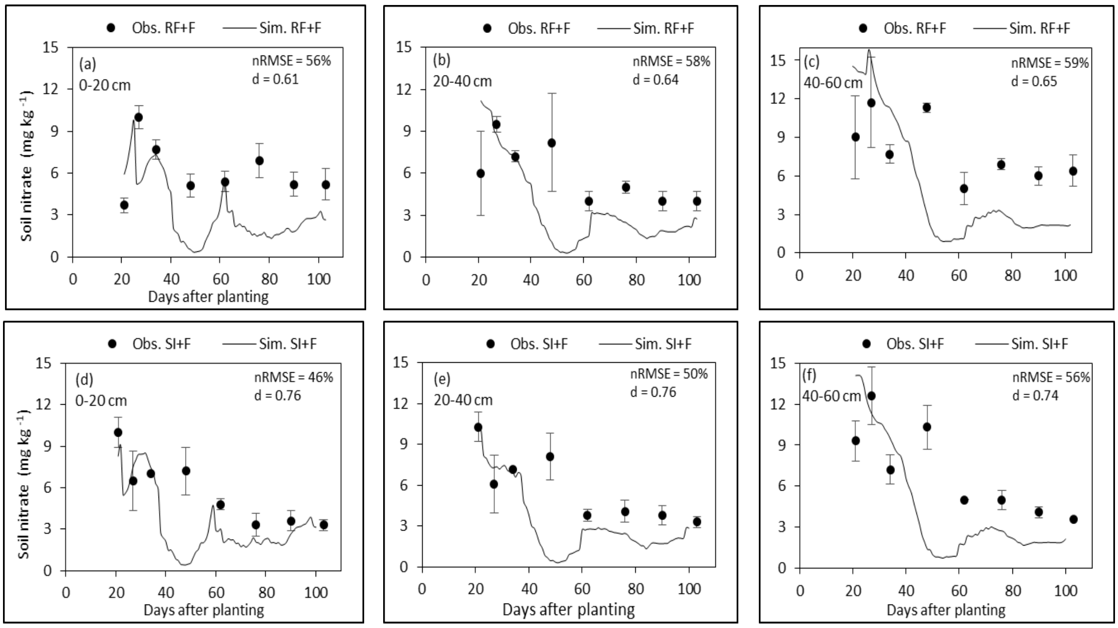

Figure 4.4 Measured (symbols) and simulated (lines) soil nitrate-nitrogen under maize rainfed with fertilization (a, b, c) and supplementary irrigation with fertilization (d, e, f) in the 0-20 cm, 20-40 cm, and 40-60 cm soil depths in experiment-2 during the 2015 cropping season.

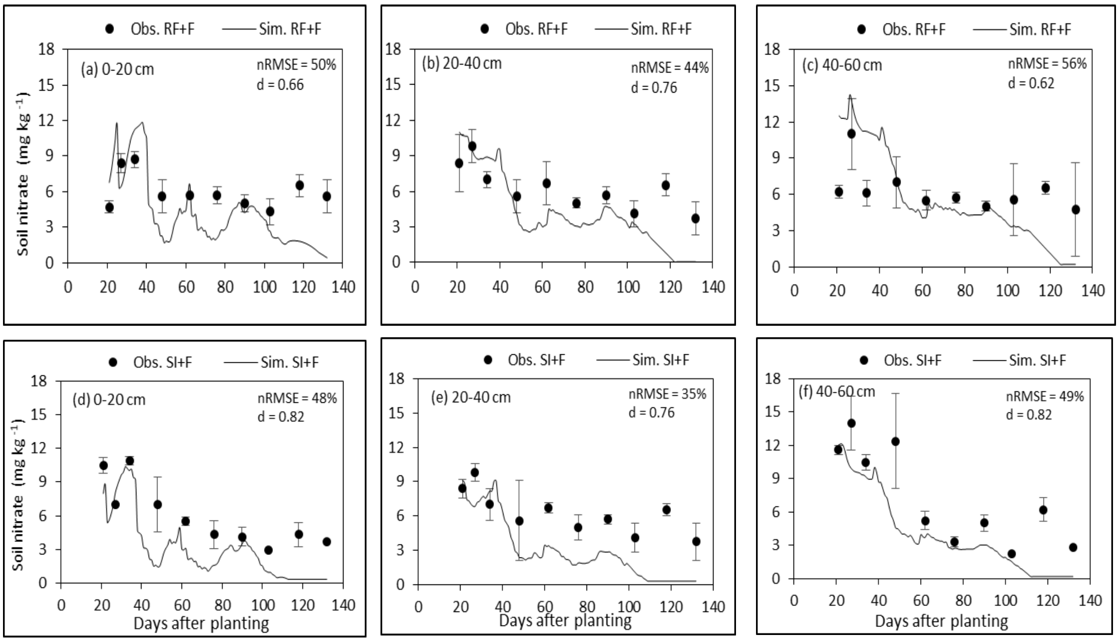

Figure 4.5 Measured (symbols) and simulated (lines) soil nitrate-nitrogen under sorghum rainfed with fertilization (a, b, c) and supplementary irrigation with fertilization (d, e, f) in the 0-20 cm, 20-40 cm, and 40-60 cm soil depths in experiment-2 during the 2015 cropping season.

Nitrogen and phosphorus uptake

Under rainfed conditions without fertilization, CERES-Maize over-predicted early-season N uptake, but under-predicted N uptake later in the season (Fig. 4.6A1). With fertilization, CERES-Maize accurately predicted the end of season N uptake (Fig. 4.6A2). Under supplementary irrigation, the model simulated the observed N uptake satisfactorily for the treatments both with and without fertilization (Fig. 4.6A3, A4). Without fertilization, CERES-Sorghum over-predicted early-season, but under-predicted late-season, N uptake under rainfed (Fig. 4.6B1) and supplementary irrigation conditions (Fig. 6B3). With fertilization, CERES-Sorghum predicted N uptake over time much more accurately under rainfed (Fig. 4.6B2) and supplementary irrigation (Fig. 4.6B4).

Under rainfed conditions without fertilization, CERES-Maize over-predicted P uptake early in the season, and under-predicted P uptake later in the season (Fig. 4.7A1).

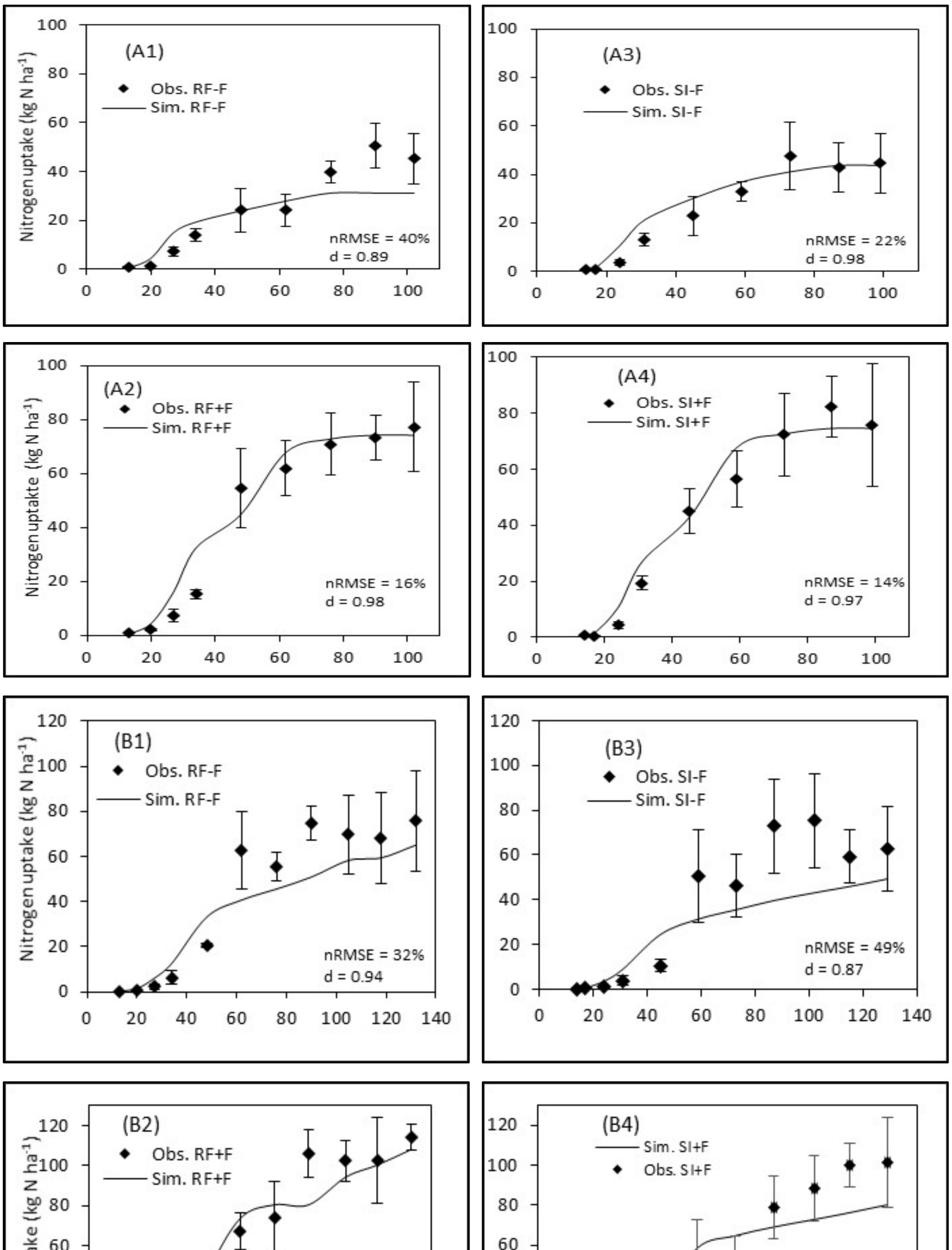

Figure 4.6 Observed (symbols) and simulated (lines) nitrogen (N) uptake over time by maize (A1, A2, A3, A4) and sorghum (B1, B2, B3, B4) under rainfed without fertilization (RF-F), rainfed with fertilization (RF+F), supplementary irrigation without fertilization (SI-F), and supplementary irrigation with fertilization (SI+F) in experiment-2 during the 2015 cropping season.

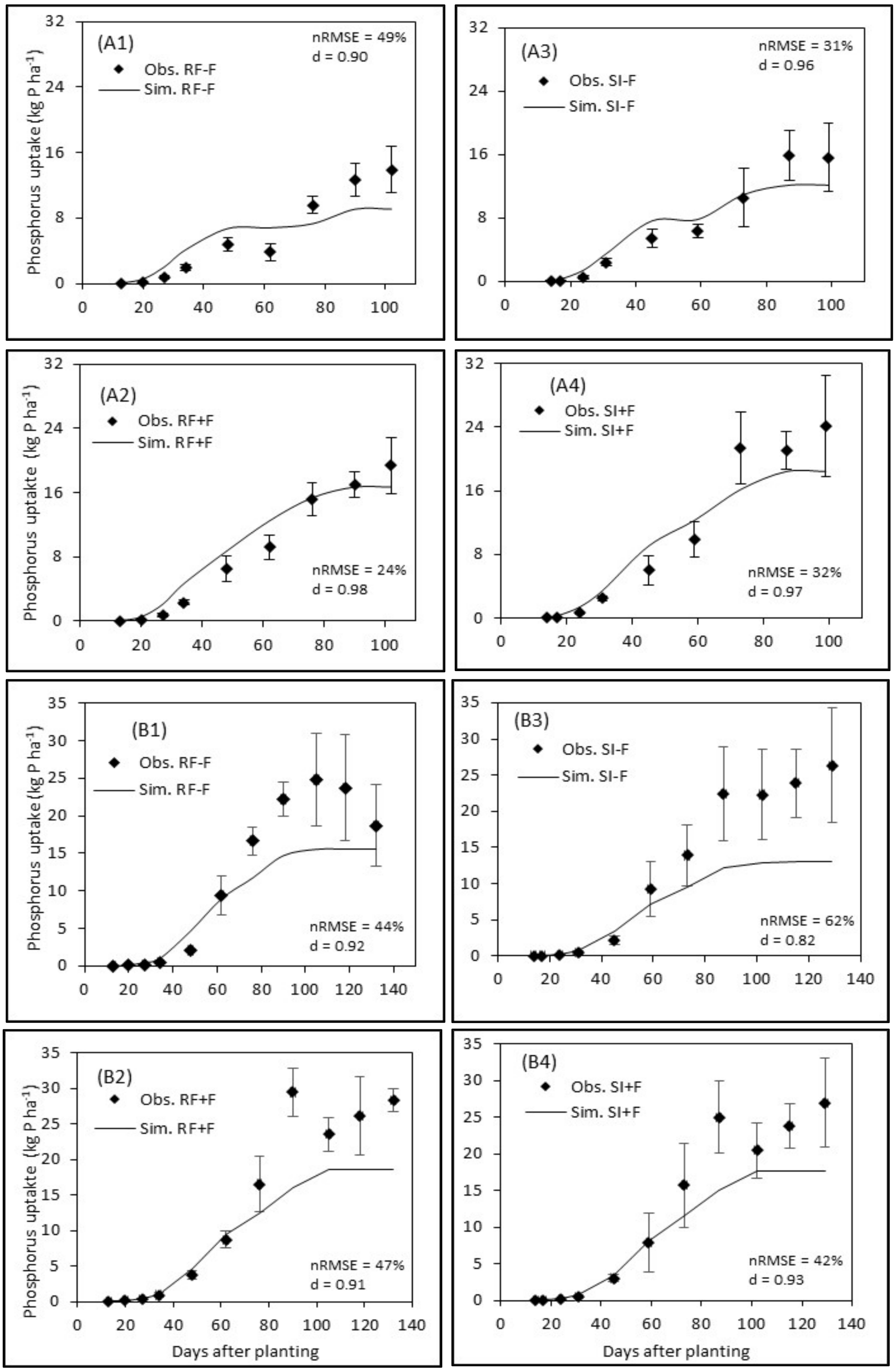

Figure 4.7 Observed (symbols) and simulated (lines) phosphorus (P) uptake over time by maize (A1, A2, A3, A4) and sorghum (B1, B2, B3, B4) under rainfed without fertilization (RF-F), rainfed with fertilization (RF+F), supplementary irrigation without fertilization (SI-F), and supplementary irrigation with fertilization (SI+F) in experiment-2 during the 2015 cropping season.

With fertilizer application, CERES-Maize predicted P uptake accurately under rainfed conditions (Fig. 4.7A2). Under supplementary irrigation, with and without fertilization, P uptake was simulated by CERES-Maize satisfactorily (Fig. 4.7A3, 4). CERES-Sorghum captured P uptake patterns well early in the season, but under-predicted this later in the season under both rainfed and supplementary irrigated sorghum with and without fertilization (Fig. 4.7B1, B2, B3, B4).

Aboveground biomass accumulation

Under rainfed and supplementary irrigation conditions in experiment-2, with and without fertilization, CERES-Maize predicted aboveground biomass accumulation with nRMSE of 10 to 22% and d-values ranging from 0.96 to 0.99 (Fig. 4.8A1, A2, A3, A4).

CERES-Sorghum predicted accurately aboveground biomass growth with nRMSE ranging from 13 to 29% and d-values from 0.97 to 0.99 (Fig. 4.8B1, B2, B3, B4).

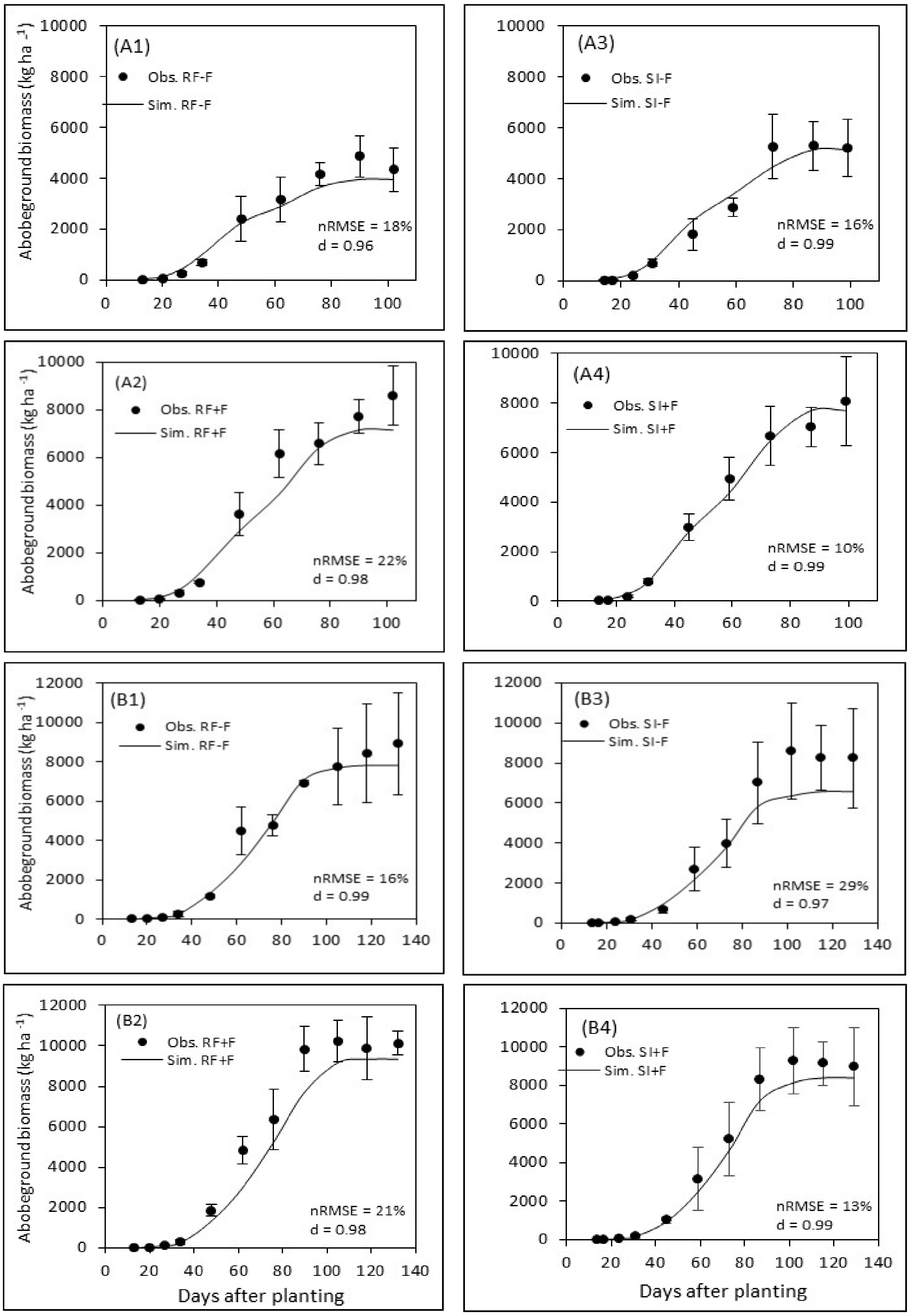

Figure 4.8 Observed (symbols) and simulated (lines) changes in aboveground biomass of maize (A1, A2, A3, A4) and sorghum (B1, B2, B3, B4) under rainfed without (RF-F) and with fertilization (RF+F), and supplementary irrigation without (SI-F) and with fertilization (SI+F) in experiment-2 during the 2015 cropping season.

Yields at final harvest

In experiment-2, CERES-Maize predicted the final biomass very well given the nRMSE of 16% and d-value of 0.94 (Fig. 4.9a). CERES-Sorghum simulated the final biomass well with nRMSE of 14% and d-value of 0.87 (Fig. 4.9b).

