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J. Luther-Mosebach

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Soil carbon stocks and dynamics in soils of the Okavango catchment



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Soil carbon stocks and dynamics in soils of the Okavango catchment

Dissertation

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submitted by

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Department of Earth Sciences UNIVERSITÄT HAMBURG

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CONTENT

1	Ge	General introduction & objectives1						
	1.1	Objectives of the study						
	1.2	Chapter overview & author contributions						
2	Stu	ıdy s	ites	7				
	2.1 Cusseque: Northern part of the catchment in the highlands of Bié							
	2.2	Caiu	undo: Central part of the catchment in the lowlands of southeast Angola	10				
	2.3	Mas	hare: Southern part of the catchment in the lowlands of north-east Namibia	12				
	2.4	Ser	onga: Southern part of the catchment at the Panhandle in north-east Botswana.	14				
3	Ma	teria	I & methods	17				
	3.1	Soil	sampling	17				
	3.2	Soil	chemical analysis	17				
	3.3	Soil	physical analysis	18				
	3.3	.1	Bulk density and soil texture	18				
	3.3	.2	Diffusion properties	18				
	3.3	.3	Flux estimation	20				
	3.4	4 Soil microbial parameters and carbon fractions						
	3.4	.1	Microbial biomass C and N	21				
	3.4	.2	Soil incubation	22				
	3.4	.3	Soil carbon quality indices	23				
3.5 <i>In situ</i>			<i>itu</i> gas measurements	23				
	3.5	.1	Flux measurements by closed chamber	23				
	3.5	.2	Flux measurement by gradient method	23				
	3.6	Stat	istical analysis	24				
4	The	e soi	s of the Okavango Catchment	25				
	4.1	Ava	ilable database on soils of the Okavango Region	25				
	4.2	Des	ign of the study and sampling	26				
	4.3	Soil	s in relation to landscape	26				
	4.3	.1	Soils of Cusseque	26				
	4.3	.2	Soils of Caiundo	29				
	4.3	.3	Soils of Mashare	31				
	4.3	.4	Soils of Seronga	34				
	4.3	.5	Soils under agricultural use	37				

	4.4	.4 Discussion on the soils of the Okavango Catchment						
5	Int	fluen	uence of climate, landscape & land use on the soil carbon stocks					
	5.1	Background of SOC in southern Africa						
	5.2	5.2 Sampling design						
	5.3	Res	ults on SOC stocks in the Okavango Catchment	42				
	5.4	- Discussion on carbon stocks						
6	CC	D₂ flu	xes in subtropical dryland soils: A comparison of the gradient & th	าย				
	clo	closed chamber method						
	6.1	6.1 Methods for flux measurements						
	6.2	6.2 Design of the study and sampling						
	6.3	Res	ults on the GM and CDCM	53				
	6.3	3.1	Soil properties	53				
	6.3	3.2	Soil CO ₂ gradients	55				
	6.3	3.3	Soil gas diffusivity	56				
	6.3	3.4	CO_2 fluxes compared for CDCM and GM	57				
	6.4 Discussion on the GM and CDCM		cussion on the GM and CDCM	59				
	6.4.1 CC		CO ₂ fluxes	59				
	6.4	4.2	CO ₂ concentration profiles	59				
	6.4	4.3	Soil gas diffusivity	60				
	6.4	4.4	Comparison of different methods for flux estimation	61				
7	La	Land-use impacts on three soil organic carbon fractions in typical soil						
	Okavango Catchment		go Catchment in Angola & Namibia	63				
	7.1 SOC fractions in dryland ecosystems		fractions in dryland ecosystems	63				
	7.2	7.2 Design of the study and sampling		64				
	7.3 Results on SOC and carbon fractions		ults on SOC and carbon fractions	64				
	7.3.1 Soil cha		Soil characteristics	64				
	7.3.2		SOC and its fractions	65				
	7.3.3		Initial carbon mineralization rate	68				
	/.:	3.4	Quality indices	68				
	7.4	Disc	cussion on the effect of land use on the carbon fractions	70				
	7.4.1		Total SOC	70				
	7.4.2		Carbon fractions	/0 71				
0	/./ c./	H.J	The effect of agriculture on C-tractions	ا / دح				
Ō	yد م	nine		د / 				
	ŏ. I	DIS	ribution of soil properties and land use	/3				

8.2	The distribution of SOC stocks				
8.3	Method comparison for CO ₂ flux measurements	78			
8.4	Carbon fractions	79			
8.5	SOC for soil quality and soil fertility	80			
9 Coi	nclusion & outlook				
References					
Summary9					
Zusammenfassung10					
List of figures10					
List of ta	List of tables				
List of p	ist of publications11				
Danksag	Danksagung				

1 GENERAL INTRODUCTION & OBJECTIVES

Globally, land-use conversions are accompanied by the loss of soil organic carbon (SOC) and soil nutrients and are thus threatening soil-bound ecosystem functions like soil fertility, carbon sequestration, and ecosystem resilience (FAO and ITPS, 2015). These ecosystem functions are strongly linked to soil organic matter (SOM), of which SOC is the main constituent. On the one hand, SOM enhances soil fertility by improving the soil nutrient level and by enhancing the cation exchange capacity, which prevents nutrients from being leached. SOM is responsible for a medium-term storage and release of nitrogen that is provided during the decay of organic material by soil (micro)organisms. Additionally, SOM plays a major role in aggregating soil particles and thus supports the soil water holding capacity and protects the soil from wind and water erosion (Lal, 2006). On the other hand, SOC being part of the terrestrial carbon pool has a high significance in the global carbon cycle by contributing to the exchange of carbon between terrestrial ecosystems and the atmosphere (Ciais et al., 2013).

The SOC pool is the largest terrestrial carbon pool in the net carbon budget with global stocks between 1500 and 2400 PgC, which is substantially more than is stored in the vegetation (450-650 PgC) (Ciais et al., 2013). The size of the SOC pool is the result of the net balance between input and output of organic material. The main input amounting to 123 PgC yr⁻¹ comes from plant residues and is directly linked to the primary productivity of ecosystems by photosynthesis. The main output is associated to respiration and bush fire, with as much as 118.7 PgC yr⁻¹ almost equalizing the gross photosynthesis (Ciais et al., 2013). The contributions of land-use and land-cover changes to annual CO₂ emissions have been estimated to be as high as 1.14 PgC yr⁻¹. This estimate has a great uncertainty in the order of ± 0.5 PgC yr⁻¹, which is attributed to the high diversity of land-use practices involved (Houghton et al., 2012). The majority of CO2 emissions from land-use change is caused by the deforestation for cropland in the tropics and subtropics, but also shifting cultivation contributes substantially to the emissions (Houghton, 2010). A rapid land-use change is particularly true for the African continent, which contributes 20 % of the global emissions from deforestation, while only accounting for 4 % of the total anthropogenic emissions from fossil fuels (Williams et al., 2007). On the African continent, high population growth is coupled with the ongoing conversion of natural woodlands and forests to agricultural land (Kim et al., 2016). This land-use conversion is proceeding exceptionally fast in savanna ecosystems that cover about half of the African landmass (Scholes and Archer, 1997). In this ecosystem, the annual losses of natural savanna areas have been estimated to be 1 %, being approximately twice as high as for rain forests (Grace et al., 2006).

There is large consensus that the impacts of agricultural use on SOC depend on the particular land-use practices (McLauchlan, 2006). SOC levels can either be enhanced or maintained by the intensive input of organic material and reduced tillage or, which is mostly the case under long-term agricultural use, it can be depleted when the net balance between carbon input and loss by heterotrophic respiration is negative (McLauchlan, 2006). Contrarily to the good knowledge of the general response of SOC to agriculture,

Chapter 1

less knowledge exists on SOC change in response to agriculture in dryland ecosystems and particularly in southern African dryland soils. Some publications dealing with the effect of agriculture on SOC are available for African savannas and woodlands (Pabst et al., 2013; Woollen et al., 2012) and some dealing with the effect on soil quality parameters in semi-arid ecosystems (Bastida et al., 2008; Bastida et al., 2006). However, to my knowledge, no studies are linking soil quality measurements to land use in southern African savannas and woodlands and a demand for research in this direction is explicitly expressed in order to evaluate land-use strategies with regard to soil fertility management and greenhouse gas balance (Ciais et al., 2011).

