Effects of transformation processes in '*jubraka*' agroforestry systems of the Nuba Mountains, Sudan, on nutrient fluxes

Sven Gönster

University of Kassel

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Erster Gutachter:	Prof. Dr. Andreas Bürkert, Universität Kassel
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1st Supervisor:	Prof. Dr. Andreas Buerkert, University of Kassel
2nd Supervisor:	Prof. Dr. Jens Gebauer, Rhine-Waal University of Applied Sciences
Examiner:	Prof. Dr. Rainer Georg Joergensen, University of Kassel
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Summary

Homegardens are a small-scale, yet widespread traditional landuse system in the Nuba Mountains, Sudan. Recent reports indicated a transformation of this agro-ecosystem, locally called *jubraka*, towards a more intensified (irrigation and use of external fertilizer) year-round production system to generate additional household income. Such intensification processes raise concerns about strongly positive carbon (C) and nutrient balances which are expected to lead to substantial element losses from these systems, in particular via soil gaseous emissions. Therefore, this thesis aimed at the quantification of C, nitrogen (N), phosphorus (P) and potassium (K) input and output fluxes with a special focus on soil gaseous losses. This allows the calculation of balances to identify substantial pathways of losses and the long-term productivity of traditional and intensified homegardens.

A further focus in this thesis was rainfall, a valuable resource for rain-fed agriculture in the Nuba Mountains. As in this semi-arid region rainfall is of highly intra-seasonal and inter-annual variability, coping strategies such as staggered planting dates or crop changing when replanting were developed by rain-fed farmers and gardeners over generations to overcome these constraints. However, these risk reducing mechanisms may lose their efficacy in the course of climate change effects predicted for East Africa. Therefore, the second objective of this study is to examine possible changes in rainfall amounts during the last 60 years and to provide reliable risk and probability statements of rainfall-induced events of agricultural importance such as the start of growing season to rain-fed farmers in the Nuba Mountains.

Soil gaseous emissions of C (in form of CO_2) and N (in form of NH_3 and N_2O) were determined with a portable dynamic closed chamber system consisting of a photo-acoustic multi-gas field monitor and a polytetrafluoroethylene coated chamber. To capture variation in gas fluxes across different management systems and times of the year, emissions from soils of two traditional and two intensified homegardens were quantified bi-weekly during the observation period. Topsoil moisture and temperature were recorded simultaneously to the gas measurements. Gaseous emission rates reached their peaks in the case of C at the onset (2,325 g CO_2-C ha^{-1} h^{-1} in an intensified garden type in August) and in the case of N during the rainy season (16 g NH_3-N ha^{-1} h^{-1} and 11.3 g N_2O-N ha^{-1} h^{-1}, both in a traditional garden type in October). Data indicated cumulative annual emissions of 5,893 kg CO_2-C ha^{-1}, 37 kg NH_3-N ha^{-1}, and 16 kg N_2O-N ha^{-1}. Flux rates were positively correlated with soil moisture and negatively with soil temperature. Significant positive correlations between management intensity and gaseous emissions were noted for CO_2-C and NH_3-N.

For the assessment of the long-term productivity of the two types of homegardens and the identification of pathways of substantial element losses, a carbon and nutrient budget approach was used. Three traditional and three intensified homegardens were selected and in each garden, four to five observation plots with site-specific crops were defined. The following variables were quantified on each plot between June and December in 2010: fluxes of C, N, P and K through management activities (include soil amendments, irrigation, and biomass removal), symbiotic N_2 fixation, C fixation by photosynthesis, atmospheric wet and dry deposition of C, N, P and K, soil gaseous emission of C and N, and leaching of N, P and K. Annual balances for C and nutrients amounted to -21 kg C ha^{-1}, -70 kg N ha^{-1}, 9 kg P ha^{-1} and -117 kg K ha^{-1} in intensified homegardens and to -1,722 kg C ha^{-1}, -167 kg N ha^{-1}, -9 kg P ha^{-1} and -74 kg K ha^{-1} in traditional homegardens. Photosynthesis C was the main C input with estimated averages of 7,047 and 5,610 kg C ha^{-1} a^{-1} in intensified and traditional systems, respectively. A significant N input by symbiotic N_2 fixation was only observed in traditional systems (17 kg N ha^{-1} a^{-1}). In both garden types, deposition of dust provided substantial K input (77 kg K ha^{-1} a^{-1}). The mentioned gaseous emissions of about 5,900 kg C ha^{-1} a^{-1} were the main pathway of losing C from both systems. In traditional and intensified gardens, the removal of biomass accounted for more than the half of total nutrient exports, of which one third resulted from weeding and removal of plant residues and two-thirds from harvest of the cultivated crops.

For the analysis of rainfall data, the INSTAT+ software was used to aggregate long-term daily rainfall records (60 years) from two weather stations, Kadugli and Rashad, into daily, monthly and annual intervals. The same software was applied to calculate rainfall-induced events of agricultural importance such as start and length of the growing season, high intensity rainfall events and dry spells. Subsequently, these calculated values and events were checked for possible monotonic trends from 1950 to 2009 and 1970 to 2009 by Mann-Kendall tests. Over the period from 1970 to 2009, annual rainfall showed no statistically significant change for either station. However, during this period an increase of low rainfall events (> 0.85 mm to ≤ 3 mm) by 15 days, coinciding with a decline in the number of medium daily rainfall events (> 10 mm to ≤ 20 mm) by 4 days was observed in Rashad. This increase is of concern since low rainfall events do not contribute to the crop water balance and therefore may hamper rainfed farmers' crop production. Furthermore, daily rainfall data enabled frequency calculations of a successful or failed start of the growing season, of high intensity rainfall events (90th, 95th and 99th percentiles) and of different dry spell length classes (> 7, > 14 and > 21 days; 1 to ≤ 7, 8 to ≤ 14, 15 to ≤ 21 and > 21 days). Additionally, probability calculation of the minimum lengths of the growing season and the occurring of dry spells lengths based on specific dates was performed. Since for these rainfall-induced agricultural events either no statistically significant changes or trends resulting only in minor changes of probabilities were observed, these risk statements seem to be reliable for the present and the next years.

Zusammenfassung

Hausgärten sind kleinflächige, aber weitverbreitete traditionelle Landnutzungssysteme in den Nuba Bergen im Sudan. Jüngste Berichte deuten auf eine Transformation dieser lokal auch *Jubraka* genannten Agroökosysteme hin in Richtung intensivierter (Bewässerung, zugeführte Düngemittel) und ganzjähriger Produktionssysteme, mit dem Ziel, zusätzliches Haushaltseinkommen zu generieren. Solche Intensivierungsprozesse sind besorgniserregend, da starke Kohlenstoff- (C) und Nährstoffüberschüsse zu erheblichen Elementverlusten aus diesen Systemen, insbesondere in Form von Bodengasemissionen, führen können. Die vorliegende Arbeit hat sich daher die Quantifizierung von C-, Stickstoff- (N), Phosphor- (P) und Kalium- (K) -einträgen und -austrägen, mit besonderem Augenmerk auf Bodengasemissionen, zum Ziel gesetzt. Dies ermöglicht die Aufstellung von Bilanzen mit deren Hilfe bedeutsame Verlustwege identifiziert und die Langzeitproduktivität der traditionellen und intensivierten Hausgärten abgeschätzt werden können.

Einen weiteren Schwerpunkt dieser Arbeit stellt der Niederschlag dar, der von besonderer Bedeutung für die regenabhängige Landwirtschaft in den Nuba Bergen ist. Da der Niederschlag innerhalb einer Regensaison, aber auch zwischen den Jahren stark variiert, entwickelten sich im Laufe von Generation Anpassungsstrategien wie zum Beispiel gestaffelte Aussaaten oder Fruchtwechsel im Fall von einer erneut notwendigen Aussaat, um die damit verbundenen Risiken zu minimieren. Es kann jedoch davon ausgegangen werden, dass diese risikoreduzierenden Mechanismen ihre Wirkung im Zuge des für Ostafrika vorhergesagten Klimawandels verlieren. Aus diesem Grunde ist es das zweite Ziel dieser Arbeit, Niederschlagsdaten der vergangenen 60 Jahren auf mögliche Veränderungen hin zu untersuchen, und, basierend darauf, den regenabhängigen Bauern in den Nuba Bergen eine zuverlässige Abschätzung der Wahrscheinlichkeit von niederschlagsabhängigen und landwirtschaftlich bedeutsamen Ereignissen wie zum Beispiel der Beginn der Vegetationsperiode zur Verfügung zu stellen.

Bodengasemissionen von C (in Form von CO_2) und N (in Form von NH_3 und N_2O) wurden mithilfe eines tragbaren dynamischen geschlossenen Kammersystems gemessen, das aus einem photoakustischen Multigasmonitor und einer mit Polytetrafluorethylen beschichteten Kammer bestand. Um managementbedingte und zeitliche Variationen der Bodengasflüsse zu berücksichtigen, wurden während des Untersuchungszeitraumes alle zwei Wochen Gasemissionen von zwei traditionellen und zwei intensivierten Hausgärten gemessen. Die Oberbodenfeuchte und -temperatur wurde zeitgleich mit den Gasmessungen erfasst. Gasemissionsraten erreichten im Fall von C ihren Höhepunkt zu Beginn (2325 g CO_2-C ha^{-1} h^{-1} in einem intensivierten Gartentyp im August) und im Fall von N während der Regenzeit (16 g NH_3-N ha^{-1} h^{-1} und 11,3 g N_2O-N ha^{-1} h^{-1} in einem traditionellen Gartentyp im Oktober). Jahreskumulativwerte lagen im Durchschnitt bei 5893 kg CO_2-C ha^{-1}, 37 kg NH_3-N ha^{-1} und 16 kg N_2O-N ha^{-1}. Die Flussraten waren positiv mit der Bodenfeuchte und negativ mit der Bodentemperatur korreliert. Signifikant positive Korrelationen zwischen Managementintensität und gasförmigen Emissionen wurden im Fall von CO_2-C und NH_3-N festgestellt.

Für die Einschätzung der Langzeitproduktivität der beiden Hausgartentypen und der Identifizierung der wichtigsten Elementaustragspfade wurde der Ansatz der Kohlenstoff- und Nährstoffbilanzierung gewählt. Drei traditionelle und drei intensivierte Hausgärten wurden ausgewählt, in denen vier bis fünf Beobachtungsflächen mit repräsentativen Feldfrüchten festgelegt wurden. Zwischen Juni und Dezember 2010 wurden für diese Beobachtungsflächen folgende Variablen quantifiziert: Stoffflüsse von C, N, P und K durch Managementmaßnahmen (beinhaltet Düngung, Bewässerung und Biomasseentfernung), symbiotische Luftstickstofffixierung, photosynthetische C Fixierung, atmosphärische Nass- und Trockendeposition (C, N, P und K), gasförmige Bodenemission von C und N sowie Auswaschung (N, P und K). Die berechneten Jahreskohlenstoff- und Nährstoffbilanzen beliefen sich für intensivierte Hausgärten auf -21 kg C ha^{-1}, -70 kg N ha^{-1}, 9 kg P ha^{-1} und -117 kg K ha^{-1} und für traditionelle Hausgärten auf -1722 kg C ha^{-1}, -167 kg N ha^{-1}, -9 kg P ha^{-1} und -74 kg K ha^{-1}. Mit Werten von durchschnittlich 7047 kg C ha^{-1} a^{-1} in intensivierten beziehungsweise 5610 kg C ha^{-1} a^{-1} in traditionellen Systemen war die photosynthetische Fixierung der Haupteintragspfad für C. Ein wichtiger Eintragspfad für N war die lediglich in traditionellen Systemen beobachtete symbiotische Luftstickstofffixierung (17 kg N ha^{-1} a^{-1}). In beiden Gartentypen war die Staubdeposition mit jährlich 77 kg K ha^{-1} ein wichtiger Eintragspfad für K. Die zuvor erwähnten gasförmige Verluste von ungefähr 5900 kg C ha^{-1} a^{-1} stellten in beiden Systemen den Hauptaustragspfad für C dar. Sowohl in traditionellen als auch in intensivierten Gärten war die Biomasseentfernung verantwortlich für mehr als die Hälfte aller exportierten Nährstoffe. Hierbei entfielen ein Drittel auf Jäten und Entfernung von Pflanzenresten, und zwei Drittel auf die Ernte der Nutzpflanzen.

Für die Analyse von Niederschlagsdaten wurden Langzeitdatenreihen zu Tagesniederschlagswerten (60 Jahre) für zwei Wetterstationen, Kadugli und Rashad, mithilfe der INSTAT+ Software zu Tages-, Monats- und Jahreswerten aggregiert. Die gleiche Software wurde zur Berechnung von regeninduzierten und landwirtschaftlich bedeutsamen Ereignissen wie der Beginn und das Ende der Vegetationsperiode, Hochniederschlagsereignisse und Trockenperioden genutzt. Anschließend wurden diese aggregierten Werte und berechneten Ereignisse mithilfe von Mann-Kendall Tests auf mögliche monotone Trends zwischen 1950 und 2009 sowie 1970 und 2009 geprüft. Für den Zeitraum von 1970 bis 2009 wurde für beide Stationen keine statistisch signifikante Veränderung der Jahresniederschlagssummen festgestellt. Für Niederschlagsereignisse geringer Menge (> 0,85 mm bis ≤ 3 mm) wurde jedoch in Rashad für den gleichen Zeitraum eine Zunahme von 15 Tagen, einhergehend mit einer Abnahme der Anzahl von Niederschlagsereignisse mittlerer Menge (> 10 mm bis ≤ 20 mm) von vier Tagen, beobachtet. Dieser Anstieg ist besorgniserregend, denn Niederschlagsereignisse geringer Menge tragen nicht zur pflanzenverfügbaren Wasserbilanz bei und könnten somit zu Problemen bei der landwirtschaftlichen Produktion führen. Darüber hinaus wurden mithilfe der Tagesniederschlagsdaten Häufigkeitsberechnungen für einen erfolgreichen sowie misslungenen Start der Vegetationsperiode, für hochintensive Niederschlagsereignisse (90., 95. und 99. Perzentil) und für verschiedene Klassen von Trockenperioden (> 7, > 14 und > 21 Tage; 1 bis ≤ 7, 8 bis ≤ 14, 15 bis ≤ 21 und > 21 Tage) durchgeführt. Zusätzlich wurden Wahrscheinlichkeiten zur minimalen Längen der Vegetationsperiode und dem Auftreten von Trockenperioden berechnet, ausgehend von einem bestimmten Datum. Da für diese regenfallinduzierten landwirtschaftlichen Ereignisse entweder keine statistisch signifikanten Veränderungen oder lediglich solche mit geringen Auswirkungen auf die Wahrscheinlichkeitsberechnungen beobachtet wurden, können diese Risikoberechnungen als aussagekräftig und verlässlich für die Gegenwart und nahe Zukunft angesehen werden.

Chapter 1

General introduction, research objectives and hypotheses

1.1 General introduction

Transformation of homegardens in the Nuba Mountains

The term ‘homegarden’ follows no commonly accepted definition (Kumar and Nair 2004), maybe due to the wide variation of homegarden characteristics according to their climatic and socio-cultural settings (Abdoellah et al. 2006). Nair and Kumar (2006) suggested a quite universal description summarizing main features of various homegarden definitions of the last decades: ‘homegardens represent intimate, multi-story combinations of various trees and crops, sometimes in association with domestic animals, around the homestead’. This description holds also true for homegardens in the Nuba Mountains of Sudan. In this region homegardens, locally called *jubraka* or *najad*, represent a widespread traditional landuse system characterized by clearly spatially defined, small-scale plots of up to 1.6 ha in the vicinity to households (Abdelgabar 1997; Pantuliano 2005). Jubrakas are considered to be a part of the house and are owned by the male household head, however the management is primarily the responsibility of women (Hassan 2005). Since animal husbandry is common in the Nuba Mountains (Pantuliano 2005), jubrakas are strongly influenced by livestock (mainly goats, sheep and cattle) either directly by corralling and stubble grazing or indirectly by manure fertilization. As typical for many homegardens in the tropics and subtropics, jubrakas show a diverse multi-layered structure of annual and perennial vegetation. Beside the cultivation of (fruit) trees, spices, medicinal and ornamental plants (Goenster et al. 2011), the main purpose of the gardens are the rain-fed production of vegetable and cereal crops such as short season varieties of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench), cowpea (*Vigna unguiculata* L. Walp.) and okra (*Abelmoschus esculentus* L. Moench). Typically, sowing of the vegetable and cereal crops starts at the onset of rainfall between May and June and harvest takes mainly place in September/October. Traditionally, the cultivation of crops in jubrakas primarily aims at the closing of a potential food gap, a period between the depletion of food stock and the main harvest of cereals from fields cropped outside the settlements (between December to January; Obeidalla and Riley 1983; Holcombe 1987). For this reason, they are mainly oriented towards subsistence production, but have additionally many cultural, socio-economic and ecological functions as is typical for homegardens worldwide (Kehlenbeck and Maass 2004; Kumar and Nair 2004; Abdoellah et al. 2006; Tesfaye Abebe et al. 2006).

Homegardening is one of the oldest land use activities practiced for instance in Southeast Asia already since 15,000 to 11,000 years before present (Wiersum 2006). Over the millennia these systems underwent a gradual intensification triggered by a shortage of arable land as a consequence of increased human pressure (Kumar and Nair 2004). Also nowadays homegardens are changing around the world as a result of recent trends in the agrarian structure and market-orientation (Kumar and Nair

2004). In particular the latter is a strong driver leading to ecological transformations of homegardens and to socio-economic changes for gardeners (Abdoellah et al. 2006; Thaman et al. 2006). Such transformations may result in additional income but could also imply, e.g. higher requirements of fertilizer and pesticides or a loss of traditional ethnobiodiversity.

Transformation processes are also indicated for homegardens in the Nuba Mountains. Commercial farming practices as the introduction of cash crops, the high external input of fertilizers, and irrigation during dry spells and in the dry season could be observed and aimed at generating of additional household income. These management intensifications towards a year-round production system start to oust traditional jubrakas which are rain-fed, receive low external inputs and are oriented towards auto-consumption (Hassan 2005).

Research area

The Nuba Mountains are situated in the state of South Kordofan in the Republic of Sudan. They cover an area of about 250 km by 165 km, extending approximately from 10° to 12°N latitude to 29° to 31° E longitude and vary between an altitude of 300 and 1,460 m asl (Bedigian and Harlan 1983; Hassan 2005).

According to Koeppen's climate classification the area is located in a typical hot semi-arid climatic zone (BSh; Peel et al. 2007). Exemplary for the Nuba Mountains, the climate is described briefly for two stations: Kadugli located in the southwest (512 m asl) and Rashad located in the northeast (885 m asl). Long-term temperature data (1961 to 1990) for Kadugli revealed an average annual temperature of 28.2°C peaking bimodally in April and May (31.7°C) and October (27.7°C). Rashad showed an average annual temperature of 26.8°C for the same period peaking bimodally in April (30.3°C) and October-November (26.9°C; MEPD and HCENR 2003). In Kadugli, annual rainfall averaged 698 mm showing a high annual variability with a coefficient of variation (CV) of 20.6%. In Rashad the annual rainfall averaged 711 mm (CV: 17.7%) from 1950 to 2009. The distribution of rainfall is restricted to the rainy season between May and October.

According to Bedigian and Harlan (1983) three ecological zones can be distinguished in the Nuba Mountains: the clay plains, the pediplains, and the hills. The clay plains between the hills are covered with clays rich of organic carbon commonly known as black cotton soil (vertisol, locally called *teen*). These fertile soils are the main production zone of late maturing cereals such as sorghum and sesame *(Sesamum indicum* L.) intercropped with cowpea or groundnut (*Arachis hypogaea* L.). The cultivation on so-called far farms starts in June and ends with the harvest in January (Pantuliano 2005). This smallholder rain-fed farming system follows traditionally a shifting cultivation regime but large agricultural schemes were introduced (Abdelgabar 1997). The cultivation of the vertisols is constrained by cracking of the soil during the dry season and waterlogging after heavy rains (Pantuliano 2005). The pediplains form an apron at the foot of the mountains and consist of detritus of gradual weathering rocks (Bedigian and Harlan 1983). Since this material provides comparably easily accessible near-surface groundwater, this zone is a preferred settlement side (Babiker et al. 1985). The pediplains are mainly covered with coarse textured, hard surfaced and compacted soils (alfisol, locally called *gardud*) which derived from *in situ* weathered igneous and metamorphic parent material. In this zone, jubrakas represent the typical type of agricultural land use. The hill regions are characterized by shallow, rocky soils (entisol, locally called *karkar*). Most of the hills in the vicinity of human settlements show remnants of partly extended terraces systems, the former traditional third plot type. The landscaping aimed at the prevention of soil erosion and the harvest of water by reducing the surface runoff. This practice enabled the cultivation of medium maturing sorghum and sesame intercropped with cowpea and groundnuts (Tothill 1948; Pantuliano 2005). However, as a result of the down-migration of entire villages due to the preferred cultivation of the fertile plains, the maintenance of these hill-side farms was suspended and their abundance has substantially declined (Abdelgabar 1997).

Gaseous carbon and nitrogen emissions from homegarden soils

Gaseous emissions are supposed to be one of the major pathways for losses of carbon (C) and nitrogen (N) from soils under semi-arid climate conditions (Makhado and Scholes 2011). This assumption is supported by reports of high gaseous losses from managed urban/periurban vegetable gardens in Niamey, Niger (Predotova et al. 2010), and from organic vegetable production systems in the coastal lowlands of Oman (Siegfried et al. 2011), both managed intensively. The previously described transformation processes of homegardens in the Nuba Mountains are coupled with an increase of management activities such as irrigation or soil preparation. These activities have a strong impact on soil moisture and soil temperature, both major driving factors of gaseous C and N losses (Bouwman 1996; Davidson et al. 1998; Wulf et al. 1999; Harrison and Webb 2001; Conant et al. 2004; Makhado and Scholes 2011). For this reason the intensification strategies in the homegardens of the Nuba Mountains raise concerns of increased C and N losses, particularly via the substantial pathway of soil gaseous emission that may negatively affect the long-term productivity of these systems (Kumar and Nair 2004; Abdoellah et al. 2006; Predotova et al. 2010).

For the measurement of soil gaseous emissions several approaches (e.g. chamber technique or eddy correlation flux estimation) and analytical methods (e.g. gas chromatography or tuneable diode laser absorption spectroscopy) exist whose advantages and disadvantages are discussed in chapter 5.1. In the small scaled homegardens of the Nuba Mountains, we used a portable dynamic closed chamber system for the quantification of gaseous C in form of CO_2 and gaseous N in form of NH3 and N_2O (chapter 2). The system consisted of a photo-acoustic multi-gas field monitor (INNOVA 1312-5, Lumasense TechnologiesA/S, Balerup, Denmark) and a polytetrafluoroethylene (PTFE) coated chamber which were connected by PTFE tubes (Buerkert et al. 2010; Predotova et al. 2010; Siegfried et al. 2011). This set-up has already been used in previous studies under different field conditions (Buerkert et al. 2010; Predotova et al. 2011; Siegfried et al. 2011). The photo-acoustic measurement is based on the principle that a sample gas is irradiated by intermittent light of a predetermined wavelength. The gas molecules to be measured absorb some of the light energy and convert it into an acoustic signal which is detected by highly sensitive microphones (Christensen 1990). This principle allows detection limits of 13 ppm for CO_2 (used filter: UA0981), 0.2 ppm for NH_3 (used filter: UA0973), and 0.03 ppm for N_2O (used filter: UA0985) at a sample integration time of 5 s for each gas.

Carbon and nutrient fluxes and balances in homegardens

Transformation processes along with intensification may lead to high inputs of elements and surpluses of nutrients which are likely to cause environmental pollution, e.g. in form of denitrification or leaching to the groundwater (Kumar and Nair 2004; Abdoellah et al. 2006; Predotova et al. 2010). Strong positive C, N, phosphorus (P) and potassium (K) balances are reported for instance from intensively managed urban and peri-urban gardens of Niamey, Niger (Diogo et al. 2010), and from vegetable and cereal production systems in Kabul, Afghanistan (Safi et al. 2011). Positive C and N balances were also shown for intensively cropped urban agriculture gardens in Khartoum, Sudan (Abdalla et al. 2012).

Such quantitative assessments from garden production systems are dominated by reports on urban/peri-urban vegetable production (Diogo et al. 2010; Safi et al. 2011; Abdalla et al. 2012). Comparatively less quantitative data are available for homegarden agroecosystems (Kumar and Nair 2004; Tesfaye Abebe et al. 2006). This is surprising since homegardens are widely regarded as sustainable (Torquebiau 1992; Kumar and Nair 2004), although this assumption often lacks the foundation of profound quantitative data (Jensen 1993; Kehlenbeck and Maass 2006). Beside the concern about strong positive carbon and nutrient balances, this gap of knowledge calls for quantitative research on homegardens in the Nuba Mountains.

The long-term sustainable use of agricultural systems can be effectively evaluated using a C and nutrient balancing approach. This allows to reveal possible disequilibria in input-output relationships and is thus a useful indicator for soil fertility development across different spatial and temporal scales (Stoorvogel and Smaling

1990; Smaling et al. 1993; Stoorvogel et al. 1993; Van den Bosch et al. 1998; Bindraban et al. 2000; Roy et al. 2003; Cobo et al. 2010). In addition to that, through the quantification of fluxes, substantial input and output pathways could be identified and corrective measures could be taken to minimize potential negative impacts on the environment.

The C and nutrient balancing process follows commonly a comparably simple sequence. The first step includes the spatial definition of a system to assess (e.g. garden or state) and its sub-components (e.g. plots or land use types). Following the identification of the substantial input and output fluxes for each sub-component, the next step comprises the quantification of these flows either by direct measurements or by applying standard values and transfer functions derived from literature. The last step includes the simple summation of the input and output flows which allows at least the calculation of a C and nutrient budget (Scoones and Toulmin 1998; Roy et al. 2003; Drechsel et al. 2004).