On farmers' fields (experiment-3), CERES-Maize predicted the observed final biomass satisfactorily (Fig. 4.10a) with nRMSE of 17% and d-value of 0.92. CERES-Sorghum showed only a moderate goodness of fit of biomass yield at final harvest (Fig. 4.10b) with nRMSE of 45% and d-value of 0.55 (Fig. 4.10b).

Under the researcher-managed conditions of experiment-2, maize grain yield was predicted with RMSE of 413.6 kg ha^{-1} (nRMSE = 19% and d = 0.93) (Fig. 4.11a), while sorghum grain yield was predicted with RMSE of 341.2 kg ha^{-1} (nRMSE = 16% and d = 0.91) (Fig. 4.11b), and hence both predictions were sufficiently accurate.

In the farmer-managed trial (experiment-3), both models predicted grain yield with greater accuracy than biomass (Fig. 4.12). CERES-Maize predicted maize grain yield more accurately with RMSE of 243 kg ha^{-1}, nRMSE of 15%, and d-value of 0.89 (Fig. 4.12a). Similarly, CERES-Sorghum predicted sorghum grain yield reasonably well with RMSE of 117 kg ha^{-1}, nRMSE of 15%, and d-value 0.80 (Fig. 4.12b).

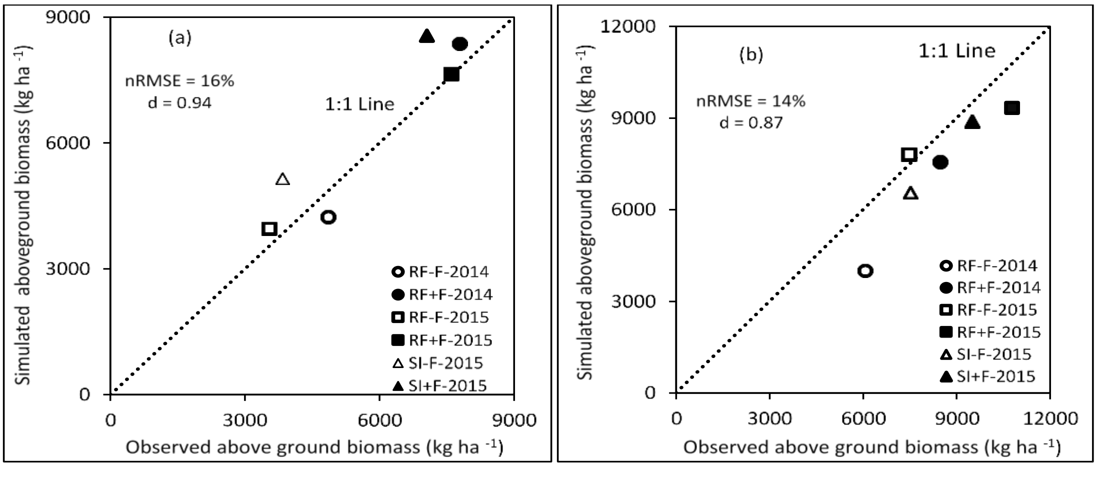

Figure 4.9 Observed and simulated aboveground biomass at final harvest for maize (a) and sorghum (b) under rainfed and supplementary irrigation without (open symbols) and with fertilization (solid symbols) in experiment-2 for the 2014 and 2015 cropping seasons.

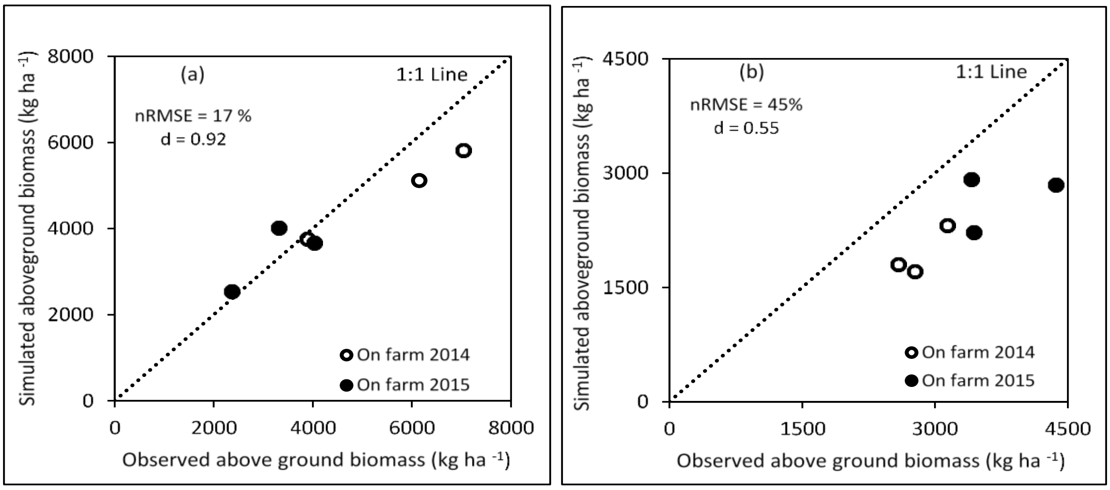

Figure 4.10 Observed and simulated aboveground biomass at final harvest for maize (a) and sorghum (b) under farmer field conditions (experiment-3) during the 2014 (open symbols) and 2015 (solid symbols) cropping seasons.

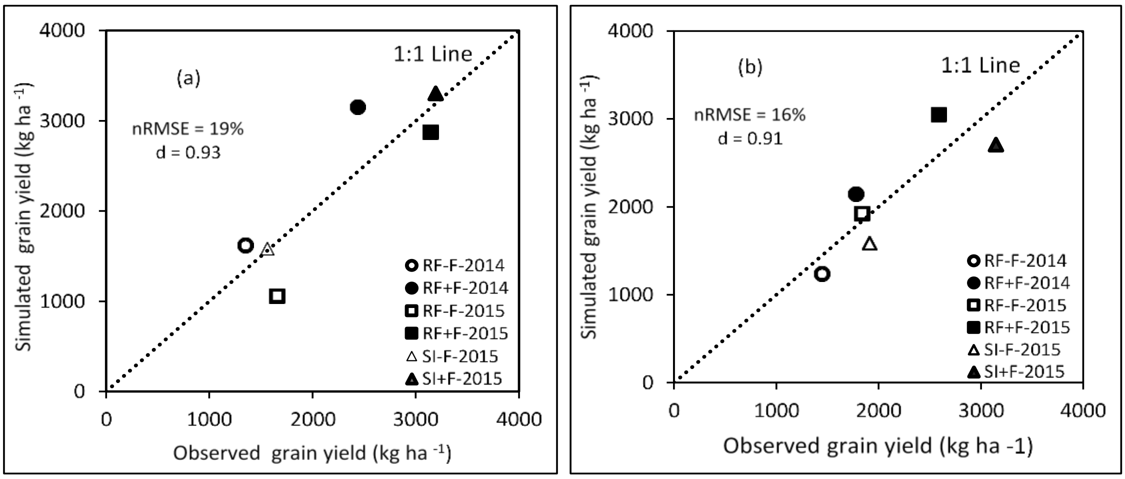

Figure 4.11 Observed and simulated final grain yields for maize (a) and sorghum (b) under rainfed and supplementary irrigation without (open symbols) and with fertilization (solid symbols) in experiment-2 for the 2014 and 2015 cropping seasons.

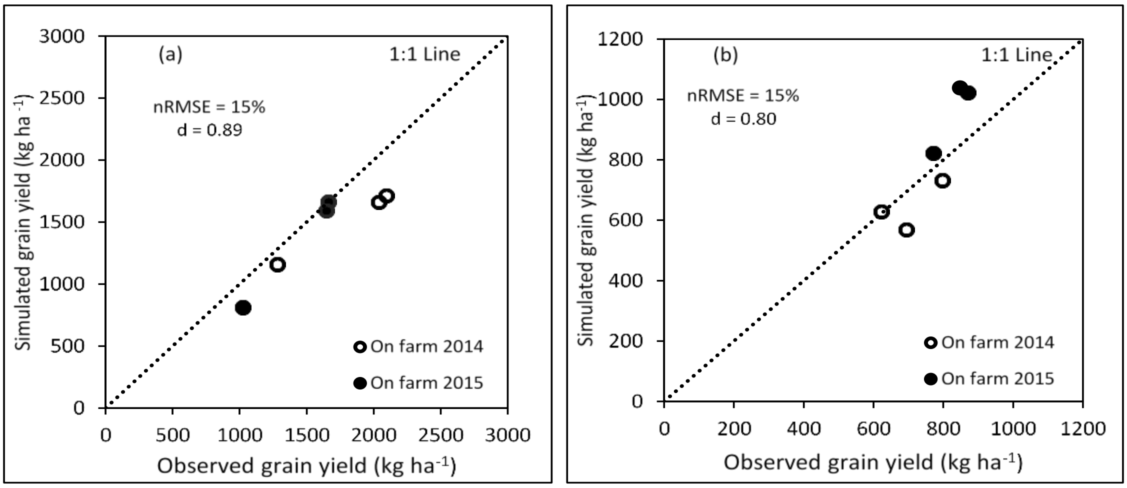

Figure 4.12 Observed and simulated grain yield at final harvest for maize (a) and sorghum (b) under farmer conditions (experiment-3) during the 2014 (open symbols) and 2015 (solid symbols) cropping seasons.

4.3.4 Application of models

Effects of soil fertility management on soil C and inorganic N

The cumulative probability function (Fig. 4.13A1) shows the highest soil total organic C with integrated soil-crop management practice and the lowest under un-amended soil and high use of mineral fertilizer in maize production systems. Weather variability hardly altered the total organic C under un-amended soil and high use of mineral fertilizer, but resulted in noticeable changes with integrated soil-crop management practice, particularly after 0.90 cumulative probability. In sorghum production systems, the simulated total organic C was different between the three soil fertility management strategies. Total soil organic C was highest with integrated soil-crop management practice and lowest with high use of mineral fertilizer (Fig. 4.13B1).

Soil inorganic N in maize production systems was affected by soil fertility management strategies and weather variability (Fig. 4.13A2). Higher soil inorganic N was predicted with integrated soil-crop management practice compared to un-amended soil and high use of mineral fertilizer. The simulated inorganic N showed similar patterns under un-amended soil and high use of mineral fertilizer up to 0.90 cumulative probability while considerable variability appeared with integrated soil-crop management practice from approximately 0.50 cumulative probability onwards. The cumulative probability function of the simulated inorganic N under sorghum production systems indicates no substantial difference between the treatments till 0.40 (Fig. 4.13B2). Thereafter, predicted inorganic N with integrated soil-crop management practice became higher than with un-amended soil or high use of mineral fertilizer.

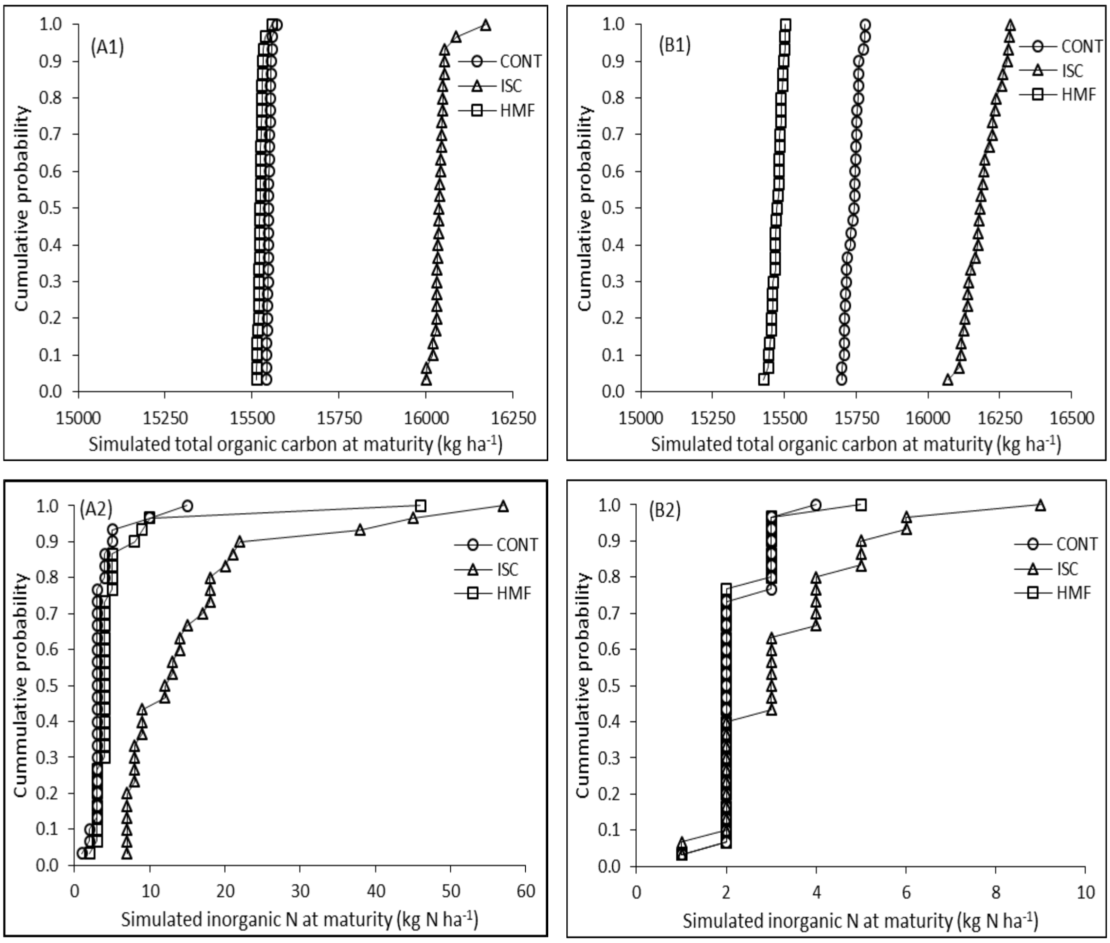

Figure 4.13 Cumulative probability function of simulated total soil organic carbon (A1, B1) and soil inorganic nitrogen (A2, B2) under maize (A1, A2) and sorghum (B1, B2) production systems, assuming an un-amended soil (CONT), integrated soil-crop management practice (ISC), and a high use of mineral fertilizer (HMF) for the historic weather variability (from 1986 to 2015).

Options for improving water use efficiency

The cumulative probability function (Fig. 4.14A1, B1) demonstrates that simulated water use efficiency of maize (Fig. 4.14A1) and sorghum (Fig. 4.14B1) were higher under integrated soil-crop management practice and high use of mineral fertilizer, and lower with un-amended soil. The effects of weather variability were substantial within soil fertility management strategies as evidenced by maize water use efficiency fluctuations ranging from 1.8-6.3 kg grain (mm ET)$^{-1}$ with un-amended soil, 7.3-11.1 kg grain (mm ET)$^{-1}$ under integrated soil-crop management practice, and 4.4 - 11.6 kg grain (mm ET)$^{-1}$ in high use of mineral fertilizer. For sorghum, the variability in water use efficiency between years was within the range of 1.7-5.0 kg grain (mm ET)$^{-1}$, 5.4-8.7 kg grain (mm ET)$^{-1}$, and 5.0-7.9 kg grain (mm ET)$^{-1}$ under un-amended soil, integrated soil-crop management practice, and high use of mineral fertilizer, respectively.

Options for improving N use efficiency

Simulated grain yield of maize or sorghum gained per unit of N fertilizer applied (N-partial factor productivity) with integrated soil-crop management practice was significantly higher than that in high use of mineral fertilizer (Fig. 4.14A2, B2). Maize grain yield per N uptake (N-internal utilization efficiency) was hardly different due to soil management strategies up to approximately 0.50 cumulative probability. Thereafter, predicted N-internal utilization efficiency of maize became greater under both un-amended soil and high use of mineral fertilizer compared to integrated soil-crop management practice. However, from 0.80 to 1.0 cumulative probability, N-internal utilization efficiency of maize under un-amended soil was the highest (Fig. 4.14A3). Simulated N-internal utilization efficiency of sorghum for un-amended soil was as high as with high use of mineral fertilizer, but greater than that with integrated soil-crop management practice. Substantial effects of weather variability were simulated by CERES-Maize and CERES-Sorghum on N-partial factor productivity and internal utilization efficiency between years (Fig. 4.14A2, A3 and B2, B3).

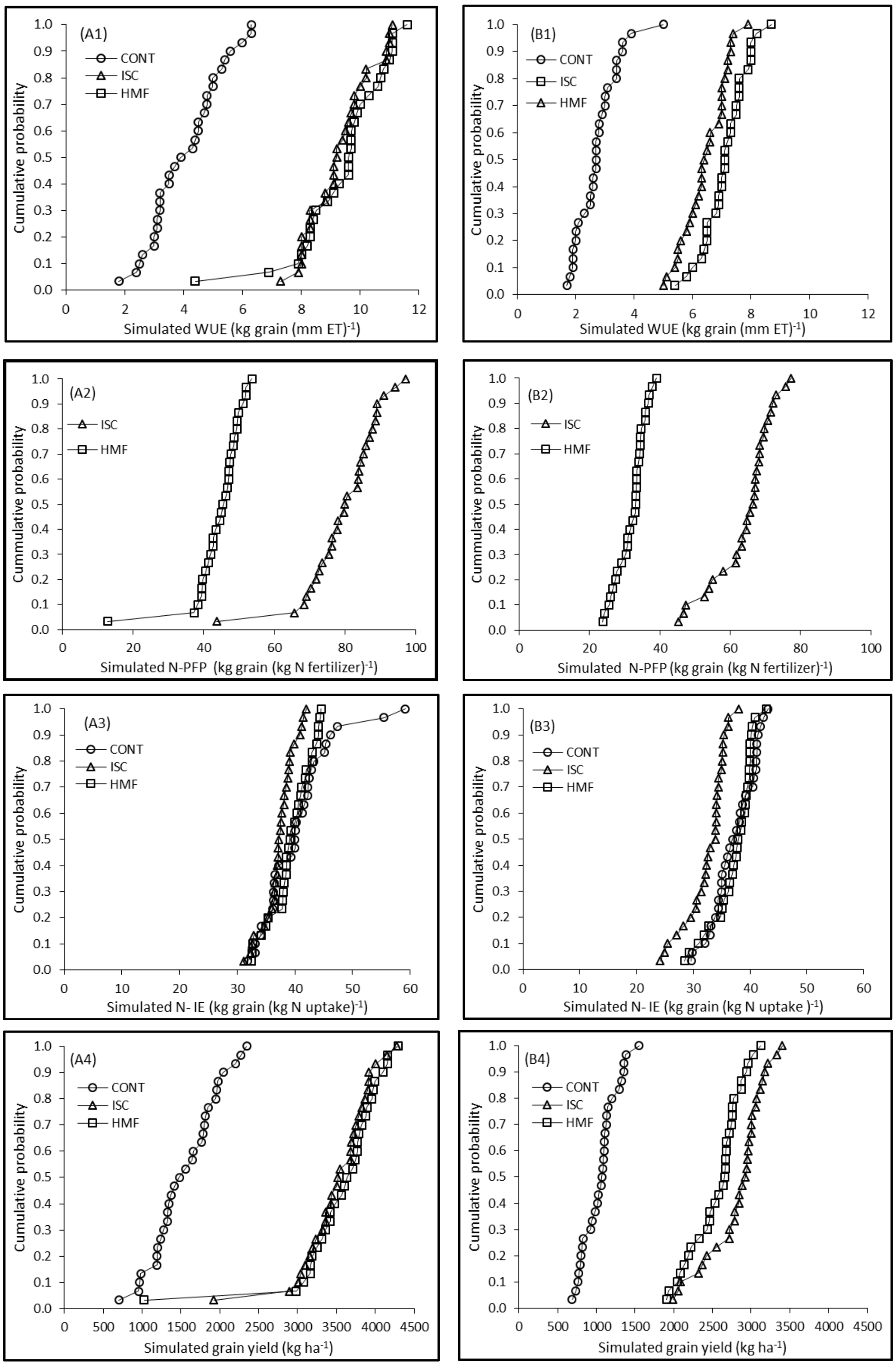

Figure 4.14 Cumulative probability function of simulated water use efficiency (WUE, A1, B1), N-partial factor productivity (N- PFP, A2, B2), N- internal utilization efficiency (N- IE, A3, B3), and grain yields (A2, B2) of maize (A1, A2, A3, A4) and sorghum (B1, B2, B3, B4) under un-amended soil (CONT), integrated soil-crop management practice (ISC), and high use of mineral fertilizer (HMF) assuming the historic weather variability (from 1986 to 2015).