SOM exists as continuum of a high variety of carbon compounds from fresh plant material like litter and roots to highly condensed compounds like aromatic systems (Lehmann and Kleber, 2015), which may be the product of oxidation processes like incomplete combustion (Preston and Schmidt, 2006) or microbial metabolism (Paul, 2016). The initial decomposition rate is associated with the chemical structure of the organic matter. The turnover rates of labile compounds like carbohydrates and peptides are much faster than those of ligneous plant material and fire-derived "black carbon" compounds (Schmidt et al., 2011). Even though the chemistry of the SOM is the major determinant of its degradability in the short term, the historic view that this also applies to long-term stability has been questioned over the last decades and evidence has emerged that accessibility of the substrate may be far more important (Lehmann and Kleber, 2015; Schmidt et al., 2011). To identify land-use effects on SOM and for modeling purposes, it is often useful to divide the SOM in different functional pools with regard to its degradability (McLauchlan and Hobbie, 2004). Most fractionation methods rely on the physical separation of particles, density fractions or chemical procedures like oxidation and hydrolysis (von Luetzow et al., 2007). In contrast to physical and chemical separation methods, incubation allows an integrated view on the degradability of SOM thereby incorporating intrinsic, chemical stability as well as SOM interactions with the mineral phase of the soil and offering the possibility to determine controlling environmental factors, like temperature and water availability (Schadel et al., 2013). Although incubation experiments give good insights into the SOM quality and degradability, the results are only of minor explanatory power of the soil activity in situ.

In situ soil respiration in the field is typically measured by monitoring the fluxes of CO_2 from soil to the atmosphere and provides information on the dynamics of soil respiration along spatiotemporal scales. On the pedon scale, the most popular direct methods for measuring fluxes are based on closed chambers placed on the soil surface. The CO_2 fluxes are measured by analyzing the increase of gas concentrations inside the chamber (closed dynamic chamber method, CDCM) or by controlling inlet and outlet gas concentrations continuously in the air stream through the chamber (Livingston and Hutchinson, 1995; Rolston, 1986). A second method for indirectly quantifying gas fluxes on the pedon scale is the gradient method (GM), which makes use of the concentration gradient of a specific gas species between the soil and the atmosphere. For the estimation of fluxes, the diffusion properties of the soil and concentration gradients of the gas within the soil must be known (De Jong and Schappert, 1972). Both methods have advantages and disadvantages concerning precision of flux estimates and applicability in the field. Regarding field applicability, CDCM has serious disadvantages for the collection of time-series data,

as the method cannot be operated for long periods without maintenance in remote areas. Compared to the CDCM, the GM possesses the advantage that it can operate independently from the observer by continuously logging the gas concentration in the soil (Tang et al., 2003). Although several studies have compared GM and CDCM (Maier et al., 2011; Pihlatie et al., 2007; Wolf et al., 2011), only very few studies were conducted in hot semi-arid and arid environments with long dry periods (e.g., Fierer et al., 2005).

Research regarding carbon stocks and CO₂ fluxes and their response to land use are particularly rare in sub-Saharan Africa. A region that is presently experiencing accelerating land-use change represents the Okavango Catchment – covering parts of Angola, Botswana and Namibia - making the region ideal for investigating the impacts of such landuse transformations while contributing to the development of perspectives for the sustainable use of natural resources (Pröpper et al., 2015). A large proportion of the rural population in this area is relying on subsistence farming for their staple food supply, which causes rapid conversions of woodlands to agricultural land (Schneibel et al., 2016). Subsistence farming is characterized by low input fertility management with very limited or no application of nutrients and organic material while fallow periods are the only mechanism to restore the nutrient level of the soil (Lal, 2006). These farming practices strongly rely on the natural soil fertility, which is determined by the initial SOM content. Even though there have been some attempts to evaluate the ecosystem carbon fluxes and balances of sub-Saharan Africa in particular (Bombelli et al., 2009; Kim et al., 2016), and the whole African continent in general (Ciais et al., 2011; Valentini et al., 2014), the basis of field data for these large-scale inventories is scarce and the cited authors highlight that more on-the-ground research is needed to improve the knowledge of the role of Africa in the global carbon cycle.

1.1 Objectives of the study

The present study aims to contribute to a better understanding of the influence of land use on SOC in a savanna region under semi-arid and semi-humid conditions. The focus lies on three aspects of the carbon cycle in the sub-Saharan Africa investigated in four study sites in the Okavango Catchment (Figure 2.1): (I) the magnitude of SOC stocks, their distribution in the landscape and response to agriculture; (II) the SOC fractions defined according to their degradability and microbial biomass; and (III) the process of soil respiration by testing two methodological approaches to quantify the CO_2 fluxes in remote areas. Furthermore, this study aims at characterizing the soil types and the pedodiversity in the Okavango catchment based on classifications according to the IUSS Working Group WRB (2006). In this study the following hypotheses were tested:

- 1. The distribution of soils and pedodiversity in the Okavango Catchment shows characteristic patterns according to climate and landscape structure.
- 2. The SOC stocks of the Okavango Catchment depend on the parent material of soils, the climate and the land-use type.
- 3. The gradient method offers a useful tool to monitor CO_2 fluxes in remote areas under semi-arid and semi-humid conditions.
- 4. The relative proportions of three different soil carbon fractions can be explained by the land-use type.

1.2 Chapter overview & author contributions

This thesis is based on three publications that resulted from research conducted in the frame of the international and interdisciplinary research project "The Future Okavango". Furthermore, I co-authored additional publications that were integrated in chapter four of this thesis (the complete list of publications is provided at the end of the thesis). Publications 1-3 are journal articles and provide the bases for the chapters 5-7 of this thesis:

- (1) Luther-Mosebach, J., Gröngröft, A., Eschenbach, A., 2015. Influence of Landscape and Land-use on the Soil Carbon Stocks in the Okavango Catchment, In: Knoblauch, C., Fiencke, C., Berger, K. (Eds.), Böden im Wandel, 77. Hamburger Bodenkundliche Arbeiten, 77, Verein zur Förderung der Bodenkunde Hamburg, Hamburg, pp. 155-166.
- (2) Luther-Mosebach, J., Kalinski, K., Gröngröft, A., Eschenbach, A., 2016. CO₂ fluxes in subtropical dryland soils—a comparison of the gradient and the closed chamber method. Journal of Plant Nutrition and Soil Science. doi: 10.1002/jpln.201600137.
- (3) **Luther-Mosebach, J.**, Gröngröft, A., Eschenbach, A., (in prep.). Land-use impacts on three soil organic carbon fractions in typical soils of the Okavango Catchment in Angola and Namibia. Journal of Arid Environments.

In cases of first authorship, I was responsible for the study design, the literature review, the data collection and interpretation, the creation of figures and the writing of the manuscripts. However, due to the collaborative character of the research project, several co-authors have contributed to the publications:

Chapter 1, "General introduction and objectives", contains an overview of the role of the African continent in the global carbon cycle, the research gaps and the deduced hypotheses for this study. Parts of the introduction are borrowed from papers 1, 2 and 3, which were written by myself as main responsible person in conjunction with the co-authors.

Chapter 2, "**Study sites**", gives an introduction in the Okavango catchment and the four study sites along the Okavango River from central Angola to central Botswana. The description contains parts from the publications 9-12, which were jointly written by the co-authors.

Chapter 3, "**Material and methods**", contains all field and laboratory methods applied in this thesis. It is composed of parts of the publications (1), (2) and (3), which were written, as mentioned above, by me in the leading position.