Assessment of changes of rainfall amount and rainfall-induced agricultural events

Rainfall is considered to be one substantial pathway of C and nutrient input into the system of a homegarden. But additionally to this asset, rainfall implies also a liability since it has a strong direct impact on soil water content and thus may trigger leaching and gaseous C and N losses. However, rainfall is far more than a sheet item in a nutrient balance; it is the key parameter for agriculture in sub-Saharan Africa: 95% of the total cultivated area depends on rainfall, determining the livelihoods of 70% of the population (Wani et al. 2009; Stern and Cooper 2011). This is also the case in the Nuba Mountains where livelihoods mainly base on rain-fed farming systems, ranging from small homegardens to large traditional or mechanized monocropped fields (Abdelgabar 1997; Pantuliano 2005). As rainfall is of high intra-seasonal and inter-annual variability in this area, coping strategies such as staggered planting dates or crop changing when replanting were developed by farmers and gardeners over generations to overcome these constraints (Cooper et al. 2008). However, these risk reducing mechanisms may lose their efficacy in the course of the climate change predicted for East Africa (likely increase of temperature, rainfall amounts and more intense extreme weather events; Christensen et al. 2007) that is likely to affect the climatically highly vulnerable provinces of Kordofan as well (MEPD and HCENR 2003).

Long-term daily rainfall data enables the analyses of changes in rainfall amounts and the calculation of risks/probabilities of rainfall-induced agricultural events such as the start of the growing season or high intensity rainfall events. Such attempts has been made successfully in many semi-arid parts of Africa and worldwide since the

1980s (Trilsbach and Hulme 1984; Sivakumar 1988; Walsh et al. 1988; Hulme 1990; Olaniran 1991; Le Barbé et al. 2002; Barron et al. 2003; Gong et al. 2004; Sen Roy and Balling 2004; Farrow et al. 2011). For detecting monotonic trends, Mann-Kendall tests were performed that are widely used in hydro-meteorological time series analysis (Yue and Wang 2004). The detection of changes during past decades allows evaluating the reliability of probability/risk calculations for agricultural events at present or the next few years. Outcomes may be useful for farmers and stakeholders to make informed decisions in view of reducing agriculture risks in the Nuba Mountains.

Thesis outline

Following this introduction, chapter 2 focuses on gaseous C and N emissions from homegarden soils, a pathway for substantial losses of these elements. Chapter 3 deals with the quantification of main C and nutrient fluxes in traditional (low input) and transformed, intensified (high input) homegardens. In chapter 4 changes in the annual rainfall amount as well as risks and probabilities of rainfall-induced agricultural events are addressed. Methods used in the various chapters are critically reviewed in chapter 5 where also final conclusions and recommendations are presented.

1.2 Research objectives and hypotheses

For garden production systems, reports of C and nutrient balances are dominated by surveys for urban/peri-urban gardens (Diogo et al. 2010; Safi et al. 2011; Abdalla et al. 2012). Comparatively less quantitative data are available for homegarden agroecosystems, particularly in the context of transformation processes driven by commercialization (Kumar and Nair 2004). Since rainfall in the Nuba Mountains is of high intra-seasonal and inter-annual variability, coping strategies such as staggered planting dates were developed by rain-fed farmers and gardeners over generations to overcome these constraints (Cooper et al. 2008; Mupangwa et al. 2011; Stern and Cooper 2011). However, these risk reducing mechanisms may lose their efficacy in the course of a predicted climate change for this region (MEPD and HCENR 2003; Christensen et al. 2007).

Therefore, the objectives of the following studies were:

- The quantification of C, N, P and K fluxes through management activity (amendments, irrigation, biomass removal), biological N fixation (BNF), C fixation by photosynthesis, atmospheric wet and dry deposition, soil gaseous emission, and leaching in traditional and intensified homegardens. Thereby, focus was laid on gaseous C and N fluxes from soils since they are assumed to be substantial. Flux quantification enables the calculation of balances to identify the long-term productivity of traditional and intensified homegardens.

- The determination of changes in rainfall amounts and in rainfall-induced events of agricultural importance such as start and length of the growing season, high intensity rainfall events and dry spells over different periods. This allows reliable risk and probability statements for rain-fed farmers for the next few years.

The presented studies were based on the following research hypotheses:

- In the course of jubrakas intensification processes, high C, N, P, and K inputs cause positive balances of the respective elements which induce substantial leaching and gaseous emission losses.
- Changing rainfall amounts in the Nuba Mountains during the last decades lead to a change of the probability/risk of rainfall-induced agricultural events.

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Chapter 2

Gaseous carbon and nitrogen emissions of homegardens in the Nuba Mountains, Sudan

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Gaseous carbon and nitrogen emissions of homegardens in the Nuba Mountains, Sudan

Sven Goenster[1], Martin Wiehle[1], Martina Predotova[1], Jens Gebauer[2], Abdalla Mohamed Ali[3], Andreas Buerkert[1]

[1] Organic Plant Production and Agroecosystems Research in the Tropics and Subtropics, University of Kassel, Steinstr. 19, 37213 Witzenhausen, Germany

[2] Sustainable Agricultural Production Systems with Special Focus on Horticulture, Rhine-Waal University of Applied Sciences, Marie-Curie-Str. 1, 47533 Kleve, Germany

[3] Department of Horticulture, Faculty of Agriculture, University of Khartoum, 13314 Shambat, Sudan

Key words

Carbon losses, closed chamber system, gaseous emissions, nitrogen losses, photo-acoustic multi-gas monitor

2.1 Abstract

Intensification has raised concerns about increased carbon (C) and nutrient losses from homegardens in the Nuba Mountains, Sudan. This study therefore aimed at determining gaseous C and nitrogen (N) fluxes from homegarden soils of different soil moisture, temperature and C and N status. Emissions of CO_2, NH_3 and N_2O from soils of two traditional and two intensified homegardens and an uncultivated control were recorded bi-weekly during the rainy season in 2010. Flux rates were determined with a portable dynamic closed chamber system consisting of a photo-acoustic multi-gas field monitor connected to a polytetrafluoroethylene coated chamber. Topsoil moisture and temperature were recorded simultaneously to the gas measurements. Data indicated average annual emissions of 5,893 kg CO_2-C ha^{-1}, 37 kg NH_3-N ha^{-1}, and 16 kg N_2O-N ha^{-1}. Flux rates were positively correlated with soil moisture and negatively with soil temperature. Significant positive correlations between management intensity and emissions were noted for CO_2-C and NH_3-N. The relatively high gaseous C and N losses in the studied homegardens call for effective

management practices to secure the soil organic carbon status of these traditional landuse systems.

2.2 Introduction

Homegardens are small-scale, yet widespread traditional landuse systems in the Nuba Mountains, Sudan. They are characterized by their vicinity to households, primarily female management and cultivation of vegetables and cereal crops (Abdelgabar 1997; Pantuliano 2005; Goenster et al. 2011). Most homegardens in Nuba Mountains are rain-fed, receive little external inputs and are oriented towards auto-consumption (Hassan 2005). Preliminary surveys by Wiehle (unpublished data) indicated that in recent years about 11% of the households introduced cash crops into their homegardens and intensified their management towards a partly-irrigated, year-round production system to generate additional household income. Such intensification strategies raise concerns about increased carbon (C) and nutrient losses that may negatively affect the sustainability of these systems (Kumar and Nair 2004; Abdoellah et al. 2006; Predotova et al. 2010a). Under the prevailing semi-arid climatic conditions, gaseous emissions are likely to be a main pathway for losses of C and nitrogen (N; Predotova et al. 2010a; Makhado and Scholes 2011). Major factors driving gaseous C and N losses are soil temperature and soil moisture both of which are heavily dependent on management practices (Bouwman 1996; Davidson et al. 1998; Wulf et al. 1999; Harrison and Webb 2001; Conant et al. 2004; Makhado and Scholes 2011).

In view of the above this study aimed at determining gaseous C and N fluxes from soils with different soil moisture and temperature and C and N status in traditional and intensified homegardens. A particular focus was to assess the effects of matter fluxes on the bio-physical and chemical sustainability of these landuse systems and on nutrient use efficiency.

2.3 Materials and methods

2.3.1 Research site

Data were collected in Sama (10°58’ N, 29°44’ E, 512 m asl), a village in the Nuba Mountains adjacent to Kadugli, the administrative center of the province of South Kordofan, Sudan. Originally, the approximately 6,000 inhabitants all belonged to the Shawabna tribe, but following the civil war-related influx of refugees from other Nuba Mountain regions over the past decades, the ethnic affiliation is now mixed (Pantuliano et al. 2007).

According to Koeppen (Peel et al. 2007) the research area has a hot semi-arid climate (BSh). Long-term data (1961-1990) show an average annual temperature of 28.2°C peaking bi-modally in April-May (31.7°C) and October (27.7°C; MEPD and HCENR 2003). Average annual rainfall (1950-2010) amounted to 698 mm with a unimodal distribution. The normal average rainy season (monthly precipitation >25 mm) lasts six months, from May to October, with an average maximum of 161 mm in August. For the study year 2010, rainfall was 818 mm between May and October with a peak of 265 mm in August and a second peak of 196 mm in October. The mean annual air temperature was 28.7°C with maxima of 34.5°C in April and 28.1°C in November.

Table 1. Selected socio-economic and botanical characteristics of the studied homegardens in Sama, Nuba Mountains, Sudan, in 2010.

Characteristics	Homegardens			
	High 1	High 2	Low 1	Low 2
Commercialization (%)^a	> 50	> 50	< 50	0
Established since (a)^b	about 60 / about 18	about 50 / about 14	> 40	about 30
Size (ha)	0.04	0.14	0.12	0.17
Gardener	Woman	2 women	3 women	Woman, man
Poverty index^c	1.50	0.28	2.28	-0.22
Input sources dry season	Irrigation, manure (goat, sheep), urea	Irrigation, manure (goat, sheep), urea	Manure (cow, donkey, goat, sheep)	Manure (cow, donkey, goat, sheep)
Input sources rainy season	Precipitation, irrigation, manure (goat, sheep)	Precipitation, irrigation, manure (goat, sheep)	Precipitation, manure (cow, goat, sheep)	Precipitation, manure (cow, donkey, goat, sheep), ash
Protection	Dense fence	Dense fence	Untight fence	No fence
Plant species number in the garden (n)^d	28	24	31	40
Crops on study plots	*Anethum graveolen* L. *Corchorus olitorius* L. *Eruca sativa* (Mill.) Thellung *Portulaca oleracea* L. *Solanum melongena* L. *Zea mays* L.	*Abelmoschus esculentus* (L.) Moench *Corchorus olitorius* L. *Eruca sativa* (Mill.) Thellung *Zea mays* L.	*Abelmoschus esculentus* (L.) Moench *Zea mays* L.	*Abelmoschus esculentus* (L.) Moench *Sesamum indicum* L. *Sorghum bicolor* (L.) Moench *Zea mays* L.

[a] Following Abdoellah et al. (2006), homegardens were classified as ‘commercial’ if more than 50% of products were sold.

[b] Reported by gardeners; for the high input homegardens: first value is related to garden establishment and second to the transformation from traditional to commercial.

[c] Poverty Index of each household was calculated by using Principal Component Analysis (PCA) according to Henry et al. (2003).

[d] Assessed at the end of rainy season, October 2010.

Four homegardens were selected to represent the range from low input (‘Low 1’ and ‘Low 2’) to high input management (‘High 1’ and ‘High 2’) and the presumably concomitant different gaseous emission rates (Table 1). Based on a preliminary survey, characteristics of high input homegardens were a strong market orientation (Abdoellah et al. 2006), application of organic and inorganic fertilizers, and irrigation during dry spells and the dry season. In contrast, crops of the two low input rain-fed homegardens were used mainly for auto-consumption and largely fertilized with manure. An uncultivated, unused area within the village was chosen as a control for emission measurements.

All homegardens and the control plot were geomorphologically situated at the pediment of the adjacent Miri Hill, a typical settlement place in the Nuba Mountains. The soils, locally known as ‘gardud’, are derived from *in situ* weathered igneous and metamorphic parent material, and in the case of Sama, from granitic detritus (Babiker et al. 1985; El Tahir et al. 2010). According to the USDA Soil Taxonomy, these soils are classified as sandy Alfisols with an ustic soil moisture and an isohyperthermic temperature regime. The surface soils’ texture (0-0.5 m) ranged from loamy sand to a sandy loam, organic C (C_{org}) concentrations were <1%, and effective cation exchange capacity ranged from 7.9-9.5 $cmol_c\ kg^{-1}$ at an acidic to neutral pH (KCl) and very variable Bray-P levels (Table 2).

Table 2. Selected physical and chemical soil properties of two high and two low input homegardens and an uncultivated control area in Sama, Nuba Mountains, Sudan, in 2010. Data represent pooled samples of two soil profiles located in a vegetable and cereal measuring site of the homegardens and two profiles within the control area.

Garden	Depth (m)	pH (KCl)	C_{org} (%)	Total-P (mg kg^{-1})	Bray-P (mg kg^{-1})	CEC_{eff} ($cmol_c\ kg^{-1}$)	Exchangeable cations ($cmol_c\ kg^{-1}$)					Texture
							Na^+	K^+	Mg^{2+}	Ca^{2+}	Al^{3+}	
High 1	0.00-0.15	7.0	0.76	411	39	9.48	0.49	1.29	2.92	4.73	0.00	loamy sand
	0.15-0.35	5.9	0.31	477	16	7.67	0.69	0.48	0.90	5.57	0.00	sandy loam
	0.35-0.80	5.6	0.05	847	4	8.67	0.81	0.35	1.07	6.42	0.00	sandy loam
High 2	0.00-0.15	7.1	0.86	988	59	8.55	0.20	2.01	0.83	5.44	0.00	loamy sand
	0.15-0.60	6.0	0.16	421	19	7.01	0.12	0.95	0.86	5.06	0.00	sandy loam
	0.60-0.80	5.6	0.03	790	7	8.47	0.21	0.89	1.29	6.04	0.00	sand
Low 1	0.00-0.15	5.9	0.71	642	21	8.68	0.15	1.14	0.72	6.62	0.00	sandy loam
	0.15-0.50	5.5	0.09	811	5	8.30	0.30	0.35	1.18	6.43	0.00	loamy sand
	0.50-0.90	5.1	0.07	425	4	7.24	0.23	0.25	0.83	5.90	0.00	sandy loam
Low 2	0.00-0.10	5.9	0.64	362	6	7.86	0.18	1.33	1.05	5.24	0.00	sandy loam
	0.10-0.30	5.4	0.34	351	3	6.61	0.15	0.28	1.03	5.11	0.00	sandy loam
	0.30-0.65	5.4	0.12	321	3	8.19	0.12	0.30	0.98	6.76	0.00	sandy loam
	0.65-0.85	5.3	0.04	554	3	6.78	0.11	0.31	0.81	5.52	0.00	sandy loam
Control	0.00-0.10	5.3	0.72	414	4	8.49	0.10	0.81	0.98	6.56	0.00	sandy loam
	0.10-0.30	5.2	0.38	377	3	7.57	0.17	0.22	1.21	5.93	0.00	sandy loam
	0.30-0.65	5.1	0.09	308	3	8.21	0.23	0.23	0.92	6.78	0.00	sandy loam
	0.65-0.90	5.1	0.04	585	2	8.15	0.33	0.19	0.84	6.74	0.00	loamy sand

2.3.2 Experimental set-up

Soil emissions of CO_2, NH_3 and N_2O were determined by a portable dynamic closed chamber system consisting of a photo-acoustic multi-gas field monitor (INNOVA 1312-5, Lumasense TechnologiesA/S, Balerup, Denmark) and a polytetrafluoroethylene (PTFE) coated cylindrical polyvinyl chloride (PVC) chamber of 0.299 m diameter and 0.11 m height (Christensen 1990a, b; Buerkert et al. 2010; Predotova et al. 2010a; Siegfried et al. 2011). Both units were connected by two 0.5 m long PTFE tubes with an internal diameter of 0.003 m serving as an inlet and outlet to the chamber. The sample integration time of the multi-gas monitor was adjusted to 5 s for each gas and the interference generated by water vapor and the measured soil gases were set to cross-compensate (Predotova et al. 2010a; Predotova et al. 2010b). The accuracy of the recorded values was controlled by verification measurements of the multi-gas monitor after field use. Compared to calibrated control gases, errors were -1.6% for CO_2, -1.0% for NH_3 and 10.4% for N_2O. To minimize irradiation-derived temperature increases in the chamber's interior, the chamber was wrapped with aluminum foil. Chamber air humidity and temperature were continuously monitored by a digital thermo-hygrometer (PCE-313A, Paper-Consult Engineering Group, Meschede, Germany; Siegfried et al. 2011). To avoid leaks between chamber and soil as well as lateral diffusion, a PVC ring of 0.299 m diameter and 0.06 m height was inserted about 0.025 m into the soil as recommended by Rochette et al. (1997) and Hutchinson and Livingston (2001). The ring was inserted the night before measurements to reduce gaseous emissions due to soil disturbance.

Soil temperatures were measured four times at depths of 0.05 and of 0.1 m around each ring using a digital penetration thermometer (Carl ROTH GmbH + Co, Karlsruhe, Germany) during each gas measurement. Simultaneously, soil moisture (volumetric water content) in 0.06 m was determined four times by a ThetaProbe ML2x FD soil moisture sensor connected to the read-out unit INFIELD 7 (UMS GmbH, Munich, Germany). Ambient air temperature and humidity were recorded by a HOBO® U23 Pro v2 data logger (Onset Computer Corporation, Bourne, USA) installed in a white painted Stevenson screen, 2 m above ground level, located in the center of Sama. Values for precipitation were obtained from the weather station at Kadugli (WMO station index number: 62810) about 2 km southeast of the experimental site.

In each of the four homegardens, two measuring sites were selected, one in a cereal and one in a vegetable zone. Each site consisted of two similar managed adjacent plots. In each of these plots three fixed measuring points were selected leading to 3 x 2 x 2 = 12 points. These were complemented by 12 points in the control area. Before measurements, all plant material was clipped to 0.03 m above ground to avoid effects of shoot respiration.

Gaseous emissions were assessed bi-weekly over two consecutive days: on the first day, measurements were taken in one vegetable and one cereal plot, on the second day, in the other two plots. To assess effects of diurnal soil temperature changes on gaseous emissions, all measurements were taken during the coolest (6 to 8 a.m.) and hottest (3 to 5 p.m.) time of the day, morning and afternoon, respectively (Smith et al. 2003; Šimek et al. 2010). For each measuring point, data were recorded over two accumulation intervals of about 4.5 min, whereby a single measurement consisted of five gas concentration readings (one data record every 62 ± 2 s). Following each accumulation interval, the chamber was disconnected from the coupling ring, aerated by swiveling and flushed for 4 min to avoid memory effects (Thomson et al. 1997).

To assess changes in the topsoil C and nutrient pool, three subsamples per plot were taken each month at a depth of 0-0.15 m, pooled, air-dried, and analyzed for C_{org}, total C, nitrate N (NO_3-N), ammonium N (NH_4-N), and total N concentration using standard methods (Diogo et al. 2010). Soil bulk density of the first 0.1 m in each measuring site was estimated on the basis of six undisturbed samples collected with 100 cm^3 soil sampling rings.

2.3.3 Data analysis

Calculations

The water filled pore space (WFPS) in percent of the total pore volume of the measuring sites' topsoil was calculated according to equation 1:

$$WFPS\ (\%) = \frac{\theta_V\ (\%)}{1 - \rho_B\ (g \times cm^{-3}) / \rho_D\ (g \times cm^{-3})}$$

(Equation 1)

where θ_V is the volumetric water content, ρ_B the soil bulk density and ρ_D the soil particle density, assumed to be 2.65 g cm^{-3} (Robertson and Groffman 2007).

The soil gaseous emission rates per unit area, that is the change in gas concentration within the closed chamber between two defined points in time, were calculated according to equation 2 which is based on the ideal gas law (Siegfried et al. 2011):

$$E_G = \left[\left(\frac{c_{M2} \times V_{CH} \times 298.15 \times \frac{3600}{t_E} \times \frac{1}{A_{CH}}}{V_{NG} \times 1000000 \times T_{CH2}} \right) - \left(\frac{c_{M1} \times V_{CH} \times 298.15 \times \frac{3600}{t_E} \times \frac{1}{A_{CH}}}{V_{NG} \times 1000000 \times T_{CH1}} \right) \right] \times m_G$$

(Equation 2)

where A_{CH} is the chamber base area (0.07022 m^2), c_{M1} and c_{M2} the gas concentrations for the first and second measurements, respectively (ppm), E_G the gaseous emission (mg m^{-2} h^{-1}), m_G the molar mass of the respective gas (g mol^{-1}), T_{CH1} and T_{CH2} the air temperature inside the closed chamber during the first and second measurement respectively (K), t_E the time period of emission (s), V_{CH} the chamber volume (0.00732 m^3 plus ring volume), and V_{NG} the volume of the normalised gas (0.02446 m^3). To minimize feedback effects of increasing gas concentrations in the chamber on microbial activity and soil respiration processes, and due to the observed early linear increase of gas concentrations in the chamber, the first period of accumulation after closing the chamber covering 62 ± 2 s was used for all calculations (Velthof and Oenema 1995; Conen and Smith 2000). In the rare cases when small negative emission rates for NH_3 and N_2O were recorded, these were set to zero.

To upscale emission data over time, monthly morning and afternoon readings for each measuring site were averaged assuming a sinusoidal distribution of daily flux rates. Subsequently, daily mean values were multiplied by the number of days between measurement intervals and aggregated annually. Missing values for the dry season period from January to May, when no measurements were taken, were extrapolated from the values measured during the dry months November and December.

Statistical analysis

The bi-weekly data of soil CO_2-C, NH_3-N and N_2O-N emissions, and the soil temperature and WFPS data for each garden and the control plots were averaged across 12 measuring points / 24 measurements. The monthly soil C and N data for each measuring site consisted of six subsamples. For most datasets, Shapiro-Wilk tests showed that residuals were not normally distributed. As ANOVA is known to be fairly robust against non-normal distribution of data if group sizes are equal and large enough (Donaldson 1968; Lunney 1970) and to facilitate data interpretation, datasets were not transformed, thereby accepting that F-values shown are only approximate. Spearman's rank correlation analyses were used to examine relationships between gaseous emission rates and management intensity, soil temperature, soil C, nutrient pools, and WFPS. The bi-weekly emission measurements were correlated with the respective monthly data for topsoil C and N. One-way ANOVA with Tukey's HSD and Dunnett's post-hoc-tests were conducted to examine group differences. All statistical tests were run in SPSS 19.0.0.1 (IBM Inc., New York, USA) at a two-tailed significance level of $P < 0.05$.

2.4 Results

2.4.1 Soil characteristics

For all plots, soil temperature at 0.05 m depth ranged from 19 to 31°C during morning and from 28 to 44°C during afternoon hours, and the means of 25°C and 36°C differed significantly (Figure 1). During the measurement period, morning temperatures declined slightly, while afternoon soil temperatures decreased from June to August and increased thereafter.

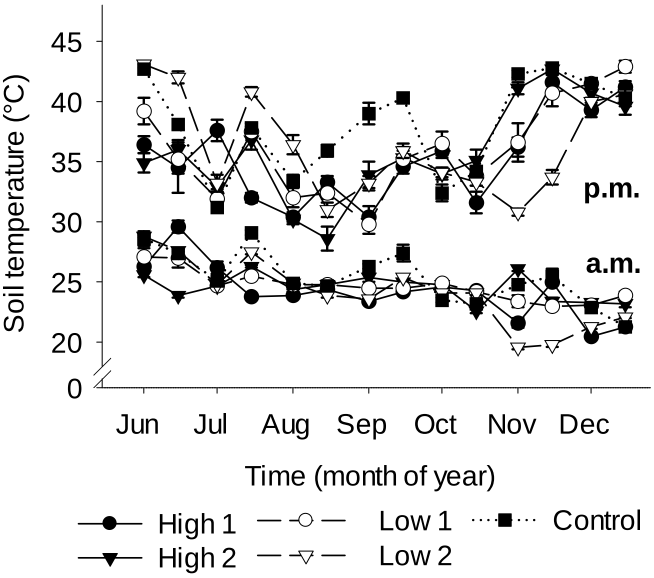

Figure 1. Changes of morning (a.m.) and afternoon (p.m.) soil temperature at 0.05 m depth of two high and two low input homegardens as well as a control in the Nuba Mountains, Sudan, in 2010. Each data point represent 48 measurements; error bars show ± standard error (n = 12).

WFPS of the topsoil was significantly related to semi-monthly cumulated rainfall events ($r_s = 0.64$, $P < 0.001$; Figure 2). After strong rainfalls in the first half of July, August and the first half of October, WFPS of all gardens increased up to 78%. Lowest values (13%) were measured in the dry season at the end of the year. Differences between morning and afternoon measurements of WFPS were not significant ($P > 0.05$).

The C_{org} concentrations in the topsoil of the homegardens and the control plots were relatively constant during the observation period (Figure 3 A), ranging from 0.7 to 1.6% in different homegarden plots and remaining steady at about 0.4% in control plots. The greatest change in C_{org} observed was a decline in homegarden High 2, particularly under cereal cultivation. The C/N ratio ranged between 7 for High 2 in December and 15 for High 1 in November (Figure 3 B).

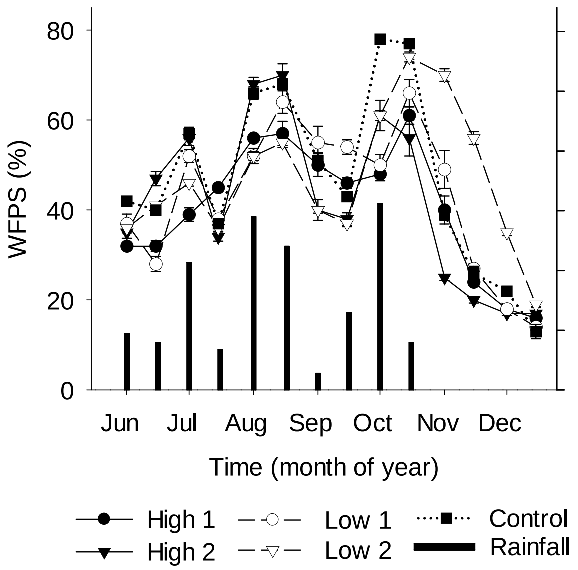

Figure 2. Changes of water filled pore space (WFPS, lines) in the topsoil (0.06 m) of two high and two low input homegardens as well as a control compared to the amount of semi-monthly cumulated rainfall (bars) in the Nuba Mountains, Sudan, in 2010. Each WFPS data point represents the average of 96 measurements; error bars show ± standard error (n = 24).