4.4 Discussion

Crop simulation models are essential tools to support the design of resilient production systems not only under on-going weather variability, but also when assuming future climate and agricultural land use change. Many features of crop production in the West African Dry Savannah challenge available crop models including the handling of nutrient deficiencies and biotic stresses. Any confidence in model predictions must be based on their ability to successfully predict performance as monitored in practice especially under the strongly contrasting environmental conditions observed in the tropics in general and in West Africa in particular.

4.4.1 Suitability of the models for growth and development, yields, and in-season water and nutrient dynamics

This study provides evidence on the capability of CERES-Maize and CERES-Sorghum to simulate growth, yields, dynamics of soil water, as well as N and P uptake in response to seasonal soil moisture availability and soil-crop management systems under the dry savannah agro-ecological conditions. The results confirm earlier findings on the suitability of CERES-Maize and CERES-sorghum to simulate growth, development, and yield of maize (Dzotsi et al. 2003; Igue et al. 2013; Jagtap et al. 1993; McCarthy et al. 2012), and sorghum (McCarthy et al. 2010; Singh et al. 2014) in West Africa. Both CERES models predicted grain yields reasonably well also under farmer management practices common in northern Benin that resemble continuous soil mining production systems. Hence, the findings confirm the capability of both models in DSSAT-CSM v4.6 to predict growth and yield of sorghum and maize in N and P-deficient environments compared to previous versions as reported earlier (Dzotsi et al. 2010; Porter et al. 2009).

Both CERES-Maize and CERES-Sorghum models have been extensively tested in West Africa in terms of crop growth and yield under both fertilized and unfertilized conditions (Adnan et al. 2017; Fosu et al. 2012; Soler et al. 2011), but less so in terms of soil water and nutrient dynamics. This study showed that CERES-Maize accurately simulated the changes in soil water in the various layers of the soil profile. Similar good simulations of the soil water balance by CERES-Maize was reported by de Vos and

Mallett (1987), Gabrielle et al. (1995), Anothai et al. (2013), and Liu et al. (2013). In contrast, CERES-Sorghum was less accurate for the lower layers due to water extraction presumably by roots at lower soil depths. These results indicate that the calibration of the models for various soil hydraulic parameters resulted in a satisfactory simulation of the soil water balance of CERES-Maize, but the root weighting parameter may not have been appropriate for the CERES-Sorghum model.

Although it has been postulated that early-seasonal soil moisture dynamics in particular trigger N and P supply and their uptake by crops (Bationo et al. 2012; Buerkert and Hiernaux 1998; Schlecht et al. 2007), few studies if any, have modeled these processes in DSSAT CERES models. Both CERES-Maize and CERES-Sorghum models captured the observed early-season flush of NO_3-N, but consistently under-predicted soil NO_3-N in all layers as the season progressed. The under-prediction of NO_3-N may have been caused by the influence of soil water availability on mineralization and leaching losses. The nRMSE values ranged from 46-59% for CERES-Maize and 35-56% for CERES-Sorghum indicating large uncertainties associated with the simulation of the soil mineral N content, which is not surprising given the complexity of soil N dynamics. Similar uncertainties in simulating soil NO_3-N were observed by Liu et al. (2011) and Yang et al. (2014). Both CERES-Maize and CERES-Sorghum predicted well the cumulative N and P uptake in the conditions of northern Benin. Differences or similarities in the uptake patterns under both rainfed and supplementary irrigations conditions could be explained by nutrient concentrations (Fig. 4.4, 4.5), soil water availability (Fig. 4.2,4.3), and root activity (Godwin and Singh 1998). Liu et al. (2012) predicted with satisfaction maize growth and its N uptake in northeastern China after optimizing both for the maize cultivar coefficients and N stress coefficients. McCarthy et al. (2010) also reported good performance of CERES-Sorghum for N uptake, but concurrently highlighted the inability of the previous version of CERES-Sorghum to simulate P-dynamics.

The good performance of both models provided a basis for modeling the long-term (30 years of weather variability) impact of different nutrient management options on soil organic C, inorganic N, water- and N- use efficiencies in the maize and sorghum-based production systems in the region.

4.4.2 Effects of soil fertility management and weather variability on soil organic carbon and inorganic nitrogen

CERES-Maize and CERES-Sorghum simulated increased soil organic C and inorganic N with integrated soil-crop management practice compared to un-amended soil and high use of mineral fertilizer as a result from the return of crop residues under integrated soil-crop management practice contrary to un-amended soil and high use of mineral fertilizer. Soler et al. (2011) simulated in Burkina Faso a decline in soil organic C under continuous crop rotation (e.g. sorghum) without fertilization and with the removal of aboveground biomass at harvest. The predicted higher soil inorganic N with integrated soil-crop management practice compared to un-amended soil and high use of mineral fertilizer, indicated more N release and availability under integrated soil-crop management practice practices due to mineralization of the incorporated crop residues and soil organic matter (Porter et al. 2009). The models predicted in addition higher year-to-year changes for soil inorganic N compared to organic C changes irrespective of the soil fertility management options tested. This indicates the dominating influence of weather variability, rainfall in particular, and corresponding soil moisture on N release (Unger et al. 2010). The accumulation of soil inorganic N at final harvest under integrated soil-crop management practice suggests that this integrated nutrient management strategy must boost N supply especially at the onset of succeeding season and is thus one option to ease N-stress on crop growth and production.

4.4.3 Effects of soil fertility management and weather variability on yields, and water- and nitrogen- use efficiencies

Soil fertility management options such as integrated soil-crop management practice and high use of mineral fertilizer increased water use efficiency of both crops. The higher water use efficiency with integrated soil-crop management practice and high use of mineral fertilizer compared to the un-amended soil can be explained by the increases in grain yields with integrated soil-crop management practice and high use of mineral fertilizer with the same amount of water. The present results together with previous findings (McCarthy et al. 2010, 2017; Ritchie and Basso 2008) confirms that, with a fixed water supply, soil fertility management options that increase yields improve water use efficiency concurrently.

The CERES-Maize and CERES-Sorghum models both simulated greater N-partial factor productivity for integrated soil-crop management practice than with high use of mineral fertilizer. The more efficient N use with integrated soil-crop management practice is explained by the combination of similar grain yields under integrated soil-crop management practice as high use of mineral fertilizer with lower amount of N fertilizer applied (almost 50% less of N applied with integrated soil-crop management practice compared to high use of mineral fertilizer). This is in much agreement with earlier findings by McCarthy et al. (2017) who reported higher N-partial factor productivity for maize with a combination of inorganic N fertilizer and manure. The predicted N-internal utilization efficiency by both models fell on the one hand within the ranges recognized for cereals (Dobermann 2007). On the other hand, the higher N-internal utilization efficiency predicted when assuming un-amended soil points at the increased capability of crops to transform the N previously taken up into grain yield in case of low-N environments (Dobermann 2007; Wang et al. 2014).

The CERES-Maize predicted no difference in grain yield patterns between integrated soil-crop management practice and high use of mineral fertilizer, while CERES-Sorghum simulated the highest sorghum grain yields with integrated soil-crop management practice. The trends of grain yields obviously are driven by the increased water use efficiency and N-partial factor productivity of both crops with favorable soil fertility management strategies such as integrated soil-crop management practice and high use of mineral fertilizer. Furthermore, the similar, or even greater grain yields simulated under integrated soil-crop management practice compared to high use of mineral fertilizer, highlights once more the importance of crop residue retention in the semi-arid and arid regions of West Africa for a balanced and improved soil fertility and plant nutrition (Buerkert et al. 1996; Lal 2006). The year-to-year variability in grain yields under the same soil fertility management strategy was caused mainly by changes in key weather parameters such as intra-annual rainfall. This became crucial because the maximum temperatures during the growing cycle remained below the optimum temperature (34°C) of both crops (Kumudini et al. 2014; White et al. 2015) thus excluding heat-stress effects. The model findings reinforce thus the potential of increasing food security in West Africa by sustainable agriculture management. These findings should support decision making for defining future nutrient markets in West Africa and provide research-based evidence on the level of resilience and sustainability of production systems, which may be of interest to decision makers and farmers alike.

4.5 Conclusions

The CERES-Maize and CERES-Sorghum models predicted with satisfaction yield components and the underlying soil water and plant N and P demands under current weather, and also increased soil C and N, water- and N- use efficiencies, and grain yields with integrated soil-crop management practice when assuming long-term weather scenario. Since the models realistically predicted seasonal soil water and nitrate-nitrogen dynamics in both maize- and sorghum-based productions systems in northern Benin, it can be concluded that both models perform well in water- and nutrient-stress-free as well as nutrient-deficient crop production environments. This evidences the robustness of both CERES-Maize and CERES-Sorghum to perform under Dry Savannah agro-ecological conditions as prevail in various parts of West Africa. Consequently, both models are appropriate tools for exploring potential impact of predicted climate change on soil water- and nutrient- use efficiencies. Such findings should support the identification of sustainable production and intensification options for the maize- and sorghum-based production systems of West Africa that would be more resilient under future climate variability and thus support better-informed decision-making.

5 IMPACT OF CLIMATE CHANGE ON WATER- AND NITROGEN- USE EFFICIENCIES AND YIELDS OF MAIZE AND SORGHUM

5.1 Introduction

Sustainable intensification is often recommended as a strategy for farmers to cope with adverse impact of climate change, sustain food security, and improve livelihoods without compromising the environment. Especially in West Africa, increasing temperatures (IPCC 2013), recurrent dry spells (Paeth et al. 2009), ongoing land degradation and soil fertility depletion (Bationo et al. 2012) threaten sustainable crop production. The predicted climate change and variability for this region will exacerbate the impact of land degradation and soil fertility depletion on crop responses even more and consequently worsen food insecurity and poverty (Wheeler and von Braun 2013).

Historically, West Africa has already experienced erratic rainfall regimes as evidenced by wet periods (e.g. 1930-1960), followed by regular dry spells (e.g. 1970-1980) and again wet years (e.g. 1990, 2000), albeit with increased spatial and temporal variability (Hulme et al. 2001; Paeth et al. 2009). Furthermore, temperatures in the region are expected to gradually increase possibly by as much as 6°C by 2100 (Riede et al. 2016). Consensus exists that the climate-driven changes in soil water and nutrient use will seriously test the resilience of the major production systems (Whitehead and Crossman 2012). The projected variability in climate and weather parameters will critically affect the Dry Savannah zones such as those of Benin, but the magnitude of the impact remains uncertain. This hampers the development and implementation of appropriate adaptation measures and policies to assist farmers and decision-makers.

Several studies have addressed climate change impact on crop yields and food security worldwide (e.g. Wheeler and von Braun 2013). Localized studies on crop yield responses to soil fertility under future climate conditions are coming on stream (Guan et al. 2017; Webber et al. 2014). Yet, little is known about the impact of climate change on water- and nutrient-use efficiencies of major cereals like maize and sorghum in the West African Dry Savannah agro-ecological zones, which presently have low to very low resource use efficiency (Christianson and Vlek 1991). Understanding the magnitude of resource use efficiency under climate change and variability is, however, crucial for the development of site- and crop-specific adaptation techniques.

Improving resource use efficiency requires understanding of the often complex genetic-environment-management interactions. Crop simulation models that integrate the soil-plant-atmosphere complex can be useful tools to predict the consequences of climate change and variability on resource use efficiency of crop, and help to design sustainable cropping systems. Among the many crop models, the DSSAT- Cropping System Models (Jones et al. 2003) permit the quantification of crop growth and yields, the evaluation of alternative production systems, and the *ex-ante* development and assessment of sustainable intensification options (Hoogenboom et al. 2015). It considers soil-water (Ritchie 1998) and nutrient-related (Godwin and Singh 1998; Godwin and Vlek 1985) as well as environmental and plant physiological processes. The DSSAT CERES-Maize and CERES-Sorghum models are therefore appropriate tools to explore potential impact of the predicted climate change on water- and nutrient-use efficiencies of these crops and to assess sustainable intensification measures for the smallholders in West Africa. The objective of this study was to assess the impact of predicted climate change on water- and N- use efficiencies, as well as on yields of maize and sorghum in the dry savannah areas of northern Benin.

5.2 Material and methods

5.2.1 Study area

A localized climate change impact assessment was conducted only on Alisols, which represent the major agriculturally used soil type (IUSS Working Group WRB 2014) at Ouri-Yori (10°49’16’’N, 1°4’7’’E) in the dry savannah of North-west Benin, West Africa. The characteristics of the case study region have been presented in chapter 2 (Section 2.1).

5.2.2 Climate change scenarios

Historical data on observed daily rainfall, minimum and maximum temperatures and solar radiation for the period 1986-2005 represents the climate baseline. Future (2080-

2099) bias-corrected ensemble mean predictions of climate parameters were estimated with the use of three Global Circulation Models (GCM: BNU-ESM, CanESM2, and MPI-ESM-MR) from the Coupled Model Inter-comparison Project Phase 5- (CMIP5) for three Representative Concentration Pathways (RCPs) of the International Panel on Climate Change (IPCC) (Gudmundsson et al. 2012; Hawkins et al. 2013). The three RCPs (2.6, 4.5, and 8.5 (IPCC 2013)) differ from each other in the assumptions of population, economic growth, energy consumption and sources, and land use (van Vuuren et al. 2011). The RCP 2.6 is a low level (peak and decline) Greenhouse Gases (GHG) forcing scenario, aiming to limit the increase in global mean temperature to 2°C (van Vuuren et al. 2011). The RCP 4.5 is a medium pathway to stabilize the radiative forcing at 4.5 W m^{-2} by 2100 without overshoot (Thomson et al. 2011), while RCP 8.5 assumes a rising GHG pathway in absence of climate change policy (Riahi et al. 2011).

The daily bias-corrected rainfall, solar radiation, minimum and maximum temperature outputs of about 21 GCM for the baseline and future periods were obtained from the data portal of the CGIAR- Research Program on Climate Change Agriculture and Food Security (CCAFS 2017). We selected three climate models among the 21 GCM available, i.e. BNU-ESM of the College of Global Change and Earth System Science, Beijing Normal University (Ji et al. 2014), CanESM2 of the Canadian Center for Climate Modeling and Analysis (Chylek et al. 2011), and MPI-ESM-MR of the Max Plank Institute for Meteorology (Jungclaus et al. 2010). Selection was based on the high correlation between historical projections and observations (Fig. 5.1), as well as on a realistic representation of the seasonal rainfall cycle with the lowest deviations in rainfall, temperatures, and solar radiation. Daily outputs of these models were calibrated using the historical (1986-2005) station observations (Fig. 5.1) and bias corrected using the “delta” (change factor), “nudging” (bias correction), and quantile mapping approaches (Gudmundsson et al. 2012; Hawkins et al. 2013). The ensemble mean (Guan et al. 2017) of the three climate models was considered for the future weather parameters (2080-2099).

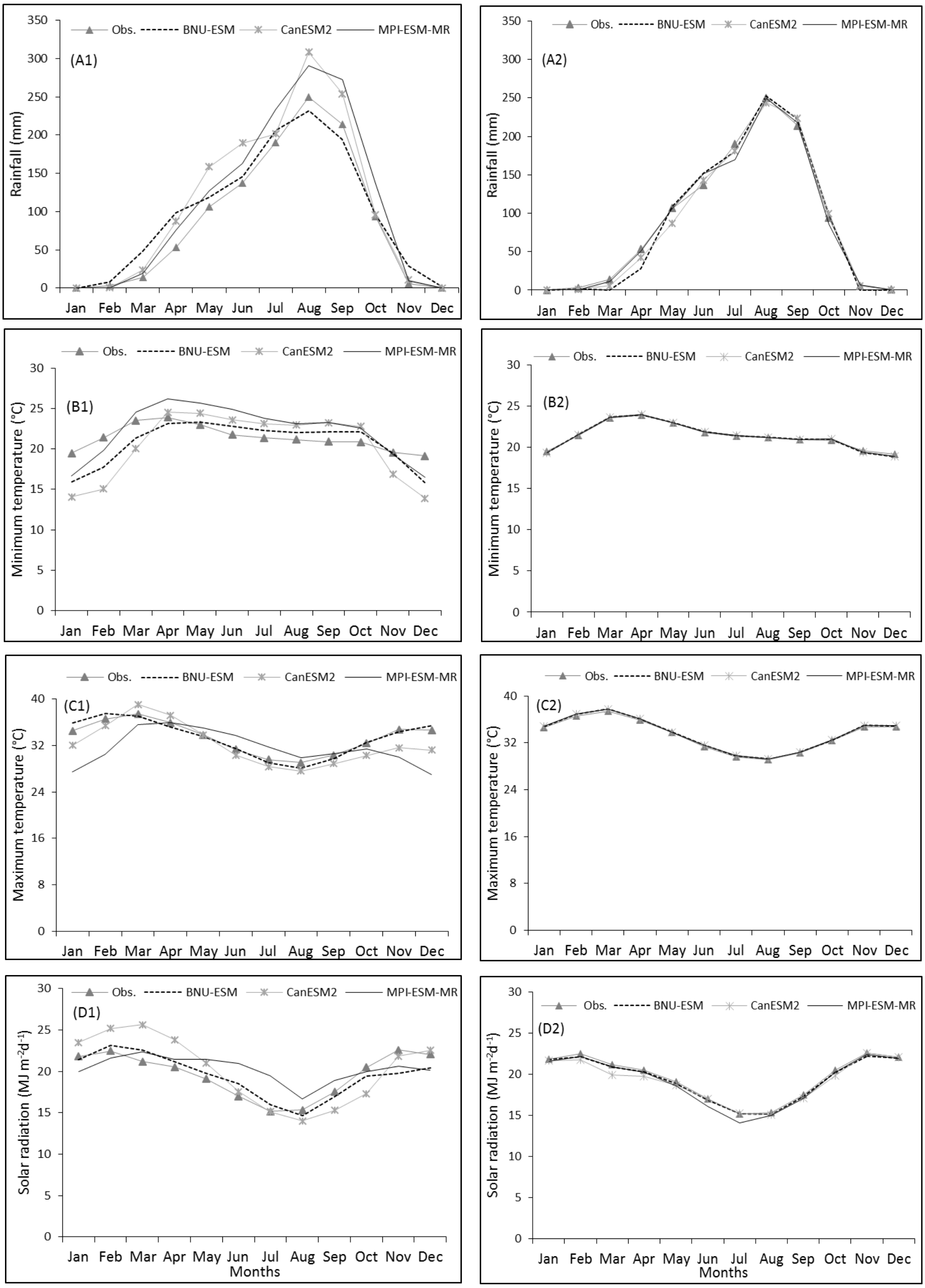

Figure 5.1 Historical observations (1986-2005) and GCM-(BNU-ESM, CanESM2, and MPI-ESM-MR)-based projections of rainfall (mm), maximum and minimum temperatures (°C), and solar radiation (MJ m^{-2} d^{-1}) before (A1, B1, C1, D1) and after calibration (A2, B2, C2, D2) of the models outputs

The default atmospheric carbon dioxide (CO_2) concentration of Mauna Loa (Hoogenboom et al. 2015) was used for the baseline period, while predicted CO_2 concentrations (Table 5.1) reported for RCP 2.6, 4.5, and 8.5 scenarios towards 2100 were used for the future period (Meinshausen et al. 2011).