Chapter 4, "**The Soils of the Okavango Catchment**", describes the soil inventories of the four study sites along the Okavango River by typical soil catenae in the landscape. It aims at giving an overview of the pedodiversity of the study sites and the associated soil properties and land-use types. It is based on the publications 6-8 in the publication list, which were jointly written by the co-authors. Graphs of the landscape catenae were created by Alexander Gröngröft and Lars Landschreiber.

Chapter 5, "Influence of climate, landscape and land-use on soil carbon stocks in the Okavango Catchment", is concerned with the SOC stocks of the four study sites. It aims at identifying potential SOC stocks of landscape units under natural conditions and

evaluates land-use impacts on the SOC stocks. It is based on publication (1) and coauthored as described for chapter 1 (see above). Additionally, data on the above ground woody biomass carbon, which are part of Figure 5.3:b, were provided by Cynthia Erb and Vera de Cauwer.

Chapter 6, "CO₂ fluxes in subtropical dryland soils – a comparison of the gradient and the closed chamber method", deals with the evaluation of a method for flux measurements in remote areas by comparing the fluxes determined by the use of two different methods. Additionally, it evaluates model-based estimates of parameters needed for the flux estimation using the gradient method. The chapter is based on publication (2) which was written by me as responsible person and reviewed by the co-authors. Gas diffusivity data were part of the BSc-thesis of Marcel Burmester. Field measurements of CO₂ fluxes and gradients were partly collected for the MSc-thesis by Kira Kalinski.

Chapter 7, "Land-use impacts on three SOC fractions on soils of the Okavango catchment", deals with the quantification of different SOC pools under different climatic conditions and the influence of agriculture on two study sites within the Okavango catchment. The aim was to distinguish the labile, rapidly degradable carbon fraction from the more stable bulk SOC. Additionally the microbial biomass was measured as a characteristic constituent of SOC and indicator of SOC quality. The chapter is based on publication (3), which was written by me in the leading position with the co-authors as critical reviewers. Data of microbial biomass and incubation experiments were partly the subject of a BSc-thesis by Ole van Allen and an MSc-thesis by Aurelie Fadette Jiope Zebaze. Both theses were planned and co-supervised by me.

Chapter 8, "**Synthesis**", gives a general discussion of the results and discusses implications for land use. It contains parts of the publications 1, 2 and 3.

Chapter 9, "**Conclusion and outlook**", an outlook for possible further research, discusses the need for further research in the light of the key findings of the study. It was written by me as the responsible author.

2 STUDY SITES

This study was conducted as part of the trans- and interdisciplinary research project "The Future Okavango" (Jürgens, 2013). Within the project, research was concentrated on four study sites situated along the Okavango River (Figure 2.1), which cover a climatic gradient with rising temperatures and falling precipitation from north to south (Wehberg and Weinzierl, 2013). In the semi-humid northern region, 95 % of the stream flow of the Okavango River that enters the semi-arid Okavango Delta is generated (Steudl et al., 2013). The annual flood peak in the delta is arriving just during the dry season thereby providing a refuge for a very rich wildlife in a water-scarce environment. Each study site includes the Okavango River or its tributaries as well as the respective local landscape units from recent and old floodplains and wetlands to the hinterland with the typical dryland soils of the Kalahari Basin (Simmonds, 1998).



Figure 2.1: The Future Okavango (TFO) research area with the four study sites Cu = Cusseque, Ca = Caiundo, Ma = Mashare, Se = Seronga. The TFO-Research Area comprises the active catchment from the highland of Bié in central Angola to the Okavango Delta in Botswana (map is from Pröpper et al., 2015).

2.1 Cusseque: Northern part of the catchment in the highlands of Bié



Figure 2.2: Study site Cusseque in the highland of Bié in central Angola and the positions of soil profiles. The colors schematically indicate the landscape units within the area. Areal picture by BingMaps.

Cusseque is situated in the highlands of Bié in central Angola at an altitude of 1,560 m a.s.l. The Holocene landscape is a product of long-lasting erosion processes, which formed a gently rolling surface on a Precambrian granitic plateau basis. The land-scape is structured by an almost rectangular grid of small creeks and medium-sized permanent streams (Figure 2.2), which are discharging into the Cusseque River, a tributary of the Okavango River. The climate is semi-humid and the rainfall pattern indicates strong seasonality with almost the total annual precipitation of 987 mm falling between October and April (Figure 2.3). The annual temperature averages at 20.4 °C with October (23 °C) and July (16.1 °C) being the hottest and the coldest month respectively (Weber, 2013b).

The vegetation pattern in Cusseque is linked to the topographic position, the elevated parts and hilltops being covered by open to close miombo woodlands and the slopes and valleys being covered by open grasslands and stands of the geoxylic suffrutex life form, a community of dwarf shrub with large underground biomass (Revermann et al., 2013), also referred to as underground forests (White, 1977). The origin of this special type of vegetation adaption is still under debate and fire as well as night frosts are discussed as their driving forces (Finckh et al., 2016; Maurin et al., 2014). Due to permanent interflow to the valleys, peatlands with wetland adapted plants developed.



Figure 2.3: Walter-Lieth climate diagram of Cusseque (Weber, 2013b). The x-axis starts with July and ends in June.

Small villages emerged along the road that connects the cities of Huambo, Kuito and Menongue. The dominant land-use practice is shifting cultivation and takes place on the hilltops. The woodlands are therefore felled and the residues are burned. On the peat-lands, horticulture takes place during the dry season. The woodlands are also increasingly used for charcoal production (Domptail et al., 2013).

2.2 Caiundo: Central part of the catchment in the lowlands of southeast Angola



Figure 2.4: Study site Caiundo at the Cubango River in south Angola and the positions of soil profiles. The colors schematically indicate the landscape units within the area. Areal picture by BingMaps.

The study site of Caiundo is located at the Cubango River, the western stream of the two main tributaries of the Okavango at an altitude of 1,160 m a.s.l. (Figure 2.1). The river with its recent floodplains is incised about 60 m in the almost flat landscape of the Kalahari Basin (Figure 2.4). On the eastern side, some hills are rising, probably with protruding bedrock underneath a thick overlay of sand. Within the Kalahari sand area, some dry riverbeds indicate that in years with intensive rainfalls some run-off may occur.

The climate is semi-arid and the rainfall pattern indicates strong seasonality with almost the total annual precipitation of 732 mm falling between November and March (Figure 2.5). The annual temperature averages at 22.5 °C with October (26.3 °C) and July (16.8 °C) being the hottest and the coldest month respectively (Weber, 2013a).

The vegetation is characterized by *Baikiaea-Burkea* woodlands on the deep Kalahari sands and only a few species belonging to the miombo woodland are present (Revermann and Finckh, 2013). The vegetation is affected by frequent fires in the area adjacent to the river (Frantz et al., 2013) that, together with human activities like livestock holding and wood collection, led to the development of open grasslands near the river. The hilltops on the eastern side of the river are covered by dense woodlands with a very distinct species composition (Revermann and Finckh, 2013). Along the slopes of the river, the change in soil and hydrological conditions coincides with changing vegetation. The gallery wood-

land coexists with extended reeds of sedges and *Phragmites mauritianus* in the recent floodplains and tall grasses on the old floodplains (Revermann and Finckh, 2013).

The area is sparsely populated with a few settlements along the river. Slash and burn practice and plowing by oxen are the prevailing technique for land preparation. The old floodplains and the hilltops are the preferred areas for agriculture.



Figure 2.5: Walter-Lieth climate diagram of Caiundo (Weber, 2013). The x-axis starts with July and ends in June.

2.3 Mashare: Southern part of the catchment in the lowlands of north-east Namibia



Figure 2.6: Study site Mashare at the Okavango River in northern Namibia and the positions of soil profiles. The colors schematically indicate the landscape units within the area. Areal picture by Bing-Maps.