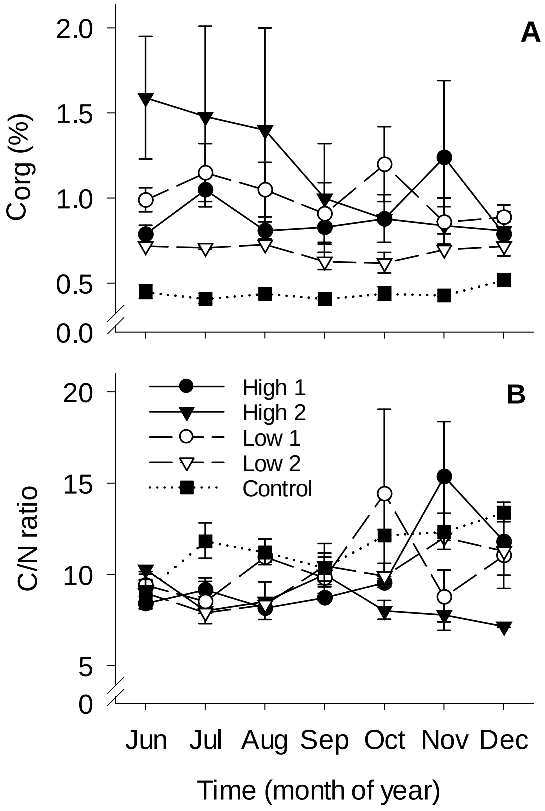

Figure 3. Changes of C_{org} (A) and C/N ratio (B) in the topsoil of two high and two low input homegardens as well as a control plot in the Nuba Mountains, Sudan, in 2010. Each data point represents the average of 2 samples, each a mixture of 6 subsamples; error bars show ± standard error (n = 2).

Mineral N (N_{min}) ranged from 5.8 in High 1 to 21.0 mg kg^{-1} in Low 2 (Figure 4). A rise over the season was only observed for the high input homegardens, where the topsoil's N_{min} strongly increased during the heavy rainfall months of July, August and October. This is particularly true for NH_4-N, which with 60 to 98% represents the prevailing form of N_{min}. At all locations, the NO_3-N concentration decreased over the season.

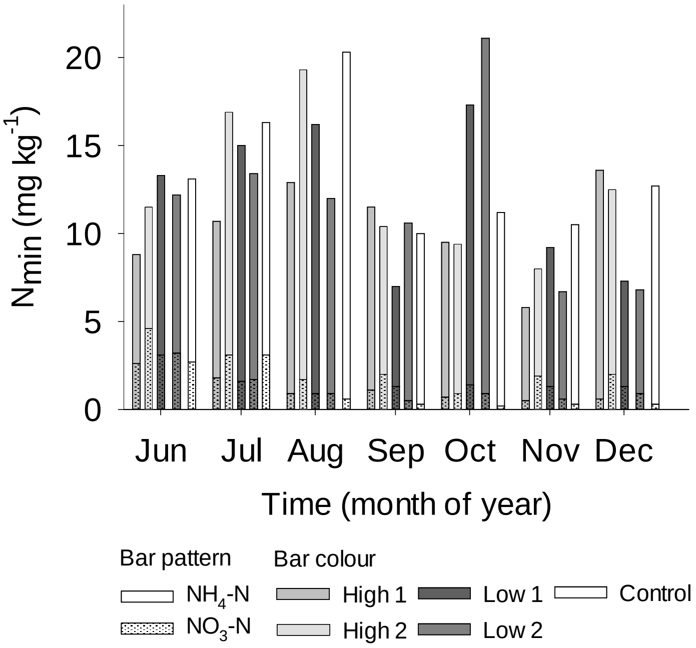

Figure 4. Changes of N_{min}, including NO_3-N and NH_4-N, in the topsoil up to 0.15 m of two high and two low input homegardens as well as a control in the Nuba Mountains, Sudan, in 2010. Each bar represents the average of 2 samples, each a mixture of 6 subsamples.

2.4.2 CO_2-C emissions

Across treatments, flux rates for CO_2-C ranged between 27 g CO_2-C ha^{-1} h^{-1} for control plots in December and 2,325 g CO_2-C ha^{-1} h^{-1} for High 1 in August (Figure 5). With 400 g CO_2-C ha^{-1} h^{-1}, control plots had the lowest mean flux rate during the observation period, whereas homegardens High 1 and Low 1 emitted more than twice as much on average (High 1: 1,051 g CO_2-C ha^{-1} h^{-1}; Low 1: 1,088 g CO_2-C g ha^{-1}; Figure 5). In general, CO_2-C flux rates declined three to five times from the onset of rainy season to the dry period, except for Low 2, where the emissions of these two periods were similar. Morning and afternoon CO_2-C flux rates were similar in High 1, Low 2 and the control. However, in High 2 and Low 1, average CO_2-C afternoon emissions were significantly higher than morning emissions (High 2: $P = 0.033$; Low 1: $P = 0.035$). CO_2-C emissions correlated either positively with soil temperature at 0.05 m depth in the morning ($r_s = 0.18$, $P = 0.034$) or negatively in the afternoon ($r_s = -0.52$, $P < 0.001$) and, positively with the WFPS of the topsoil (a.m.: $r_s = 0.38$, $P < 0.001$; p.m.: $r_s = 0.34$, $P < 0.001$). The emission rates of the locations correlated positively with C_{org} (a.m.: $r_s = 0.43$, $P < 0.001$; p.m.: $r_s = 0.44$, $P < 0.001$)

and total N (a.m.: $r_s = 0.47$, $P < 0.001$; p.m.: $r_s = 0.49$, $P < 0.001$). Mean CO_2-C flux rates also rose significantly with increasing input intensity (Control < Low < High; a.m.: $r_s = 0.34$, $P < 0.001$; p.m.: $r_s = 0.32$, $P < 0.001$).

2.4.3 NH_3-N emissions

Flux rates for NH_3-N ranged from 0.7 g NH_3-N ha^{-1} h^{-1} for High 1 in September to about 16 g NH_3-N ha^{-1} h^{-1} for Low 2 and the control in October and November (Figure 5). Mean NH_3-N emissions varied between 3.9 g NH_3-N ha^{-1} h^{-1} for Low 1 and 5.0 g NH_3-N ha^{-1} h^{-1} for High 2, though differences were not significant (Figure 5). However, on average, mean afternoon emissions were 2.5 to 3 times higher than morning emissions. Emissions generally peaked at the onset of rains in June and during heavy rainfall periods in October and November. Across locations the correlation of afternoon emissions with WFPS confirmed this observation ($r_s = 0.46$, $P < 0.001$). Furthermore, a negative relationship between afternoon NH_3-N fluxes and soil temperature at 0.05 m depth was observed ($r_s = -0.35$, $P < 0.001$). Morning emissions reflected the NO_3-N concentration in the soil and the management intensity in as much as higher concentrations and intensification resulted in higher morning NH_3-N emissions (NO_3-N: $r_s = 0.20$, $P = 0.021$; intensity: $r_s = 0.17$, $P = 0.049$).

2.4.4 N_2O-N emissions

Values of N_2O-N ranged from 0.3 g N_2O-N ha^{-1} h^{-1} for High 2 in November and 11.3 g N_2O-N ha^{-1} h^{-1} for Low 2 in October (Figure 5). Average N_2O-N fluxes ranged from 2.0 g N_2O-N ha^{-1} h^{-1} in High 2 to 2.4 g N_2O-N ha^{-1} h^{-1} in High 1 homegardens and were thus similar across locations (Figure 5). Afternoon emissions were 3 to 3.5 times higher than morning fluxes and for all locations differed significantly from morning emissions. While morning emissions did not fluctuate much, afternoon fluxes peaked in July, August and October. Only Low 2 and control plots showed no afternoon peaks in July, but pronounced ones in October. The N_2O-N afternoon flux was negatively correlated with soil temperature at 0.05 m depth ($r_s = -0.60$, $P < 0.001$) and positively with the WFPS ($r_s = 0.73$, $P < 0.001$) and the NH_4-N and N_{min} soil pools (NH_4-N: $r_s = 0.26$, $P = 0.002$; N_{min}: : $r_s = 0.25$, $P = 0.004$). However, morning fluctuation did not correlate with the assessed parameters nor did management intensity affect N_2O-N emission rates.

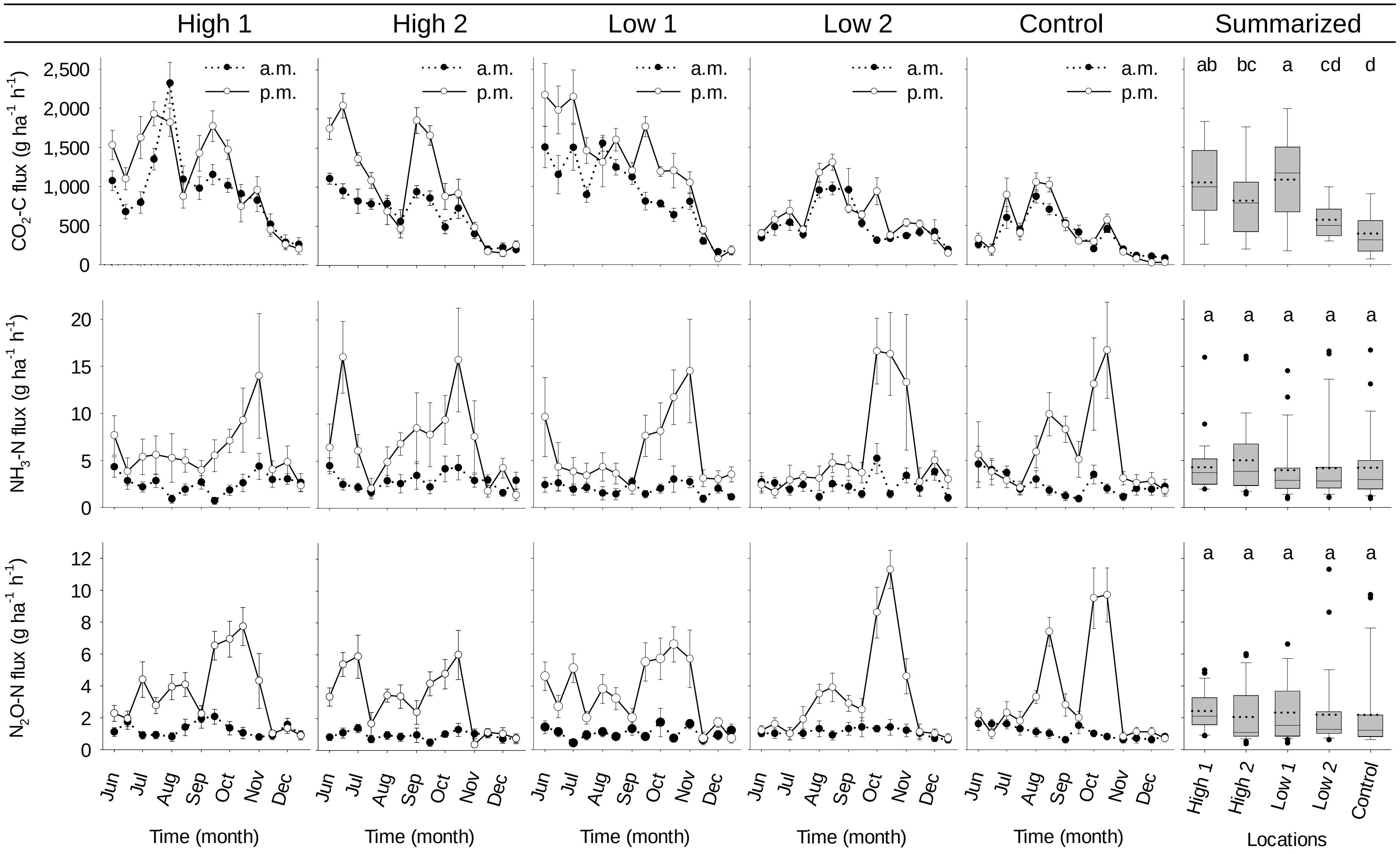

Figure 5. Temporal course of morning (a.m.; dotted line and filled circles) and afternoon (p.m.; solid line and blank circles) gaseous emission rates of CO_2-C, NH_3-N and N_2O-N in two high and two low input homegardens and an uncultivated area in the Nuba Mountains, Sudan, in 2010. Each data point represent 24 measurements; error bars show ± standard error (n = 12). Boxplots summarize the flux data of the observation period shown on the left side together with the respective median (solid line) and mean (dotted line). Different small letters over boxplots indicate significant differences ($P < 0.05$).

2.4.5 Cumulative C and N losses

Estimated cumulative CO_2-C emissions from homegardens were 1.5 to 3.3 fold larger than fluxes from the control plots (Figure 6). Average cumulative CO_2-C emissions for all homegardens amounted to 5,893 kg ha^{-1} a^{-1}, whereas a maximum of 8,406 kg CO_2-C ha^{-1} a^{-1} was reached at the vegetable site High 1 and a minimum of 3,848 kg ha^{-1} a^{-1} at vegetable site Low 2.

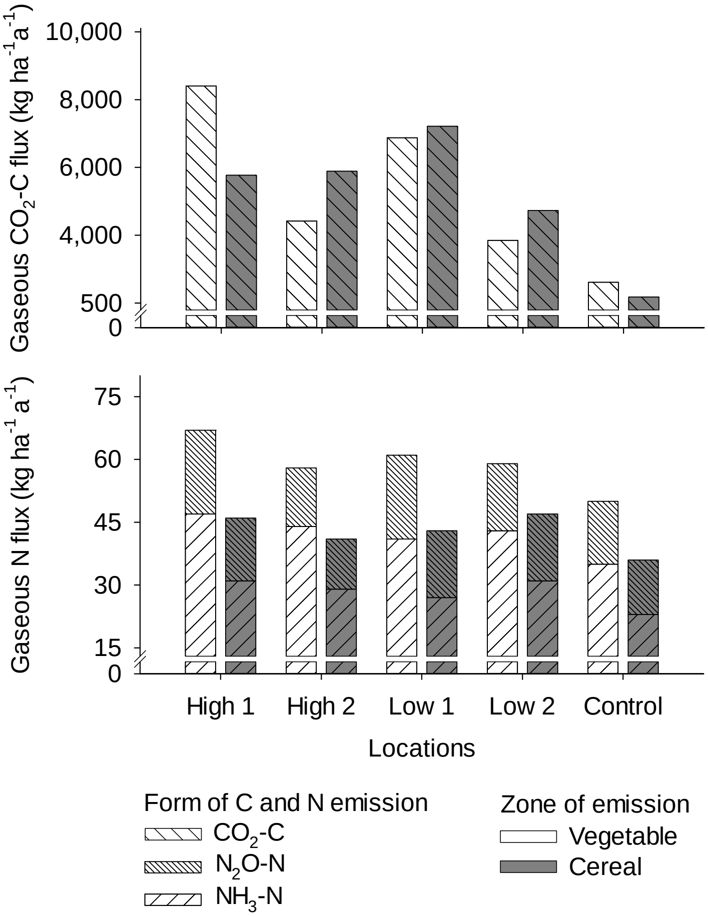

Figure 6. Estimated annual cumulative gaseous C and N emissions for vegetable and cereal plots in two high and two low input homegardens and an uncultivated control in the Nuba Mountains, Sudan, in 2010.

Management effects on N fluxes were not as pronounced as for C (Figure 6). NH_3-N increased by factor 1.2 for both measuring sites of Low 1 and by factor 1.4 for the cereal site High 1. Compared to control plots N_2O-N fluxes were up to 1.3 fold higher at the vegetable sites High 1 and Low 1, but similar to homegarden High 2. Averaged cumulative NH_3-N fluxes across all homegardens amounted to 37 kg ha^{-1} a^{-1} with a maximum of 47 kg ha^{-1} a^{-1} for the vegetable site High 1 and a minimum of 27 kg ha^{-1} a^{-1} for the cereal site Low 1. About one-third of gaseous N was emitted as N_2O-N. Average cumulative annual N_2O-N fluxes amounted to 16 kg ha^{-1}, whereby rates were with 12 kg ha^{-1} lowest at the cereal site High 2 and with 20 kg ha^{-1} highest at the vegetable site High 1. Average total N fluxes amounted to 57 kg ha^{-1} for High 1, 50 kg ha^{-1} for High 2, 52 kg ha^{-1} for Low 1, 53 kg ha^{-1} for Low 2 and 43 kg ha^{-1} for control plots.

2.5 Discussion

2.5.1 Partial horizontal balances and soil parameters

Partial horizontal balances in all homegardens were positive for C and negative for N (Table 3). Low 2 showed significantly lower C and N inputs than the high input homegardens, whereas inputs of Low 1 were similar to those of High 2. However, 85% of Low 1 inputs came from manure of gardener's cattle kept in the homegarden during December. About 65% of the relatively high C and N outputs from Low 1 were removed in weeds during the first months of observation. In general, the measured horizontal C surpluses were substantially smaller than those in urban and peri-urban gardens of Niamey, Niger (Diogo et al. 2010), but similar to those reported from Kabul, Afghanistan (Safi et al. 2011). The negative N balances illustrate the soil mining in many smallholder systems of sub-Saharan West Africa that has been reported in several previous studies (Henao and Baanante 1999, 2006; Cobo et al. 2010).

Table 3. Partial horizontal balances for carbon (C) and nitrogen (N) in kg ha^{-1} a^{-1} for two high and two low input homegardens in the Nuba Mountains, Sudan, in 2010.

Garden	High 1		High 2		Low 1		Low 2	
Element	C	N	C	N	C	N	C	N
Amendments	2,106	81	1,551	83	1,590	48	224	8
Irrigation water	24	31	43	57	2	2	0	0
Photosynthesis C	5,338	0	7,302	0	6,581	0	3,147	0
Biological N fixation	0	0	0	0	0	0	0	22
Biomass output	-3,813	-135	-5,216	-211	-4,701	-288	-2,248	-61
Partial balance	*3,655*	*-23*	*3,680*	*-71*	*3,472*	*-238*	*1,123*	*-31*

The lower soil temperature in the homegardens compared to those of the control plots during August and September may reflect the dense garden vegetation cover protecting the topsoil more effectively from radiation than in the uncultivated area. This plant cover had vanished by October which coincided with the start of the main harvest period. Additionally, the soil water buffered the increase of topsoil temperature due to its high specific heat capacity. This buffering effect was especially visible in Low 2 at the end of the year. The persistently higher WFPS and resulting lower soil temperature may be related to the slightly higher content of silt in the soils of Low 2. The increased irrigation intensity of the high input homegardens did not significantly affect the WFPS nor the topsoil temperature. This may be related to a higher evapotranspiration of the greater leafy plant composition with its higher water requirement and a more intensified cultivation of the topsoil.

The C_{org} concentrations of the different garden soils were similar and represent typical values for a semi-arid region. The higher C_{org} levels in the homegardens compared to the control plots may reflect the effects of the above and below-ground biomass production in the former (Kumar 2006). The strong decline of C_{org} at the cereal site High 2 may be related to the removal of weeds together with roots and adhesive soil particles from the garden system during the first months of observation. The C/N ratios between 7 and 15 were typical for soils in this climatic region and provide good conditions for mineralization through microbial biomass (Joergensen 2010). The increase of these ratios at an almost constant C_{org} concentration reflects a decreasing N concentration in the topsoil, whereas the decrease of C/N ratio in High 2 likely results from the high N input in this garden.

The peaking N_{min} values in July, August and October may result from an accumulation of NH_4-N due to limited nitrification as result of a lack of oxygen or a high WFPS (Robertson and Groffman 2007). The dominance of NH_4-N in N_{min} may be related to the high topsoil temperatures leading to a faster ammonification than nitrification process (Beck 1983; Agehara and Warncke 2005). Additionally, the produced NO_3-N may be increasingly leached, denitrified or taken up by growing homegarden plant biomass during the main rainy season.

2.5.2 CO_2-C

The average CO_2-C fluxes determined in our homegardens are comparable to those reported by Makhado and Scholes (2011) for semi-arid savanna ecosystems and are also within the ranges published by Wichern et al. (2004). However, the C emission rates are substantially lower than the 1,300 to 5,500 g CO_2-C ha^{-1} h^{-1} reported by Predotova et al. (2010a) from urban gardens in Niger which reflect much higher horizontal C and N balances in these more intensively managed horticultural systems. Therefore, the annual gaseous C losses were three to eight times lower than in Niger and two times lower than the cumulative gaseous C emissions reported by Siegfried et al. (2011) from irrigated vegetable production systems in the intensively managed organic systems of the coastal lowlands of Oman.

The main source of soil emitted CO_2-C is respiration by soil organisms and plant roots which itself is directly affected by soil temperature and soil water content (Raich and Schlesinger 1992; Raich and Potter 1995; Davidson et al. 1998; Smith et al. 2003). Both factors explain up to 89% of the temporal variation of soil respiration (Qi and Xu 2001). These interactions were also apparent in the present study by the positive correlations of CO_2-C flux with topsoil temperature and WFPS. Rising soil temperature up to 31°C in the morning led to enhanced soil respiration (Singh and Gupta 1977; Lloyd and Taylor 1994; Conant et al. 2004). The decline of CO_2-C fluxes in the afternoon may be related to the drying out of the surface soil or a declining WFPS as reported previously (Wichern et al. 2004; Tang and Baldocchi 2005; Makhado and Scholes 2011). The measured WFPS at 0.05 m in the morning and afternoon hours were similar, but the uppermost soil layer dried out strongly during hot, non-rainy days which might reduce respiration in this layer which likely contributed most to CO_2-C. The importance of soil moisture for respiration became evident in the homegardens during the dry season months November and December, when WFPS values dropped under 20% and CO_2-C fluxes strongly declined (Rey et al. 2002). This supports results of Conant et al. (2004) who observed that soil respiration may decline with soil moisture despite increasing temperature. At high WFPS of up to 60% after rainfall events, peaks in respiration were detected since the optimum for respiration ranges between 40 to 60% (Linn and Doran 1984; Skopp et al. 1990; Sey et al. 2008). Higher WFPS values suppressed soil respiration which might be due to limited O_2 diffusion in the soil matrix (Kiese and Butterbach-Bahl 2002). In addition to soil temperature and WFPS, CO_2-C fluxes were positively related to C_{org} and total N, likely reflecting microbial biomass growth and, thus an increase of respiration (Robertson and Groffman 2007). Since no significant differences in measured soil parameters existed, the significant positive correlation of the increased management intensity and CO_2-C emission may indicate different root growth intensities (Wichern et al. 2004).

2.5.3 NH_3-N

The observed NH_3-N flux rates are comparable with the 3.5 to 10 g NH_3-N ha^{-1} h^{-1} reported from urban gardens in Niamey, Niger (Predotova et al. 2010a). Cumulative volatile NH_3-N losses exceeded the 1 to 2 kg NH_3-N ha^{-1} a^{-1} estimated for growing arable crops (Kirchmann et al. 1998) as well as the 3.9 to 12.8 kg NH_3-N ha^{-1} a^{-1} estimated for savannah soils (Delon et al. 2010), but are again similar to data reported by Predotova et al. (2010a).

The volatilization of NH_3-N from the soil to the atmosphere is a complex process driven among others by the presence of free NH_3 near the surface, by soil temperature and by the pH of the soil solution (Harrison and Webb 2001; McNeill and Unkovich 2007). Our data indicate that NH_4-N is the prevailing form of N_{min} suggesting a high potential for NH_3-N volatilization in all homegardens. This should result in higher NH_3-N losses in the afternoon (Sherlock and Goh 1985). However, soil temperature seems to negatively affect NH_3-N fluxes at higher temperatures which is likely related to the strong drying of the soil surface. This limits the direct air-soil water interface and thus the possible exchange of NH_3-N. The observed positive correlation of WFPS and NH_3-N flux supports this assumption. These observations are in contrast to Carran et al. (1982) and Stewart (1970), but in accordance to data of Catchpoole (1975) and Milchunas et al. (1988). Since our year of measurements was characterized by above average rainfall, overestimations of NH_3-N emissions are likely. The correlation of NH_3-N fluxes in the morning and management intensity may be related to the pH, as soils with higher pH values, as is the case in the high input homegardens, favor increased volatilization (Harrison and Webb 2001; Sherlock and Goh 1985).

2.5.4 N_2O-N

Measured N_2O-N fluxes exceeded the -0.08 to 0.3 g N_2O-N ha^{-1} h^{-1} from semi-arid Australian soils (Barton et al. 2008), the -0.02 to 1.5 g N_2O-N ha^{-1} h^{-1} from savannah and agricultural land in Burkina Faso (Brümmer et al. 2008) and the 0.02 to 0.33 g N_2O-N ha^{-1} h^{-1} from run-off irrigated and rainfed soils in semi-arid north-west Kenya (Wulf et al. 1999). This might be related to a lower N_{min} pool in the upper soil layer compared to the present study. Total N and presumably N_{min} concentrations of homegarden soils were 21 to 249% higher than those of adjacent areas (Kumar and Nair 2004). However, our data are in good agreement with those from urban gardens in Niamey, Niger, where N_{min} concentrations were higher and fluxes reached up to 30 g N_2O-N ha^{-1} h^{-1} (Predotova et al. 2010a). In the latter study, cumulative values of 20 to 63 kg N_2O-N ha^{-1} a^{-1} substantially exceeded the data calculated in the present study. However, annual values of 4.4 to 6.9 kg N_2O-N ha^{-1} measured in tropical forest soils in Australia (Kiese and Butterbach-Bahl 2002) and 0.09 to 0.11 kg N_2O-N ha^{-1} by Barton et al. (2008) in the same study mentioned before were much lower than ours.