Table 5.1 Climate change scenarios used in the weather input files and the environmental modifications

Scenario	GCM	Variables	Atmospheric CO_2 (ppm)
Baseline	Observation	Rainfall	347-380
RCP 2.6	BNU-ESM	Min. and max. temperatures, and solar radiation	421
RCP 4.5	CanESM2		538
RCP 8.5	MPI-ESM-MR		936

5.2.3 Soil fertility management scenarios

Crop responses under the historical and future climate were assessed based on the three soil fertility management strategies, namely the (1) un-amended soil as control, (2) integrated soil-crop management practice, and (3) high use of mineral fertilizer (Table 2.2, Sections 2.2). The combination of climate change scenarios and soil fertility management strategies was run with each crop model in a seasonal mode to simulate various parameters as a proxy for crop responses including aboveground biomass accumulation, N and P uptake, water- and N-use efficiencies as well as yields.

5.2.4 Crop simulation models

The CERES-Maize and CERES-Sorghum models, which are part of the DSSAT V4.6 (Hoogenboom et al. 2015; Jones et al. 2003), were used to assess the impact of selected climate change factors on water- and N-use efficiencies and yields of maize and sorghum. The models have been described in chapter 4 (Section 4.2.1). Both models account for temperature effects on crop growth and grain filling rate (Section 4.2.1). Atmospheric CO_2 effect on potential biomass production is incorporated into both models through a PCO_2 factor that modifies radiation use efficiency (RUE), with PCO_2 values being increased following an increment of the CO_2 concentration (White et al. 2015). Soil fertility effect (other than N) on daily biomass growth rate is integrated through a generic soil fertility factor (SLPF) (Hoogenboom et al. 2010; White et al. 2015).

These crop models have not only been widely tested in Sub-Saharan Africa (e.g. Adnan et al. 2017; McCarthy et al. 2010) but have also been used for assessing climate change impact (Jones and Thornton 2003; Singh et al. 2014). Both models have been successfully calibrated and validated for maize (cv. EVDT-97 STR) and sorghum (cv. local) varieties typical for the study region (Chapter 4). They are suitable tools for exploring water- and N-use efficiencies and yields of maize and sorghum as affected by the current and improved soil fertility management regimes in the face of predicted climate change and variability in the region.

The historical and future climate datasets served as inputs to run the models for investigating the responses of both crops to the soil fertility management options under the three climate change scenarios (RCPs 2.6, 4.5, and 8.5). Climate change impact on grain yields, N and P uptake, and water- and N-use efficiencies were evaluated by comparing predicted responses of maize and sorghum to each of the three soil fertility management options under historical climate (1986-2005) with responses to the same options assuming the same initial soil conditions under a future climate (2080-2099) for the RCPs 2.6, 4.5, and 8.5. The models outputs for water use efficiency, N-partial productivity, and N-internal utilization efficiency were expressed as described in chapter 4 (Section 4.2.6).

5.3 Results

5.3.1 Predicted changes in key climatic parameters

Based on the averages across the climate models BNU-ESM, CanESM2, and MPI-ESM-MR, the predicted seasonal rainfall change (%) reached -2±6 (RCP 2.6), -4±8 (RCP 4.5), and +1±9 (RCP 8.5) (Fig. 5.2A1, A2). Temperatures (°C) are predicted to increase, i.e. minimum temperatures (Fig. 5.2B1, B2) by +1.0±0.2, +2.0±0.2 and +4.7±0.4, and maximum temperatures (Fig. 5.2C1, C2) by +1.1±0.2, +2.0±0.3 and +4.6 ±0.5, for RCPs 2.6, 4.5 and 8.5, respectively. Solar radiation (MJ $m^{-2}d^{-1}$) is predicted to decrease by -0.4±0.6 for RCP 2.6, -0.3 ±0.6 for RCP 4.5, and -0.5±0.4 for RCP 8.5 (Fig. 5.2D1, D2).

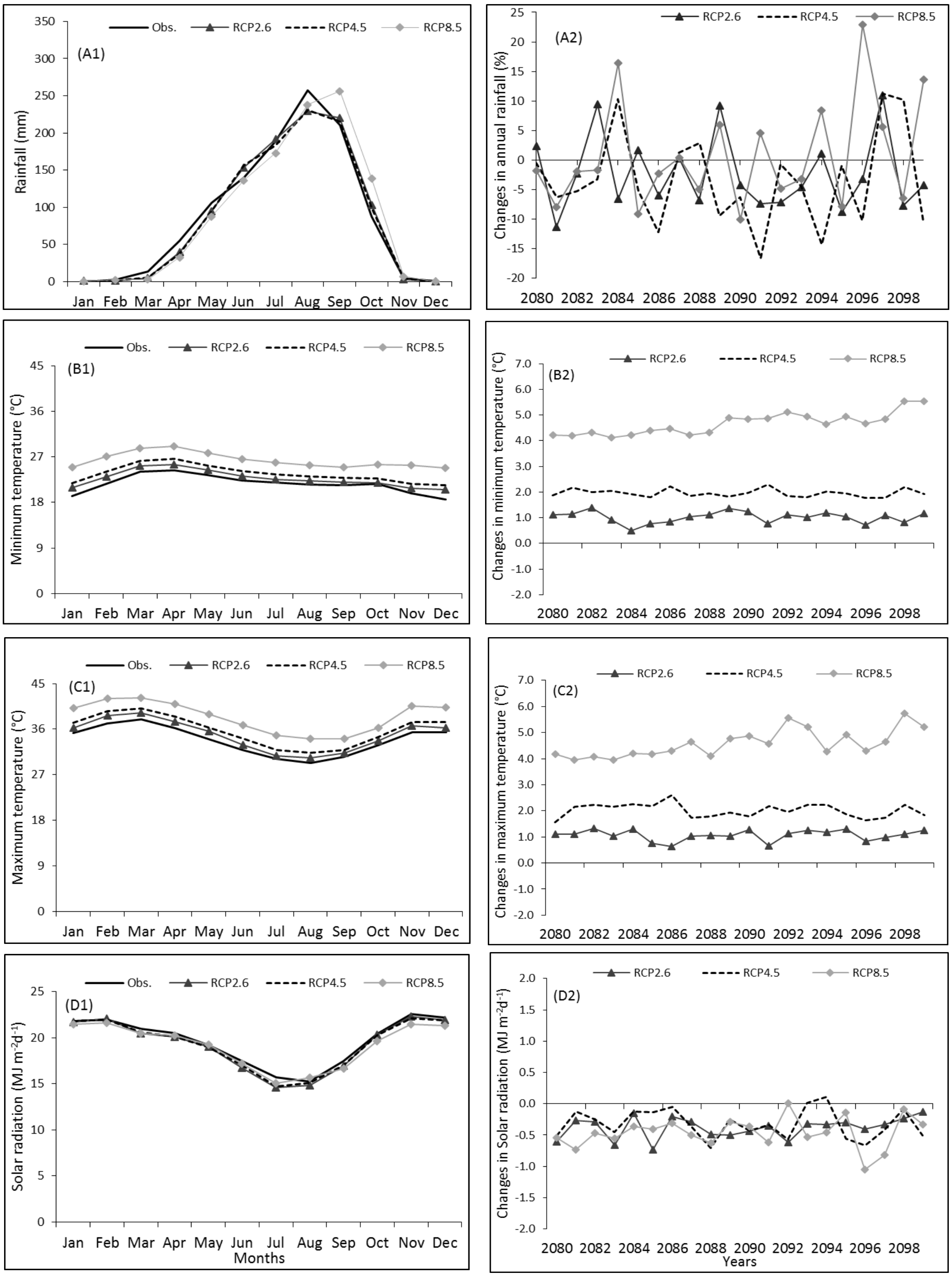

Figure 5.2 Changes in seasonal cycles (A1, B1, C1, D1) and inter-annual trends (A2, B2, C2, D2) based on averages of bias-corrected predictions of BNU-ESM, CanESM2, and MPI-ESM-MR models (2080-2099) for rainfall (A1, A2), minimum temperature (B1, B2), maximum temperature (C1, C2), and solar radiation (D1, D2). Changes are relative to baseline mean (1986-2005) under three Representative Concentration Pathways (RCPs) of the International Panel on Climate Change (IPCC): RCP 2.6, 4.5, and 8.5.

5.3.2 Changes in cumulative aboveground biomass

Under the projected climate, both CERES-Maize and CERES-Sorghum predicted more vigorous aboveground biomass accrual in the 2080-2099 run than in the historical run, albeit only during the vegetative growth (Fig. 5.3).

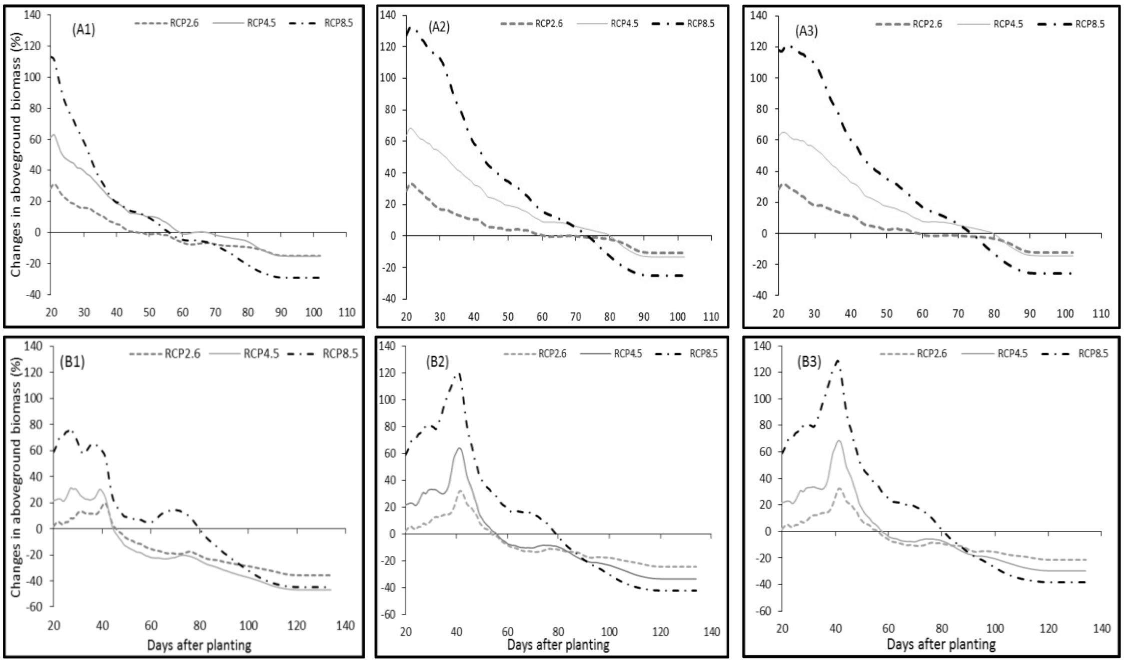

Figure 5.3 Changes in cumulative aboveground biomass responses of maize (A1, A2, A3) and sorghum (B1, B2, B3) under future climate (2080-2099) relative to historical means (1986-2005) assuming an un-amended soil as control (A1, B1), integrated soil-crop management practice (A2, B2), and high use of mineral fertilizer (A3, B3) and three Representative Concentration Pathways (RCPs) of the International Panel on Climate Change (IPCC): RCP 2.6, 4.5, and 8.5.

The predicted enhanced initial aboveground biomass growth was crop specific and in general greater for RCP 8.5 and RCP 4.5 and lower for RCP 2.6. With integrated soil-crop management practice or high use of mineral fertilizer, the vegetative growth enhancement was greater than for the un-amended soil conditions. According to CERES-Maize, biomass accrual in the 2080-2099 run is less than in the historical run from ≈ 60 days after planting (Fig. 5.3A1) under all three climate scenarios in the un-amended treatment, whereas this would occur from approximately 70 days after planting with integrated soil-crop management practice or high use of mineral fertilizer (Fig. 5.3A2, 3). Regardless of the soil fertility management strategy, the comparative loss in growth in the future scenario modeled by CERES-Maize increased from RCPs 2.6 to 4.5 and to RCP 8.5 (Fig. 5.3A1, 2, 3). CERES-Sorghum predicted an extended period of enhanced biomass accumulation for 2080-2099 with RCP 8.5 (up to ≈ 80 days after planting) compared to RCP 2.6 and 4.5 (< 60 days after planting). CERES-Sorghum simulated also a smaller difference in biomass accrual after those periods with RCPs 2.6 and 4.5, except for the un-amended conditions (Fig. 5.3B1, 2, 3).

5.3.3 Impacts on water- and N- use efficiencies

Water-use efficiencies are consistently lower in all future scenarios than between 1986 and 2005 and more so for the more drastic climate change scenarios. The impact is greater for maize than for sorghum, and both methods of soil fertility management (sole mineral and combined mineral and organic amendment) enhanced water-use efficiency significantly as compared to the control (Fig. 5.4A1 and B1). CERES-Maize predicted a decrease in water-use efficiency of 17-53% and CERES-Sorghum of 23-51%. The response of water-use efficiency to soil fertility management systems was, however, higher for maize than for sorghum.

Compared to the period 1986-2005, the partial factor productivity of applied N was significantly reduced in 2080-2099, and more so with greater climate change. The N-partial factor productivity for the integrated soil-crop management treatment was much higher than for the high use of mineral fertilizers alone. The projected decreases in the N-partial factor productivity varied from 10 to 47% with CERES-Maize and 22 to 49% with CERES-Sorghum.

The simulated N-internal utilization efficiency showed a declining trend between the baseline and the RCP 2.6 and 4.5 scenarios, regardless of soil fertility management (Fig. 5.4A2, B2). However, under RCP 8.5 the predicted changes in N-internal utilization efficiency dropped by about 33% with CERES-Maize and by 47% with CRES-Sorghum. Hence, the climate assumptions under RCP 8.5 would considerably reduce water- and N-use efficiencies of both maize and sorghum.

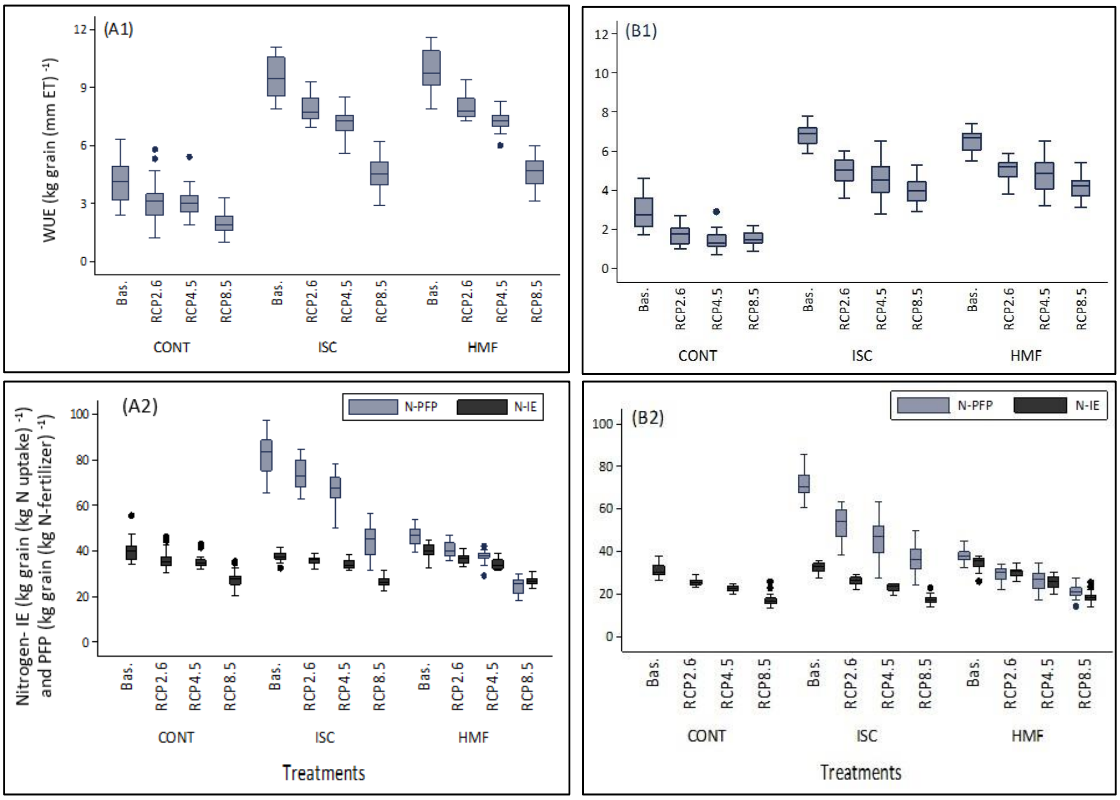

Figure 5.4 Simulated water-use efficiency (WUE), nitrogen-internal use efficiency (N-IE) and partial factor productivity (N-PFP) of maize (A1, A2) and sorghum (B1, B2) under an un-amended soil as control (CONT), integrated soil-crop management practice (ISC), and high use of mineral fertilizer (HMF) considering the historical climate (Baseline: Bas.,1986-2005) and future climate (2080-2099) and according to three Representative Concentration Pathways (RCPs) of the International Panel on Climate Change (IPCC): RCP 2.6, 4.5, and 8.5.

5.3.4 Impact on seasonal N and P uptake

The CERES-Maize model predicted general decreases in N- (Fig. 5.5A1) and P- (Fig. 5.5A2) uptake by maize under future climate conditions, but the extent of the reductions depended on soil fertility management options and RCPs. The decreases in N and P uptake by maize were predicted to be higher with RCP 8.5, irrespective of the soil fertility management scenarios. CERES-Sorghum also predicted declines in N and P uptake (Fig. 5.5B1, B2).