The study site of Mashare is situated at the middle reaches of the Okavango River in the Kavango Region of Namibia at an altitude of 1,090 m a.s.l. The landscape is flat to very slightly undulating and solely the area adjacent to the river is slightly incised (Figure 2.6). The region is formed by eolian sand drifts and dunes of the Kalahari Basin which are deposited on calcrete erosion surfaces (Simmonds, 2000). Former longitudinal dunes were running in west-east direction, however, they have been reworked and leveled in the study area. Within the area, only a few signs of surface runoff exist as dry riverbeds, socalled omuramba. These omuramba were formed during wetter climate conditions and exhibit a mixture of fluvial sediments, sandy eolian deposits and former calcretes on their bottom (Simmonds, 2000). Along the west-east perennial flowing of the Okavango River, characteristic morphological elements of slow-flowing rivers like sandy levees, scroll and point bars, meanders and ox-bow lakes have developed (Simmonds, 2000). These elements are embedded in recent floodplains on both sides of the river that are frequently flooded under high water conditions. Between the recent floodplains and the dune area, old floodplains of varying extension are spreading alongside the river. Here, a thin layer of fluvial deposits and eolian sands are occasionally covering the calcretes.

The high infiltrability of the sand plains leaves a landscape with challenging living conditions for humans. Villages are thus primarily oriented along the river and only with

modern-aged bore holes new villages within the sandy areas have emerged (Pröpper et al., 2010). Fields are preferably located on areas in the old floodplains or along the omiramba that consist of fine-grained fluvial deposits. With increasing population density, fields have been extended to the south on the Kalahari sands. Commonly, grazing by cattle and small stock takes place on all landscape units as far as water and fodder are available. Thus, the grazing influence concentrates on the recent floodplains and declines with growing distance to the river.

The climate is semi-arid with a pronounced seasonal rainfall pattern. The majority of the annual precipitation of MAP = 571 mm occurs between November and March (Figure 2.7). The annual temperature averages at 22.3 °C with October (26.2 °C) and July (16.2 °C) being the hottest and the coldest month respectively (Weber, 2013c).



Figure 2.7: Walter-Lieth climate diagram of Mashare (Weber, 2013b). The x-axis starts with July and ends in June.

The vegetation reflects the varying site conditions of the landscape. In the recent floodplains, reeds and grasslands are prominent, the pristine woody vegetation here and on the old floodplains is predominantly converted to open vegetation or secondary thorn bushes by human land use (De Cauwer, 2013). The remaining trees of the riverine vegetation may grow up to 22 m height and form high productive woodlands (De Cauwer, 2013). On the Kalahari sands, the pristine vegetation represents the open woodland of the ecoregion 'Zambezian *Baikiaea* woodlands' according to Olson et al. (2001), the same as for the study site 'Caiundo'. Most common trees are *Terminalia sericea*, *Burkea africana* and *Baikiaea plurijuga* (De Cauwer, 2013).

The area adjacent to the river in the Mashare region is relatively densely populated and almost all areas of the old floodplains are either used for agricultural fields, or as rangeland. Only sporadically the dense riverine forests have been preserved. The agriculture in both sites is characterized by subsistence crop production. In Mashare dryland agriculture is the dominant type of agricultural land use, however, industrial irrigation schemes are emerging as well and are focused on the more fertile old floodplain soils (Kowalski et al., 2013). 2.4 Seronga: Southern part of the catchment at the Panhandle in north-east Botswana



Figure 2.8: Study site Seronga at the transition of the "Panhandle" to the Okavango Delta in Botswana and the positions of soil profiles. The colors schematically indicate the landscape units within the area. Areal picture by BingMaps.

Seronga is situated east of the Okavango River, at the so-called "Panhandle", just before the river fans out into the Okavango Delta. Two clearly distinct landscape units can be distinguished (Figure 2.8): the floodplains of the Panhandle and the Kalahari dune area with degraded dunes (Ringrose et al., 2008). At the border of Namibia, 100 km north of Seronga, the floodplains of the Panhandle widen from 800 m to 10 km within a distance of only 16 km (Figure 2.1). The flow direction follows a fault line perpendicular to the Gumare fault line that marks the entry into the delta (Ringrose et al., 2008). Large parts of the Panhandle are permanently inundated and have a swamp-like character but also sandy levees, termite humps, small channels, and lagoons are landscape features characterizing the floodplains. The Kalahari dune area lies about 10 m above the floodplains and is similar to the respective landscape at Mashare and Caiundo. At Seronga, the sand dunes are strongly degraded resulting in a plain landscape. Ringrose et al. (2008) described the process of dune erosion as "over-washing", however, sources of water and nature of the events are still under debate.

The climate is semi-arid with a pronounced seasonal rainfall pattern. The majority of the annual precipitation of 478 mm on average occurs between November and March (Figure 2.9). The annual temperature averages at 23.2 °C with October (27.1 °C) and July (16.5 °C) being the hottest and the coldest month respectively (Weber, 2013d).



Figure 2.9: Walter-Lieth climate diagram of Seronga (Weber, 2013b). The x-axis starts with July and ends in June.

Within the floodplains of the Okavango, the microtopography forms a diverse pattern of channels, lakes, and islands of different form and origin, which are habitats for a large diversity of plants and animals. Hydrophyte plants on the water bodies like the floating-stemmed grass *Vossia cuspidata* and reeds of *Cyperus papyrus* and *Phragmites* spp. are mixed with linear and island structures of riverine woodlands and patches of saline and sandy shores (Mendelsohn et al., 2010; Murray-Hudson et al., 2013). As in Mashare and Caiundo, the vegetation on the Kalahari dune area belongs to the 'Zambezian *Baikiaea* woodlands' (Olson et al., 2001). There are two main vegetation units on the Kalahari sandveld: the Mopane woodlands with more or less dense and pure stands of the tree *Colophospermum mopane* and the more species-rich and open *Burkea* woodlands with several abundant tree species (Murray-Hudson et al., 2013).

Compared to the other three research sites, livelihoods in Seronga are more diverse. However, agriculture and livestock keeping remain important strategies to buffer shortcomings in market food supplies. Agriculture is focused on the Kalahari dune area. Fields have to be fenced thoroughly to protect the crops from the highly abundant elephant herds (Große et al., 2013).

3 MATERIAL & METHODS

The soil sampling and the field measurements were conducted during five biannual field trips from 2011 to 2013. Some of the described methods were only applied at certain study sites mentioned in the subchapter "Design of the study and sampling" in each of the main chapters.

3.1 Soil sampling

Mixed topsoil samples were taken from 0 to 10 cm depth from 13 locations on a cross of two diagonal lines of 30 m each at each plot. These subsamples were combined and mixed to get a representative topsoil sample. The soil profiles were described in standardized forms by estimating bulk density, root density, carbonate content, soil color, humus content and texture for each soil horizon according to Ad-hoc-AG Boden (2005). Samples were taken for each soil horizon separately. The classification of soil profiles was done according to the IUSS Working Group WRB (2006). Bulk density was measured by taking undisturbed soil samples using 100 cm³ steel rings and weighing the dry soil material.

3.2 Soil chemical analysis

The mixed topsoil samples were analyzed for total nitrogen and total carbon content on fine-ground samples using an element analyzer (Vario MAX, Elementar Analysensysteme). For measurements of inorganic carbon, a fine-ground and dry sample (0.1-2.0 g) was treated with 5 ml phosphoric acid (43 %) in a closed vial with defined volume. The released CO₂ was measured by gas chromatography (Shimadzu GC 14B). Organic carbon (SOC) was calculated by subtraction. For calculating the SOC stocks (kg m⁻²), the SOC concentrations were multiplied with the bulk density and sampling depth.

Soil pH and electrical conductivity were measured with a pH-electrode and a conductivity sensor respectively in a 1:2.5 soil H_2O suspension after 1 h of repeated stirring. Moreover, soil pH was measured in a suspension with 0.01 M CaCl₂ (1:2.5 ratio).