N_2O-N production is strongly linked to soil parameters such as C_{org}, N_{min}, soil moisture or *vice versa* oxygen availability, soil temperature and pH (Yamulki et al. 1995; Bouwman 1996; Scholes et al. 1997; Harrison and Webb 2001). The presented results confirm the effects of soil temperature on N_2O-N fluxes. The higher temperatures in the afternoon led to higher emission compared to those in the morning. However, very high soil temperatures can reduce the flux rate since the optimum temperature range varies from 25 to 35 °C (Saad and Conrad 1993; Gödde and Conrad 1999). WFPS strongly affects N_2O-N and wetter soil conditions typically coincide with higher N_2O-N emissions (Skiba and Ball 2002). This is presumably related to denitrification processes due to limited O_2 diffusion in the soil matrix at WFPS > 60% (Dobbie and Smith 2001; Kiese and Butterbach-Bahl 2002; Skiba and Ball 2002; Bateman and Baggs 2005; Khalil and Baggs 2005). Overestimations may have occurred due to the above average amount of annual rainfall.

2.6 Conclusions

Our data indicate relatively high gaseous C and N losses in the traditional and intensified homegardens of the semi-arid Nuba Mountains. These high fluxes raise concerns about the sustainability and nutrient use efficiency of these small-scaled agro-ecosystems. However, the annual rainfall in our study exceeded the long-term average, thus results might be slightly overestimated. Significant positive correlations between management intensity and emissions were observed for CO_2-C and NH_3-N fluxes. Our results also show the impact of soil temperature and soil moisture on C and N fluxes. In contrast to positive correlations between topsoil moisture and gaseous emissions, losses were negatively correlated with topsoil temperature. To better understand the effects of garden management and bio-physical and chemical soil conditions on turnover processes of organic matter, experiments under controlled conditions would be needed.

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Chapter 3

Carbon and nutrient fluxes and balances in Nuba Mountains homegardens, Sudan

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Carbon and nutrient fluxes and balances in Nuba Mountains homegardens, Sudan

Sven Goenster[1], Martin Wiehle[1], Jens Gebauer[2], Abdalla Mohamed Ali[3], Andreas Buerkert[1]

[1] Organic Plant Production and Agroecosystems Research in the Tropics and Subtropics, University of Kassel, Steinstr. 19, 37213 Witzenhausen, Germany
[2] Sustainable Agricultural Production Systems with Special Focus on Horticulture, Rhine-Waal University of Applied Sciences, Marie-Curie-Str. 1, 47533 Kleve, Germany
[3] Department of Horticulture, Faculty of Agriculture, University of Khartoum, 13314 Shambat, Sudan

Key words

Gaseous emissions, horizontal fluxes, jubraka, leaching, soil pool

3.1 Abstract

Management intensification has raised concerns about the sustainability of homegardens in the Nuba Mountains, Sudan. This study aimed at assessing the sustainability of these agroecosystems following the approach of carbon (C) and nutrient balances. Three traditional (low input) and three intensified (high input) homegardens were selected for monitoring of relevant input and output fluxes of C, nitrogen (N), phosphorus (P) and potassium (K). The fluxes comprise those related to management activities (soil amendments, irrigation, and biomass removal) as well as estimates of biological N_2 fixation, C fixation by photosynthesis, wet and dry deposition, gaseous emission, and leaching. Annual balances for C and nutrients amounted to -21 kg C ha^{-1}, -70 kg N ha^{-1}, 9 kg P ha^{-1} and -117 kg K ha^{-1} in high input homegardens and to -1,722 kg C ha^{-1}, -167 kg N ha^{-1}, -9 kg P ha^{-1} and -74 kg K ha^{-1} in low input homegardens. Photosynthesis C was the main C input flux with averaged of 7,047 and 5,610 kg C ha^{-1} a^{-1} in high and low input systems, respectively. Biological N_2 fixation (17 kg N ha^{-1} a^{-1}) was relevant only in low input systems. In both systems, the annual input of 77 kg K ha^{-1} through dust was highly significant and annual gaseous C losses of about 5,900 kg C ha^{-1} were the main C output flux. In both garden types, the removal of biomass accounted for more than half of total nutrient exports of which one third resulted from weeding and removal of plant residues and two-third from harvest. The observed negative nutrient balances may lead to a long-term decline of crop yields. The reuse of C and nutrients in biomass removals during the cleaning of homegardens may allow to partially close C and nutrient cycles.

3.2 Introduction

Homegardens are small-scale, yet widespread traditional landuse systems in the Nuba Mountains, Sudan. They are characterized by their vicinity to households, primarily female management and cultivation of vegetables and cereal crops (Abdelgabar 1997; Pantuliano 2005; Goenster et al. 2011). Traditionally, homegardens in the Nuba Mountains are rain-fed, receive low external inputs and are oriented towards auto-consumption (Hassan 2005). Preliminary surveys by Wiehle (unpublished data) indicated that in recent years about 11% of gardeners intensified their management efforts towards a year-round production system to generate additional household income. Beside the introduction of cash crops, this process is likely linked to high external inputs of fertilizers and irrigation water during dry spells and the dry season. The transformation of traditional homegardens to more intensified production systems raises concerns about increased carbon (C) and nutrient losses that may negatively affect the sustainability of these systems (Kumar and Nair 2004; Abdoellah et al. 2006; Predotova et al. 2010a).

It has been repeatedly stated that the long-term sustainable use of agricultural systems can be effectively evaluated using C and nutrient balancing approaches that allow to identify possible disequilibria in input-output relationships and are thus useful indicators for soil fertility development across different spatial and temporal scales (Stoorvogel and Smaling 1990; Smaling et al. 1993; Stoorvogel et al. 1993; Van den Bosch et al. 1998; Bindraban et al. 2000; Cobo et al. 2010; Roy et al. 2003). For garden production systems, reports of C and nutrient balances are dominated by surveys on urban/peri-urban vegetable production (Diogo et al. 2010; Safi et al. 2011; Abdalla et al. 2012). In contrast, comparatively little quantitative data is available for homegarden agroecosystems and their presumed level of sustainability (Kumar and Nair 2004).

In view of this our study aimed at the quantification of major C, nitrogen (N), phosphorus (P) and potassium (K) fluxes as affected by human management activity (soil amendments, irrigation, biomass removal), biological N_2 fixation (BNF), estimated C fixation by photosynthesis, wet and dry deposition, gaseous emission, and leaching in traditional and intensified homegardens of the Nuba Mountains as a proxy for the productivity of these systems.

3.3 Materials and Methods

3.3.1 Research site

The study was carried out in Sama (10°58'N, 29°44'E, 512 m asl), a village adjacent to Kadugli, the administrative center of the South Kordofan Province, Sudan. According to Koeppen's climate classification, the research site is located in a typical hot semi-arid climate (Peel et al. 2007). The locally recorded average annual rainfall from 1950 to 2009 was 698 mm (variation coefficient: 20.6%; Goenster 2013, unpublished); however, for the study year 2010, rainfall amounted to 818 mm between May and October. Average annual air temperature was 28.2°C between 1961 and 1990 compared to 28.7 °C during the study year.

Six homegardens were selected to represent the range from low input to high input management typically found in the region (Table 1). In each of these homegardens, 4 to 5 plots with an area of 4 to 109 m^2 were selected for monitoring of the C, N, P and K input and output fluxes (Table 1). The observation plots were located in vegetable and cereal areas of the gardens and planted with site-specific crops (Table 1). Daily measurements were conducted during the rainy season from June to December 2010. This time span covered the complete cultivation period in traditionally managed homegardens and the cereal cultivation in the intensified ones as it is restricted to the rainy season. For vegetable plots in high input gardens that were managed year-round, measurements from January to May were not recorded, but extrapolated.

According to the USDA Soil Taxonomy system, the soils of the selected homegardens are classified as sandy Alfisols with an ustic soil moisture and an isohyperthermic temperature regime. The surface soils' texture (0-0.1 m) ranged from a loamy sand to a sandy loam. The soil nutrient status was determined at the beginning of the observation period (Table 2). In the topsoil, N concentration was <0.15%, Bray-P varied from 6 to 59 $mg\ kg^{-1}$, exchangeable K from 0.3 to 2.0 $cmol_c\ kg^{-1}$, and organic C (C_{org}) concentration was <1%. Effective cation exchange capacity (CEC_{eff}) ranged from 7.9 to 9.5 $cmol_c\ kg^{-1}$ at an acidic to neutral pH (KCl).

Table 1. Selected socio-economic, management and botanical characteristics of three high input (HI) and three low input (LI) homegardens in Sama, Nuba Mountains, Sudan, in 2010. Quantified C and nutrient fluxes for each garden are listed below. Numbers in brackets indicate the number of observation plots.

	Homegardens	HI 1	HI 2	HI 3	LI 1	LI 2	LI 3
Socio-economic characteristics	Commercialization (%)[a]	> 50	> 50	> 75	< 50	0	0
	Established since (a)[b]	about 60 / about 18	about 50 / about 14	unknown / about 4	> 40	about 30	about 15
	Size (ha)	0.04	0.14	0.11	0.12	0.17	0.05
	Gardener	Woman	2 women	Woman, man	3 women	Woman, man	Woman
	Poverty index[c]	1.50	0.28	0.88	2.28	-0.22	2.51
Managment characteristics	Input sources dry season	Irrigation, manure, urea	Irrigation, manure, urea	Irrigation, manure, urea	Manure	Manure	Manure
	Input sources rainy season	Precipitation, irrigation, manure	Precipitation, irrigation, manure	Precipitation, irrigation, manure	Precipitation, manure	Precipitation, manure, ash	Precipitation, manure
	Protection	Dense fence	Dense fence	Dense fence	Untight fence	No fence	Untight fence
Botanical characteristics	Species number (n)[d]	28	24	21	31	40	36
	Crops on observed plots	*Abelmoschus esculentus* (L.) Moench, *Anethum graveolens* L., *Cucumis* spec., *Corchorus olitorius* L., *Eruca sativa* (Mill.) Thellung, *Portulaca oleracea* L., *Solanum melongena* L., *Zea mays* L.	*Abelmoschus esculentus* (L.) Moench, *Cucurbita* spec., *Cucumis* spec., *Corchorus olitorius* L., *Eruca sativa* (Mill.) Thellung, *Sorghum bicolor* (L.) Moench, *Zea mays* L.	*Abelmoschus esculentus* (L.) Moench, *Cucumis* spec., *Solanum melongena* L., *Solanum lycopersicum* L., *Zea mays* L.	*Abelmoschus esculentus* (L.) Moench, *Arachis hypogaea* L., *Capsicum frutescens* L., *Sesamum indicum* L., *Solanum melongena* L., *Sorghum bicolor* (L.) Moench, *Zea mays* L.	*Arachis hypogaea* L., *Abelmoschus esculentus* (L.) Moench, *Cucumis* spec., *Sesamum indicum* L., *Sorghum bicolor* (L:) Moench, *Vigna unguiculata* (L.) Walp., *Zea mays* L.	*Abelmoschus esculentus* (L.) Moench, *Arachis hypogaea* L., *Vigna unguiculata* (L.) Walp., *Cucumis* spec., *Solanum lycopersicum* L., *Zea mays* L.
Quantified fluxes	Amendments	X (5)	X (4)	X (4)	X (4)	X (5)	X (4)
	Photosynthesis C	X (5)	X (4)	X (4)	X (4)	X (5)	X (4)
	Biological N fixation	X (5)	X (4)	X (4)	X (4)	X (5)	X (4)
	Irrigation	X (5)	X (4)	X (4)	X (4)	X (5)	X (4)
	Wet / dry deposition	X	X	X	X	X	X
	Harvest	X (5)	X (4)	X (4)	X (4)	X (5)	X (4)
	Gaseous emissions	X (4)	X (4)	-	X (4)	X (4)	-
	Leaching	X (4)	X (4)	X (4)	X (4)	X (4)	X (4)

[a] Following Abdoellah et al. (2006) for the definition of commercialization.

[b] Reported by gardeners; for the high input homegardens: first value is related to the set up and second to the transformation.

[c] Poverty Index of each household was calculated by using Principal Component Analysis (PCA) according to Henry et al. (2003). Poverty increases with decreasing value.

[d] Assessed at the end of rainy season, October 2010.

Table 2. Selected physical and chemical soil properties of the six studied homegardens in the Nuba Mountains, Sudan, in 2010. Data represent pooled samples of two soil profiles located in the vegetable and cereal cropped areas of the homegardens.

Garden	Depth (m)	pH (KCl)	C_{org} (%)	N (%)	Total-P (mg kg^{-1})	Bray-P (mg kg^{-1})	CEC_{eff} (cmol$_c$ kg^{-1})	Exchangeable cations					Texture
								Na^+	K^+	Mg^{2+}	Ca^{2+}	Al^{3+}	
								(cmolc kg^{-1})					
HI 1	0.00-0.15	7.0	0.8	0.09	411	39	9.5	0.49	1.29	2.92	4.73	0.00	loamy sand
	0.15-0.35	5.9	0.3	n.a.	477	16	7.7	0.69	0.48	0.90	5.57	0.00	sandy loam
	0.35-0.80	5.6	0.1	n.a.	847	4	8.7	0.81	0.35	1.07	6.42	0.00	sandy loam
HI 2	0.00-0.15	7.1	0.9	0.15	988	59	8.6	0.20	2.01	0.83	5.44	0.00	loamy sand
	0.15-0.60	6.0	0.2	n.a.	421	19	7.0	0.12	0.95	0.86	5.06	0.00	sandy loam
	0.60-0.80	5.6	0.0	n.a.	790	7	8.5	0.21	0.89	1.29	6.04	0.00	sand
HI 3	0.00-0.15	6.7	0.4	0.03	570	31	9.4	0.09	1.13	1.33	6.84	0.00	loamy sand
	0.15-0.30	5.1	0.3	n.a.	482	8	7.8	0.34	0.90	1.03	5.51	0.00	sandy loam
	0.30-0.60	5.4	0.3	n.a.	482	6	8.0	0.60	0.23	1.53	5.59	0.00	sandy loam
	0.60-0.80	5.1	0.2	n.a.	510	6	8.5	0.22	0.64	1.51	6.12	0.00	sandy loam
LI 1	0.00-0.15	5.9	0.7	0.10	642	21	8.7	0.15	1.14	0.72	6.62	0.00	sandy loam
	0.15-0.50	5.5	0.1	n.a.	811	5	8.3	0.30	0.35	1.18	6.43	0.00	loamy sand
	0.50-0.90	5.1	0.1	n.a.	425	4	7.2	0.23	0.25	0.83	5.90	0.00	sandy loam
LI 2	0.00-0.10	5.9	0.6	0.08	362	6	7.9	0.18	1.33	1.05	5.24	0.00	sandy loam
	0.10-0.30	5.4	0.3	n.a.	351	3	6.6	0.15	0.28	1.03	5.11	0.00	sandy loam
	0.30-0.65	5.4	0.1	n.a.	321	3	8.2	0.12	0.30	0.98	6.76	0.00	sandy loam
	0.65-0.85	5.3	0.0	n.a.	554	3	6.8	0.11	0.31	0.81	5.52	0.00	sandy loam
LI 3	0.00-0.10	6.1	0.6	0.09	364	28	8.7	0.10	0.30	1.17	7.05	0.00	sandy loam
	0.10-0.50	5.8	0.3	n.a.	173	2	7.9	0.21	0.17	1.33	6.13	0.00	sandy clay
	0.50-0.75	6.9	0.2	n.a.	220	3	9.0	0.27	0.17	0.94	7.47	0.00	clay loam
	0.75-1.00	6.9	0.2	n.a.	236	3	9.3	0.14	0.17	0.74	8.14	0.00	clay loam

3.3.2 Calculation of element balances

A matter balance reflects the change in a pool (Khai et al. 2007) and in our study the change of C, N, P and K in the soil pool was calculated according to the following equation (Smaling et al. 1993; Stoorvogel et al. 1993; Diogo et al. 2010).

$$\Delta\, Soil_E = \left(A_E + I_E + P_E + WD_E + BNF_E \right) - \left(B_E + L_E + G_E \right)$$

(Equation 1)

where the net change of an element E in the soil pool (Δ $Soil_E$) is the result of the input flux of soil amendments (A_E), irrigation water (I_E), photosynthetic fixation (P_E), wet and dry depositions (WD_E), biological N_2 fixation (BNF_E) and the output fluxes through biomass removal (B_E), leaching losses (L_E) and gaseous emissions (G_E).

3.3.3 Quantification of input fluxes

Soil amendments

The term ‘soil amendments’ comprises not only applied inorganic and organic fertilizers including ash, but also manure that remained on the soil surface from roaming or corralled livestock. The quantity of each amendment per observation plot was recorded daily by weighing the total amount either of applied fertilizer or manure. Also recorded was the amount of manure remaining on the soil surface prior to the installation of the study plots using a sampling frame of 5 x 1 m^2 (Diogo et al. 2010). For laboratory analyses, samples were taken at each event, air dried and pooled by plot and amendment type.

Photosynthesis C and BNF

Carbon assimilated through photosynthesis and diazotrophically fixed N_2 (BNF) were estimated by transfer functions on the basis of C and N contents in the above-ground biomass that was removed from the observed plots (Diogo et al. 2010; Safi et al. 2011). Estimated photosynthetic C comprised both the fixation of C in roots and shoots and the root derived C (Kuzyakov and Domanski 2000). In our study the total C content of the dry matter of harvested biomass was multiplied by the factor 2 (Diogo et al. 2010). To estimate BNF, first the N content in the above ground legume biomass was multiplied by a factor of 1.4 to obtain the total plant N content. This value was then multiplied by 0.68 based on the assumption that this percentage of the total N in groundnut (*Arachis hypogaea* L.), the most dominant legume in the observed homegardens, was fixed biologically from atmospheric N_2 (Herridge et al. 2008).

Irrigation, wet and dry deposition

Homegardens were irrigated manually using plastic jerry cans with well water pumped by hand. The total amount of applied water was estimated by multiplying the individual volume of each watering can (7.5 to 18 l) with the number of irrigation events that were recorded from daily observations or gardener information. Data of total rainfall were obtained from the weather station at Kadugli (WMO station index number: 62810) about 2 km southeast of the research site. To determine the concentration of C and nutrients, 50 ml samples of all liquids were collected three times during the observation period into a polyethylene bottle to which two drops of concentrated (32%) HCl were added before freezing until analysis (Abdu et al. 2011).

Carbon and nutrient input fluxes through dry depositions were estimated by means of a dust trap that consisted of an open plastic jerry can (opening 0.09 m^2)

covered with a wire gauze to reduce coarse contaminations such as by leaves or bird droppings (Abdu et al. 2011). The dust trap was installed at 2 m above ground level on the roof of a gardener's dwelling in the center of the village in mid-May. For laboratory analyses, samples were taken when the rain water in the trap had completely evaporated after the rainy season.

3.3.4 Quantification of output fluxes

Biomass

In the context of this study, the term 'biomass' was not only used for harvested agricultural products for sale or auto-consumption, but also for weeds and other plant residues such as stalks or rotten field crops that were removed from the homegardens. Total C, N, P and K output through biomass removal was measured either directly at each event or, if clearly attributable to a specific observation plot, shortly thereafter. Missed observations of biomass removal by harvest were reproduced through interviews with gardeners and the weighing of the reported number of crops from neighboring plots. These numbers were validated by counting leftovers of the harvest in the kitchen or by comparison of the actual with the previous, pre-counted number of crops in the observation plots. For the quantification of harvested biomass of maize (*Zea mays* L.), sesame (*Sesamum indicum* L.) or sorghum (*Sorghum bicolor* L. Moench), the yield average of five previous marked representative plants of each crop within each observation plot were multiplied by the total number of plants of each crop within the respective plot. For laboratory analyses, samples were taken at each event, air dried and pooled by plot and type of crop.

Leaching

Cumulative leaching losses of nitrate-N (NO_3-N) and ammonium-N (NH_4-N), phosphate-P (PO_4-P), and K were estimated by cation-anion exchange resins (Self-Integrating Accumulators SIA; Bischoff 2007). The SIA consisted of polyvinyl chloride (PVC) cartridges of 0.12 m height and 0.10 m diameter with a nylon net at the bottom to fill the cartridges with a mixture of local silica sand and basic/acid ion exchange resins (Rohm & Haas, Frankfurt, Germany; Predotova et al. 2011). To exclude background contaminations, the resins were pre-treated with a 0.5 M NaCl solution (Siegfried et al. 2012). To mimic texture classes comparable to the surrounding soil material, the sand was sieved and then pretreated with a 0.1 M HCl solution. The installation of the SIA was carried out in the six monitored homegardens at the beginning of June (cumulative rainfall < 15 mm) according to the guidelines of TerrAquat Consultants (Stuttgart, Germany), the patent holder of this method (Table 1). In each homegarden 20 cartridges were installed, 10 cartridges under the main rooting zone of vegetables (in two adjacent, similar managed plots at 0.4 m depth) and cereals (in two adjacent, similar managed plots at 0.6 m depth), respectively. After excavating the cartridges in mid-December, two months after the last rainfall, samples of the sand-resin mixture were taken from five equal layers of each SIA and stored frozen until laboratory analyses.

Gaseous emissions

Out of the six gardens, two high and two low input ones were selected for the quantification of soil gaseous emissions (Table 1). Soil emissions of CO_2, NH_3 and N_2O were determined by a portable dynamic closed chamber system consisting of a photoacoustic multi-gas field monitor (INNOVA 1312-5, Lumasense Technologies Inc., Balerup, Denmark) and a polytetrafluoroethylene (PTFE) coated cylindrical PVC chamber of 0.30 m diameter and 0.11 m height. Both units were connected by two 0.5 m long PTFE tubes with an internal diameter of 0.003 m serving as an inlet and outlet to the chamber (Christensen 1990a, b; Predotova et al. 2010a; Predotova et al. 2010b; Siegfried et al. 2011). Measurements in each homegarden were conducted twice a month over a 7-month period including the rainy season and the begin of the dry season. Measured C and N emissions were averaged for each of the two high and for low input gardens and assumed to represent losses from all gardens of these two management types.

3.3.5 Chemical analyses and flux calculations

Concentrations of C, N, P and K in solid and liquid samples were analyzed according to standard methods (Safi et al. 2011). Potassium was determined using a BWB-XP flame photometer (BWB Technologies, Braintree, UK). C, N, P and K fluxes were quantified by multiplying the element concentrations either with the oven-dried mass of solids or with the volume of liquids according to following equation (Khai et al. 2007).

$$F = \sum_{i=1}^{n} C_i \; Q_i$$

(Equation 2)

where F is the total input or output mass flux (amendments, irrigation water, wet and dry deposition, biomass removal), n the number of events, C_i the element concentration of the material at event i and Q_i the oven-dried mass at event i. Input and output fluxes from observation plots of different sizes were computed at a per ha basis. To estimate annual input and output fluxes of C, N, P and K with the exception of wet and dry depositions, leaching and gaseous emissions, the results of the first month of monitoring which was representative for the dry season was multiplied by six to cover the missing observation period. Fluxes of C, N, P and K through dust were corrected for rainfall inputs in the dust trap by subtracting respective contents. Since the meteorological conditions for main dry depositions, the downdrafts of single cell thunderstorms (haboobs), occur from May to July (Goudie and Middleton 2001), the measured period represents annual inputs. Recordings of gaseous emissions from the soil surface were processed according to Predotova et al. (2010a) to quantify C and N losses in kg ha^{-1} a^{-1}. The sampled sand-resin mixtures of the leaching cartridges were extracted according to Predotova et al. (2011). Subsequently, concentrations of NO_3-N and NH_4-N were determined with a continuous flow analyzer (Evolution II auto analyzer, Alliance Instruments, Cergy-Pontoise, France). Concentrations of PO_4-P were measured with the spectrophotometric molybden blue method at 710 mm (Hitachi U-2000, Tokyo, Japan) according to Hoffmann (1991), and K with the BWB-XP flame photometer. To quantify N, P and K leaching losses in kg ha^{-1} over the accumulation period, data for each element were processed according to Predotova et al. (2011). Accumulation during the 6.5 months represents annual leaching losses since there is good data from the West African Sahel that in rainfed agriculture of this climate zone significant drainage only occurs during the rainy season (Sangare et al. 2012).

3.3.6 Statistical analysis

Independent sample t-tests were conducted to examine differences between the fluxes and balances of high and low input homegardens. Datasets were assumed to have a normal distribution. All statistical tests were run in SPSS 19.0.0.1 (IBM Inc., New York, USA) at a two-tailed significance level of $P \leq 0.05$.

3.4 Results

3.4.1 Input fluxes

Soil amendments

Main nutrient inputs for both homegarden types resulted from manure amendments through gardener's application and roaming or corralled livestock, as well as ash from kitchens or dumped and burned materials. High input homegardens received significantly more manure resulting in higher input amounts of C ($P = 0.02$), N ($P = 0.05$) and P ($P = 0.03$) than low input homegardens (Figure 1 and 2). In high input gardens, 90% of total C and nutrient inputs through amendments originated from manure applied by gardeners compared with only 40% in low input (data not shown). For the latter, manure of roaming or corralled livestock was a more important C and nutrient source and accounted for about 50% of total amendments (data not shown). Additionally, ash was an important P and K source with 15% and 20%, respectively, of total amendment input in traditional gardens (data not shown). Apart from manure and ash, several other materials were applied, but in substantially lower quantities. For instance, during the entire observation period, urea was applied only once with an annual application rate of 44 kg ha^{-1} equivalent to 20 kg N ha^{-1} in a single intensified homegarden. One single chemical pesticide application was recorded in a high input homegarden (15 l ha^{-1} a^{-1}), while kitchen ash, a traditional pesticide, was repeatedly applied in one low input homegarden (56 kg ha^{-1} a^{-1}), primarily on ladyfinger (*Abelmoschus esculentus* L. Moench). Total annual amounts of applied amendments were 2,272 kg C ha^{-1}, 114 kg N ha^{-1}, 27 kg P ha^{-1} and 66 kg K ha^{-1} which accounted for 24%, 69%, 94% and 44% of total input of the respective element used in high input homegardens. Input levels tended to be higher in intensified compared to traditional homegardens (C: P = 0.09; N: P = 0.07; P: P = 0.09; K: P = 0.20), in which annual inputs were 866 kg C ha^{-1}, 30 kg N ha^{-1}, 10 kg P ha^{-1}, 20 kg K ha^{-1} accounting for 13%, 46%, 85% and 20% of total inputs of the respective elements.