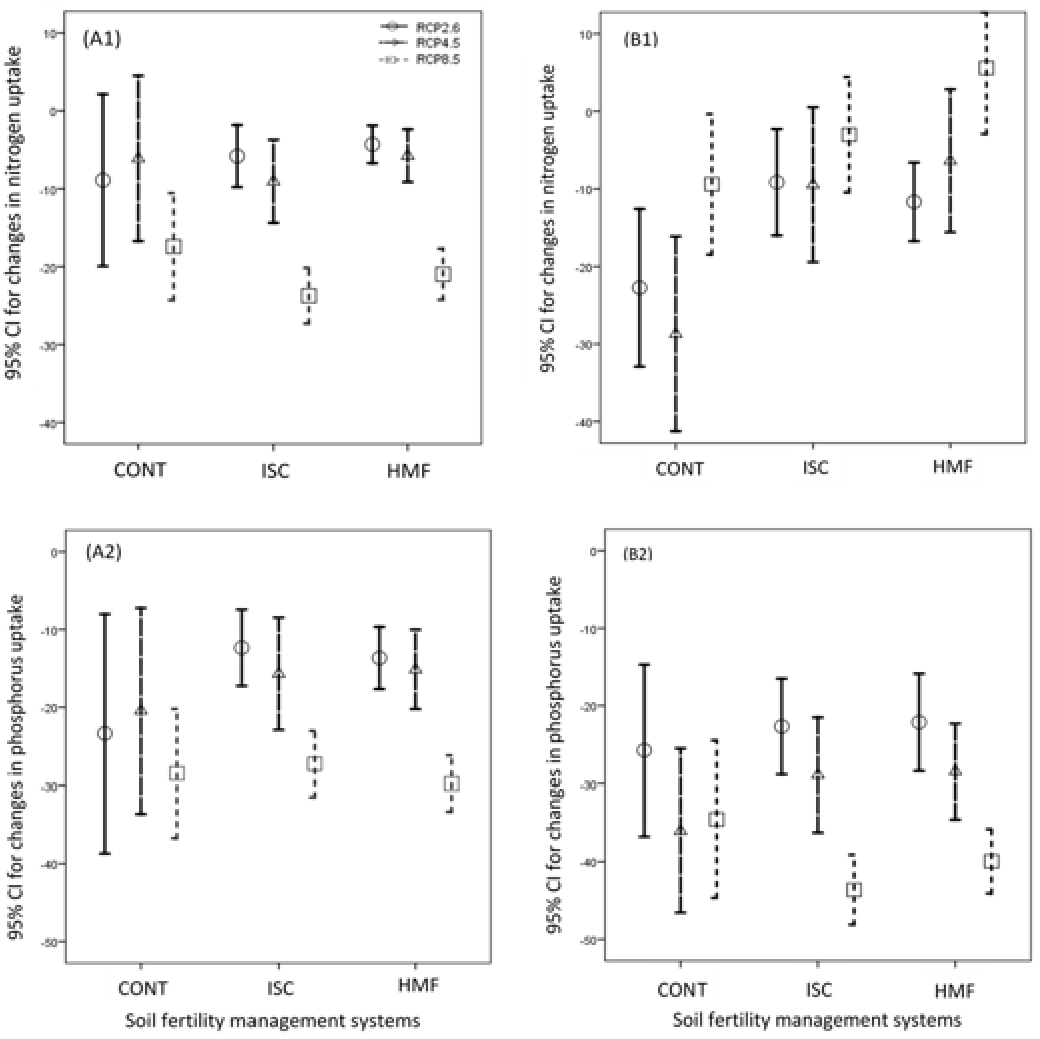

Figure 5.5 Confidence intervals (CI, 95%) for changes in seasonal N (A1, B1) and P (A2, B2) uptake by maize (A1, A2) and sorghum (B1, B2) relative to historical means (1986-2005) assuming three soil fertility management levels un-amended soil as control (CONT), integrated soil-crop management practice (ISC), and high use of mineral fertilizer (HMF) under future climate (2080-2099) under three Representative Concentration Pathways (RCPs) of the International Panel on Climate Change (IPCC): RCP 2.6, 4.5, and 8.5.

5.3.5 Yield comparisons at harvest

Overall, the predicted climate change resulted in decreased biomass and grain yields for both crops (Fig. 5.6). The CERES-Maize simulated a decrease in harvested maize biomass of 11-15%, 13-15% and 25-26%, and in grain yield of 10-17%, 17-19% and 44-46% for RCP 2.6, 4.5, and 8.5, respectively.

The decreases in the predicted total sorghum biomass at harvest reached 21-35% for RCP 2.6, 30-47% for RCP 4.5, and 38-45% for RCP 8.5. CERES-Sorghum predicted decline in grain yields by 22-38%, 31-49%, and 44-51%, for RCPs 2.6, 4.5 and 8.5, respectively. The largest reductions in grain yield and biomass were estimated assuming RCP 8.5, irrespective of crops and soil fertility management options (Fig. 5.6). While increasing future grain yields above the non-amended soil, integrated soil-crop management practice or high use of mineral fertilizer application will not be sufficient to maintain current yield levels.

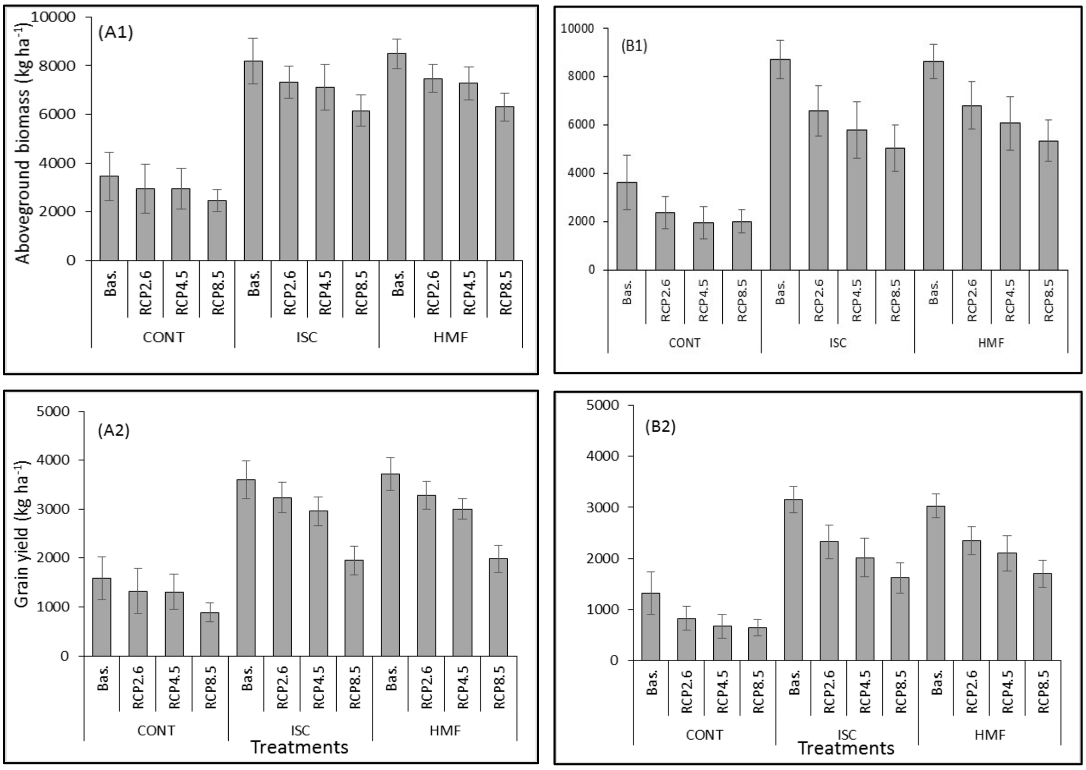

Figure 5.6 Predicted aboveground biomass (A1, B1) and grain yield (A2, B2) of maize (A1, A2) and sorghum (B1, B2) as impacted by an un-amended soil as control (CONT), integrated soil-crop management practice (ISC), and high use of mineral fertilizer (HMF) assuming a historical climate (Baseline: Bas., 1986-2005) and future climate (2080-2099) and considering three Representative Concentration Pathways (RCPs) of the International Panel on Climate Change (IPCC): RCP 2.6, 4.5, and 8.5.

5.4 Discussion

Future trends of rainfall, temperatures, and solar radiation under the low (RCP 2.6), medium (RCP 4.5), or high (RCP 8.5) level of GHG-forcing scenarios for the dry savannah region of northern Benin were used for the first time to quantify the impact of projected climate change on water- and N-use efficiency, N and P uptake as well as on biomass and grain yields of maize and sorghum considering three soil fertility management strategies.

5.4.1 Future climate trends

The predicted changes in temperatures for the study region are in line with existing estimates of warming trends (Dike et al. 2015; Riede et al. 2016). For instance, the Benin Second National Communication on Climate Change predicts temperature increases varying from 2.6°C in South-west to 3.3°C in northern Benin (MEHU 2011). In contrast, large discrepancies in seasonal rainfall cycles were previously reported (Sylla et al. 2013) for the whole of West Africa, including the study region. The MEHU (2011) reported an increase in mean annual rainfall by 13% in the North-west and by 15% in the North-east of Benin. The bias-corrected predictions, as estimated here with the ensemble mean of BNU-ESM, CanESM2, and MPI-ESM-MR models (Fig. 5.2), matched these previous estimates quite well and thus served as input for the crop models simulations reported here.

5.4.2 Climate effects on biomass accrual and resource use efficiency

Key climate projections for the dry savannah region of Benin generally depict a warming trend regardless of the assumptions under RCP 2.6, 4.5, or 8.5. Of particular interest in this context, therefore, is the impact of an enrichment of atmospheric CO_2 that occurs under all three scenarios, since increased biomass accumulation is commonly reported in CO_2-enriched environments particularly for C4-plants such as maize and sorghum (Leakey 2009; Poorter 1993). CERES-Maize and CERES-Sorghum are capable of handling such effects of CO_2-fertilization, hence potential biomass production can be simulated while assuming an enhanced radiation use efficiency in response to CO_2-enriched environments (Hoogenboom et al. 2010; White et al. 2015). In addition, the recent improvements of CERES-Maize and CERES-Sorghum permit concurrently accounting for effects of soil fertility (other than N) on biomass production through a soil fertility factor (SLPF) (Hoogenboom et al. 2010). The findings we report here are in line with the expected growth enhancement due to increased CO_2 levels for both maize and sorghum, albeit only for the vegetative stages of both crops, and more so if soil fertility was improved. The higher temperatures and elevated CO_2 levels appear to stimulate early crop development at the expense of soil water, which is then not available for grain filling.

This is reflected in reduced water-use efficiency and harvest index, a phenomena known as haying-off (van Herwaarden et al. 1998). Integrated soil-crop management practice or high use of mineral fertilizer both enhanced overall biomass production and grain yield, but again only during the vegetative growth stages, and the yield index dropped even further. Using a controlled environment experiment, Prasad et al. (2006) showed that at high temperatures, elevated CO_2 increased vegetative growth of sorghum but not grain yield, thus leading to a decreased harvest index.

The combination of the predicted warming and shift in rainfall for the dry savannah region of Benin will impact water- and N-use efficiencies in the maize and sorghum-based production systems under elevated CO_2 environment scenarios. Positive responses of water-use efficiency to elevated atmospheric CO_2 was simulated for rainfed sorghum in Manhattan, Kansas, USA (White et al. 2015), and maize in China (Guo et al. 2010). However, given the dry climate conditions, increases in temperature and early drought as predicted for northern Benin could both more than offset the early boost in photosynthesis caused by elevated CO_2 levels (Allen et al. 2003). This is reflected in the decline in water-use efficiency simulated for the study region. The projected warming will also threaten nutrient uptake and use efficiency because impact on crop water use by climate change also alter nutrient assimilation (Brouder and Volenec 2008).

5.4.3 Climate effects on grain yields

The simulations reveal an overall future decrease in biomass but also in grain yields of both crops with the latter decrease being relatively greater. This is in line with findings in other regions although the simulated impact of climate change shows strong spatial variability. Using CERES-Maize and CERES-Sorghum, Chipanshi et al. (2003) reported that climate change in the arid zones of Botswana would decrease maize grain yields by 36% and sorghum grain yields by 31%, at least when grown on sandy soil. But these predictions were made without the latest improvements in DSSAT-Cropping System Models (Hoogenboom et al. 2010; White et al. 2015). Based on CERES-maize simulations, Rosenzweig et al. (2014) reported severe negative impact of climate change on maize grain yield in tropical zones compared to mid- and high-latitude regions across the world, including West Africa. Thornton et al. (2011) estimated a decrease of 23% for maize grain yield in West Africa due to climate change, whilst climate change predictions with CERES-Sorghum indicated grain yield losses of 6% in Akola and 18% in Indore, India, and 12% in Samako and 30% in Cinzana, Mali (Singh et al. 2014). A decrease in sorghum grain yield of up to 20% was predicted for the semi-arid region of Ghana using APSIM (McCarthy and Vlek 2012), and by more than 40% for the Sudan Savannah zone of Togo and Benin, and Sahelian region of Senegal, Mali, and Burkina Faso with the SARRAH model (Sultan et al. 2013). In contrast, for the Guinean zone of Ghana, Srivastava et al. (2017), using the LINTUL5 crop model, predicted an increase in maize grain by 57% and biomass yield by 59% due to climate change. The high variation among these results is mainly due to differences in the type of climate models and scenarios assumed, reference and future time horizons considered, robustness of the crop models applied, crop cultivars and management practices used, and agro-ecological boundary selected (Rosenzweig et al. 2014; Roudier et al. 2011). Yet the present results combined with those of a comprehensive review of climate change impact on crop yields in West Africa (Roudier et al. 2011) indicate that negative impact is most likely to prevail in the Dry Savannah agro-ecological zone.

The simulated decreases in maize and sorghum grain yields are claimed to be caused in particular by the depressive effects owing to increasing temperatures and corresponding heat stress, particularly during key phenological stages such as anthesis and grain filling (Deryng et al. 2014; Gabaldón-Leal et al. 2016). Both maize and sorghum respond to heat stress by regulating water and gas exchange (Sultan et al. 2013) and thus reducing photosynthesis (Sunoj et al. 2017), particularly during the reproductive stages. In contrast, high atmospheric CO_2 concentrations could result in a reduction of the stomata opening and thus a decrease in transpiration, but an increase in photosynthesis and in turn improved yields (Rosenzweig and Iglesias 1998). Increased yields due to increased atmospheric CO_2 concentrations cannot be expected unless temperatures approximate the optimum for crop growth and water remains available for grain filling. Reportedly, high-temperature episodes or heat stress close to anthesis will be more detrimental for crop yields than the effects of the increases in mean seasonal temperature (Tesfaye et al. 2016). When air temperatures are near the upper limit, growth and yield reductions are predicted irrespective of the CO_2 concentrations (Polley 2002). Testing effects of maximum and minimum temperature regimes of 32/22, 36/26, 40/30, and 44/34°C at ambient and elevated CO_2 on reproductive processes and yields of sorghum, Prasad et al. (2006) reported that elevated CO_2 increased grain yield at 32/22°C, but decreased it at 36/26°C.

The findings reported here suggest an increase in the average maximum and minimum temperatures during the growing cycle of maize and sorghum from currently 30/21°C up to 35/25°C for the RCP 8.5 scenario. Therefore, the grain yield depressions predicted with CERES-Maize and CERES-Sorghum under RCP 8.5 for northern Benin are most plausible due to the predicted warming, but those with RCPs 2.6 and 4.5 underscored again haying-off. The high-temperature effects on seed set and growth can be captured by CERES-Maize and CERES-Sorghum through the cardinal temperatures, assuming 34°C as the optimum temperature (Hoogenboom et al. 2010; White et al. 2015). Reportedly, heat stress leads to a tremendous reduction in pollen germination (Prasad et al. 2006; Sunoj et al. 2017) that in turn decreases seed numbers and hence yields (Deryng et al. 2014; Sultan et al. 2013). Therefore, irrespective of the initial growth-enhancing effects due to CO_2-fertilization, the most likely, overall trend under the climate change predicted for the dry savannah region of Benin in West Africa with high GHG forcing is a decline in maize and sorghum yields.

5.4.4 Mitigating future climate effects

To ease the climate change and variability implications for maize and sorghum supply in the region, climate-smart actions are thus urgent. It recently has been postulated that for many regions in Sub-Saharan Africa, such actions include the use of inorganic and organic fertilizers (Montpellier Panel 2013; Vanlauwe et al. 2014) as strategies to enable a sustainable intensification of smallholder maize- and sorghum-based production systems. On the one hand, the simulations in this study show that both an integrated soil-crop management practice and high use of mineral fertilizer is likely to sustain higher water-use efficiency and grain yields compared to a non-amended soil, even when assuming different future climate conditions. Furthermore, the current projections reveal that an integrated soil-crop management practice would result in higher N-partial factor productivity compared to a high use of mineral fertilizer. Since integrated soil fertility management aims at enhancing both productivity and resource use efficiency, it is acknowledged as an important strategy for sustainable intensification of smallholder agriculture in Sub-Saharan Africa, including Benin (Vanlauwe et al. 2014). The estimates, however, indicate that these increases will still not be able to offset the decreasing effects due to late-season heat stress and dry conditions.

5.5 Conclusions

Irrespective of the predicted biomass production-enhancing effects due to CO_2-fertilization during the vegetative growth stages of sorghum and maize, the projected climate change for the dry savannah in northern Benin will depress water- and N-use efficiencies and grain yields of both crops. This is likely to occur irrespective of presently known and recommended soil fertility management strategies for the region. The magnitude of the predicted impact of climate change on the productivity of both crops will likely increase food insecurity in the region especially given the expected population growth and ongoing urbanization, which will increase future food demand even more. This could exacerbate hunger and poverty in the region unless robust mitigation and adaptation measures are taken and effectively implemented by key stakeholders, including farmers and policy makers.

6 EVALUATION AND APPLICATION OF CROPGRO-COTTON MODEL FOR DETERMINING OPTIMUM PLANTING DATES AND CLIMATE CHANGE IMPACT ON YIELD, WATER- AND N- USE EFFICIENCIES

6.1 Introduction

Cotton plays an important role in the social and economic development globally and especially of West African countries. To this end, its sustainable production may support livelihoods of the farming population and help ease wide-spread poverty. Cotton production in West and central African countries (e.g. Benin, Burkina Faso, Mali, Ivory Coast, Togo, Chad) accounts for 5% of world production (Hussein et al. 2006), representing 2-10% of the Gross Domestic Product (GDP) and 30-56% of total exports of these countries (Hussein et al. 2006; Vitale et al. 2011).

Cotton production systems are typical examples of crop intensification, however, with considerable investments in soil fertility restoration and agricultural land expansion and resulting in seed cotton productivity improvement (Pieri 1992; Vitale et al. 2011). Subsequent staple crops like maize, sorghum, or millet often benefit from the inputs on cotton (Ripoche et al. 2015; Vitale et al. 2009). The intensification of cotton production has undeniably increased cotton yields in the past decades in West Africa (Pieri 1992; Theriault and Tschirley 2014), but lately progress has stagnated or even declined, due to increased costs of inputs without compensation in the seed cotton prices (Baquedano et al. 2010) as well as biotic and abiotic-stresses (Sultan et al. 2010). In fact, the performance of the current cotton production systems is constrained by rainfall variability and drought (Sultan et al. 2010), declining soil fertility (Bationo et al. 2012; Pieri 1992; Vitale et al. 2011), and inadequate soil-crop management such as late planting (Lançon et al. 1989, 2007). Sustainable cotton-production systems are needed if this commodity has to maintain its role in the overall national and regional economy and to secure the livelihoods of farmers in West Africa. Measures to be introduced must aim at enhancing productivity and increasing the resilience of the farming systems.

Changes in the biogeochemical cycle of carbon through atmospheric carbon dioxide enrichments (IPCC 2013) and climate change, especially changes in rainfall

(Gbobaniyi et al. 2014; Sylla et al. 2013) and increase in temperatures (Dike et al. 2015; Riede et al. 2016), are expected to alter cotton production in the future (Gérardeaux et al. 2013; Reddy et al. 2002). The role of N-fertilization is reportedly affected by these changes, particularly by CO_2 enrichment (Prior et al. 1998; Singh et al. 2013). However, little is known about the extent to which cotton will respond to soil fertility management options under future climate change in the West African Dry Savannah environments.