The exchangeable cations were extracted with an excess of ammonium (5 g of airdried soil, five extractions with 25 ml 1 M NH₄Cl each) and were quantified by atomic absorption and atomic emission spectroscopy (AAS). The ionic strength of ammonium was reduced to 0.01 M NH₄Cl and the adsorbed NH₄ afterwards extracted with 1 M KCl. The concentration of NH₄ was measured by photometry; the CEC was corrected for the dissolved proportion of NH₄ (Petersen, 2008). The content of available phosphorus was measured in a Ca-lactate extract (VDLUFA, 1991).

3.3 Soil physical analysis

Bulk density and soil texture 3.3.1

To measure bulk density, 100 cm³ soil were sampled using steel rings of the respective size and weighing the soil material after drying. Hence, it was not possible to measure bulk density at each plot; the mean of own measurements $(1.5 \pm 0.1 \text{ g cm}^{-3})$ was used instead. Soil texture was determined by the use of the pipette method, distinguishing the fractions clay (< 0.002 mm) and silt (0.002 - 0.063 mm), and by sieving for the sand fractions (0.63 - 2 mm).

3.3.2 Diffusion properties

On five of the seven plots, three undisturbed soil cores of 100 cm^3 (height = 4.0 cm, diameter = 5.6 cm) were sampled from the first $(5.8 \pm 1.2 \text{ cm soil depth})$ and the second $(20 \pm 1.7 \text{ cm soil depth})$ horizon. For the plot-pairs F-D/F-B and M-W/M-D respectively, only one set of soil cores was sampled at the agricultural site. As the respective soils were weekly aggregated, depicted similar soil properties relevant for diffusion (esp. texture and bulk density) and were in close distance (30 m/300 m), the diffusion data from the dryland agriculture was transferred to the bushveld or woodland.

The water content of our samples was adjusted to levels corresponding to matric potentials below field capacity (<6 kPa), field capacity (6 kPa), upper limit of field capacity (30 kPa) and oven dry (105 °C) to measure the dependence of soil gas diffusivity on the air-filled porosity (ɛ). The levels 6 kPa and 30 kPa were adjusted according to the retention curves of the respective samples measured by a pressure plate apparatus (Soilmoisture Equipment Corp, Santa Barbara, USA). For each soil core, the soil gas diffusivity was determined by the single chamber method with a volume of about 3000 cm³ gas space (Gebert et al., 2011). The soil cores were fitted on the diffusion chamber and purged with excessive N₂. Diffusive re-entry of atmospheric O₂ into the chamber via the soil core was monitored four times by gas chromatography GC-TCD analysis (Agilent 6890, Agilent Technologies) at an interval of thirty minutes for the water content levels 1-3 and sixty minutes for the wettest level. The first measurement was taken after allowing the gradient within the soil core to become linear after the length of one interval. The soil gas diffusivity (D_s) was calculated using the analytical solution described by Kühne et al. (2012), based on Fick's first law and the integration of the concentration gradient between the start and the end of the measuring interval:

$$D_s = \frac{x \times V_c}{A} \cdot \frac{1}{t'} \cdot \ln\left(\frac{c_c(t_0) - c_A}{c_c(t') - c_A}\right)$$
(1)

where $D_s = \text{soil gas diffusivity } [m^2 \text{ s}^{-1}]; x = \text{sample length } [m]; V_c = \text{chamber volume } [1];$ A = sample area $[m^2]$; $c_c = O_2$ concentration inside the chamber $[mol m^{-3}]$; $c_A = O_2$ concentration outside the chamber [mol m⁻³]; t_0 = time at start of the interval [s]; t' = time at end of the interval [s]. The individual measurements from each of the three subsequent intervals were averaged to attain the final value of D_s. Oxygen consumption by soil respi-18

ration during measurement intervals was neglected following Schjonning et al. (2013), who found no significant effects of oxygen consumption.

Fitting of the ε and D_s/D_0 relationship was done according to Troeh et al. (1982) including the third parameter C (referred to in the following as Troeh82):

$$\frac{D_s}{D_0} = C(\varepsilon - u)^{\nu} \tag{2}$$

where $\varepsilon =$ the air-filled pore space and *C*, *u* and *v* are fitting parameters. The parameter *C* represents the offset from the D_s/D₀ at the total porosity $\varepsilon = \Phi = 1$. The application of the model in the form of equation 2 ensures a better fit within the range of the observed ε , as it does not force the model to meet D_s/D₀ = 1 when $\varepsilon = 1$. The parameters *u* and *v* can be interpreted as being physically driven. The parameter *u* denotes the air-filled porosity ε at which the diffusivity reaches D_s/D₀ = 0, and *v* is the curvature parameter which has values > 1, meaning the soil particles decelerate the diffusion process (Troeh et al. 1982). The Troeh82 equation was chosen because of its flexibility. It usually fits measured diffusivities very well and is therefore frequently used in GM-studies (e.g., Pihlatie et al., 2007; Wolf et al., 2011). The advantage according to Troeh et al. (1982) is that it yields a curvilinear function, which can fit the D_s/D₀ = 0 at $\varepsilon = 0$). Fitting of the function was done using the data from the six soil cores of the two uppermost horizons per plot in order to get a more representative fit. This was appropriate as only minor differences in the diffusion properties of the topsoil horizons were observed.

At low air-filled porosity, diffusion through the gaseous phase becomes negligible in favor of diffusion through the liquid phase, which is about 10^{-4} times lower (Jassal et al., 2004). Accordingly, we assumed diffusion to be 0 at air-filled porosity of $\varepsilon < 0.1$ as a conservative threshold which was also used by Troeh et al. (1982) and is close to the value of Jassal et al. (2004), who report a threshold of $\varepsilon < 0.12$. Consequently, we only included data for the curve fitting that were above the threshold to avoid situations where $u \ge \varepsilon$, which would be beyond the limits of the equation (Troeh et al., 1982). We estimated the model parameters using a Levenberg-Marquardt type of non-linear least-squares fitting algorithm implemented in the nlsLM function of the r-package "minpack.lm" (Elzhov et al., 2016). Goodness of fit was tested by calculating the Pearson correlation coefficient between observed and predicted values.

To check whether modeled diffusivity might be suitable for substituting the measurement of diffusion properties, we compared the D_s/D_0 obtained by the Troeh82 method with those from selected models. Although there is a variety of diffusion models available (for overview see Allaire et al., 2008), we restricted the set to the most commonly used models that do not need input data other than air-filled porosity and total porosity and were developed for porous materials, including intact soils (Table 3-1). The congruence of the modeled and the measured D_s/D_0 values was checked visually and only the three models Buck04, MQ61b and Mold97, which were in a feasible agreement, were chosen for flux estimation. Chapter 3

Table 3-1: Models used in this study to estimate the diffusivity Ds/D0 in soil with air-filled porosity (ϵ
and total porosity (Φ) as input parameters.

Number	Abbr.	Author	Model	Comments
3	Buck04	Buckingham (1904)	$\frac{D_s}{D_0} = \varepsilon^2$	exponent repre- sents the tortuos- ity of the soil, only tested on four soils
4	Pen40	Penman (1940)	$\frac{D_s}{D_0} = 0.66 \cdot \varepsilon$	
5	Mar59	Marshall (1959)	$\frac{D_s}{D_0} = \mathcal{E}^{3/2}$	
6	MQ61a	Millington and Quirk (1961)	$\frac{D_s}{D_0} = \frac{\varepsilon^2}{\Phi^{2/3}}$	
7	MQ61b	Millington and Quirk (1961)	$\frac{D_s}{D_0} = \frac{\varepsilon^{10/3}}{\Phi^2}$	
8	Mold97	Moldrup (1997)	$\frac{D_s}{D_0} = 0.66\varepsilon \left(\frac{\varepsilon}{\Phi}\right)^{\frac{12-m}{3}}$	Combination of the Pen40 and the MQ models; m = 3 for intact soils

3.3.3 Flux estimation

For the calculation of fluxes, the diffusivity was adjusted to the pressure and temperature conditions at the time of flux measurement in the field using

$$D_{0(T/P)} = D_0 \left(\frac{P_{ref}}{P}\right) \left(\frac{T}{T_{ref}}\right)^a$$
(9)

with an exponent of 1.81 for CO₂ (Massman, 1998).