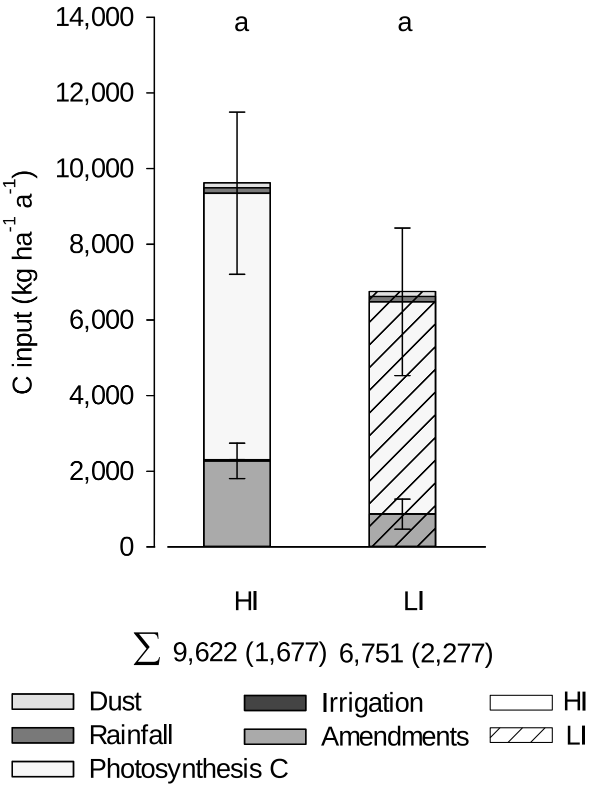

Figure 1. Annual cumulative input fluxes of carbon (C) in high input (HI, n = 3) and low input (LI, n = 3) homegardens in the Nuba Mountains, Sudan, 2010. No significant difference was detected between the annual total C input fluxes of the two types of homegardens (P > 0.05). The total amount of C input fluxes are noted below; numbers in brackets indicate ± one standard error of the mean. Bars show ± standard error of the means for the fluxes through photosynthesis C, irrigation and amendments.

Photosynthesis C and BNF

Photosynthesis C was the main C input in both homegardens (Figure 1). Annually an estimated 7,047 kg C ha^{-1} were assimilated by plants in high input homegardens, whereas only 5,610 kg C ha^{-1} were captured in low input ones. These values accounted for 73% and 83% of total C in high and low input gardens, respectively. In traditional systems legumes contributed an estimated 17 kg of fixed N_2 ha^{-1} a^{-1}, accounting for about 26% of the total N input (Figure 2). This contribution was numerically, but not statistically different ($P = 0.12$) to high input homegardens in which no legumes were grown.

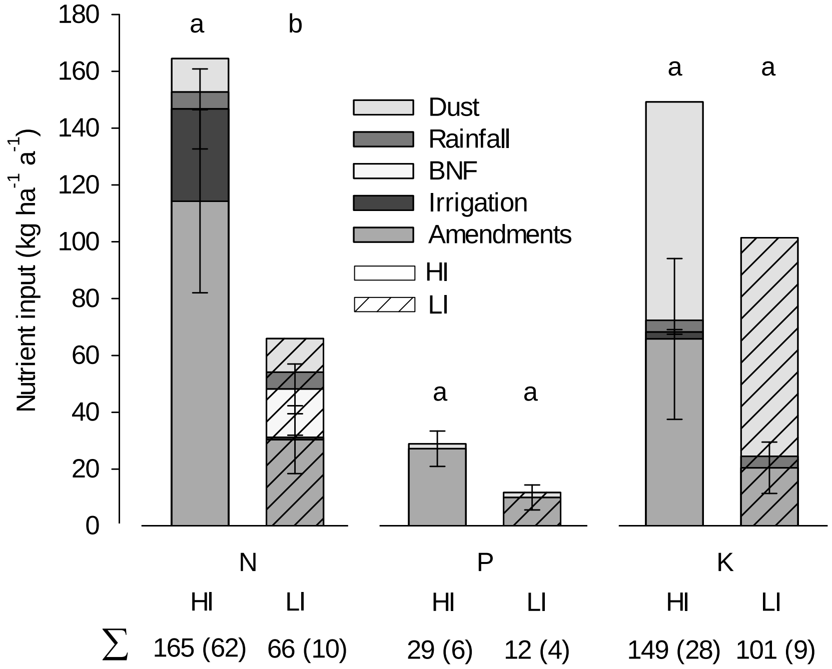

Figure 2. Annual cumulative input fluxes of nitrogen (N), phosphorus (P), potassium (K) in high input (HI, n = 3) and low input (LI, n = 3) homegardens in the Nuba Mountains, Sudan, 2010. Different letters indicate significant differences ($P \leq 0.05$) between the total nutrient inputs of the two types of homegardens. The total amount of nutrient input fluxes are noted below; numbers in brackets indicate ± one standard error of the means. Bars show ± one standard error of the mean for the fluxes through biological N_2 fixation (BNF), irrigation and amendments.

Irrigation, wet and dry deposition

The quantity of irrigation water differed significantly between the two management types ($P = 0.02$). An average of 1,304 m^3 irrigation water ha^{-1} was applied to high input gardens, whereas traditional homegardens received only 25 m^3 ha^{-1} when dry spells occurred in the rainy season (data not shown). Accordingly, annual C and nutrient input fluxes from irrigation differed significantly with 29 and 1 kg C ha^{-1} ($P = 0.02$) and 2 and 0 kg K ha^{-1} ($P = 0.04$) for intensified and traditional homegardens, respectively (Figure 1 and 2). Differences were only indicated for N, of which 32 kg ha^{-1} a^{-1} were applied with irrigation water in high and only 1 kg ha^{-1} a^{-1} in low input gardens (P = 0.09). Phosphorus concentrations of the water samples were below the detection limit. Due to low average concentrations of C (20 mg C l^{-1}) and nutrients (27 mg N l^{-1}, 2 mg K l^{-1}), such inputs through irrigation water were regarded as negligible for traditional gardens. However, the intense irrigation activity in high input homegardens resulted in a significant N input with such water (20% of total N).

Average C, N and K concentrations of the rain water were 17.5 mg l^{-1}, 0.7 mg l^{-1} and 0.5 mg l^{-1}, respectively, resulting in annual inputs of 143 kg C ha^{-1}, 6 kg N ha^{-1} and 4 kg K ha^{-1} from the rainfall amount of 818 mm (8,180 m^3 ha^{-1}) in 2010 (Figure 1 and 2). Phosphorus concentrations of the samples were below detection limit. Annual inputs through rainfall were insignificant in relation to total inputs (≤ 4%) except for N in traditional homegardens (9%; high input: 4%).

The dry deposition was a significant source of K in both garden types, but less for N, P and in particular for C. During 2010 1,498 kg dust ha^{-1} accumulated on the surface of the garden soils which resulted to an annual influx of 132 kg C ha^{-1}, 12 kg N ha^{-1}, 2 kg P ha^{-1} and 77 kg K ha^{-1} (Figure 1 and 2). This accounted for 1% and 2% of total C, 7% and 18% of total N, 6% and 15% of total P as well as 52% and 76% of total K added annually to the intensified and traditional homegardens, respectively.

3.4.2 Output fluxes

Biomass

Annual C losses through biomass removal (high input: 3,523 kg ha^{-1}; low input: 2,805 kg ha^{-1}) accounted for about one-third of the total C output (Figure 3). For nutrients, the export through biomass removal was much larger (Figure 4). Annual N losses for high and low input gardens were similar with 129 kg ha^{-1} and 136 kg ha^{-1}, respectively and accounted for 55% and 58% of total N output. Likewise, similar annual P losses were measured for both homegarden systems (about 20 kg ha^{-1}). Phosphorus output through biomass removal represented the most significant loss with 96% of annual total P loss for high and 99% for low input gardens. Annual accumulated K outputs via biomass were higher for intensified gardens with 233 kg ha^{-1} (87% of total K output) than for traditional ones with 142 kg ha^{-1} (81% of total K output), though they did not differ significantly. In general, two-third of exported element mass in both production systems was harvested; however, one-third was exported through weeds and other plant residues (data not shown). The export of C and nutrients through harvested maize (*Zea mays* L.), sorghum and sesame accounted for 16% in high input gardens, whereas this output flux accounted for 39% in low input gardens (data not shown).

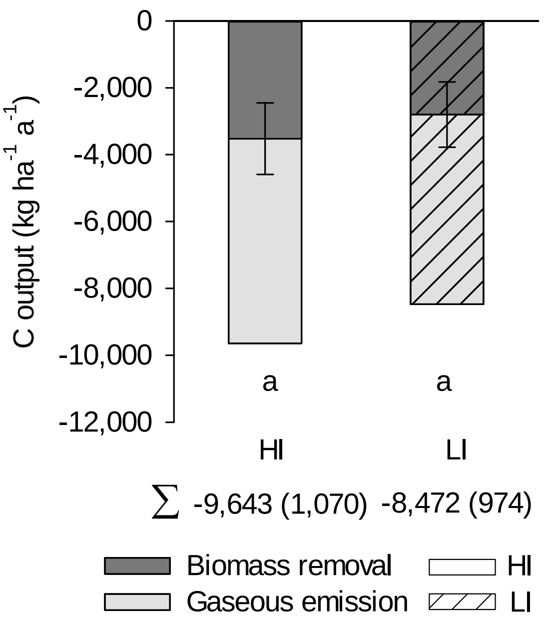

Figure 3. Annual cumulative output fluxes of carbon (C) in high input (HI, n = 3) and low input (LI, n = 3) homegardens in the Nuba Mountains, Sudan, 2010. No significant difference was detected between the annual total C output fluxes of the two types of homegardens ($P > 0.05$). The total amount of C output fluxes are noted below; numbers in brackets indicate ± one standard error of the mean. Bars show the ± standard error of the means for the flux through biomass removal.

Leaching

Leaching of N, P and K was an only minor pathway of nutrient losses compared to the biomass output (extraction) of homegardens, but still significant (Figure 4). Annually, mineral N leaching losses amounted to 53 kg ha^{-1} (22% of total N output) and 45 kg ha^{-1} (19%) for high and low input homegardens, respectively. Since NH_4-N concentrations in the extracted solutions of the sampled sand-resin mixtures were below the detection limit, leached mineral N data mainly reflected NO_3-N. Over the year, P losses amounted to 0.7 kg ha^{-1} (4% of annual total P losses) in intensified and 0.2 kg ha^{-1} (1%) in traditional homegardens. With 13% and 19% of total K losses in high (34 kg ha^{-1}) and low input (33 kg ha^{-1}) homegardens, respectively, leaching was a significant pathway of K losses from these agricultural systems.

Gaseous emissions

In both types of homegardens, gaseous losses accounted for two-third of the total C output and for a quarter of total N losses. Annual gaseous C losses were about 10% larger in high input gardens (6,119 kg ha^{-1}) than in low input ones (5,667 kg ha^{-1}) though these differences were not statistically significantly (Figure 4). The cumulative N emissions of 53 kg ha^{-1} a^{-1} were similar for both management types. Thereby about two-third of gaseous N was emitted as NH_3-N (high input: 38 kg ha^{-1} a^{-1}, low input: 36

kg ha^{-1} a^{-1}) and one-third as N_2O-N (high input: 15 kg ha^{-1} a^{-1}, low input: 17 kg ha^{-1} a^{-1}; data not shown).

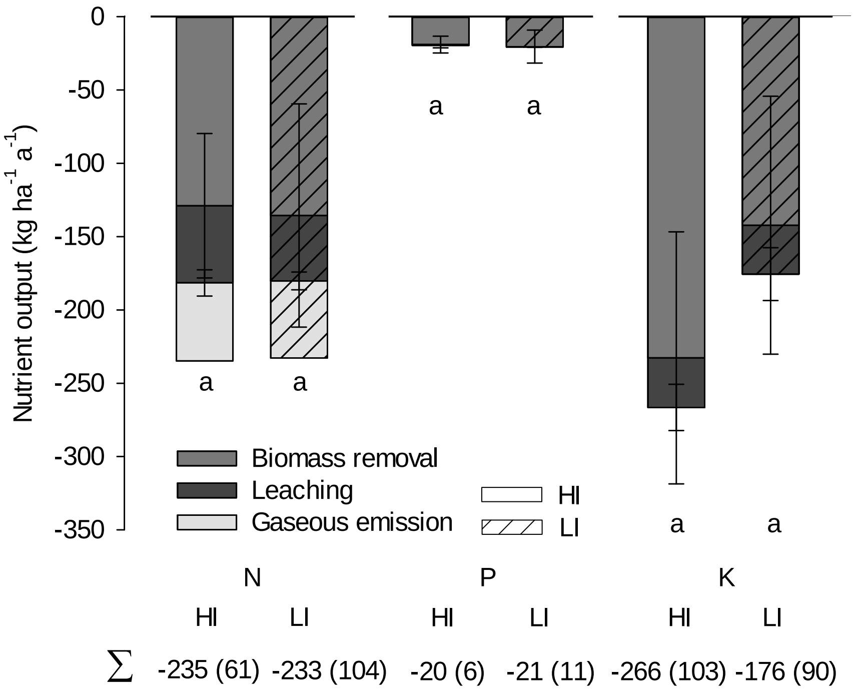

Figure 4. Annual cumulative output fluxes of nitrogen (N), phosphorus (P), potassium (K) in high input (HI, n = 3) and low input (LI, n = 3) homegardens in the Nuba Mountains, Sudan, 2010. No significant differences were detected between the annual total nutrient outputs of the two types of homegardens ($P > 0.05$). The total amount of nutrient output fluxes are noted below; numbers in brackets indicate the ± standard error of the means. Bars show ± one standard error of the mean for the fluxes through biomass removal and leaching.

3.4.3 Element balances

The two types of homegardens in the Nuba Mountains are characterized by partially significant different total input fluxes. The annual total C input of 9,622 kg ha^{-1} for high and of 6,751 kg ha^{-1} for low input homegardens were statistically not significant (Figure 1). The total annual N input of 165 kg ha^{-1} to intensified homegardens differed significantly ($P = 0.02$) from the annual input of 66 kg N ha^{-1} to traditional ones (Figure 2). Estimated annual input fluxes of 29 kg P ha^{-1} and 149 kg K ha^{-1} for high input and 12 kg P ha^{-1} and 101 kg K ha^{-1} for low input gardens differed numerically but not statistically (P: $P = 0.08$; K: $P = 0.18$).

In contrast to input fluxes, total output fluxes for intensified and traditional homegardens were similar (Figure 3 and 4). Over the study year, differences were observed for total C (high input: 9,643 kg ha^{-1}; low input: 8,472 kg ha^{-1}) and total K output (high input: 266 kg ha^{-1}; low input: 176 kg ha^{-1}) though they were not significant. Annual total N and P output for both management types of homegardens amounted to about 234 kg N ha^{-1} and 20 kg P ha^{-1}.

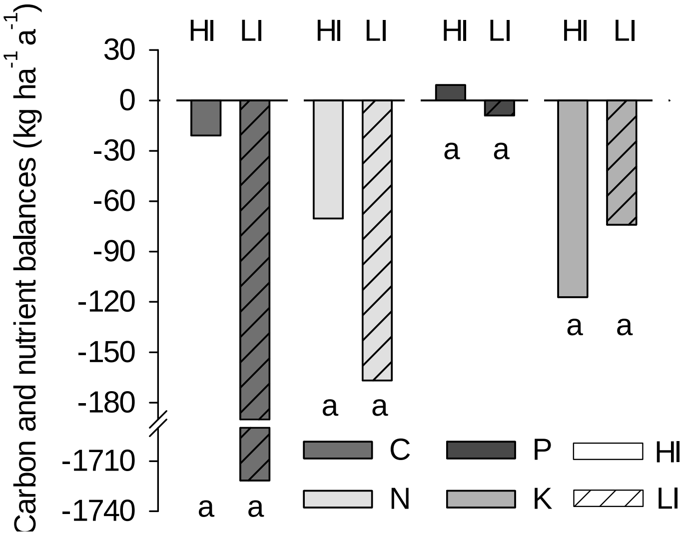

Figure 5. Annual balances of carbon (C), phosphorus (P), potassium (K) and nitrogen (N) in high input (HI, n = 3) and low input (LI, n = 3) homegardens in the Nuba Mountains, Sudan, 2010. No significant differences were detected between the annual C and nutrient balances of the two types of homegardens ($P > 0.05$).

Since total outputs of C and nutrients exceeded their total inputs, annual nutrient balances were negative for both management types and all elements, with the exception for P in high input homegardens (9 kg P ha^{-1}, low input: -9 kg ha^{-1}, Figure 5). The difference between annual C input and output was almost balanced in high input gardens (-21 kg ha^{-1}). However, in traditional gardens, annual C balance was -1,722 kg ha^{-1}. Annual balances were most negative in traditional homegardens for N (-167 kg ha^{-1}, high input: -70 kg ha^{-1}) and in intensified systems for K (-117 kg ha^{-1}, low input: -74 kg ha^{-1}) though they were not statistically significantly different.

3.5 Discussion

3.5.1 Input fluxes

Amendments

Our data showed that the amounts of amendments applied to traditional and intensified gardens differed, however, the intensification in our study was still only limited. Application rates in the high input homegardens are up to 15 times lower for N and K and up to 40 times lower for P than in intensively managed peri-urban vegetable gardens in Kumasi, Ghana (Drechsel et al. 2004). Likewise, total nutrient inputs in similarly managed vegetable gardens in Niamey, Niger, exceed our values for intensified systems: up to 20 times for N and K and up to 15 times for P (Diogo et al. 2010). In comparison to data from vegetable gardens in Kabul, Afghanistan, however, our results are up to 2.5 times lower (Safi et al. 2011). In addition to manure, significant C and nutrient inputs into the gardens of the mentioned studies resulted from inorganic fertilizers or other amendments such as night soil or bio-waste. However, in the Nuba Mountains traditional and intensified homegardens rely primarily on manure as a source of non-photosynthetic C and nutrients which illustrates the relatively low level of management intensification.

Our data shows that in traditional gardens the application of manure through roaming (access to gardens *via* poor or non-existing fences) and corralled livestock during the rainy season and during the dry season (no fences) is important for the preservation of the C and nutrient soil pools in homegardens. The permanent fences surrounding intensified systems in the Nuba Mountains preserves the valuable cash crops, but at the same time prevents a significant input of manure through roaming livestock.

In this management system, the removal of C and nutrients through harvest is partly compensated through application of manure by the gardeners and urea in case of one garden. In the low input gardens, wood ash is used as a cheap and easy to use pesticide which is typical for traditional smallholder production systems (Katanga Apuuli and Villet 1996; Achiano et al. 1999). However the amount used in our study gardens (56 kg ha^{-1} a^{-1}) is substantially lower than the amount of 1,100 kg ha^{-1} a^{-1} reported by Khai et al. (2007).

Photosynthesis C and BNF

The amount of plant assimilated C is similar to data published for vegetable gardens in Kabul, Afghanistan (Safi et al. 2011). Even though another factor (1.4) for the estimation of captured C was used in this study, data are plausible since the harvested biomass in Kabul is slightly higher than in our study. The amount of translocated photosynthesis C below the soil surface is subject to considerable uncertainty in the available literature. Data vary widely from 30% to 80% depending on age of plant and plant species (Kuzyakov and Domanski 2000; Guo and Gifford 2002). To take into account the diverse plant species composition of homegardens, an intermediate portion of 50% was considered. The numerically higher amounts of assimilated C in intensified systems of the present study reflect the higher biomass productivity due to the year-round cropping activity, compared to the only seasonal cultivation of traditional gardens.

The estimated annual atmospheric N input is below the 40 kg N ha^{-1} assumed as input from legumes in gardens of Niger (Diogo et al. 2010) and below values for groundnuts from several studies in similar climatic conditions ranging from 32 to 175 kg N ha^{-1} (Unkovich and Pate 2000). However, the ratio of N derived from the atmosphere to total amount of N in groundnuts varies widely in literature from 0% to 95% (Herridge et al. 2008) depending on additional N fertilization, the germplasm used and soil conditions which affect the ability of groundnuts to biologically fix atmospheric N_2 (Fujita et al. 1992; Khan and Yoshida 1995; Liu et al. 2011). Herridge et al. (2008) suggested an average percentage of 68% for BNF calculations for groundnut which we used. The occurence of legumes and thus BNF only in traditional homegarden systems suggests furthermore scope for a possible change of plant species composition through intensification towards non-N fixing cash crops.

Irrigation, wet and dry deposition

In contrast to traditional homegardens, the high water demanding composition of cash crops such as dill (*Anethum graveolens* L.) or rocket (*Eruca sativa* Mill. Thellung) in intensified systems requires irrigation not only in the dry season, but also in the rainy season to mitigate recurrent water deficits due to widely fluctuating intra- and inter-seasonal rainfall (Sangare et al. 2012). This is reflected by the differences in the amount of water input and applied C, N and K through irrigation water between both homegarden systems. Compared to other studies, applied amounts of irrigation water exceed the quantity used for vegetable fields in Khartoum, Sudan (Abdalla et al. 2012). However, values are about 80% lower than those reported for vegetable fields in Hanoi, Vietnam (Khai et al. 2007). Concentrations of C, N, P and K in the irrigation water used are low and are no cause for concern of groundwater contamination. The annual rainfall amount in our study year exceeded the long-term average of 698 mm by 15%. Nutrient additions through rainfall fall are within the range of values reported by the IPI (1983).

The total mass influx through dry deposition is comparable to values from similar climatic conditions ranging from 1,090 to 2,000 kg ha^{-1} a^{-1} (Goudie and Middleton 2001). The observed 1,498 kg dust ha^{-1} is equivalent to an accumulation (without deflation) of about 10 mm on the surface in 100 years assuming a bulk density of 1.5 g cm^{-3} (Drees et al. 1993) which seems plausible. The C and nutrient concentrations in the dust as well as available annual nutrient deposition amounts are comparable to literature values (Stahr and Herrmann 1996; Sterk et al. 1996). However, our K concentration exceeds equivalent values reported by Diogo et al. (2010) and Sterk et al. (1996) by a factor of 2.5 to 4.5. This may be due to the location of the homegardens within the villages leading to substantial deposition of wood ash from kitchen fires with a K concentration of 7%. Nevertheless, the possibility of dry deposition as a significant source of C, N, P and especially of K may need to be investigated further.

3.5.2 Output fluxes

Biomass

The annual removal of N, P and K through biomass from homegardens in the Nuba Mountains is low. Estimated export is within the range of data reported for irrigated urban gardens of Khartoum, Sudan (Abdalla et al. 2012). These data are in good agreement with values measured for vegetable gardens and cereal fields in Kabul, Afghanistan (Safi et al. 2011) though these values are about 1.2 to 1.6 times higher. In contrast to this, annual N, P and K removals reported for peri-urban vegetable farming systems in Hanoi, Vietnam (Khai et al. 2007) and in Niamey, Niger (Diogo et al. 2010), exceed our data substantially by factors between 1.6 and 19. As for N, P and K removal, estimated C export is within the data range reported by Abdalla et al. (2012) and slightly higher than the annual 3,300 (vegetable garden) to 5,000 kg ha^{-1} (cereal fields) published by Safi et al. (2011). However, data from Niamey which ranges from 7,000 to 30,000 kg ha^{-1} a^{-1}, is up to 10 times higher (Diogo et al. 2010).

The removal of biomass is the main pathway of nutrient losses from our homegarden systems. While high input homegardens are cultivated throughout the year, no differences between the C and nutrient losses at both intensity levels were evident. However, since low input gardens produce similar annual biomass in a shorter period by focusing on higher biomass plants such as sesame, sorghum and maize which are removed together with their stalks, the difference between both systems evened out. This is in contrast to observations by Safi et al. (2011) who assumed a larger extraction of nutrients by vegetable than cereal cultivation. Additionally, one third of C and nutrients were removed by weeds and other plant residues. This quantity offers a valuable pool of C and nutrients that could be used to improve the nutrient cycle within the homegardens through recycling such as composting.

Leaching

Measured mineral N leaching data were substantially lower compared to values from 69 to 207 kg ha^{-1} a^{-1} reported by Safi et al. (2011), but higher than the 7.3 kg ha^{-1} a^{-1} and 28 kg ha^{-1} a^{-1} reported by Predotova et al. (2011) and Siegfried et al. (2011), respectively. Annual accumulated values of up to 9 kg P ha^{-1} reported by Safi et al. (2011) and Brouwer and Powell (1995), both from sandy soils, exceeded by far the P leaching measured in our study, which were nevertheless comparable to data reported by Predotova et al. (2011). Estimated data for cumulative K leaching losses exceeded three times the maximum value of 10 kg ha^{-1} a^{-1} reported by IPI (1983). The known low mobility of NH_4-N, P and K in soils typically results in low leaching as reported in previous studies (Krogh 1997; Predotova et al. 2011; Safi et al. 2011). This is in accordance with our observations except for K. Surprisingly high cumulative

K leaching values were observed which may be related to the high K inputs, the high exchangeable K pool in soil and the low clay content of the soil profiles.

The accumulation period of the resin cartridges was restricted to the rainy season, since single rainfall events with more than 40 to 50 mm are necessary on such soils to trigger significant leaching losses (Hafner et al. 1993; Predotova et al. 2011; Sangare et al. 2012). Consequently, even the heavy irrigation in the high input gardens (maximum monitored irrigation event: 100 m^3 ha^{-1}) were insufficient to induce significant leaching without additional rainfall. Since in 2010 total rainfall was higher than the long-term average, leaching may be overestimated (Sangare et al. 2012). However, on the other side substantial underestimations for leached N and P may occur since the ion exchange resins used are unable to capture organic compounds of these elements, which are likely to contribute to total N and in some cases also for P losses (Siemens and Kaupenjohann 2002; Langlois et al. 2003; van Kessel et al. 2009).