Crop simulation models are valuable tools to quantify responses in cotton yields and resource use efficiency to different soil fertility management strategies. Previous studies investigated cotton productivity with cotton-specific models such as GOSSYM (Baker et al. 1983), Cotton2K (Marani 2004), COTCO2 (Wall et al. 1994), OZCOT (Hearn 1994), and CROPGRO-Cotton (Hoogenboom et al. 2015; Jones et al. 2003). Likewise, generic crop models like EPIC, WOFOST, SUCROS, GRAMI, Cropsysts, and Aquacrop have been used to simulate cotton production (Thorp et al. 2014a). CROPGRO-Cotton has been widely applied for assessing soil fertility and water management options (Garcia y Garcia et al. 2010; Modola et al. 2015; Paz et al. 2012; Wajid et al. 2014) and the impact of climate change on cotton production (Adhikari et al. 2016; Gérardeaux et al. 2013; Thorp et al. 2014b). Little has been reported about the evaluation and application of CROPGRO-Cotton for assessing climate change impact on resource use efficiency in West Africa. The objectives therefore were: (i) Parameterize the CROPGRO-Cotton model to simulate growth, yield, and in-season soil water dynamics and N uptake, and (ii) apply the model to determine optimum planting dates and potential climate change impact on cotton growth, yields, and water- and N-productivity under different soil fertility management practices in northern Benin, West Africa.

6.2 Material and methods

6.2.1 Description of the CROPGRO-Cotton model

CROPGRO-Cotton is a process-based model developed from CROPGRO (Jones et al., 2003), which is a generic crop model based on the SOYGRO, PNUTGRO, and BEANGRO models (Boote et al. 1998). CROPGRO-Cotton simulates growth, development, and yields of cotton in response to soil, weather, and management conditions and combinations thereof (Hoogenboom et al. 2015; Thorp et al. 2014b). The model computes biophysical processes on a daily time step routine (Jones et al. 2003). The growth stages are based on photo-thermal time, carbon assimilation, and the partitioning of biomass into roots, stems, leaves, and bolls (Thorp et al. 2014a). The canopy photosynthesis is computed using leaf-level photosynthesis parameters and the hedgerow light interception (Boote et al. 1998) while yield components are derived from boll mass, seed cotton mass, seed number, and unit seed weight (Thorp et al. 2014a). CROPGRO-Cotton can hence account for stress effects from soil water and nitrogen deficits (Thorp et al. 2014b), and air temperature (Thorp et al. 2014a) on cotton growth and development. CROPGRO-Cotton integrates effects of atmospheric carbon dioxide (CO_2) on photosynthesis and transpiration (Thorp et al. 2014a) and computes evapotranspiration (Boote et al. 1998), and simulates soil C, N (Gijsman et al. 2002; Godwin and Singh 1998), and water balances (Ritchie 1998).

6.2.2 Field experiments and data

The datasets needed for the calibration and evaluation of CROPGRO-Cotton were collected from the three field experiments (Table 2.2, Sections 2.2, 2.3) conducted on Alisols, Plinthosols, and Luvisols (IUSS Working Group WRB 2014; Steup 2016) in 2014 and 2015 at Ouri-Yori village (10°49’16’’N, 1°4’7’’E) located in North Benin, West Africa. The experimental sites, design, and factors, as well as crop and soil management were previously described in detail for each experiment (Table 2.2, Sections 2.2, 2.3). Each experiment used maize, sorghum, and cotton as test crops, but only data for the cotton-based treatments are considered here. The experiments-2 and 3 were rainfed in both years, however, experiment-2 was re-designed in 2015 to include supplementary irrigation as an additional factor (Chapter 4, Section 4.2.2).

Cotton phenology (e.g. days to 50% anthesis and physiological maturity), biomass accrual, and biomass and seed cotton yields were collected in experiment-1. In experiment-2, in-season biomass growth, soil water, and N uptake as well as final biomass and seed cotton yields were measured. Biomass and seed cotton yields were collected in experiment-3 also. Additional details on the methods, measurements, and processing of soil and plant samples were previously reported (Chapter 2, Chapter 4).

6.2.3 Model calibration and evaluation

CROPGRO-Cotton was calibrated using empirical data on growth, development, and yields from experiment-1 in 2014. The independent measurements in 2015 from the same experiment were used to validate the parameterized model.

The locally improved cotton variety H-279-1 was parameterized by adjusting manually various genetic coefficients to get an accurate goodness of fit between simulated and measured values in the absence of water and N deficits. Cotton, cv. Delapine 555 in DSSAT-CSM, was used as the starting cultivar for calibration. The phenological traits such as critical short day length (CSDL) and photo-thermal days from emergence to flower appearance (EM-FL) were adjusted to match the observed anthesis date. The default photo-thermal days from first seed to physiological maturity (SD-PM) were modified to match simulated with observed physiological maturity date. Next, the maximum leaf photosynthesis rate (LFMAX), photo-thermal days for seed filling duration for pod cohort (SFDUR), maximum fraction of daily growth partitioned to seed + shell (XFRT), and maximum size of full leaf (SIZLF), maximum weight per seed (WTRSD), and threshing percentage (THRSH) were optimized for final seed cotton and biomass yields (Table 6.1). The soil fertility factor (SLPF) was optimized during the calibration of aboveground biomass and seed cotton yield (Section 4.2.3).

The validated CROPGRO model was evaluated using the empirical data from experiments-2 and 3, without a modification of the genetic coefficients, but using the SLPF values and soil water-holding characteristics as previously reported for the different sites (Section 4.2.3).

Table 6.1 Defaults genetic coefficients of cotton cv. Delapine used during calibration and the adjusted coefficients for cotton cv. H-279-1 used during model validation

Codes	Definitions	Default values Delapine 555	Calibrated H-279-1
CSDL	Critical Short Day Length below which reproductive development progresses with no day length effect (hour)	23	12.5
PPSEN	Slope of the relative response of development to photoperiod with time (1/hour)	0.1	0.1
EM-FL	Photo-thermal days between plant emergence and flower appearance	38	39
FL-SH	Photo-thermal days between first flower and first pod	11	11
FL-SD	Photo-thermal days between first flower and first seed	16	16
SD-PM	Photo-thermal days between first seed and physiological maturity	43	48
FL-LF	Photo-thermal days between first flower and end of leaf expansion	65	65
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 vpm CO_2, and high light(mg $CO_2/m^2/s$)	1.1	3.0
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2/g)	170	170
SIZLF	Maximum size of full leaf (cm^2)	300	350
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.76	0.72
WTPSD	Maximum weight per seed (g)	0.18	0.10
SFDUR	Photo-thermal days for seed filling duration for pod cohort	35	30
SDPDV	Average seed per pod (n./pod)	27	27
PODUR	Photo-thermal days required to reach final pod load	12	12
THRSH	Threshing percentage	70	85
SDPRO	Fraction protein in seeds	0.153	0.153
SDLIP	Fraction oil in seeds	0.120	0.120

6.2.4 Model input data

Initial soil profile data for the three different soils (Table 2.1) and weather data of the 2014 and 2015 growing seasons were obtained from Steup (2016). CROPGRO-Cotton inputs files were prepared using the appropriate tools in DSSAT-CSM v.4.6, SBuild utility program for initial soil input, Weatherman for weather data, XBuild with cotton management data, and AT Create for system performance datasets.

6.2.5 Assessment of models performance

The performance of the CROPGRO-Cotton model was assessed with the root mean square error (RMSE), normalized-RMSE (nRMSE), and Index of agreements (d). The formulas of these statistics were reported in section 4.2.6.

6.2.6 Simulation of cotton seed yield responses to planting dates

To capture effects of an increasingly erratic onset of the growing season in the region (Fig. 2.2; Ouorou Barre 2014) on cotton, seed cotton yield response to different planting dates in the case study region were simulated assuming the three soil fertility management options (Table 2.2, Section 2.2) under Alisols for 20 years weather variability (1986-2005). Four planting dates (June 10th, June 25th, July 10th, and July 25th) were simulated using the seasonal analysis option in DSSAT V.4.6. With the tested cotton cultivar (H-279-1), "early" planting refers to planting between mid to late June and "late or delayed" planting to late July (Lançon et al. 1989; Sekloka et al. 2008).

6.2.7 Simulation of climate change impact on growth, water- and N- use efficiencies

Climate change impact was simulated using the historical and projected weather parameters (Sections 5.2.2, 5.2.3) as inputs to run the CROPGRO-Cotton model in a seasonal mode with the three soil fertility management options (Table 2.2, Section 2.2) while considering the planting date of June 25th (176 DOY) on Alisols. The impact on cotton were evaluated using the CROPGRO-Cotton model outputs for water-use efficiency, N-partial factor productivity, and N-internal utilization efficiency as indicators (Section 4.2.6) by comparing predicted responses of cotton to each of the three soil fertility management options under historical climate (1986-2005) to the performance of the same options under future climate (2080-2099) for the RCPs 2.6, 4.5, and 8.5.

6.3 Results

6.3.1 Calibration and validation of CROPGRO-Cotton

In experiment-1 (2014), CROPGRO-Cotton simulated both observed anthesis (50±5 days after planting) and physiological maturity (121±8 days after planting) with RMSE (nRMSE) of 0 day (0%). In the validation period, the calibrated CROPGRO-Cotton predicted anthesis of cotton (51±4 days after planting) with RMSE of 2 days and nRMSE of 4%, and physiological maturity (126±6 days after planting) with RMSE of 4 days and nRMSE of 3%.

During the 2014 season, aboveground biomass accumulation of cotton was predicted satisfactorily with nRMSE of 32% and d-value of 0.94. In 2015, GROPGRO-Cotton showed good accuracy in predicting time series of aboveground biomass accrual with nRMSE of 33% and d-value of 0.92.

At final harvest in 2014, RMSE and nRMSE between measured biomass yield (3408±880 kg ha^{-1}) and the simulated yield by CROPGRO-Cotton were 128 kg ha^{-1} and 4%, respectively. The calibrated model predicted biomass yield (6144±508 kg ha^{-1}) satisfactorily in 2015 (RMSE of 626 kg ha^{-1} and nRMSE of 10%). Likewise, CROPGRO-Cotton simulated satisfactorily the observed seed-cotton yield (1426±350 kg ha^{-1}) well with RMSE of 254 kg ha^{-1} and nRMSE of 18%. Harvested seed-cotton in experiment-1 amounted to 2373±135 kg ha^{-1} in 2015 and was well predicted also by CROPGRO-Cotton (RMSE of 418 kg ha^{-1} and nRMSE of 18%).

6.3.2 Evaluation of model

In-season soil water content dynamics

Based on the empirical data from experiment-2 in 2015, CROPGRO-Cotton reasonably simulated in-season soil moisture dynamics under rainfed (Fig. 6.1a, b, c) and supplementary irrigated (Fig. 6.1d, e) conditions. However, the model under-predicted soil moisture at 40-60 cm soil depth for the rainfed treatment up to approximately 90 days after planting and predicted accurately thereafter until harvest (Fig. 6.1c). In the supplementary irrigated conditions, the model adequately simulated the observed soil moisture dynamics at 40-60 cm soil depth from 20 to 70 days after planting and under-predicted thereafter (Fig. 6.1f).

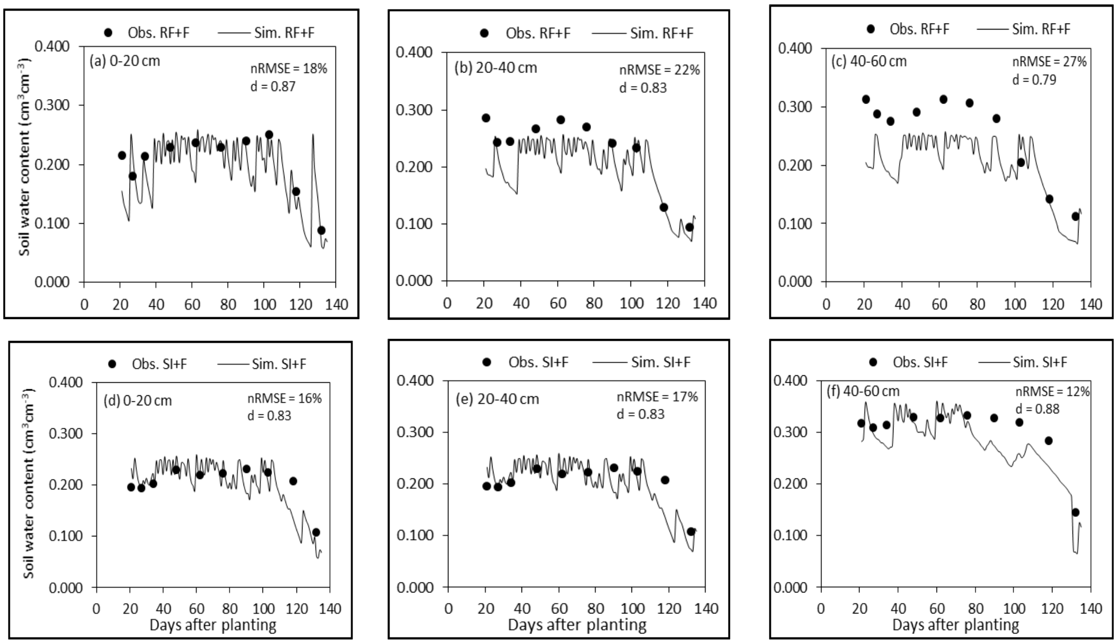

Figure 6.1 Measured (symbols) and simulated (lines) soil water content in the 0-20, 20-40, and 40-60 cm soil depths under cotton rainfed + fertilization (RF+F, a, b, c) and supplementary irrigation + fertilization (SI+F, d, e, f) conditions during the 2015 cropping season of experiment-2.

Nitrogen uptake

CROPGRO-Cotton predicted N uptake by cotton early in the season fairly well under both the rainfed and supplementary irrigation environments with and without fertilization in experiment-2 (Fig. 6.2). Without fertilizer, the model predicted N uptake accurately up to 50 days after planting, but under-predicted thereafter until harvest under rainfed and supplementary irrigated conditions (Fig. 6.2A1, A3). For rainfed with fertilizer application (Fig. 6.2 A2), the CROPGRO-Cotton model predicted N uptake accurately up to 80 days after planting and over-predicted thereafter. With fertilizer and supplementary irrigation (Fig. 6.2A4), the N-uptake was predicted accurately up to 50 days after planting and over-predicted thereafter.

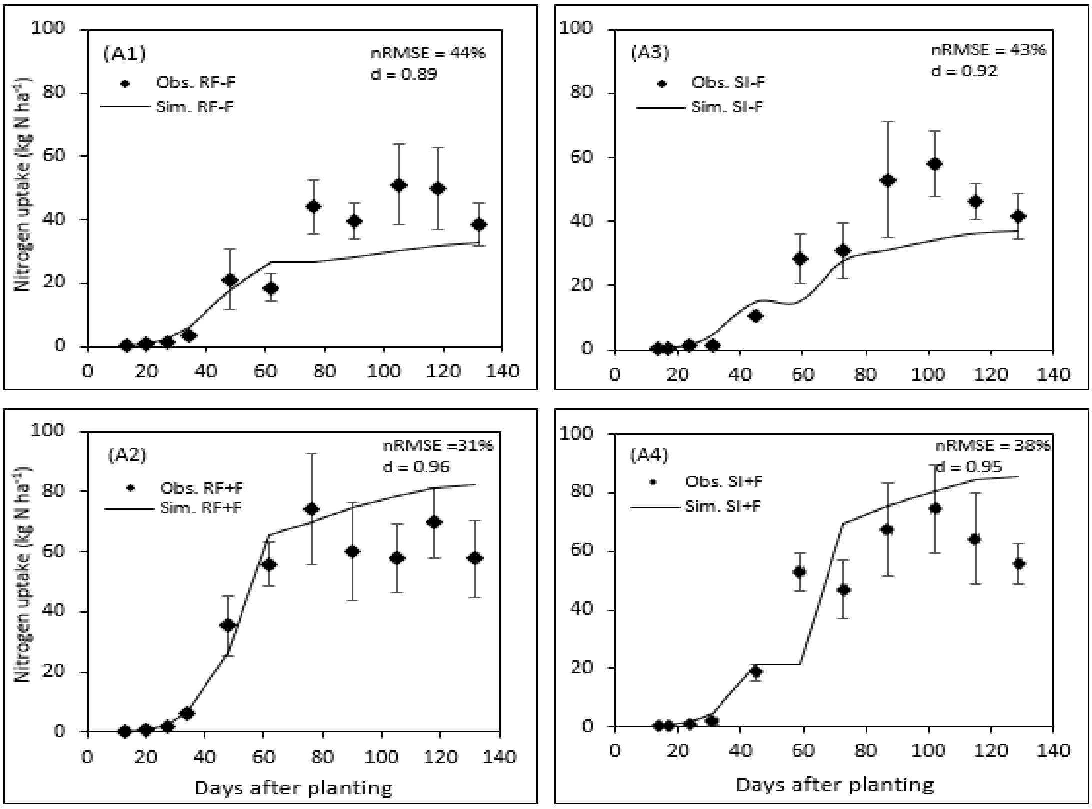

Figure 6.2 Observed (symbols) and simulated (lines) nitrogen uptake of cotton under rainfed conditions without (RF-F, A1) and with fertilization (RF+F, A2), and supplementary irrigation without (SI-F, A3) and with fertilization (SI+F, A4) in experiment-2 during the 2015 cropping season.

Aboveground biomass accumulation

CROPGRO-Cotton predicted early biomass accurately (up to 50 days after planting) under rainfed and supplementary irrigation conditions with and without fertilization. Thereafter, the model under-predicted the biomass accrual. The predictions of the model were more accurate for the treatments with fertilization (Fig. 6.3).

Under rainfed and supplementary irrigated conditions (experiment-2) during 2014 and 2015, the model predicted with good accuracy biomass yield at final harvest as substantiated by nRMSE of 21% and d-value of 0.83 (Fig. 6.4a). Under farmer-management practices (experiment-3), the predictions of the model reached an accuracy of 17% and 0.87 for nRMSE and d-value, respectively (Fig. 6.4b).

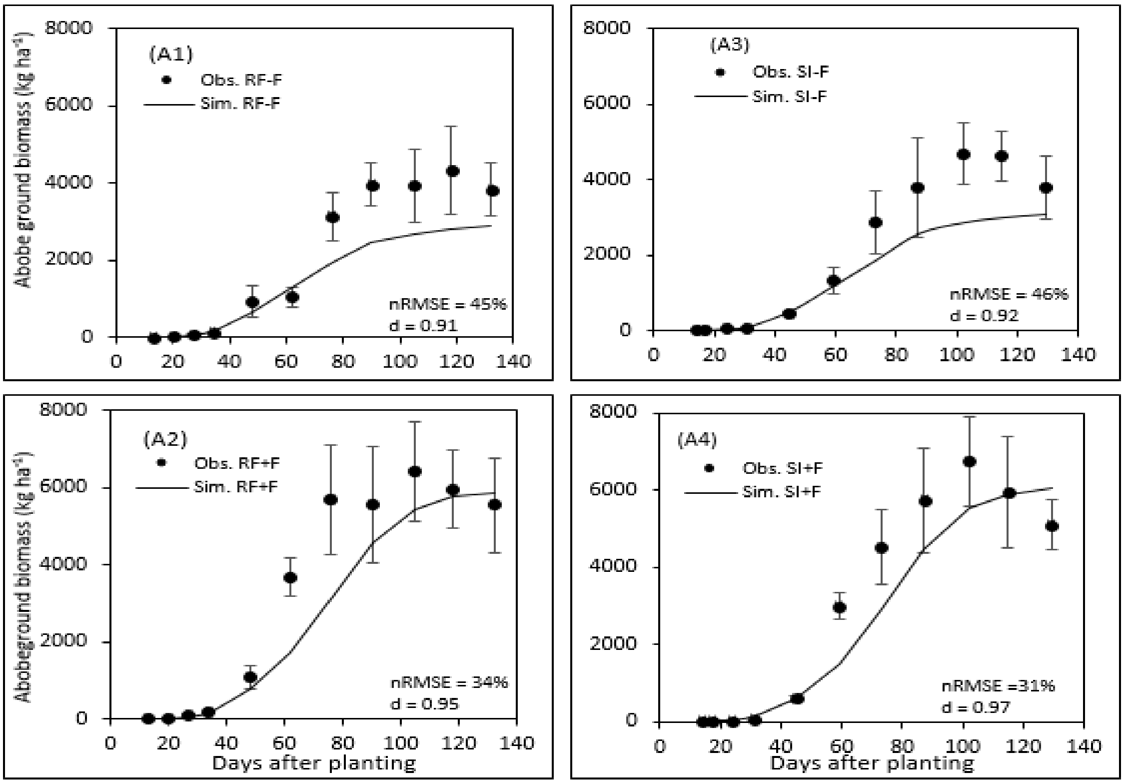

Figure 6.3 Observed (symbols) and simulated (lines) changes in aboveground biomass of cotton under rainfed without (RF-F, A1) and with fertilization (RF+F, A2), and supplementary irrigation without (SI-F, A3) and with fertilization (SI+F, A4) in the researcher-managed experiment-2 during the 2015 cropping season.