Fluxes were calculated using Fick's law according to De Jong and Schappert (1972). However, the equation was modified according to the recommendations of Sanchez-Canete and Kowalski (2014) as well as Maier and Schack-Kirchner (2014a) by including the mean air density (ρ_a) to account for large temperature gradients between soil surface and sampling position within the soil:

$$F = -D_s \rho_a \frac{\Delta c}{\Delta x} \tag{10}$$

where $F = \text{flux} \ [\mu \text{mol} \ \text{m}^{-2} \ \text{s}^{-1}]$; $D_s = \text{soil gas diffusivity} \ [\text{m}^2 \ \text{s}^{-1}]$; $\Delta c = \text{difference in } CO_2$ concentrations between soil and atmosphere in molar fraction (ppm); $\Delta x = \text{distance over}$ which the diffusion occurs; $\rho_a = \text{mean air density} \ [\mu \text{mol} \ \text{m}^{-3}]$. Fluxes were calculated

based on CO_2 concentrations at a depth of 10 cm because the gas sampling method of soil air via syringe turned out to be unsuitable for collecting samples from shallower depths, where samples were usually contaminated by atmospheric air.

The values of the gradient method and closed dynamic chamber method measurements were compared and indices were calculated using the "modeval" function from the R-package "sirad" (Bojanowski, 2015). The following statistics were chosen: Root mean square errors (RMSE) for which lower values indicate more precise forecasts of predicted values. The Nash-Sutcliffe efficiency (NSE) ranges between $-\infty$ and 1. It describes how well the observed and predicted values meet the 1:1 line. The closer the value is to 1, the better the fit. Values > 0 generally indicate acceptable performance whereas values < 0 imply that the mean observed value is better than predicted (Moriasi et al., 2007). The coefficient of residual mass (CRM) is a measure of systematical overestimation (value < 0) or underestimation (value > 0).

3.4 Soil microbial parameters and carbon fractions

3.4.1 Microbial biomass C and N

Prior to the analysis for microbial biomass, the air-dried samples were rewetted to 40 % water holding capacity and incubated for 10 days at 20°C. This was done in order to compensate for different sampling dates and storage periods and to adjust the microbial community to the same conditions in all samples.

 C_{mic} and N_{mic} were detected using the chloroform fumigation-extraction method according to Vance et al. (1987) on the pre-treated samples The samples were separated into two aliquots one of which was directly extracted and the other was fumigated with chloroform for 24 hours in an exicator. The chloroform was removed from the samples by repeated evacuation of the exicator. Successful removal of chloroform was tested by incubating a sample of sterile sand as a control together with the samples. All samples were extracted with 0.5 M K₂SO₄ and extracts were analyzed for N and C using a TOC/TN Analyzer (TNML-L series, Shimadzu, Kyoto, Japan). C_{mic} and N_{mic} were calculated using:

$$C_{mic} = \frac{C_f - C_{nf}}{k_c} \tag{11}$$

$$N_{mic} = \frac{N_f - N_{nf}}{k_N} \tag{12}$$

where C_f and N_f = the amount of C and N in the fumigated and C_{nf} and N_{nf} = the amount of C and N in the unfumigated aliquots respectively. An extraction factor $k_C = 0.45$ for C_{mic} and $k_N = 0.54$ for N_{mic} originally developed for temperate soils was applied according to Vance et al. (1987) and Joergensen and Mueller (1996) respectively.

3.4.2 Soil incubation

The carbon fractions C_{labile} , C_{stable} and the initial respiration rate were measured by an incubation experiment adapted from McLauchlan and Hobbie (2004). The labile pool was defined by fitting a decomposition model to soil incubation data and the model extrapolated until the respiration rate reaches zero. At this hypothetical point, all labile carbon has been respired. As a third fraction, the microbial biomass C was analyzed. Even though microbial biomass has been proposed to be the chief component of the active SOM pool and has been found to be best suitable compared to other fractionation methods (von Luetzow et al., 2007), recent studies suggest that important amounts of the stable fraction and intermediate fraction is attributed to microbial products (Kallenbach et al., 2016). For this reason, in this study microbial biomass carbon was not interpreted to be entirely part of the labile fraction.

For analyzing C_{labile} and C_{stable} , three sets of samples were incubated for 219, 93 and 65 days respectively in 250 ml gas-tight glass bottles. The CO₂ content within the bottles was measured by gas chromatography GC-TCD analysis (Agilent 6890, Agilent Technologies) at a frequency of about twice a week in the beginning of the experiment and subsequently extended to once a week, and to once a month after 150 days of incubation. The bottles were purged with ambient air when the carbon dioxide reached 3% to avoid the limitation of respiration due to oxygen deficiency.

For the calculation of the mineralizable amount of carbon, we selected a second-order kinetic model (equation 13) according to Whitmore (1996) and modified by Sleutel et al. (2005), whose performance to calculate a labile fraction has been found to be reasonably independent of the incubation time (Sleutel et al., 2005). In the second-order kinetic model it is assumed that the rate of decomposition is proportional to the product of the concertation of the substrate and of the microorganisms derived from substrate (Sleutel et al., 2005). It can be written as:

$$\frac{dC}{dt} = -k_2 a C (1-a)C \tag{13}$$

where it is assumed that a fraction (aC) of the substrate (C) becomes microbial biomass that itself participates in the mineralization of the substrate. Hereby, the proportionality factor k_2 is the second-order mineralization rate constant. The cumulative amount of C mineralized at time t can be estimated using the model in its integrated form:

$$C(t) = C_{labile} - \frac{C_{labile}}{1 + k_2 a(1-a)C_{labile} t}$$
(14)

The model can be fitted to the cumulative respiration data whereby C(t) is the cumulative amount of C mineralized till time *t*, and C_{labile} is the amount of mineralizable carbon. The parameters k_2 and *a* can only be estimated as pooled value, $k_2a(1-a)$ by model fitting. The fitting was done with the Levenberg-Marquardt type of nonlinear least squares fitting from r-package "minpack.lm" (Elzhov et al., 2016). The fraction of C_{stable} was calculated by subtraction of the C_{labile} from the total SOC. The initial respiration rate, which is comparable to basal respiration, was estimated as the slope of the model at t_0 using the first derivative of the fitted model.

3.4.3 Soil carbon quality indices

For the characterization of the carbon fractions, we calculated the following microbial indices: The C_{mic} :SOC ratio is the amount of microbial biomass C per unit organic C and denotes the carbon available for microbial growth. The qCO_2 was calculated as the ratio of the initial respiration rate and the C_{mic} in mg CO₂C gC_{mic}⁻¹ day⁻¹ and determines the energetic efficiency of the microbial community (Anderson, 2003). Furthermore, we calculated the ratios of C_{labile}:SOC and C_{mic}:C_{labile} to draw conclusions on the composition of the respective larger fraction.

3.5 *In situ* gas measurements

3.5.1 Flux measurements by closed chamber

 CO_2 efflux was measured with a vented steady-state closed chamber system connected to an infrared gas analyzer (IRGA) (LI- 8100A, LICOR Inc). PVC collars with a 20 cm inner diameter were inserted about 2 cm into the upper soil layer. Fluxes of CO_2 were measured for at least two minutes with CO_2 concentration measurements at one second intervals. The CO_2 efflux rate was calculated by fitting a linear regression to the data after refusing a dead band of fifteen seconds to account for closing effects of the chamber on the CO_2 efflux. Soil temperature and volumetric soil moisture (Theta Probe ML2x sensor, Delta-T Devices) were measured simultaneously for the top 10 cm soil depth next to the collar.