Gaseous emissions

Estimated annual gaseous C losses were three to eight times lower than values reported from irrigated peri-urban gardens of Niamey, Niger (Predotova et al. 2010a) and two times lower than the cumulative gaseous C emissions reported by Siegfried et al. (2011) from irrigated vegetable production systems in organic systems of the coastal lowlands of Oman. Likewise annual cumulative N_2O-N emissions were substantially lower than the reported 20 to 63 kg N_2O-N ha^{-1} a^{-1} from Niamey. However, our estimated cumulative NH_3-N emissions were in good agreement with data from Niger. Both above mentioned studies were conducted in more intensively managed systems which may explain the substantially lower gaseous losses that we recorded. The annual rainfall in our study exceeded the long-term average, thus, results might be slightly overestimated (Goenster et al. 2013, unpublished). Nevertheless, the high gaseous C and N emission from the homegarden soils in relation to their total losses supports the assumption of gaseous emissions being an important pathway for losses of C and N under semi-arid climatic conditions (Predotova et al. 2010a; Makhado and Scholes 2011).

3.5.3 Element balances

The estimated balanced or negative C budgets are in contrast to the surpluses reported from intensively managed urban and peri-urban gardens of Niamey, Niger (Diogo et al. 2010) and from vegetable and cereal production systems in Kabul, Afghanistan (Safi et al. 2011). The negative N, P and K balances, with the exception of P in high input homegardens, illustrate that soil nutrient mining occurs in smallholder systems of the Nuba Mountains as is the case in sub-Saharan West

Africa reported in several previous studies (Bationo et al. 1998; Henao and Baanante 1999, 2006; Cobo et al. 2010). This is in contrast to the often propagated view of homegardens as a *per se* sustainable system given the low export of produce (Kumar and Nair 2004) and efficient nutrient cycling (Torquebiau 1992). However, since the rainfall of the study year was higher than the long-term average, the C and nutrient outputs are likely to be overestimated. A monitoring period of several years would be necessary to assess the effects of rainfall fluctuations.

Nevertheless, outputs were similar between the two systems despite the significant higher inputs in intensified gardens leading to less negative balances of C and nutrients in high input than low input gardens. This holds true in particular for C resulting from higher C inputs through manure application and year-round C assimilation through photosynthesis in intensified gardens. Nonetheless, both systems are likely to lead to long-term declines of crop yields since C and nutrients are mined from the soil pool. This is confirmed by gardeners who reported declining yields over the last years.

Our C and nutrient balances are based on a close monitoring of matters flowing in and out of observation plots. However, some components that are likely to contain significant amount of elements, were not sampled due to cultural and analytical constraints. These include human faeces and urine as well as miscellaneous waste. Such waste collected from a cereal plot (109 m^2) after harvest on a single day in November included the following: batteries (60 g), belt (leather, 86 g), ceramics (glazed, 154 g), clothing (cotton, 489 g), glass (146 g), paper (145 g), plastic (3,564 g), shoes (leather, 335 g), tin (aluminum, 170 g) and wood (925 g).

3.6 Conclusions

Our data reveal differences of inputs between traditional and intensified garden systems; however, the in the gardens observed intensification is still at a low level compared to other regions. Photosynthetically captured C was the main input pathway for C in both high and low input systems. Symbiotic N_2 fixation contributed to the N-balance only in low input systems indicating a shift of plant composition during the process of intensification. In both systems dust was responsible for significant K input. The main C output in both systems was gaseous losses, whereas for nutrients the removal of biomass accounts for two-third of total output. Weeds and other removed plant residues make up one third of this removed biomass. However, the annual rainfall of the study year exceeded the long-term average, thus, C and nutrient losses might be slightly overestimated. The balances indicated C and nutrient deficits in both production systems which might result in long-term declines of crop yields. The reuse of C and nutrients which were removed during the cleaning of homegardens may allow a partial closing of C and nutrient cycles and merits further studies.

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Chapter 4

Daily rainfall data to identify trends in rainfall amount and rainfall-induced agricultural events in the Nuba Mountains of Sudan

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Daily rainfall data to identify trends in rainfall amount and rainfall-induced agricultural events in the Nuba Mountains of Sudan

Sven Goenster[1], Martin Wiehle[1], Jens Gebauer[2], Abdalla Mohamed Ali[3], Roger D. Stern[4], Andreas Buerkert[1]

[1] Organic Plant Production and Agroecosystems Research in the Tropics and Subtropics, University of Kassel, Steinstr. 19, 37213 Witzenhausen, Germany
[2] Sustainable Agricultural Production Systems with Special Focus on Horticulture, Rhine-Waal University of Applied Sciences, Marie-Curie-Str. 1, 47533 Kleve, Germany
[3] Department of Horticulture, Faculty of Agriculture, University of Khartoum, 13314 Shambat, Sudan
[4] Statistical Services Centre, University of Reading, Harry Pitt Building, Whiteknights Road, P.O. Box 240, Reading, RG6 6FN, United Kingdom

Key words

Dry spells, East Africa, growing season, high intensity rainfall events, Mann-Kendall tests, risk statements

4.1 Abstract

Variable inter- and intra-seasonal rainfall increases risks of agricultural production in the Nuba Mountains of Sudan. Long-term daily rainfall records (60 years) from two weather stations, Kadugli and Rashad, were calculated to daily, monthly and annual values and rainfall-induced events were calculated using the INSTAT+ software. Subsequently, these calculated values and events were checked for possible monotonic trends from 1950 to 2009 and 1970 to 2009 by Mann-Kendall tests.

Over the period from 1970 to 2009, annual rainfall showed no statistically significant change for either station. However, during this period an increase of low rainfall events (> 0.85 mm to ≤ 3 mm) by 15 days coinciding with a decline in the number of medium daily rainfall classes (> 10 mm to ≤ 20 mm) by 4 days was observed in Rashad. Daily rainfall data enabled frequency calculations of a

successful or failed start of the growing season, of high intensity rainfall events (90th, 95th and 99th percentiles), of different dry spell length classes, and of probability calculations of the minimum lengths of growing season and the occurring of dry spells lengths based on specific dates.

4.2 Introduction

Rainfed farming characterizes most of sub-Saharan Africa where 95% of the total cultivated area depends on rainfall determining the livelihoods of 70% of the population (Wani et al. 2009; Stern and Cooper 2011). This is also the case in the Nuba Mountains, a region in the South Kordofan province, which contributes greatly to Sudan’s annual crop production in particular of millet (*Pennisetum glaucum* L. R.Br.), sorghum (*Sorghum bicolor* L. Moench), groundnut (*Arachis hypogaea* L.), sesame (*Sesamum indicum* L.), okra (*Abelmoschus esculentus* L. Moench) and eggplant (*Solanum melongena* L.). Livelihoods in this region are mainly based on farming with systems ranging from small diverse homegardens to large traditional or mechanized monocropped fields (Abdelgabar 1997; Pantuliano 2005). All of these agricultural systems strongly depend on rainfall which is characterized, as typical for sub-Saharan Africa, by a wide inter-annual and intra-seasonal variability (Cooper et al. 2008). This variability represents a substantial risk for famers, since water supply and rainfall-induced events of agricultural importance such as start (planting) and length of growing season, frequency of high intensity (erosive) rainfall events and frequency of dry spells are difficult to predict (Mupangwa et al. 2011; Stern and Cooper 2011). To confront these risks, different coping strategies such as diversification (e.g. staggered planting dates) or response (e.g. changing crops when replanting is necessary) were developed over generations (Cooper et al. 2008). However, these risk reducing mechanisms may become increasingly ineffective since climate change models for Eastern Africa predict that temperature and rainfall amounts as well as more intense extreme weather events are likely to increase, which makes rain-fed agriculture even riskier (Christensen et al. 2007). This may be particularly true for the Nuba Mountains, since the Kordofan provinces are one of Sudan’s areas that are reportedly most affected by climate change (MEPD and HCENR 2003).

Cooper et al. (2008) pointed out that daily rainfall is a key parameter in rainfed agriculture, since crops respond directly to rainfall. Long-term daily rainfall records are useful for the calculation of probabilities and revealing of trends of rainfall-induced events (Cooper et al. 2008; Stern and Cooper 2011). A better understanding of such probabilities and trends may help stakeholders such as extension services, development NGOs, disaster relief agencies, policy makers or the private sector (e.g. grain traders) and ultimately rainfed farmers to make more informed decisions with respect to risk assessment, risk management, effective coping strategies and midand long-term strategic planning to reduce rainfall-induced calamities to agriculture and food production (Cooper et al. 2008). Attempts to use long-term rainfall data for agricultural risk assessment have been made successfully in many semi-arid parts of Africa and worldwide since the 1980s (Trilsbach and Hulme 1984; Sivakumar 1988; Walsh et al. 1988; Hulme 1990; Olaniran 1991; Le Barbé et al. 2002; Barron et al. 2003; Gong et al. 2004; Sen Roy and Balling 2004; Farrow et al. 2011).

With this, study were aimed at using long-term daily rainfall data aggregated into different time intervals of years, months and days to calculate rainfall-induced events of particular agricultural importance such as start and length of the growing season, high intensity rainfall events and dry spells. Trend tests are used to detect potential changes over different periods. Additionally, practical implications of such changes are to be evaluated and risk statements in form of probability calculations of events provided.

4.3 Materials and methods

4.3.1 Study sites

Data from six meteorological stations in the Nuba Mountains were available: Kadugli, Rashad, Dilling, Heiban, Kalogi and Umm Berembeita (Figure 1). However, only two stations, Kadugli and Rashad, allowed a more detailed study since both had an almost complete set of daily rainfall records covering the period from 1950 to 2009. For the additional four stations, rainfall records were available for the period between 1950 and 1979 in which, however, some records are missing for individual years.

The Kadugli station is located in the southwest of the Nuba Mountains (10.96º N, 29.75º E, 512 m asl, WMO index number 62810), while the Rashad station is situated about 370 m higher than Kadugli in the northeast of the study area (11.86º N, 31.05º E, 885 m asl, WMO index number 62803). According to Koeppen’s climate classification the Nuba Mountains are located in a typical hot semi-arid climate zone (BSh; Peel et al. 2007). For Kadugli, long-term temperature data (1961 to 1990) revealed an average annual temperature of 28.2°C peaking bimodally in April and May (31.7°C) and October (27.7°C). For Rashad, average annual temperature was 26.8°C with bimodal peaks in April (30.3°C) and October-November (26.9°C; MEPD and HCENR 2003).

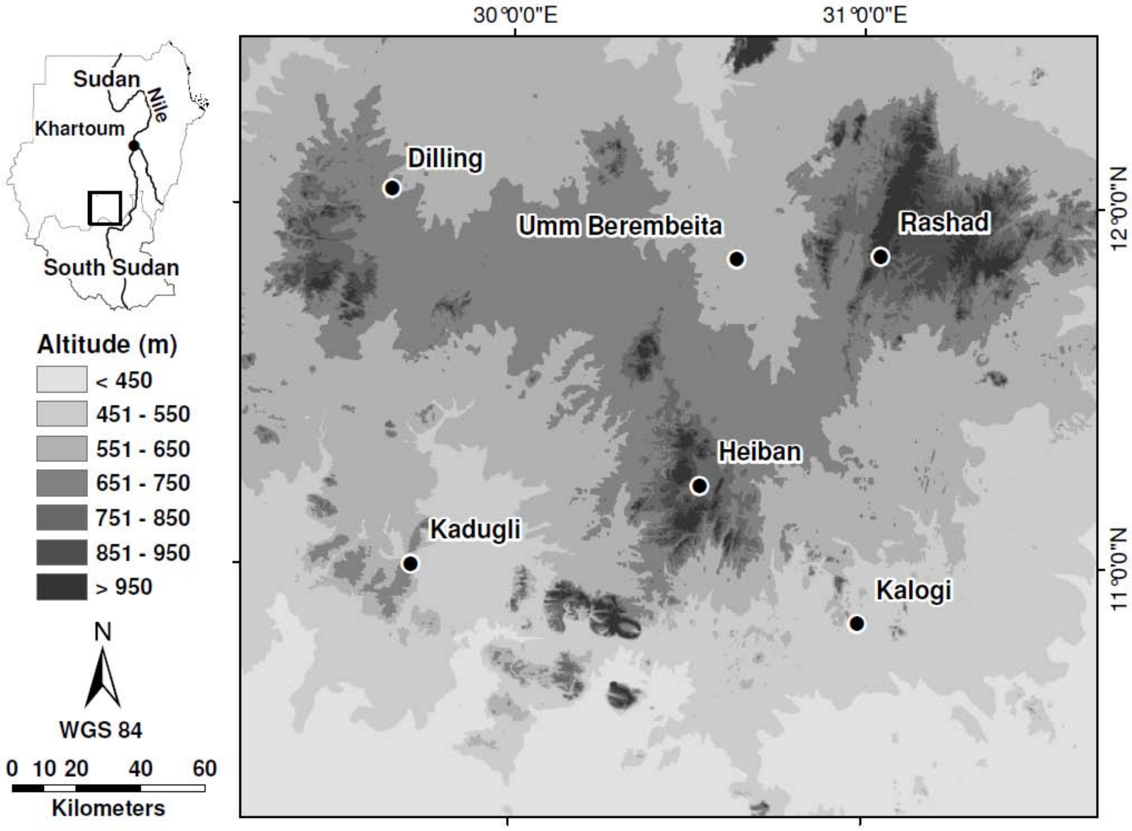

Figure 1. Topographic location of the weather stations in the Nuba Mountains, Sudan (Data source: Centre for Development and Environment, University of Berne, Switzerland).

4.3.2 Data source and quality

For all stations daily rainfall data were obtained from the Sudan Meteorological Authority in Khartoum in 2010 and subjected to simple plausibility tests which, however, did not indicate any anomalies. The records from Kadugli showed one hundred 1 to 19 day gaps in the rainy seasons of 1986, 1987, 1990 and 1993, but long-term gaps of two months (May and June) were only found for 1993. In contrast to Kadugli, the dataset for Rashad was almost complete: in the years 2004 and 2006 data entries were missing for only three days.

4.3.3 Data analyses

Statistics

The aggregation of daily rainfall data into different time intervals and the query of defined rainfall-induced events were performed using INSTAT+ software for Windows (Version 3.036, Statistical Services Centre, University of Reading, Reading, United Kingdom). Normal distribution of residuals of rainfall amount during these temporal classes and climate risks was checked by the Shapiro-Wilk test. The Wilcoxon signed-rank test was used to determine differences between the stations. Spearman's rank correlation analyses were conducted to examine relationships between events. Statistical tests were run in SPSS 19.0.0.1 (IBM Inc., New York, USA). The Mann-Kendall test was performed to determine monotonic trends using the VisualBasic macro MULTITEST (Version 6.1, Department of Computer and Information Science, Linköping University and Swedish Institute for the Marine Environment, Gothenburg University, Gothenburg, Sweden). This test is widely used for detecting trends in hydro-meteorological time series (Yue and Wang 2004). Serial correlations were examined according to Hirsch and Slack (1984) and Wahlin and Grimvall (2010). The Sen slope estimating the change per unit of time in linear trends were calculated following Wahlin and Grimvall (2010). Unless stated otherwise, results were regarded as statistically significant at a two-tailed significance level of $P \leq 0.05$.

Rainfall amount

Daily data were aggregated to monthly and yearly intervals. The average rainfall amount per rainy day was calculated by dividing the total amount of annual rainfall by the number of rainy days per year. For this and for the following analyses, only days with > 0.85 mm rainfall were used (Stern et al. 1981). Since for crop growth not only the average rainfall amount is important, but also the rainfall distribution, frequency analyses of daily rainfall size classes of > 0.85 to ≤ 3 mm, > 3 to ≤ 10 mm, > 10 to ≤ 20 mm, > 20 mm to ≤ 30 mm, etc. were conducted (Hoogmoed and Stroosnijder 1984; Lebel et al. 2000; Romero et al. 2007). To detect changes in the amount of rainfall, the number of rainy days and the number of daily rainfall size classes, data were tested for statistical significance over time (trend tests). In addition to the entire 60 year data set, trend tests were also conducted for the period of 1970 to 2009. This period was chosen since the 1950s and 1960s were characterized by extraordinary wet conditions in Kordofan and the entire Sahel (Eldredge et al. 1988; Trilsbach and Hulme 1984; Nicholson 2001) and thus the rainfall of the following years may reflect a relative decline. In view of this and to avoid misleading conclusions and risk statements, the period since 1970 may be more appropriate for the analyses of recent trends. Likewise, these periods were used for trend tests of the following rain-induced agricultural events.

Start and length of growing season

A successful start of the growing season for crops commonly cultivated in homegardens or fields such as eggplant, okra or sorghum requires not only a strong first rainfall, but also no extended dry spells (> 10 days) during the 30 days after seeding (Allen et al. 1998). Thus, the following definition for the start of the growing season was used: the first day of the year preceded by 1 to 2 days in which the accumulated rainfall is at least 20 mm and followed by 30 days without a period of > 10 consecutive days with rainfall ≤ 0.85 mm (Stern et al. 1982; Mupangwa et al. 2011).

The length of the growing season was defined as the number of days between the start of the growing season and the last day of the rainy season (Mugalavai et al. 2008; Mupangwa et al. 2011). Following Walsh et al. (1988) the latter was estimated by a simple water balance approach considering evapotranspiration, capacity of the soil to hold plant available water and rainfall. The evapotranspiration for an ideal reference crop resembling green grass of uniform height, actively growing and adequately watered (Allen et al. 1998) was calculated with the Penman-Monteith equation in INSTAT+ whereby the decline of evapotranspiration at lower soil water contents was accounted for. Required input data were delivered by the CLIMWAT 2.0 database (FAO, 2006). The soils' capacity to hold plant available water was derived by pedotransfer functions taking into account effective rooting depth, humus content and texture of six soil profiles examined near the meteorological station in Kadugli (10.97° N, 29.73° E). Applying the principle of prudence, sandy soils (Alfisols) from a typical rainfed cultivation area in the Nuba Mountains were used as a reference although in the likewise cultivated clay plains plant available water is likely to be higher. The last day of the rainy season was defined as the first day after the 1st of October, the last month of the main rainfall season in which the water balance dropped down to 0 mm.

Predictions about the possible length of the upcoming growing season are crucial not only for farmers to possibly reduce risks of unsuccessful cropping activities, but also for stakeholders such as disaster relief agencies or grain traders to assess the likelihood of food shortages and human tragedies. For this reason, the probability of an expected minimum length of growing season if the onset of rain is either early, normal or delayed was calculated by conditional analyses following the approach of Sivakumar et al. (1993).

High intensity rainfall events

Possible changes of high intensity (erosive) rainfall events were examined for the following indicators: the maximum daily rainfall for each year and the number of heavy rainfall events per year. The annual maximum day values were processed to estimate return periods according to Critchley and Siegert (1991) and Stern et al. (2006). Rainfall events were defined as highly intense, if the daily rainfall amount exceeded the 90th, 95th and 99th percentile of each station's complete data set (Nicholls and Murray 1999; Moonen et al. 2002; Sen Roy and Balling 2004).

Dry spells

Dry spells are periods of continuous non-rainy days (≤ 0.85 mm; Barron et al. 2003). To identify changes in dry spells over time, the number of dry spells of > 7, > 14 and > 21 days over the main season from May to October were considered. For frequency analyses, data were divided into following dry spell classes: 1 to ≤ 7 days, 8 to ≤ 14, 15 to ≤ 21 and > 21. Moreover, to calculate the probability of different dry spell incidences of different lengths within 30 days after specific dates, conditional analyses were conducted according to Sivakumar et al. (1993) which may trigger decisions in farmer’s cropping strategy.

4.4 Results

4.4.1 Rainfall amount

In Kadugli, annual rainfall from 1950 to 2009 averaged 698 mm (median: 690 mm) with a coefficient of variation (CV) of 20.6%. Both minimum and maximum annual rainfall occurred in the 1960s, with 457 mm rainfall in 1968 and 1,046 mm in 1964 (Figure 2a). For the period between 1970 and 2009 rainfall averaged 671 mm (median: 657 mm; CV: 19.6%). While both, a negative and a positive trend were observed over the 60-year period and from 1970 to 2009, respectively, these were not statistically significant (Figure 2a). In Rashad, annual rainfall averaged 711 mm (CV: 17.7%, median: 691 mm) over the 60 years ranging between 456 mm in 1987 and 1,042 mm in 1967 (Figure 2b). Between 1970 and 2009 the average rainfall was 669 mm (median: 647 mm; CV: 16.7%). In contrast to Kadugli, a negative trend ($P < 0.001$) of annual rainfall was noted for Rashad with a Sen slope of about -3 mm per year over the 60 year period; however, for the period between 1970 and 2009 no statistically significant trend was observed (Figure 2b). At the other four stations, data from 1950 to 1979 showed a decline in total rainfall for Heiban ($P = 0.003$, Sen slope: -12.2 mm per year), Kalogi ($P < 0.001$, Sen slope: -10.9 mm per year) and Umm Berembeita ($P = 0.037$, Sen slope: -4.6 mm per year), but not for Dilling.

Monthly values for both stations revealed that rainfall between May and October amounted to about 98% of average annual rainfall (Figure 3). Normally, rainfall peaks in August with an average of 159 mm in Kadugli and 179 mm in Rashad and abruptly declines thereafter (Figure 3). No statistically significant changes in the amount of monthly rainfall during the observed periods were detected for either station.

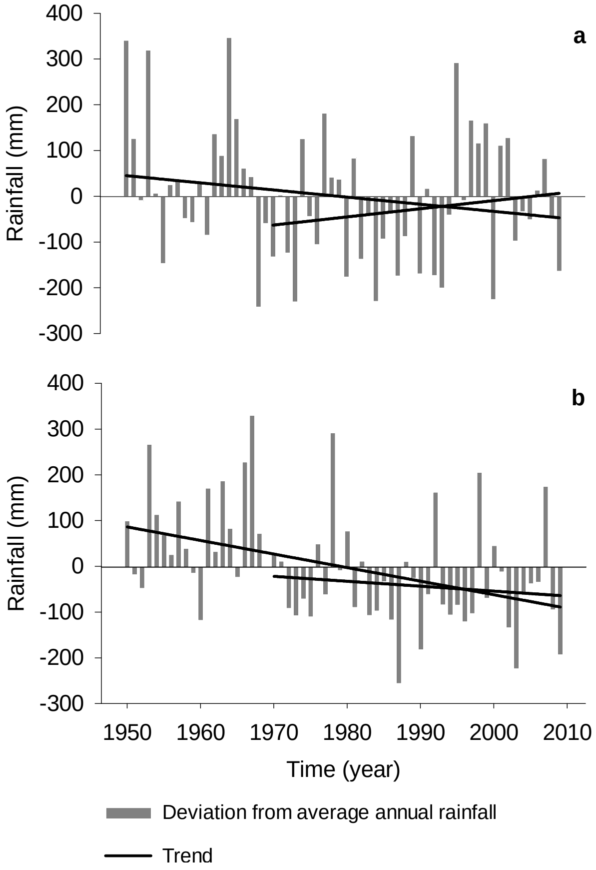

Figure 2. Annual ± deviation in mm from long-term average rainfall amounts in Kadugli (a; 60-years average: 698 mm) and Rashad (b; 60-years average: 711 mm), Nuba Mountains, Sudan, between 1950 and 2009. Only the monotonic trend for Rashad from 1950 to 2009 is statistically significant (P < 0.001, Sen slope: -3 mm / year).

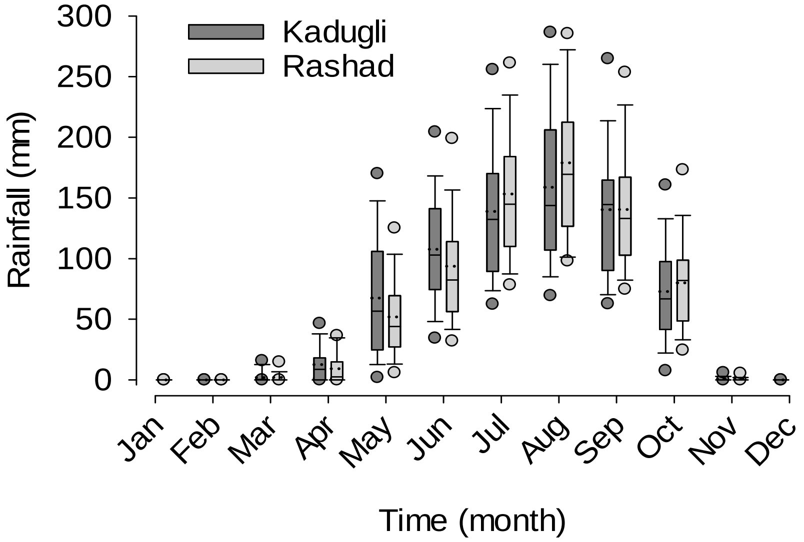

Figure 3. Monthly rainfall amount (mm) for Kadugli and Rashad, Nuba Mountains, Sudan, from 1950 to 2009. Dots represent the 5th and 95th percentile outliers, the dotted lines show the mean and the solid lines the median.

Results showed an average of 61 rainy days for Kadulgi (CV: 14.7%), one day more than for Rashad (60 days, CV: 15.2%), for both test periods. No significant statistically changes were observed for Kadugli (Figure 4a). However, data for Rashad indicated an increase in the number of rainy days between 1970 and 2009 (P = 0.030, Sen slope: 0.3 days per year; Figure 4b). Heiban and Kalogi experienced a decline of 2.5 and 1 rainy day(s) per year, respectively, during the first 30 years (Heiban: P < 0.001; Kalogi: P = 0.002).