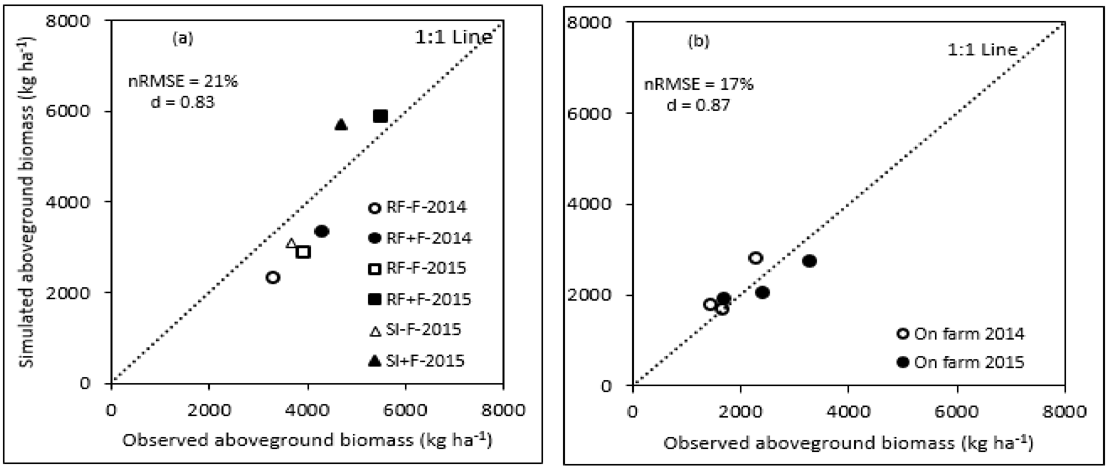

Figure 6.4 Observed and simulated aboveground biomass at final harvest for cotton under researcher-managed (experiment-2, a) and farmer-managed (experiment-3, b) conditions during the 2014 (open symbols) and 2015 (solid symbols) cropping seasons.

Yields at final harvest

CROPGRO-Cotton predicted reasonably well the measured seed-cotton yield at harvest in experiment-2 with nRMSE (d-value) of 24% (0.82) (Fig 6.5a). The accuracy of CROPGRO-cotton in predicting seed-cotton yield under the farmer-managed conditions (experiment-3) was 39% for nRMSE and 0.81 for d-value (Fig 6.5b).

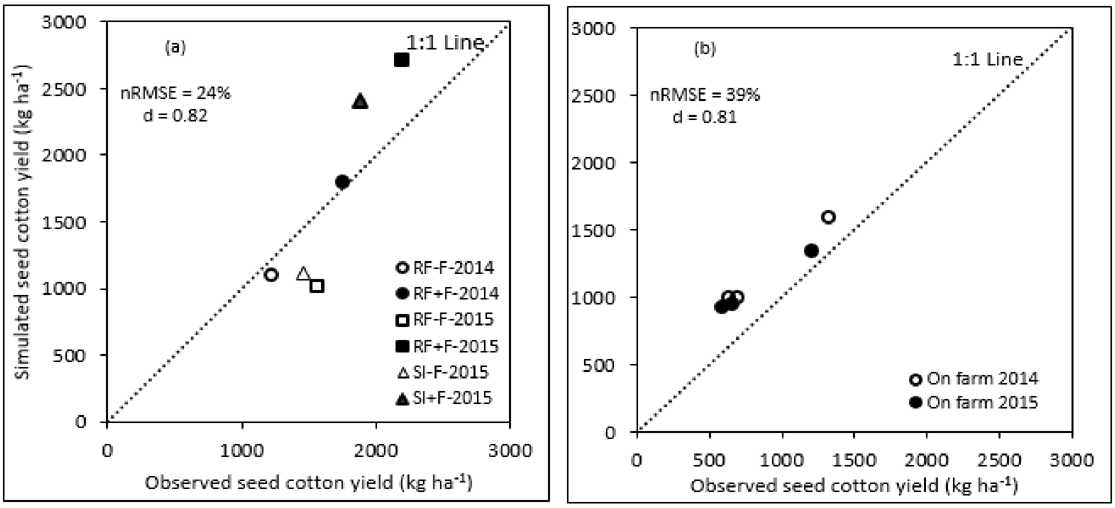

Figure 6.5 Observed and simulated seed cotton yield at final harvest of cotton under researcher-managed (a) and farmer-managed (b) conditions during the 2014 (open symbols) and 2015 (solid symbols) cropping seasons.

6.3.3 Long term simulation of seed cotton yield responses to planting dates and soil fertility management

CROPGRO-Cotton model simulations showed that, varying planting dates and soil fertility management options resulted in significant effects on seed cotton yields. The model also simulated well the year-to-year variability of seed cotton yields for each planting date across the soil fertility management options (Fig. 6.6). The highest yields were simulated with planting date 161 DOY followed by the planting date 176 DOY, irrespective of the soil fertility management options. However, seed cotton yield was highest with high use of mineral fertilizer (Fig. 6.6c) and integrated soil-crop management practice (Fig. 6.6b) and lowest with un-amended soil (Fig. 6.6a). The planting of cotton from 191 DOY onwards decreased seed cotton yields substantially.

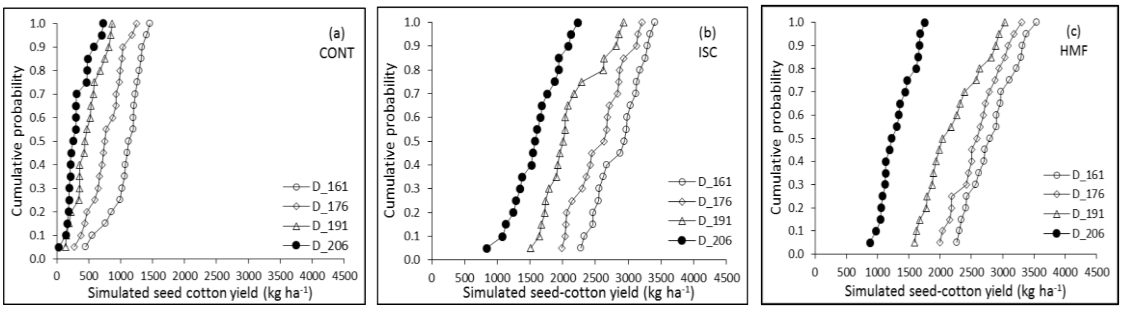

Figure 6.6 Simulated seed cotton yield responses at 161 DOY (Day of the Year, D_161), 176 DOY (D_176), 191 DOY (D_191), and 206 DOY (D_206) under un-amended soil (CONT), integrated soil-crop management practice (ISC), and high use of mineral fertilizer (HMF) assuming the historical weather variability from 1986 to 2005.

6.3.4 Climate change impact on cotton

Changes in biomass accrual

CROPGRO-Cotton predicted increases in biomass accrual of cotton under the projected climate change (2080-2099) relative to the historical means (1986-2005), irrespective of soil fertility management options across the climate scenarios (Fig. 6.7a, b, c), with the exception of RCP 2.6 under un-amended soil (Fig. 6.7a). In the latter case, the model predicted a decrease starting from approximately 70 days after planting (Fig. 6.7a). The predicted increases in biomass growth of cotton peaked towards the beginning of reproductive growth (≈ 45 days after planting) before declining sharply until harvest.

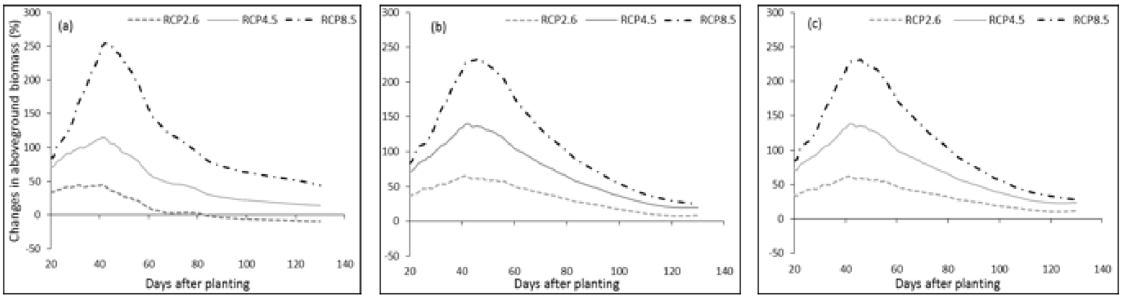

Figure 6.7 Changes in cumulative aboveground biomass responses of cotton under future climate (2080-2099) relative to their historical means (1986-2005) assuming an unamended soil as control (a), integrated soil-crop management practice (b), and high use of mineral fertilizer (c) and while assuming three Representative Concentration Pathways of IPCC (RCPs 2.6, 4.5, and 8.5).

Changes in water- and nitrogen- use efficiencies

For un-amended soil, CROPGRO-Cotton predicted an increase of 15% in cotton water-use efficiency under RCP 8.5, but decreases of 1% for RCP4.5 and 20% with RCP 2.6 relative to the baseline (1986-2005). With integrated soil-crop management practice, changes in water-use efficiency were -4% for RCP 2.6, +9% with RCP 4.5, and +7% under RCP 8.5. Assuming high mineral fertilizer use, the average increase in the predicted WUE with RCP2.6, 4.5, and 8.5 was 2%, 17%, and 13% over the historical runs respectively (Fig. 6.8a).

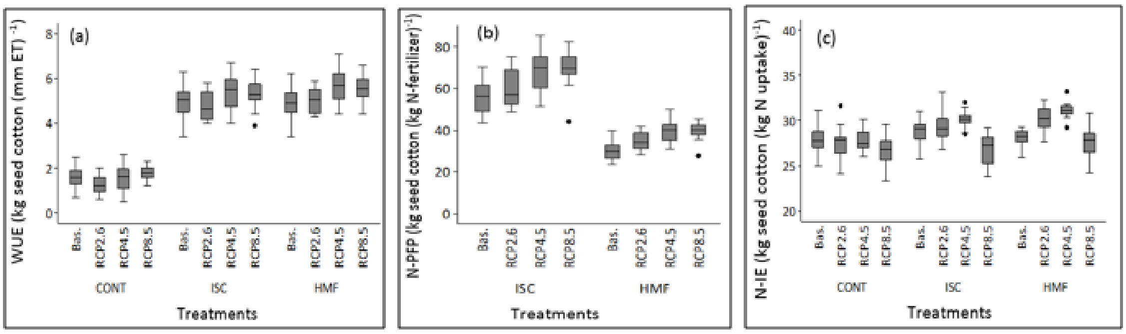

Figure 6.8 Simulated changes in water- use efficiency (WUE, a), partial factor productivity (N-PFP, b), and nitrogen- internal use efficiency (N-IE, c) of cotton under an unamended soil as control (CONT), integrated soil-crop management practice (ISC), and high use of mineral fertilizer (HMF), while considering historical climate (Bas., 1986-2005) and future climate (2080-2099) and according to RCPs 2.6, 4.5, and 8.5.

Under projected climate change, CROPGRO-Cotton predicted 7%, 22%, and 24% increases in N-partial factor productivity with integrated soil-crop management practice and 14%, 30%, and 31% increases with high use of mineral fertilizer for RCPs 2.6, 4.5, and 8.5, respectively (Fig. 8b). With un-amended conditions, CROPGRO-Cotton predicted changes in N-internal utilization efficiency by -1% (RCP2.6), +0.2% (RCP 4.5), and -4% (RCP 8.5). With integrated soil-crop management practice, CROPGRO-Cotton predicted an increase in N-internal utilization efficiency by 2% for RCP 2.6 and 5% for RCP 4.5, but a decrease of 7% under RCP8.5. N-internal utilization efficiency was projected to change by +8% with RCP 2.6, +11% for RCP 4.5, and -2% under RCP 8.5 assuming high use of mineral fertilizer (Fig. 6.8c).

Changes in seasonal N uptake

Under all future climate scenarios assumed, CROPGRO-Cotton predicted the largest increases in seasonal N uptake under RCP8.5 (Fig. 6.9). Under integrated soil-crop management option and high use of mineral fertilizer, the predicted increases in N uptake were about 6, 17, and 33% under RCPs 2.6, 4.5, and 8.5, respectively. In soil without any amendment, N uptake is expected to improve by 46% under RCP 8.5 and by 14% under RCP 4.5, but decrease by 7% under RCP 2.6 (Fig 6.9).

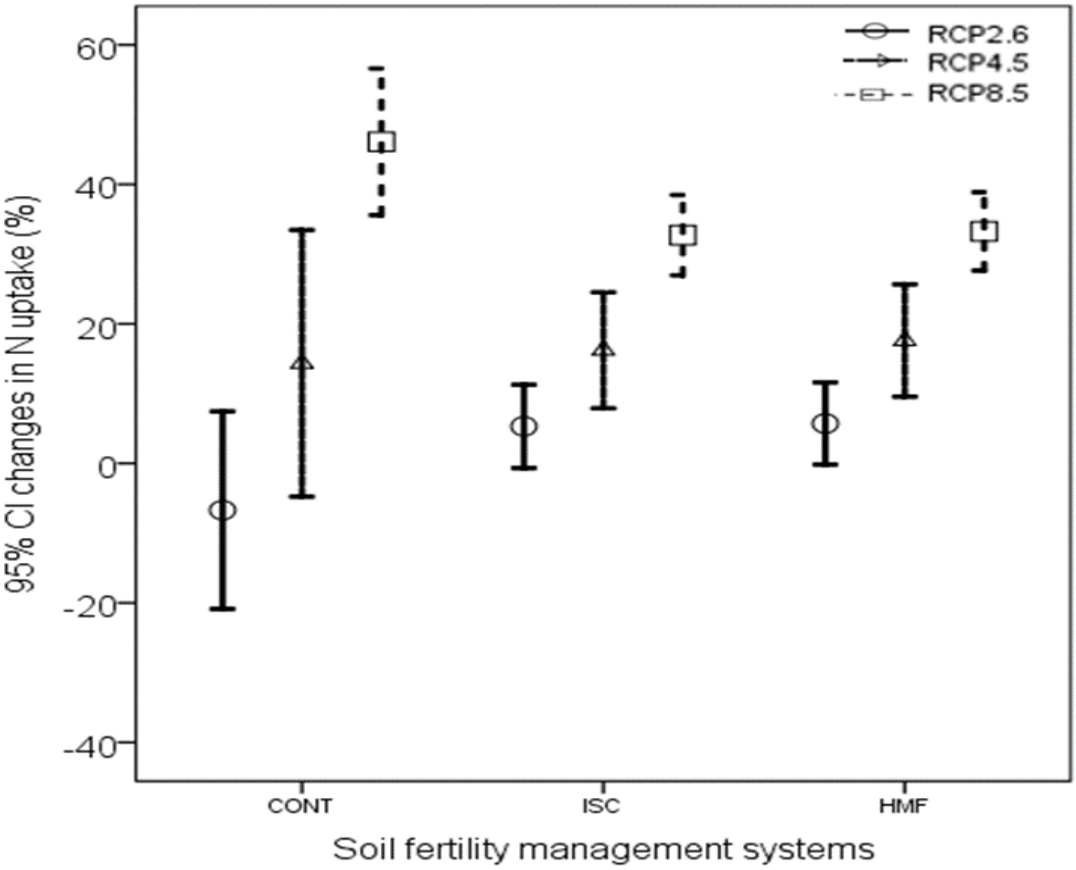

Figure 6.9 Confidence intervals (CI, 95%) for changes in seasonal nitrogen uptake by cotton relative to historical uptake means (1986-2005) assuming three fertility management levels (an unamended control (CONT), integrated soil-crop management practice (ISC), and high use of mineral fertilizer (HMF) under future climate (2080-2099) for RCPs, 2.6, 4.5, and 8.5.

Variation in biomass and seed cotton yields

The CROPGRO-Cotton simulations showed significant variability in biomass and seed cotton yields between years under historic and projected climate (Fig. 6.10).

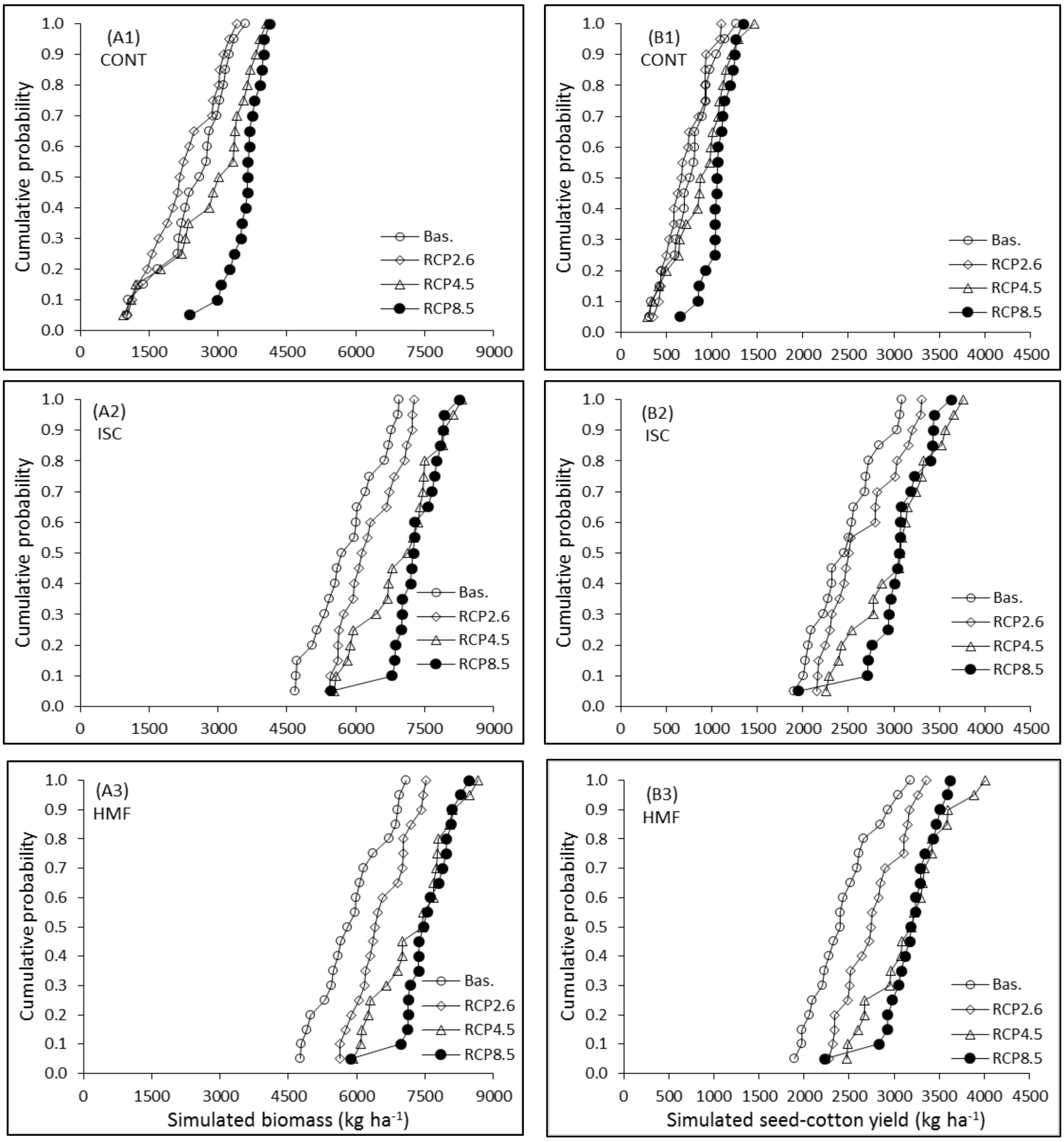

Figure 6.10 Predicted aboveground cotton biomass (A) and seed cotton yields (B) as impacted by an un-amended soil control (CONT), integrated soil-crop management practice (ISC), and high use of mineral fertilizer (HMF) under a historic climate (Bas., 1986-2005) and future climate (2080-2099) and while considering RCPs 2.6, 4.5, and 8.5.