3.5.2 Flux measurement by gradient method

The soil's CO₂ concentration profile was determined by collecting soil gas samples from the soil depths of 5, 10, 20, 40, 60 and 100 cm by permanently installed aluminum tubes (inner diameter of 7 mm) inserted vertically into the soil up to the respective depth. For plots F-B and F-D (for definitions of acronyms refer to chapter 6.1Methods for flux measurements), the sampling was only possible to a depth of 40 and 60 cm respectively because of calcrete layers in the subsoil. The aboveground ends of the tubes were sealed with a septum. One set of tubes was installed next to each location of chamber measurement. Soil gas samples were taken with a 2 ml syringe and injected into the CO₂ free airflow (scrubbed with soda lime) of the LI-8100 System. The area under the measured peaks was integrated and calibrated against a calibration line, which was generated from three known gas mixtures with CO₂ concentrations between 0.1 and 1 %. Three to four gas samples were taken per soil depth and the measured concentrations were averaged after excluding outliers. The mean overall precision of the method was \pm 7.7 % of the measured value. At each plot and date the CDCM was applied on three collars and the GM with three sets of collecting tubes to account for small-scale variability.

3.6 Statistical analysis

To test the effect of land-use type on the stock of all fractions and the microbial indices, we used one-way analysis of variance (ANOVA) followed by Tukey's HSD post-hoc test for more than two land-use types per landscape unit. We tested the data for equality of variances with the Levene's test. Data were log transformed whenever Levene's test indicated unequal variances. The significance level for ANOVA and the post-hoc test was conservatively set to p = 0.01 to account for violations of normal distribution following (Quinn and Keough, 2002). Pearson correlation was performed between the carbon fraction, N_{mic} and the initial rate and environmental parameters. Outliers with high leverage were identified using Cook's distance. All statistical analyses were done using the statistical software R version 3.3.2 (R Core Team, 2016).

4 THE SOILS OF THE OKAVANGO CATCHMENT

4.1 Available database on soils of the Okavango Region

Studies on the soils within the Okavango Catchment are rare. There are practically no detailed studies on soil distributions in Angola available. Only before the civil war, for the Angolan part of the catchment a rough description of the landscape structure has been prepared by Diniz (1973) based on the physiography of the area and including information about soil and plant distribution. (Asanzi et al., 2006) described some soils in the region of Huambo in central Angola with the aim to evaluate their land-use potential. Founded by the FAO, a report on the agricultural situation of the province Bié, which is situated in the northern part of the catchment, was written by Abdelli and Jouen (2012).

Challenges concerning the millet-based smallholder agriculture with emphasis on soil conditions in the Namibian part of the catchment were highlighted by Matanyair (1996), and the Ministry of Environment and Tourism (2000) prepared a study of the natural resources of the Kavango Region, which encompasses only a few soil analysis and schemes on the relation between soil and vegetation distribution. Simmonds (1998) and Simmonds (2000) prepared a baseline survey of the soils of the catchment, with strong emphasis on the Namibian part. This study included ground checking, soil classification and laboratory analysis. It mentions the dominance of Arenosols for the Okavango basin with significant contributions of Calcisols. Recently, the "Soil Atlas of Africa" was published (Jones et al., 2013), in which the knowledge on soil distribution in the scale 1:300.000 is summarized. Petersen (2008) prepared a comprehensive study dealing with pedodiversity along a transect from the cape region in South Africa to northern Namibia and Haarmeyer et al. (2010) comprise an overview of the soil types and properties occurring on the same sites. Wang et al. (2007) gave an overview of the soils of the Kalahari. The report highlights the sandy, nutrient poor and acidic nature of the Kalahari soils. Beyond that, to my knowledge, a comprehensive study on the distribution of soils, their properties and the influence of land use on soil ecosystem services is, up to now, not available for the southern African region including Angola.

It became evident, that, while on the broad scale some studies are available describing the soils of the Okavango basin, especially for the Kalahari sandy soils, almost no studies are concerned with the distribution of soils along the Okavango River. This chapter aims at

- giving a detailed description of soils using soil catenae,
- depicting the distributions of pedodiversity addressed by comparing the diversity of soil types in the study sites and land use units, and
- investigating the land-use pattern and its relation to fertile soils.

4.2 Design of the study and sampling

Prior to sampling, the research sites were stratified according to their dominant land use and landscape structure. Afterwards, the field work aimed at the description and sampling of all respective units of the combination of land use and landscape. In total, 1,382 soil samples were taken from 410 point locations, 267 of which were soil profiles and 143 were mixed topsoil samples. The soil classification was done on the location of which profile information were available. For details about the soil sampling refer to Chapter 3.1.

4.3 Soils in relation to landscape

4.3.1 Soils of Cusseque

On the study site Cusseque, the Holocene landscape is a product of long-lasting erosion processes, which formed a gently rolling surface on a Precambrian granitic plateau basis. The landscape is structured by an almost rectangular grid of small creeks to medium sized streams.



Figure 4.1: Number of soils within the respective WRB soil reference group for the study site Cusseque with the first preafix qualifier.

The underlying bedrock is covered by a layer of medium sized sands of varying color and thickness, which links the area to the Kalahari Basin. Even though the sampling was not evenly distributed within the study site, the frequency of occurrences suggests that Arenosols are the dominant soil type of the area (Figure 4.1). They predominantly occur as sand layers above the bed rock of at least 2 m thickness on the hilltops and are covered by miombo woodlands (Figure 4.2).



Figure 4.2: The main WRB reference groups in the study site Cusseque and location of the idealized catena (orange line). Areal picture by BingMaps.



Figure 4.3: Idealized catena for the study site Cusseque with typical soil profiles: a) Hypoluvic Arenosol; b) Rubic Arenosol; c) Pisoplinthic Plinthosol; d) Haplic Gleysol; e) Sapric Histosol; f) Pisoplinthic Acrisol; g) Haplic Cambisol; h) Rubic Arenosol.

Chapter 4

Table 4-1: Soil properties in the topsoil (0-10 cm) of the catena on the study site Cusseque. The texture
is indicated for the topsoil and subsoil if different from topsoil. Height = height above deepest soil
profile; SOC = Soil organic carbon; P = plant available phosphorous; K = plant available potassium;
Sum of bases = sum of exchangeable bases (Na, K, Mg, Ca). The profile number denotes the soil profile
corresponding to Figure 4.3.

Profile								
number	а	b	c	d	e	f	g	h
Height (m)	62	72	22	15	0	10	33	32
Landscape unit	hilltop	hilltop	sandy slope	mineral wetland	peaty wetland	shallow slope	hilltop	hilltop
Land use	dryland agriculture	miombo woodland	grassland	unused	unused	grassland	miombo wood- land	miombo wood- land
Classification	Hypoluvi- Rubi- Brunic Arenosol, Dystric	Rubic Arenosol, Dystric, Greyic	Pisoplinth- Stagnic Plinthosol, Abruptic, Alumic, Dystric	Haplic Gleysol, Dystric, Greyic, Arenic	Sapri- Rheic Histosol, Dystric	Pisoplinthic Acrisol, Alumic, Hyper- dystri, Greyic, Arenic	Haplic Cambi- sol, Dys- tric, Greyic	Rubic Areno- sol, Dys- tric
Texture topsoil - sub- soil	LS - SL	LS - SL	LS - C	SL - SCL	n.d n.d.	LS - SL	LS - SL	LS - LS
pH_{CaCl}	4.8	3.6	5.1	4.5	3.8	3.8	3.7	3.6
SOC (g kg ⁻¹)	11.06	8.42	15.44	13.18	375.05	7.32	8.45	14.78
$TN (g kg^{-1})$	0.63	0.53	0.83	0.83	15.79	0.40	0.53	0.63
C/N	17.6	15.9	18.6	15.9	23.8	18.3	15.9	23.5
$P(mg kg^{-1})$	7.0	8.0	5.0	10.0	0.0	5.0	5.0	7.0
K (mg kg ⁻¹)	22.0	14.0	61.0	68.0	0.0	14.0	7.0	14.0
sum of bases (mmol eq/kg)	10.3	n.a.	n.a.	9.1	105.7	n.a.	n.a.	n.a.