Between 1950 and 2009 daily rainfall averaged 11.5 mm (CV: 19%) for Kadugli (Figure 4a) and 12 mm (CV: 20.4%) for Rashad (Figure 4b). For the period between 1970 and 2009, Kadugli showed a similar value for the average rainfall per day, while for Rashad the values amounted to 11.3 mm. The Kadugli data did not reveal any statistically significant change over the years; however, for Rashad results indicated a negative trend (P < 0.001) for the period from 1950 to 2009 with a Sen slope of -0.07 mm per year and a decline (P = 0.014) between 1970 and 2009 with an annual Sen slope of -0.08 mm.

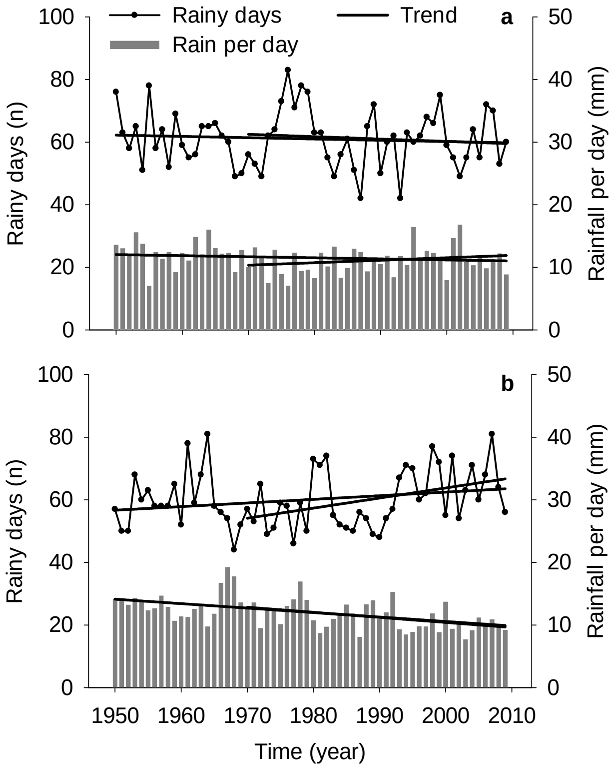

Figure 4. Annual number of rainy days and annual rainfall per day (mm) in Kadugli (a) and Rashad (b), Nuba Mountains, Sudan, between 1950 and 2009. Monotonic trends were only statistically significant in Rashad for the number of rainy days from 1970 to 2009 (P = 0.030, Sen slope: +0.31 events / year) and for the rainfall per day from 1950 to 2009 (P < 0.001, Sen slope: -0.07 mm / year) and from 1970 to 2009 (P = 0.014, Sen slope: -0.08 mm / year).

The frequency analyses of daily rainfall size classes showed that for both stations on average about one third of the total annual rainy days could be attributed to the rainfall size class > 0.85 to ≤ 3 mm (Table 1). For another third, amounts between > 3 and ≤ 10 mm could be observed and for the last third rainy days with > 10 mm were recorded. Differences between the period of 1950 to 2009 and 1970 to 2009 were observed for both stations particularly for the rainfall size classes of > 0.85 to ≤ 3 mm, > 3 to ≤ 10 mm and > 10 to ≤ 20 mm though they were not statistically significant. Considering the total dataset of 60 years rainfall events of > 20 and ≤ 30 mm occurred less frequently for Kadugli (average: 4.8 times per year) than for Rashad (average: 5.9 times per year; $P = 0.031$). An increase in the number of rainfall events of > 0.85 to ≤ 3 mm (Kadugli: $P = 0.008$, Sen slope: 0.16 days per year; Rashad: $P < 0.001$, Sen slope: 0.31 days per year; data not shown) was indicated by data from both stations over the entire 60 years. This positive trend was also observed for Rashad between 1970 and 2009 ($P = 0.008$, Sen slope: 0.38 days per year), but not for Kadugli. Besides this trend of more days with low daily rainfall, declines of medium daily rainfall size classes with up to 30 mm were observed for both stations during the entire 60 years (Kadugli: > 3 to ≤ 10 mm ($P = 0.013$, Sen slope: -0.13 days per year); Rashad: > 10 to ≤ 20 mm ($P < 0.001$, Sen slope: -0.11 days per year) and > 20 mm to ≤ 30 mm ($P = 0.041$, Sen slope: -0.04 days per year)). For Rashad such observations were only made for the daily rainfall size class of > 10 mm to ≤ 20 mm during 1970 to 2009 ($P = 0.027$, Sen slope: -0.10 days per year).

Table 1. Averaged frequency values (number of days, n) of daily rainfall size classes per year for Kadugli and Rashad, Sudan, based on data from 1950 to 2009 and from 1950 to 2009. Values in brackets represent the percentage related to total rainfall days.

Rainfall size classes (mm)		Total	0.85-3		>3-10		>10-20		>20-30		>30-40		>40-50		>50	
		n	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Kadugli	1950 - 2009	61.1	20.5	(34)	18.8	(31)	10.9	(18)	4.8	(8)	2.8	(5)	1.7	(3)	1.6	(3)
	1970 - 2009	61.1	23.4	(38)	16.7	(27)	10.3	(17)	4.8	(8)	2.7	(4)	1.7	(3)	1.6	(3)
Rashad	1950 - 2009	60.1	17.9	(30)	19.7	(33)	11.3	(19)	5.9	(10)	2.6	(4)	1.3	(2)	1.5	(2)
	1970 - 2009	60.4	20.9	(35)	18.8	(31)	10.3	(17)	5.3	(9)	2.3	(4)	1.4	(2)	1.4	(2)

4.4.2 Start and length of growing season

For both Kadugli and Rashad, the growing season started at the beginning of June (Table 2). The date of the successful onset of rain differed by about two days between the two stations ($P > 0.05$): the mean date was 5 June for Kadugli and 7 June for Rashad. However, the range of the earliest and latest start date was with

104 days larger for Kadugli than for Rashad with 84 days (Table 2). Furthermore, analyses revealed that failed sowings as a consequence of a dry spell shortly after the first high rainfall occurred on average every three years, with a slightly lower risk for Kadugli (28%) than for Rashad (35%; Figure 5). Neither a statistically significant shift in the start of the rainy season nor a change in the frequency of a failed start of the rainy season was detected for either station for any of the two tested periods (Figure 5).

In contrast to the wide range of start dates, the dates for the end of the growing season were spread over a shorter period (Kadugli: 5 November to 5 December; Rashad: 6 November to 5 December) whereas the average end date was the 21 November for both stations (Kadugli standard deviation (SD): 6.2 days; Rashad SD: 6.0 days; Table 2).

Table 2. Mean, minimum (earliest) and maximum (latest) dates for the start, end and the average length of the growing season in days for Kadugli and Rashad, Nuba Mountains, Sudan. Values in brackets show ± one standard deviation in days (n = 60).

Station	Start			End			Length
	Mean	Earliest	Latest	Mean	Earliest	Latest	
Kadugli	05.06. (22.3)	22.04.	04.08.	21.11. (6.2)	05.11.	05.12.	169 (24.2)
Rashad	07.06. (19.1)	02.05.	25.07.	21.11. (6.0)	06.11.	05.12.	167 (19.6)

The calculated average length of the growing season was 169 days (SD: 24.2) for Kadugli and 167 (SD: 19.6) for Rashad (Table 2). No statistically significant trends in the end date or length of the growing season were detected for either test period. Data from both stations showed no correlation between the start and the end of the growing season.

A practical implication of this correlation is that conditional analyses allow to calculate probabilities of specified minimum length of the growing season for different dates of the successful onset of the rains (Table 3). In general, the results showed that a delayed start of the rainy season reduced the chance of a given growing season length. For example if the rainy season started successfully in Kadugli on 29 May, the probability of the growing season exceeding 169 days is 87%. However, if the onset of rain is delayed until 12 June, the probability of this growing season length dropped to only 14%. Given the occasional very late onset of rains (Table 2) and the results of these conditional analyses, the drastic effects of such delayed events become evident: if the rain would start in mid-July the probability that the growing season exceeds 148 days amounted to almost 0%.

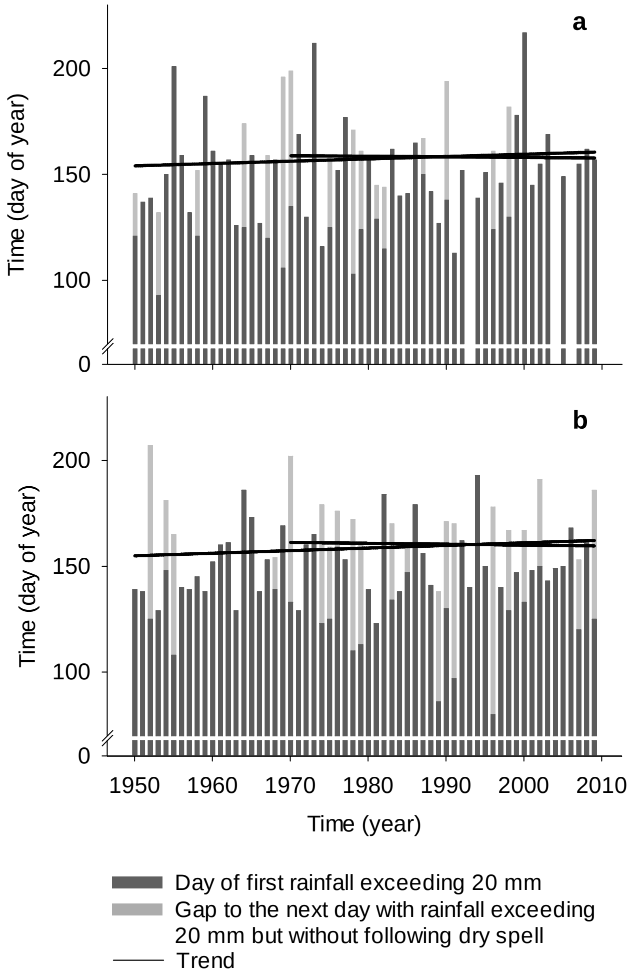

Figure 5. Annual successful or failed start of the rainy season in Kadugli (a) and Rashad (b), Nuba Mountains, Sudan, between 1950 and 2009. The successful start is defined by rainfall of 20 mm accumulated over 2 days without any dry spell of > 10 consecutive days within the subsequent 30 days. Monotonic trends for a successful start were not significant at $P \leq 0.05$.

Table 3. Probabilities (%) of specified minimum lengths of growing season for early, normal and latest dates of successful onset of rains at Kadugli (left) and Rashad (right), Nuba Mountains, Sudan. Bold prints indicate average values.

Onset of rain in Kadugli	Length of growing season (days) exceeding						
	148	155	162	**169**	176	183	190
15. May	100	100	100	100	99	87	51
22. May	100	100	100	99	87	51	14
29. May	100	100	99	87	51	14	1
05. Jun	100	99	87	50	13	1	0
12. Jun	99	87	51	14	1	0	0
19. Jun	87	51	14	1	0	0	0
26. Jun	51	14	1	0	0	0	0

Onset of rain in Rashad	Length of growing season (days) exceeding						
	146	153	160	**167**	174	181	188
17. May	100	100	100	100	99	88	50
24. May	100	100	100	99	88	50	12
31. May	100	100	99	88	50	12	1
07. Jun	100	99	88	50	12	1	0
14. Jun	99	88	50	12	1	0	0
21. Jun	88	50	12	1	0	0	0
28. Jun	50	12	1	0	0	0	0

4.4.3 High intensity rainfall events

The annual maximum daily rainfall observed over the entire data set for each station ranged from 41 mm in 1968 and 2009 to 176 mm in 1995 for Kadugli, and from 35 mm in 1987 to 125 mm in 1992 for Rashad. Daily rainfall events of about 40 mm occurred normally every year (Figure 6). Every five years values of about 75 mm and every 20 years rainfall amounts of about 100 mm were expected at both stations. Records of 176 and 125 mm had return periods of 120 years. No significant change of maxima values was detected for either station for both test periods.

The number of high intensity rainfall events was variable during the 60 years period (Figure 7). 90th percentile events (Kadugli: > 32 mm daily rainfall amount; Rashad: > 30 mm) occurred annually between 1 and 12 times for Kadugli and between 1 and 11 times for Rashad. Likewise, farmers at both sites should expect every year up to seven 95th percentile events (Kadugli: > 42.7 mm; Rashad: > 40 mm). However, 99th percentile events (Kadugli: > 67.4 mm; Rashad: > 65.2 mm) occurred biennially either never or up to twice per year for Kadugli and up to 3 times per year for Rashad. The number of high intensity rainfall events for each of the percentile levels for both stations revealed no significant trends for either station over the entire 60 years and over the period from 1970 to 2009 (Figure 7).

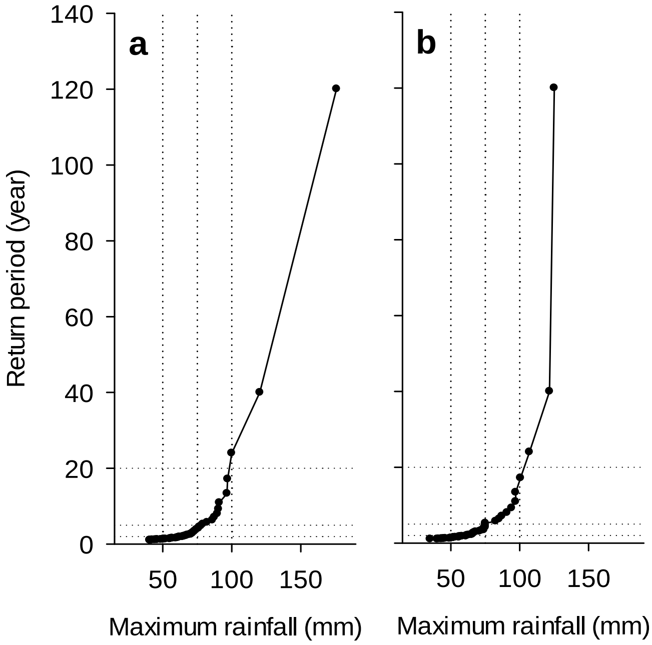

Figure 6. Return periods of maximum daily rainfall events for Kadugli (a) and Rashad (b), Nuba Mountains, Sudan, based on daily rainfall data from 1950 to 2009. X-reference lines represent the 2-, 5- and 20-years return period. Y-reference lines represent 50, 75 and 100 mm.

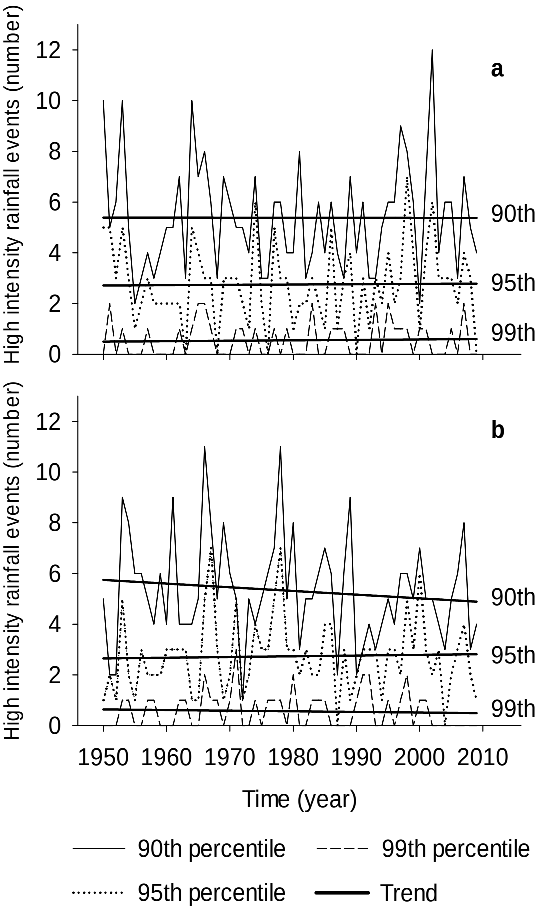

Figure 7. Annual number of high intensity daily rainfall events exceeding the 90th, 95th and 99th percentile of the entire daily rainfall records for Kadugli (a) and Rashad (b), Nuba Mountains, Sudan, between 1950 and 2009. Monotonic trends were not significant at P ≤ 0.05.

4.4.4 Dry spells

The analyses of the 60 year data set revealed that rainfed farmers in the surroundings of both stations face at least one and up to six dry spells per season exceeding one week (Table 4). Dry spells of > 14 days occurred at least once and up to three times for Kadugli in about 60% of the years, while for Rashad up to two dry spells were recorded in two of three years. At both stations dry periods of > 21 days are to be expected every fourth year. Such long dry spells occurred up to three times a year for Kadugli and up to twice a year for Rashad. The analyses of the period from 1970 to 2009 indicated the same incidence values, but frequencies differed up to 3% for Kadugli and up to 7.5% for Rashad compared with the 60 years data set (data not shown). The only trend observed was a decline in the number of dry spells of > 7 days in Kadugli from 1980 to 2009 (P = 0.006, Sen slope: -0.09 per year; data not shown). Exceptionally, trends for the last 30 years were calculated since, in contrast to the last 40 years, a relevant change was observed within this period that is of practical importance for present rainfed farming. Increases in the number of dry spells exceeding one week were observed during 1950 and 1979 for Heiban (P = 0.005) and Kalogi (P < 0.001), of spells of more than two weeks for Heiban (P = 0.006), and of spells of more than three weeks for Dilling (P = 0.023) and Heiban (P = 0.015).

Table 4. Minima (Min), maxima (Max) and average incidence (n) per year as well as frequencies in % of dry spell length classes for Kadugli and Rashad, Sudan, based on data from 1950 to 2009. Values in brackets represent the ± standard deviation (n=60).

Dry spell classes	Min	Max	Average		Frequency
	n	n	n		%
Kadugli					
>7	1	6	3.1	(1.5)	100
>14	0	3	0.8	(0.8)	57
>21	0	3	0.3	(0.6)	23
1 to <=7	18	45	35.1	(5.6)	100
8 to <=14	0	7	2.5	(1.6)	95
15 to <=21	0	2	0.6	(0.7)	45
>21	0	2	0.3	(0.5)	23
Rashad					
>7	1	6	3.4	(1.2)	100
>14	0	2	0.9	(0.7)	70
>21	0	2	0.3	(0.5)	25
1 to <=7	27	46	34.4	(4.4)	100
8 to <=14	0	5	2.5	(1.3)	93
15 to <=21	0	2	0.6	(0.6)	50
>21	0	2	0.3	(0.5)	25

The frequency analyses of different classes of dry spell lengths showed that in almost every year farmers should expect on average 2.5 dry spells lasting 8 to ≤ 14 days (Table 4). Up to two spells of 15 to ≤ 21 days may occur every second year near either station. Based on the 60 years data longer periods of no rainfall of > 0.85 mm were recorded up to two times at both stations every four years In comparison to the last 40 years, differences in frequency are negligible, but for the dry spell class of 15 to ≤ 21 in Rashad. This class showed a 12% lower frequency (38%) for the last 40 years. Additionally, for this location and dry spell class a negative trend (P = 0.008) during the main seasons from 1950 to 2009 were revealed, but not for the last 30 and 40 years (data not shown). Results for Kadugli showed a decline (P = 0.008, Sen slope: -0.11 per year) of 8 to ≤ 14 day dry spells restricted to the last 30 years (data not shown).

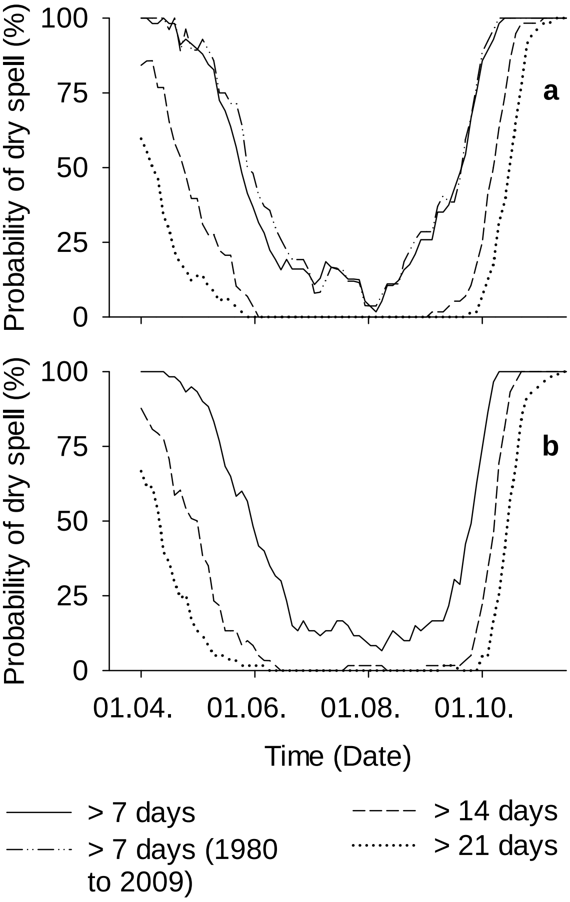

Figure 8. Probabilities of dry spells within 30 days after specific dates for Kadugli (a) and Rashad (b), Nuba Mountains, Sudan. The calculations are based on daily rainfall data from 1950 to 2009 with the exception of the curve of dry spells > 7 days (dashed/dotted line) which is based on data from 1980 to 2009.

The conditional analyses of the incidence of dry spells > 7, > 14 and > 21 days at specific dates between April and the end of September showed similar results for both stations (Figure 8). The chances for a dry spell of > 14 or > 21 days occurring 30 days after a specific date dropped strongly from 70 to 80% in April to 0% at the beginning of June and increased sharply up to 100% in October. However, a risk of a dry spell > 7 days existed throughout the year. The probability was 100% in the dry season (October-May) for both sites. From mid-June to mid-September, the probability ranged from 2 to 19% for Kadugli and from 7 to 23% for Rashad. The calculated risks of a dry spell > 7 days that based on data from 1980 to 2009, the period in which a significant decline in the number of such dry spells was observed, is similar to the risks based on the entire data set (Figure 8). Values calculated for this period differed numerically by an average of -2% (SD: 4.1; maximum: 16%; minimum: -6%) compared to results calculated for the 60 years period.

4.5 Discussion

4.5.1 Rainfall amount

Following the prevailing climatic circulation patterns over Africa, the spatial distribution of rainfall in Sudan shows a decline from south to north, partly modified by the topographic relief (Hulme 1990; Nicholson 2000). Due to the latter, the average annual rainfall calculated for the different test periods of our data set for Rashad is similar than for Kadugli, even though the former is located further north. The orographic position may also be the reason for the lower CV in Rashad for the period from 1970 to 2009 since rainfall is typically more reliable at higher altitudes and on windward slopes. The CV of both stations is comparable with stations in similar African climatic regions and for this part of Sudan (Bunting et al. 1976; Osman and Shamseldin 2002).

In contrast to Kadugli, where no change of total rainfall was observed for either period, contradictory trends were revealed for Rashad. The observed negative rainfall trend of about -3 mm per year since the 1950s may lead to an assumption of a 180 mm decline in total annual rainfall. However, this putative decline may largely result from the extraordinary wet period between 1950 and the end of the 1960s (Trilsbach and Hulme 1984; Eldredge et al. 1988; Nicholson 2001) which led to a relative decline of rainfall in the following years. This decline is indicated by the observed lower average amount of annual rainfall in the latest period for either station compared to the wet period and by the observed negative rainfall trends for Heiban, Kalogi and Umm Berembeita between 1950 and 1979. For this reason, the additional consideration of the period between 1970 and 2009, which shows no trend for Rashad, may be more reliable and relevant to reveal the rainfall development of the present and near future and helps to avoid misleading recommendations for the rainfed agricultural sector. The use of different trend models, which seem appropriate given different time periods, underscores the importance of period selection and necessary attention to extrapolate results into the future. The latter is particularly the case if data sets include only single periods such as the rainfall records from 1950 to 1979 of our four stations. Negative Sen slopes of -12.2 mm per year as observed for instance for Heiban, should not consequently lead to an assumption of a total decline of 366 mm during the last 30 years. Since observations of annual total rainfall records did not show a clear trend, the breakdown into its constituent parts may facilitate a more meaningful analysis.

The rainfall pattern in Sudan over the months is largely governed by the seasonal meridional migration of the Intertropical Convergence Zone (ITCZ) likely modified by the African and Tropical Easterly Jets (Nicholson 2008; Nicholson 2009). Following the sun’s zenith point, the northward shift of the ITCZ leads to heavy rainfall in the Nuba Mountains with a peak in August, when the discontinuity reaches its most northerly position between 18 and 20°N (Trilsbach and Hulme 1984; El Gamri et al. 2009). The southward retreat of the ITCZ begins in September and is much faster than the northward movement resulting in the abrupt decline of rainfall within two months after peaking in August (Figure 3). Since monthly rainfall did not change at either station in both test periods, a similar distribution of rainfall over the year may be assumed in the near future.

The assumed decline of total rainfall in Rashad between 1950 and 2009 could be attributed to the observed decline in the amount of rainfall per day by in total -4.2 mm (intensity) rather than to a reduction in the number of rainy days (frequency). More specifically, the overall reduction may be explained by a shift in the number of medium rainfall days (total decline of > 10 to ≤ 20 mm class by -6.6 days and of > 20 mm to ≤ 30 mm class by -2.4 days) to days with low rainfall (total increase of > 0.85 to ≤ 3 mm class by 18.6 days). An increase in the number of low rainfall days was also observed for Kadugli during this period (total increase of > 0.85 to ≤ 3 mm class by 9.6 events), but this shift was insufficient to yield a significant annual rainfall decline over the 60 year study period. This is in contrast to reports that described a reduction of rainfall primarily related to a decline in the number of rainy days in the Sudan (Eldredge et al. 1988; Hulme 1990), though this was observed for Heiban and Kalogi for the period between 1950 and 1979. The revealed total increase of rainy days by 12 days in Rashad between 1970 and 2009 did not result in an increase of annual rainfall over this period since at the same time daily rainfall declined by 3.2 mm. This is supported by the observed increase of low rainfall events (> 0.85 to ≤ 3 mm) by 15 days and decrease in the number of medium rainfall classes (> 10 mm to ≤ 20 mm) by 4 days during this period.