Under the assumed future climate scenarios of RCP 4.5 and 8.5, the cumulative probability function shows a consistent enhancement of biomass (Fig. 6.10A1, 2, 3) and seed-cotton yields (Fig. 6.10B1, 2, 3) relative to the simulated historical baseline conditions, irrespective of the soil fertility options. CROPGRO-Cotton predicted decreases in biomass (-9%) as well as of seed-cotton yields (-7%) under RCP 2.6 as compared to the historical runs in an un-amended soil (Fig. 6.10A1, B1). However, substantial increases in biomass and seed-cotton yields were predicted without fertilization with the magnitude reaching 14% and 15% under RCP 4.5 and 44% and 41% with RCP 8.5, respectively. When assuming integrated soil-crop management practice or high use of mineral fertilizer, the predicted enhancements were within 8-28% for biomass yield and 7-31% for seed-cotton yield across RCPs 2.6, 4.5, and 8.5.

6.4 Discussion

Adequate soil fertility management practices are still needed to ensure efficient and sustainable responses of cotton, which is an important cash crop in West Africa, under projected climate change. The CROPGRO-Cotton model was parameterized and evaluated for modeling growth, yields, soil moisture dynamics, and N uptake in cotton production systems under current weather conditions in the dry savannah of northern Benin. The evaluated model was applied for the first time, to determine optimum planting dates of cotton and to assess responses of the crop to different fertility management strategies under historical and future climate conditions.

6.4.1 Suitability of CROPGRO-cotton for growth, yields, and in-season water and nitrogen dynamics

The evaluation of the CROPGRO-Cotton model for the dry savannah conditions in Benin shows that the model performs reasonably well in simulating final biomass accrual although in-season biomass is generally underestimated by the model. In-season soil water dynamics, N uptake and seed cotton yields generally fit observed values. Similarly satisfactory CROPGRO-Cotton performance was reported for phenology and yields in Burkina Faso (Soler et al. 2011) and Cameroon (Gérardeaux et al. 2013). Even though the evaluation of CROPGRO-Cotton for predicting in-season soil moisture dynamics and N uptake needs to be extended still, a satisfactory agreement between measured and predicted soil water content was reported by Gérardeaux et al. (2013) for the periods of 0-30 and 30-60 days after planting cotton. The deviations between simulated and measured soil water contents in deeper layers (Fig. 6.1), particularly under rainfed conditions may have been caused by inadequate modeling of root activity by CROPGRO-Cotton. The under-predicted patterns of aboveground biomass accrual late in season might be explained by failure to adequately simulate defoliation in these semi-arid conditions (Thorp et al. 2014b).

6.4.2 Optimum planting date of cotton

The results of the simulations by CROPGRO-Cotton under varying planting dates is typical for the cultivar (H-279-1) with better performance of this cultivar under early planting conditions as it is late flowering (Sekloka et al. 2008). The model predicted yield losses as much as 94 to 278 kg ha^{-1} per week of delay, confirming the range of 150 to 200 kg ha^{-1} per week of delay reported by Lançon et al. (1989, 2007) for the region when planting cotton later (between mid to late July). The CROPGRO-Cotton model predictions show that planting of cotton in June is optimal as it gives the highest seed cotton yield especially with high use of mineral fertilizer or integrated soil-crop management practice.

6.4.3 Increased responses of cotton to predicted climate change

The CROPGRO-Cotton model predicted increases in biomass accrual of cotton under the projected climate change. This increase is likely caused by the combined effects of increased CO_2 levels and air temperatures on biomass productivity as previously reported for cotton varieties in controlled field experiments (Kimball and Mauney 1993; Mauney et al. 1994; Reddy et al. 1995). The predicted sharp decline in biomass accrual after the vegetative growth stage was reportedly attributed to the impact of high temperatures on boll set and growth under elevated CO_2 (Reddy et al. 1999). The positive effects of elevated CO_2 concentrations on cotton biomass accrual have been explained by a reduction in canopy transpiration, increased photosynthesis, and water-use efficiency (Hatfield et al. 2011; Mauney et al. 1994; Reddy et al. 1995). CROPGRO-Cotton seems able to benefit from these underlying processes as reflected in enhanced water use efficiency, predominantly for RCP4.5 and 8.5. However, the decrease in biomass and water use efficiency in an un-amended soil with RCP2.6 suggests that soil N deficits constrain the response of cotton to changing CO_2 levels (Rogers et al. 1993).

According to the model simulations, the projected climate change will increase the efficiency of the applied N-fertilizer. Such change in the applied N-use efficiency was reported also by Prior et al. (1998) in controlled experiments. The downward trend of N-internal utilization efficiencies under RCP 8.5 results from the enhanced biomass accrual with a concomitant decrease in plant N concentration. This is known as the "dilution effect" (Loladze 2002; Yuan and Chen 2015) in response to elevated CO_2 regardless of the overall enhanced seasonal N uptake (Prior et al. 1998; Singh et al. 2013).

Similar to the findings reported here, positive effects of climate change was predicted for cotton yields owing to CO_2 enrichment in northern Cameroon with an increase of seed cotton by 1.3 kg ha^{-1} $year^{-1}$ (Gérardeaux et al. 2013). Adhikari et al. (2016) simulated an enhancement of seed-cotton yield by 14-29% in the Texas high plains (USA), under a climate change scenario with elevated CO_2 concentrations. In contrast, Reddy et al. (2002) using the GOSSYM crop model simulated a decrease of 9% in cotton yield in the Mississippi Delta, USA, when considering all projected climatic variables. Likewise, Hatfield et al. (2011) reviewed free atmospheric CO_2 enrichment experiments and reported an increase of 36% for biomass and 44% for seed cotton in response to doubling CO_2 concentration.

The significant enhancement of cotton yields even for amended soil owing to climatic changes occurred however at the expense of soil nutrient depletion and thus soil mining (Stoorvogel and Smaling 1990; Stoorvogel et al. 1993). This is evidenced by the larger increases in N uptake across the soil fertility management options tested when assuming the medium and high GHG forcing scenarios. As fertilization usually is an integrated part of cotton cultivation in West Africa, the projected climate change for the region will likely improve cotton productivity in the Dry Savannah region when the application of fertilizers is increased. This is in contrast with the severe decreases predicted for cereals, particularly maize and sorghum (Chapter 5). Consequently, a high use of mineral fertilizers is indispensable to sustain higher cotton yields in the future.

On the other hand, cotton would, under such conditions, respond more efficiently to N fertilization when applied under an integrated soil-crop management practice (Fig. 6.8).

6.5 Conclusions

CROPGRO-Cotton is capable of predicting accurately growth and development, in-season soil water dynamics and N uptake, and final yields of cotton. Planting of cotton in June optimizes cotton yield in northern Benin, but beyond this month the yield decreases. Climate change will likely increase water- and N- use efficiencies and yields of cotton at least when assuming a high use of mineral fertilizers or an integrated soil-crop management practice. Given that the tested fertilizers levels are almost double the current recommendations for cotton, it appears necessary to update the current soil fertilization recommendation for cotton while ensuring adequate soil organic pools to sustain improved N-use efficiency and reduce environmental concerns in the Dry Savannah region of Benin. This is needed to benefit effectively from the positive effects of the projected climate change and thus keep pace with the highly needed sustainability of cotton production systems.

7 GENERAL DISCUSSION AND CONCLUSIONS

7.1 Introductory remarks

Adaptation to climate change is compulsory for the farming population in West Africa to sustain or even enhance agricultural productivity growth. Yet, site-specific evidence is needed for producers and decision-makers alike to facilitate e.g. policy-making. This study therefore analyzed the impact of predicted climate change on growth, yields, and water- and nutrient- use efficiencies of maize-, sorghum-, and cotton-based production systems in the dry savannah region of northern Benin, West Africa. Own field trials were conducted, to generate essential empirical data to aliment process-based crop models that increased insight into crop responses to the changing environments. The increased knowledge and understanding of maize, sorghum, and cotton growth, their yields and nutrient use efficiencies (here N and P), as well as partial balances of N and P will help framing sustainable production practices in the region that is considered most vulnerable to the anticipated climate change. Based on the findings of targeted field research, conducted in the case study region during the 2014 and 2015 cropping seasons, three Cropping System Models of DSSAT v 4.6, namely CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton were successfully parameterized and evaluated for modeling growth, development, yields, and in-season soil water and nutrient uptake according to the characteristics of the region. The evaluated models turned out to be credible decision-support tools, which permitted to explore soil fertility management options to enhance water- and nutrient-use efficiencies, and yields in the prevailing maize-, sorghum-, and cotton-based production systems under both historical and future climates in the study region.

7.2 Integrated soil-crop management is most efficient to sustain nutrient demands and high yields

A high use of mineral fertilizer as well as an integrated soil-crop management option improved yields of maize, sorghum, and cotton, but only the integrated soil-crop management practice submerged as the most efficient practice of nutrient use over the entire growing season (Chapters 3, 4). Together with previous findings (e.g. Chen et al. 2011; Zhang et al. 2011), the current results thus underlined that an integration of nutrient applications stemming from various sources (e.g. soil, fertilizers, crops residues, manures, etc.) has the highest potential to result in significant increases in crop yields compared to the use of one practice alone. In addition, the improved nutrient use efficiency consequently resulted in reduced environmental risks. Such soil fertility management options, recurrently referred to as “Integrated Soil Fertility Management Strategies” (ISFM) aiming at enhancing both productivity and resource use efficiency, are acknowledged practices for sustainable agriculture practices (Carsky et al. 1999; Sanginga and Woomer 2009; Vanlauwe et al. 2014). These options are thus highly needed for the dry savannah agro-ecological zone of Benin to ensure sustainable resource use and crop productivity.

When assuming the projected climate for the region, the findings showed furthermore that the use of inorganic and organic fertilization, or combinations thereof, were likely to increase maize and sorghum yields compared to un-amended conditions irrespective of the RCP scenarios. These increases are however insufficient to offset completely the yield decreasing effects owing to haying-off or predicted heat-stress during reproductive growth (Chapter 5). The resulting overall decline in yields predicted for both staples will thus increase food stress or food import dependency in the region and certainly when considering the expected population growth and ongoing urbanization as also previously suggested for other regions in Africa (van Ittersum et al. 2016; Wheeler and von Braun 2013). Given that, with the exception of Senegal and Ghana, the current hunger index for various West Africa countries vary already between “alarming” to “serious” (von Grebmer et al. 2017), reaching food security and consequent poverty alleviation thus is seriously endangered because climate change will very likely exacerbate food availability in the region as was postulated for other regions in Africa (Chapter 5; Wheeler and von Braun 2013). Based on the projected climate, achieving the zero hunger and no poverty targets set for the region are thus unlikely to be met unless more efficient and resilient production systems, including integrated soil-crop management and water conservation options, are taken and effectively implemented.

The current findings confirmed on the one hand the importance of improved soil fertility management as a highly needed strategy for the future. Yet, a more resilient productivity and resource use efficiency *per se* is unlikely reached by such measures alone (Chapter 5). These therefore should be complemented by other means such as both drought and heat tolerant crops as optional coping strategies to climate change (Singh et al. 2014; Tesfaye et al. 2016). Also, supplementary irrigation can offset, at least to some extent, the effects of dry spells at critical plant growth stages (Fox and Rockström 2003; Reddy 2016). These, and others, may thus serve as (complementing) coping strategies next to soil fertility innovative practices under the foretold climate change and variability in the region.

The impact of climate change on cotton responses are, compared to the fate of the two staple crops examined, less grim. However, the significant increases predicted for N uptake by cotton under the projected climate suggest that the latent increases will occur at the expense of soil fertility and thus subject to further soil mining (Chapter 6), unless the increased demand for nutrients is met. However, further and more attention is needed also since N-stress moderates CO_2 fertilization effects (Boote et al., 2011). Without arresting the current, continuous soil nutrient mining during cotton production (Chapters 3, 6), significant yield depressions may occur in the future even with cotton. Also these aspects need to be considered when designing soil fertility management options to counterbalance the alarming soil fertility depletion in future cotton production systems.

7.3 CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton complement field research and support localized application

The calibrated and validated CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton models are now sufficiently robust to become functional in the case study region. Each of the three models gave sufficient evidence to predict accurately soil water, and N-related processes during crop growth. Whilst in-season N and P uptake were assessed with CERES-Maize and CERES-Sorghum under both historical and future climate conditions (Chapters 4, 5), only N uptake was assessed for cotton (chapter 6) because CROPGRO-Cotton is not responsive to P yet (Hoogenboom et al. 2015). CROPGRO-Cotton therefore needs to be adapted for soil and plant P dynamics, which is for the region highly relevant since P remains one of the most limiting factors for agricultural production growth (Bationo et al. 2012; Buerkert et al. 1996). The improvement of CROPGRO-Cotton is important also because the stimulatory effects of elevated atmospheric CO_2 is highly reduced under P-stress environments (Singh et al. 2013).

Each of the three tested crop models was sensitive to the variability of, and changes in temperatures, as can be learned from the comparison of simulation results under historical and future climate conditions (Chapters 5, 6). However, all three models do not currently consider (yet) effects of canopy temperatures, which used to be “cooler” than air temperatures (Adhikari et al. 2016; McKenney and Rosenberg 1993). Accounting for canopy temperatures, instead of air temperatures as presently is the case with the CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton models, will obviously increase the accuracy for transpiration influences experienced by crops that in particular are temperature driven (Webber et al. 2016, 2017).

The physiological effects of elevated CO_2-levels were predicted to be larger with the C3-plant cotton than for maize and sorghum, which are both C4-plants. The differential response of crops to enriched CO_2-environments was largely reported, but predominantly under controlled environments (Kimball and Mauney 1993; Leakey 2009; Mauney et al. 1994; Poorter 1993; Reddy et al. 1995). Yet, these effects can be captured by the current version of CROPGRO-Cotton and CERES-Maize and CERES-Sorghum (Boote et al. 2011; Hoogenboom et al. 2010, 2015; White et al. 2015), which allowed conducting future climate analyses for the region. All three crop models were responsive to rainfall variability, as evidenced by the year-to-year significant changes in the predictions with either past, current, and future weather parameters (Chapters 4, 5, 6). Irrespective of the crops, elevated atmospheric CO_2-levels, increasing temperatures, and rainfall variability interactively will drive the impact of climate change in the dry savannah agro-ecological zone (Chapters 5, 6) and possibly beyond. Therefore, it is important that crop models are continuously upgraded with the aim of reducing the uncertainties in weather parameters (e.g. temperature) response functions and in turn increasing the accuracy of crop productivity projections (Wang et al. 2017) to the benefit of decision-makers and planners and support ensuring local, national, regional, and global food security under predicted climate change.

7.4 Conclusions and outlook

Soil fertility management practices must embrace a combination of inorganic fertilizer and organic matter from various sources to sustain soil quality, high yields, and enhanced N- and P- use efficiencies of maize, sorghum, and cotton in the dry savannah of northern Benin, West Africa. Under projected climate, CO_2-fertilization will enhance maize and sorghum biomass production early in the season only. Overall, it is most likely that water- and N- use efficiencies, and N and P uptake of maize and sorghum decrease as well as grain yields that in turn will considerably enhance food stress in the region. The impact of climate change are likely to be positive for cotton and it is inferred that future increases in water and N productivity of cotton will be driven by CO_2-fertilization, increases in temperatures as well as rainfall variability.

The findings overall increase the understanding of water- and nutrient- use efficiencies of major crops in the dry savannah of northern Benin. This can contribute to updating soil fertility management recommendations for sustainable agricultural practices in this region. The evaluated and applied CERES-Maize, CERES-Sorghum, and CROPGRO-Cotton models have now turned into appropriate tools for framing sustainable site- and crop-specific management options in the dry savannah region of Benin, West Africa. Yet, despite the satisfactory results obtained with the present versions, efforts should be directed also to continuously improve the models, reduce still existing uncertainties and increase the accuracy of crop productivity estimates. This will ease the tasks of decision-makers, planners, and farmers alike to increase resilience of the production systems and reach food security under predicted climate change.

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ACKNOWLEDGEMENT

This work was supported by the German Federal Ministry of Education and Research (BMBF), University of Bonn, Center for Development Research (ZEF), and West African Science Service Center on Climate Change and Adapted Land Use (WASCAL). I express my gratitude to CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS) for providing climate change datasets.

I would like to thank Prof. Dr. Mathias Becker, my first supervisor, for his guidance, advice for academic procedure, and constructive comments. I am also grateful to Prof. Dr. Christian Borgemeister, my second supervisor, whose inspiring leadership as head of the department of Ecology and Natural Resource Management was an important source of motivation through this academic journey. I am thankful to him for his constructive criticisms. I express my sincere thanks to Prof. Dr. Bernd Diekkrüger, who agreed to be external evaluator of my thesis, for his valuable contributions. I would like to express my gratitude to Prof. Dr. Karl-Heinz Südekum, who accepted to be chair of my exam committee, for his useful comments. I specially acknowledge Prof. Dr. Paul L. G. Vlek, who initiated this research in the WASCAL framework jointly with my tutors, for his precious inputs owing to his experience. I would like to thank Prof. Dr. Asia Khamzina for her support and advice. To my main tutor, Dr. John Lamers, I hereby acknowledge his thorough mentorship. I am thankful to Dr. Jesse Naab, my second tutor, for his incredible support through this exciting journey. I am grateful to Prof. Jean Sogbedji and Dr. Guillaume Ezui for their inspirational guidance.

I thank so much Dr. Manske Günther, Mrs. Maike Retat-Amin, and all the staff of ZEF Doctoral Studies Program. I am grateful to Dr. Nadine Worou, Dr. Aymar Bossa, and Mr. Adolphe Avocanh of WASCAL-Competence Center for their advice and support during my field work. I would like to express my sincere thanks to the local extension service of Tanguieta, Materi, and Malanville (Benin), the farmers who participated in this study, and my field Assistants. I am grateful to my colleagues ZEF Junior Researchers from Africa, Asia, Europe, and Latine America for their support and splendid moments we have shared.

I am thankful to my wife, Eugenie Necker, for her prayers, love, and patience. I express my sincere gratitude to my family for the unconditional support.