In summary, for Kadugli no shift of annual and monthly rainfall amount, rainy days and rainfall per day were found for the recent period between 1970 and 2009. Likewise no change in annual rainfall was observed in Rashad, but the number of rainfall events increased which coincided with a decline of rainfall per day triggered by a rise of low and a decrease of medium rainfall events. In particular the increase of low rainfall days may raises concern since such events do not have importance in the water balance and may hamper farmers' crop production (Romero et al. 2007; Stroosnijder and Hoogmoed 1984). This might be in particular the case in homegarden systems with their partly cultivation of highly water demanding cash crops such as tomatoes (*Solanum lycopersicum* L.) or rocket (*Eruca sativa* Mill. Thellung). Soil surface management practices such as leveling, stone bunds on slopes, earth bunds or conservation (reduced) tillage may be low-cost options to use water more efficiently, and thus to mitigate possible deficits in the water balance (Critchley and Siegert 1991).

4.5.2 Start and length of growing season

The start of the rainy season and subsequently of the growing period both depend on the timing of the annual northward shift of the ITCZ (Nicholson 2008; El Gamri et al. 2009; Nicholson 2009). Since the meridional distance between the stations is only about 100 km, the difference of the mean starting date is only two days. The higher frequency of failed starts of the growing season in Rashad may be related to the higher number of rainfall events between > 20 and ≤ 30 mm. These fulfill the first of our criteria for the start of a growing season, but not the second one (30 days without a > 10-day dry spell). For the same period, the threshold for the successful start of a growing season was more often exceeded in Rashad than in Kadugli, though no statistically significant differences in the number of rainy days nor in the frequency of dry spells were observed. The relative small range of growing season ends may be related to the rapid southward movement of the ITCZ in East Africa. The shorter length of growing season in Rashad compared to Kadugli is the result of the northernmore location of this station and, thus, the shorter influence of air masses south of the ITCZ. In general, the season length is at the upper limit typical for this region (Nicholson 1980).

No correlation between the start and the end of the growing season was observed for Kadugli and Rashad which severely hampers seasonal forecasting. Conditional analyses thus allow to develop adapted risk management strategies for this specific region. Famers may lower risks of reduced crop yields by selecting appropriate varieties or choosing an alternative crop that both reach maturity within the probable length of the growing season (Sivakumar 1988; Cooper et al. 2008; Abdalla and Gamar 2011). Disaster relief agencies and policy makers could improve their risk assessment on lower crop yields and food supply, respectively, as a consequence of an early warning about an approaching short growing season length. Since no statistically significant changes for the onset of rain and the length of growing season were detected for all considered periods, these probability calculations seem to be reliable for the next years.

4.5.3 High intensity rainfall events

Maximum daily rainfall events of > 100 mm were very rare. However, several reports documented strong rainfall events such as in 1988 and 1999 north of the Nuba Mountains with estimated return periods of 400 to 700 years (Sutcliffe et al. 1989; Andah and Siccardi 1991; Williams and Nottage 2006). In this context, our calculated return periods seem plausible; nonetheless, they should be interpreted with caution since the observation period is much lower than the return period.

The annual incidences of high intensity rainfalls with more than 30 mm per day underscore the permanent risk of soil erosion in the Nuba Mountains. This affects particularly the cultivated area of the sloped pediments where above mentioned soil surface management practices may be recommendable to reduce topsoil losses. Partially practiced intercropping of sorghum or maize with cover crops such as cowpea (*Vigna unguiculata* (L.) Walp.) or pumpkin (*Cucurbita* spec.) in fields of smallholders and homegardens are a good example for another effective technique against runoff and soil erosion (Zougmorea et al. 2000).

Even though the annual rainfall amount and the average rainfall amount per day declined in Rashad during some of the test periods, there was no statistically significant change in the number of high intensity rainfall events per year exceeding the 90^{th}, 95^{th} and 99^{th} percentile. Rather the observed changes of rainfall amount may be attributed to an increase in the number of low daily rainfall size classes and a decrease in the number of other daily rainfall size classes.

4.5.4 Dry spells

The high probability of having years with extended dry spells makes cropping risky in the Nuba Mountains and illustrates the general need of drought resistant crop varieties and/or water retentive / efficient field management. The observed decline in the number of dry spells > 7 days by -2.7 events in Kadugli within the last 30 years, but not of those of > 14 or > 21 days, was reflected in a decline of the number of dry spells lasting 8 to ≤ 14 days by -3.2 events for the same period rather than in longer dry spells classes. In principle, such decrease in the frequency of dry spells may be explained by a significant increase in the amount of annual rainfall or the number of rainy days, however, this was not observed for Kadugli in our study.

The change in the number of dry spells lasting 8 to ≤ 14 days rather may be attributed to the statistically non-significant increase in the frequency of dry spell in the other classes. For Kadugli, the number of dry spells of ≤ 7 days increased by 6.5 events in the last 30 years, while for Rashad, where the frequency of dry spells lasting 15 to ≤ 21 days decreased during 1950 and 2009, dry spells between 8 to ≤ 14 and > 21 days increased. However, for the latter these changes could not be observed during the last 30 or 40 years and thus may have no practical importance for the surrounding of this station nowadays. An increase in the frequency of dry spells in Dilling, Heiban and Kalogi of up to 5.7 events was detected for the first 30 years of observation, a period which coincided with an intense drought in the 1970s after the wet two decades before (Trilsbach and Hulme 1984; Elagib and Elhag 2011). The cases of Rashad and the three other stations highlight the importance of the choice of interval into which events are grouped for the analysis and interpretation of rainfall related data. Possible causes for the observed shift of the lengths of dry spells are speculative and thus not further elaborated.

The risk of dry spells within the first 30 days after sowing declines with the progress of the rainy season from May to September. The strong increase around the beginning of October coincides with the rapid retreat of the ITCZ. The analyses underline the constant risk of dry spells, in particular of spells exceeding 7 days that potentially hamper initial growth of water demanding cash crops occasionally cultivated in homegardens. Since the frequency of dry spells of > 7 days significantly declines in Kadugli between 1980 and 2009, the probability for this dry spell length should be handled with caution. However, described differences between percentages for this period and values for the entire dataset of 60 years were negligible. Dry spells at sensitive crop development stages can strongly affect plant growth and final yield (Barron et al. 2003; Assefa et al. 2010). For this reason, information about the probability of occurring dry spells lengths related to specific dates and crop growth stages, respectively, should guide management decisions. Such management decision might affect the timing of groundnut harvest since hardened surface soils as result of dry periods makes this process difficult (Sivakumar 1992). Due to the absence of significant changes within the considered periods, with the exception of the number of dry spells >7 days in Kadugli which, however, did not change the risks substantially, our risk calculations for the probability of dry spells within 30 days after specific dates therefore seem to be useful.

4.6 Conclusions

Our analyses indicate that the use of long-term daily rainfall data allow the identification of changes in rainfall amounts and rainfall-induced agricultural events for two sites in the Nuba Mountains. A decline in the amount of annual rainfall was identified for Rashad over the last 60 years; however, this trend was not evident for the period 1970 to 2009. The results emphasize the importance of interval selection and necessary caution to extrapolate detected trends into the future. The observed increase of low rainfall events in Rashad during the last 40 years raises concern since they do not contribute to the crop water balance and may hamper rainfed farmers' crop production in the climatically vulnerable Nuba Mountain region.

Furthermore, rainfall-induced agricultural events showed either no statistically significant changes or trends resulting only in minor changes of probabilities. For this reason, presented probability calculations based on the entire dataset such as the conditional analyses for the estimation of probabilities for growing season lengths and dry spell lengths related to specific dates could be considered as reliable. These risk statements may be useful for farmers and stakeholders for the next few years to make informed decisions to reduce the rainfall-induced risks to agriculture in the climatically vulnerable Nuba Mountain region.

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Chapter 5

General discussion and conclusions

5.1 Review of the method for the quantification of soil gaseous emissions

For the quantification of the gaseous emissions carbon (C) and nitrogen (N) in form of CO_2, NH_3 and N_2O a portable dynamic closed chamber system was used in the homegardens of the Nuba Mountains (chapter 2). The system consisted of a photo-acoustic multi-gas field monitor operated with a car battery (INNOVA 1312-5, Lumasense TechnologiesA/S, Balerup, Denmark) and a polytetrafluoroethylene (PTFE) coated chamber which were connected by PTFE tubes (Christensen 1990a, b; Buerkert et al. 2010; Predotova et al. 2010; Siegfried et al. 2011). This set-up has already been used in previous studies under different field conditions and proved again its functionality (Buerkert et al. 2010; Predotova et al. 2011; Siegfried et al. 2011). The system allows rapid (< 5 to 6 minutes) *in situ* measurements of the concentrations of multiple emitted soil gases that can be directly checked on the display. In the present case the quick measurements and the easily portable set-up allowed to take a high number of replicate measurements within and across plots resulting in an increased statistical power and a sampling design which accounted for the high spatial and temporal heterogeneity of gaseous emissions from the soil (Velthof and Oenema 1995; Tang and Baldocchi 2005; Sey et al. 2008). At the same time, negative effects of long chamber closure time on microclimate and gas diffusion were avoided (Livingston and Hutchinson 1995; Davidson et al. 2002). The field monitor is able to quantify five different gases within one measurement according to the used filters (Christensen 1990b). Thereby the monitor automatically compensates for cross-interference between gases and water vapor interference (Christensen 1990a). In particular the latter feature was important to obtain reliable emission data under the humid climate conditions in the Nuba Mountains during the rainy season and the high relative humidity values in a closed chamber system, respectively. However, the precision and accuracy of the data measured by the photo-acoustic multi-gas field monitor are subject of recent discussions. While gas concentrations measured by a gas chromatograph and by a photo-acoustic monitor in a laboratory environment were comparable (Iqbal et al. 2013), measurements of gas samples of known concentration by photo-acoustic field monitors showed for instance overestimations of up to 364% for $CH_{4,}$ underestimations of up to -16% for $N_2O_,$ but acceptable deviations ranging from 1% to -4% for CO_2 (Rosenstock et al. 2013). Since the number of comparative studies is low and causes for deviations are still unclear, such contradictory results call for further research. However, CH_4 and N_2O emissions are substantial lower under the prevailing water filled pore space of the homegardens' topsoil (maximum 78% at the peak of rainy season) compared to flux rates of CO_2 and NH_3. For this reason, the measurement deviation of these gases is relatively less important for the assessment of C and nutrient fluxes and balances than for greenhouse gas studies.

An alternative analytical method for measuring soil gases in a closed chamber system is gas chromatography. This conventional method enables simultaneous analysis of several gas species by the use of different detectors. A significant disadvantage of gas chromatography is the usually stationary set-up of this system which allows only *ex situ* measurements of soil gas concentrations. This makes measurements logistically more complicated, in particular if experiments are conducted in remote areas such as the Nuba Mountains. Gas samples have to be taken from the chambers on the plots by syringes into pre-evacuated glass vials or gas bags, which first have to be transported to the sampling location, adequately stored after sampling and transported back to the laboratory for analyses. In the laboratory, this method requires a comparably high amount of work, analysis and maintenance costs, and time input per measurement compared to the photo-acoustic method (Iqbal et al. 2013). Beside gas chromatography and infrared spectrometry, an alternative analytical method to determine soil gas concentrations that combine rapid *in situ* measurements with high precision and accuracy (interference free) is the tuneable diode laser absorption spectroscopy which is operating in the near infrared range. However, such analyzers as for instance the ultra-portable greenhouse gas (CH_4, CO_2, H_2O) analyzer (Los Gatos Research, Mountain View, CA, USA) are limited by the number of gas species that can be measured simultaneously. Moreover, the portable laser systems still have to proof their reliability in the field.

The approach of using a chamber to estimate soil gaseous emissions implies inevitably errors mainly caused by perturbations of microclimate and soil gas diffusion (Rochette and Hutchinson 2005) which can be minimized by suitable chamber designs and optimum measurement protocols (Livingston and Hutchinson 1995; Rochette and Hutchinson 2005; de Klein and Harvey 2012). An alternative approach which causes less soil and climatic interferences is the eddy correlation flux estimation using tower-based micrometeorological techniques. This technique integrates fluxes over large areas and is thus able to overcome errors in flux measurements caused by the small-scale spatial heterogeneity of soil gaseous emissions. Measurements are continuous, interrupted only by calm or maintenance periods (Baldocchi et al. 1988). However, this method is much more costly than chamber techniques, requires uniform and extensive areas and is not able to separate sources and sinks of soil gases over the measured surface (Norman et al. 1992; Yamulki and Jarvis 1999; Fowler et al. 2001; Neftel et al. 2006). Such restrictions make the micrometeorological technique recommendable for net ecosystem fluxes, but inadequate to assess gaseous emissions from homegardens in the Nuba Mountains due the horizontal heterogeneity of these systems and their surroundings (settlements) as well as their relatively small size.

In conclusion, despite the ongoing discussion on its precision and accuracy, the photo-acoustic multi-gas field monitor connected to a closed chamber seems to be the most adequate method at present for measurements of soil gaseous emissions in remote areas such as the Nuba Mountains where technical and logistical possibilities are strongly limited. However, calibration runs are strongly recommended before and after field use. In addition to that, the target-actual comparison of the calibration after field use (deviation of known gas concentration to values measured by the monitor) should be published together with the results to allow proper assessment of data reliability.

5.2 Review of methods for the quantification of carbon and nutrient fluxes

Carbon and nutrient balance calculations represent a useful and widely accepted approach to delineate soil fertility changes of agricultural systems and thus serve as an indicator for its sustainable use (Stoorvogel and Smaling 1990; Smaling et al. 1993; Stoorvogel et al. 1993; Van den Bosch et al. 1998; Bindraban et al. 2000; Roy et al. 2003; Cobo et al. 2010). Most nutrient balance studies focus on the macronutrients N, P and K, as it is the case in this thesis. However, plant growth is determined by the most limiting nutrient which could be a micronutrient. This is in particular true for agricultural systems with a high input of mineral fertilizers that consist mostly of combinations of only N, P and K and may lead to a surplus of macro- and a deficiency of micronutrients (Roy et al. 2003). Homegardens in the Nuba Mountains are comparably low input systems where mineral fertilizer plays only a minor role (chapter 3). Nonetheless, shortages of micronutrients may occur since the soil texture of these horticultural systems is quite coarse (sandy loam to loamy sand). For this reason, mobile micronutrients, e.g. molybdenum and boron which are essential for instance for the nodulation and seed development of groundnuts (Gad et al. 2012), are likely to leach in particular during the rainy season or in the year-round irrigated commercial gardens.

Carbon and nutrient balances summarize input and output flows from a spatially predefined system ranging from a micro- (e.g. plot or farm) to a macro-scale (e.g. nation or continent) over a defined time period (e.g. season or year; Scoones and Toulmin 1998; Roy et al. 2003). During the process of balancing, a wide range of possible errors and biases exists as classified and discussed by Oenema et al. (2003). Beside possible sampling and measurement errors and biases, respectively, significant over- or underestimations in the C and nutrient balances presented in this thesis may exist since some fluxes that are likely to transport elements were not sampled due to cultural and methodological constraints. According to the empirical knowledge, this comprises flows in particular through erosion including deposition, human excrements, and livestock urine. While exposed roots and building foundations in the study village seem to reflect past erosion events, recent significant erosion processes were observed on the pediments of the Nuba Mountains during the rainy season peak in August 2010. During intense rainfall events substantial amounts of soil particles were transported not only out of some observation plots, but also into plots that were located at lower altitudes of the pediment (deposition), likely leading to substantial losses (or gains) of elements (Bationo et al. 1998; Wortmann and Kaizzi 1998). For the direct quantification of erosion processes erosion pins, profile meters or catchpits are recommendable (Hudson 1993). However, the implementation of such methods is difficult as agricultural activities in the homegardens prevent reliable measurements of the soil surface level. The small extent of the homegardens makes adequate installations of volumetric measurement devices difficult since high potential storage capacities of runoff collectors are needed (Hudson 1993). Furthermore, reliable measurements of erosion require long-term trials given the slow nature of this process and the low frequency of intense rainfall events triggering strong erosion. A further potentially substantial input of elements which was not considered due to methodological difficulties is the influx of N and K through urine of corralled or roaming livestock (Buerkert et al. 2012). However, while dropped faeces could be collected easily from the surface of the observation plots, quantitative field measurements of urine are methodologically difficult and would require trace techniques. Possible estimations require observations which are not available for the present study. As shown by Buerkert et al. (2005) human faeces contributed substantially to the total nutrient input in mountain oases of Oman. This is also very likely the case in the homegarden systems in the Nuba Mountains as the gardens are located in direct vicinity to households and some households do not own toilet facilities. However, the quantification or estimation of element inputs via human excrements is difficult due to cultural constraints and was therefore not determined.

Beside the selection of relevant input and output fluxes, also the choice of an adequate length of the observation period is important since C and nutrient fluxes and balance calculations vary with time (Scoones and Toulmin 1998; Roy et al. 2003). Such temporal dynamics have biophysical and socio-economic reasons and have a strong impact on the soil nutrient pool of homegardens. Rainfall for instance showed a strong inter-annual variation in the Nuba Mountains (chapter 4). This variation is not only affecting the quantity of C and nutrient input through rainfall and reduced or increased irrigation activities, but also the output of elements since rainfall is likely to trigger mineralization and subsequent soil gaseous emission and leaching (chapter 2 and 3). Likewise, the number of livestock whose manure input plays a significant role for the maintenance of soil fertility in homegardens (chapter 3) underlies fluctuations within and between years as it is affected by dry spells (e.g. movement of livestock to better pastures) and drought events (e.g. death or slaughtering of livestock). In addition to these biophysical also various socio-economic causes affect fluxes in homegardens. These comprise for example temporary absence of the gardener such as participation in social events (marriages, bereavements) and illness (in particular malaria) that reduce gardening activities and thus affect the flow of carbon and nutrients. Other occasional events such as cattle theft led some gardeners to the decision to keep their cattle within the garden overnight, resulting in a strong increase of manure input. Resurgence of armed conflicts in the Nuba Mountains during the last decades induced many gardeners to translocate food production (in particular cereals) frequently to the homegardens due to insecurity on fields outside of the villages (Pantuliano et al. 2007). Change of crops as a consequence of this translocation is likely to affect management practices and thus C and nutrient balances. The effects of these examples on matter fluxes are difficult to account for if studies, such as the present one, are restricted to a season or a year. In view of this, continuous monitoring of input and output fluxes over several years would be recommendable to better cover occasional biophysical and socio-economic events.

In conclusion, the quantification of carbon and nutrient balances was a feasible and appropriate tool to capture changes in soil fertility of the homegardens in the Nuba Mountains. However, the short-term assessments of one season allow only a snap-shot that does not taken into account long-term dynamics of soil fertility. In addition, due to the described constraints the present balancing model may not comprise all major input and output fluxes in homegardens, which may lead to a distorted picture of changes of the C and nutrient soil pool in this system. Moreover, in homegardens of the Nuba Mountains soil fertility is likely to be limited by micronutrients as a result of the coarse texture of the pediment soils in combination with high rainfall and irrigation amounts. In view of this, longer-term trials are strongly recommended which consider further assumed substantial input and output fluxes as well as micronutrients.

5.3 Review of methods for the assessment of changes in rainfall amounts and rainfall-induced agricultural events

The approach for the assessment of daily rainfall data based on the calculation of monotonic linear trends to detect changes in the rainfall amount and rainfall-induced events (chapter 4). Compared to non-linear trend estimations, the advantage of this approach is that it provides a definite result of a data decline or increase over time in form of a single slope. This enables the formulation of a clear trend statement including information about the change in the observed variable per unit of time which is particularly important for studies aiming at providing relevant and reliable forecasts, e.g. for development NGOs or policy makers. However, the approach implies the risk of misinterpretations since linear trends do not reproduce long-term fluctuations like, for instance, the calculation of moving averages. This is clearly illustrated by the dataset used in this study, which comprises a wet period during the first two decades (1950 to 1969) and a drier period during the last 40 years (1970 to 2009). Without the consideration of the wet period a statistically significant decline of rainfall during the entire 60 years could be observed. However, once this anomalous rainy period was excluded, no change of rainfall for the last four decades was observed. This shows that, depending on the considered period, different results are obtained that may lead to two different recommendations to rain-fed farmers or other stakeholders as for example: ‘*Change to short-season crops*’ in case of a decreasing precipitation trend and ‘*Stay with your cropping system*’ in case of no change.

For the processing of the daily rainfall data the free downloadable statistics package INSTAT+ software for Windows (Version 3.036, Statistical Services Centre, University of Reading, Reading, United Kingdom) was used. This easy-to-use software includes an add-on function that facilitates the analysis of climatic data, particularly the identification of specific events (Stern et al. 2006). Identified events for each year were subsequently tested for changes over time by the VisualBasic macro MULTITEST running in Excel (Version 6.1, Department of Computer and Information Science, Linköping University, and Swedish Institute for the Marine Environment, Gothenburg University, Gothenburg, Sweden). This program enables an user-friendly computation of Mann-Kendall tests for the determination of monotonic trends including the consideration of serial correlations and the calculation of Sen slopes (Wahlin and Grimvall 2010). One of the most common techniques for determining trends is the linear regression method which is mainly characterized by its sensitiveness to outliers and its reliance on a normal distribution of values. However, rainfall data are commonly not in accordance with a Gaussian distribution curve and are characterized by data gaps, and, as typical for the semi-arid areas of sub-Saharan Africa, by frequent outliers and long-term fluctuations. For such data sets, the nonparametric Mann-Kendall test is highly suitable since it does not rely on a specific distribution curve, is relatively unaffected by skewed data, tolerates missing values, and calculates with relative values or ranks and thus does not overvalue extreme values (Yue and Wang 2004). A disadvantage of this trend test is its sensitivity to serial correlation which may decline the quality of the results (Yue et al. 2002; Yue and Wang 2004). The present work (chapter 4) buffers this disadvantage by adjusting the dataset according to Hirsch and Slack (1984) and Wahlin and Grimvall (2010) during the calculations in MULTITEST. Beside the Mann-Kendall-statistic and its statistical significance, MULTITEST provides the slope of the linear trend. The latter is calculated by the Theil-Sen-Estimator (Sen slope) which is commonly used in combination with Mann-Kendall tests. The Sen slope represents the median of slopes calculated for every possible pair of variates within the observed time period. Compared to the linear regression, this method is more robust against outliers.

In view of this, the Mann-Kendall test in combination with the Sen slope provides a useful method to assess changes in rainfall data which enables clear trend statements for the rain-fed farming sector and its stakeholders. However, anomalous rainfall periods should be taken into account during calculations to avoid misinterpretations and thus misleading recommendations.

5.4 Conclusions and recommendations

Homegardens in the Nuba Mountains are exposed to transformation processes in form of intensification with the goal of generating additional household income. As shown for other regions, intensification of gardens may jeopardize the sustainability of these systems, in particular in terms of soil fertility and negative environmental impacts. Therefore effects of these processes should be analyzed and addressed. The results of this study allow to conclude that:

- The mostly negative C, N, P and K balances in intensified and traditional homegarden systems alike may result in a long-term decline of crop yields.
- Although intensified homegardens receive a higher total input of C and macronutrients as compared to traditional gardens, the intensification is still at a low level.
- In contrast to the initial hypothesis, no substantial leaching losses were detected. However, the considerable element losses through soil gaseous emission support the proposed significance of this pathway of loss in semiarid areas.
- Since rainfall in the study year exceeded the long-term average, the estimation of element exports through weeding and harvest as well as through leaching and gaseous emissions must not be based on data from this exceptional year (rainfall above long-term average) only.

Long-term daily rainfall data enabled the analyses of changes and calculation of probabilities and risks of rainfall amounts and rainfall-induced agricultural events for two stations in the Nuba Mountains. The results of this study allow to conclude that:

- Different trends in the amount of annual rainfall for the two tested periods in Rashad (1950 to 2009: decline; 1970 to 2009: no trend) emphasize the importance of interval selection and necessary caution to extrapolate detected trends into the future.
- The increase of low daily rainfall events with a concurrently decline of medium rainfall events in Rashad rises concerns because they do not contribute to the crop water balance and may hamper rainfed farmers’ crop production.
- Since no significant trends in the annual and monthly amount of rainfall and rainfall-induced agricultural events were detected during the last 40 years,

presented probability and risk calculations could be considered as reliable for the present and the near future.

The following recommendations and remarks can be given:

- The transformation process of homegardens seems to be at an early stage and is not yet wide-spread. For this reason, researchers and extension services have the opportunity to take part in these processes.
- The reuse of exported weeds and plant residues after composting may help to balance the disequilibrium of C and nutrient budgets in both homegarden types.
- The reduction of soil gaseous emissions would decrease particularly C losses. This could be achieved e.g. by the incorporation of manure into the topsoil directly after application or by prevention of excessive soil wetness e.g. through opening of earth bunds after heavy rainfalls. In the long-term, intensive organic matter recycling e.g. by use of the composted weeds and plant residues would be advisable to increase the infiltration capability.
- A long-term monitoring of C, N, P and K fluxes in homegardens is encouraged to cover dynamics of soil fertility. This monitoring should consider micronutrients and the additional flows discussed above as well.
- Stakeholders focusing rain-fed farming (development NGOs, disaster relief agencies, policy makers, etc.) are encouraged to make use of easy-to-use software such as INSTAT+ for the analyses of daily rainfall data. Such analyses allow to develop profound concepts to reduce rainfall-induced calamities to rain-fed agriculture and food production.

5.5 References

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Affidavit

I assure that this dissertation was written independently and without non-permissible help and that I used no sources other than those specified in the dissertation. All quotations that have been extracted from published or unpublished sources have been marked as such. No part of this work has been used in other PhD processes.

Hiermit versichere ich, dass ich die vorliegende Dissertation selbstständig und ohne unerlaubte Hilfe angefertigt und andere als die in der Dissertation angegebenen Hilfsmittel nicht genutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten oder unveröffentlichten Schriften entnommen sind, habe ich als solche kenntlich gemacht. Kein Teil dieser Arbeit ist in einem anderen Promotions- oder Habilitationsverfahren verwendet worden.

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