The sand coverage allows the deep percolation of the rain water and thus the soils do not exhibit signs of hydromorphology (Figure 4.3). The soils are the most acidic in the land-scape with topsoil pH-values of about 3.6 (in CaCl₂). The natural fertility of the soils is low, indicated by the low availability of P and K and a high C/N ratio between 16 and 24. The topsoil concentrations of SOC are comparably low (8 - 15 g kg⁻¹), but the soil surfaces are often covered by patchy accumulation of litter.

The soils on the slopes were more diverse depending on the thickness of the sand cover and soil development but are dominated by Acrisols (Figure 4.3). On places with reduced sand coverage, especially on the western slopes of the Cusseque River, Plithosols have been formed during long-term tropical development. These Plinthosols are characterized by an abrupt change from sandy topsoil to clayey soil texture in the subsoil and a mixture of pisoplinthic material within the upper soil layer. The intensively colored clayey subsoils are the result of granite weathering and prevent deep drainage of water and thus support the development of iron concretions in the zone of alternating redox potentials by stagnating water. At places with slightly larger sand coverage, a Pisoplinthic Acrisol has been found where the deeper subsoil shows similar hydromorphic features as the Plinthosol. The topsoil is acidic (pH 3.8 in CaCl₂) and low-activity clays have been enriched in the subsoil. On the broad, open vegetated slopes east of the Cusseque River (see 28 bright colored areas in (Figure 4.2) the sandy layer is > 2m in depth. Depending on the intensity of weathering, Arenosols and Cambisols are developed, both soil types low in pH (dystric), in nutrient content and SOC concentration.

In the valleys, wetlands are formed by permanently inter-flowing groundwater from the higher areas. This water preserves water-logged conditions during the whole year and is the reason for the accumulation of peats on the mineral surface. Depending on the topography of that surface, the peat layer thickness varies between few decimeters up to > 2 m and the soils are classified as Sapri-rheic Histosols. The peat is of highly decomposed organic material, acidic (pH = 3.8 in CaCl₂) and the relative amount of nitrogen within the topsoil (C/N ratio 23.8) is low, even though the total level is the highest of all profiles (15.79 g kg^{-1} , Table 4-1). Uphill at the transition from the peatlands to the slopes, a band of mineral soils with varying groundwater level has developed, partly covered by grasses, partly being nearly uncovered. The sands may be totally bleached or enriched with blackish organic material. They are classified as Gleysols, which are all dystric and may exhibit irregular accumulation of SOC. Signs of hydromorphic features are weakly developed.

4.3.2 Soils of Caiundo

The upper areas exhibit a fairly homogenous soil cover of the dominant soil types, rubic Arenosols and haplic Cambisols (Figure 4.4, Figure 4.5). Both soil types differ slightly in their clay and silt content of the subsoil. For the Cambisols, the subsoils texture is sandy loam, whereas the Arenosols are composed of sand or loamy sand (Table 4-2). The colors of the prevailing sands are slightly variable with the more reddish sands occurring on the hills east of the river. Compared to the northern study site, the soil pH on the Kalahari sands is less acid (in the mean 4.9 in CaCl₂), the SOC of the topsoil is about 4 g kg⁻¹ with a C/N ratio of about 10.6.



Figure 4.4: Number of soils within the respective WRB soil reference group for the study site Caiundo with the first preafix qualifier.


Figure 4.5: The main WRB reference groups of the study site Caiundo and location of the idealized catena (orange line). Areal picture by BingMaps.



Figure 4.6: Idealized catena for the study site Caiundo with typical soil profiles: a) Rubic Arenosol; b) Hypoluvic Arenosol; c) Endogleyic Cambisol; d) Fluvic Gleysol; e) Gleyic Fluvisol; f) Rubic Arenosol; g) Haplic Cambisol.

The availability of phosphorous is low (< 3 g kg⁻¹ P_{DL}, 6.2 g kg⁻¹ P_{Bray}), that of potassium slightly better (24 g kg⁻¹). Along the slopes to the river, the influence deposition of fluvial sediments as well as groundwater fluctuation has produced diverse soil properties.

Upper parts are dominated by endogleyic and haplic Cambisols with patches of Calcisols included whereas in the low-lying recent floodplains a mixture of gleyic or mollic Fluvisols and different types of Gleysols are prominent (Figure 4.5). Here, the soil texture covers the full range of pure sands on ridges and clays in depressions. At places with calcretes in the subsoil the pH is neutral, at other places slightly acid. In the topsoil of the recent floodplains, SOC is substantially enriched $(23 - 50 \text{ g kg}^{-1})$. The C/N-ratio averages about 15 and the phosphorous availability varies between < 3 and 47 mg kg⁻¹. The topsoil with high amounts of SOC and clay sum of bases was found to be up to 367 mmol_c kg⁻¹.

Table 4-2: Soil properties in the topsoil (0-10 cm) of the catena on the study site Caiundo. The texture is indicated for the topsoil and subsoil if different from topsoil. Height = height above deepest soil profile; SOC = Soil organic carbon; P = plant available phosphorous; K = plant available potassium; Sum of bases = sum of exchangeable bases (Na, K, Mg, Ca). The profile number denotes the soil profile corresponding to Figure 4.6.

Profile							
number	а	b	с	d	e	f	g
Height (m)	13	69	63	79	80	0	0
Landscape unit	Kalahari dunes	Kalahari dunes	slope	floodplai n	floodplain	hilltop	hilltop
Land use	woodland	grassland	grassland	grass- land	grassland	woodland	dryland agricul- ture
Classification	Rubic Are- nosol, Dys- tric, Greyic	Hypoluvic Arenosol, Eutric, Greyic	Endogleyic Cambisol, Eutric, Greyic	Fluvi- Luvic Gleysol, Dystric, Clayic	Gleyic Fluvisol, Calcaric, Eutric	Rubic Are- nosol, Dys- tric	Haplic Cam- bisol, Dystric
Texture topsoil - sub- soil	LS - S	S - LS	SL - SCL	SiL - C	SiL - S	S - SL	LS - SL
pH_{CaCl}	4.9	5.2	5.6	4.3	7.3	3.9	5.4
SOC $(g kg^{-1})$	4.45	8.16	7.83	23.03	24.89	2.78	3.54
$TN (g kg^{-1})$	0.36	0.61	0.55	1.51	2.03	0.30	0.37
C/N	12.4	13.4	14.2	15.3	12.3	9.3	9.6
$P (mg kg^{-1})$	< 3	< 3	< 3	< 3	21.0	< 3	10.0
$K (mg kg^{-1})$	14.0	42.0	56.0	36.0	74.0	20.0	33.0
sum of bases (mmol eq/kg)	9.5	28.6	n.a.	95.4	300.2	n.a.	3.8

4.3.3 Soils of Mashare

The soilscape in Mashare is defined by a characteristic sequence of three landscape units, namely recent floodplains, old floodplaines and Kalahari dunes. Along the river, eutric Fluvisols have been formed by sediment during flood events. Arenosols are the dominant

Chapter 4

soil type on the Kalahari dunes but also occur on the old floodplains and levees on recent floodplains (Figure 4.7, Figure 4.8).

Within the recent floodplains, a mixture of soils with varying properties from the reference groups Fluvisols, Gleysols, Arenosols, Cambisols and Solonetz were found. Here, a gleyic Fluvisol occur (Figure 4.9) that is characterized by layers of recent high-flood fine-grained sediments (silty clay, clay and silty loam) of the Okavango River. Iron mottling indicates the frequent inundation and the long-lasting groundwater influence. Due to the clean water of the Okavango, topsoil nutrient concentrations are low (phosphorous) to moderate (potassium). The pH is acidic and the level of SOC in the topsoil the highest in the catena (Table 4-3).



Figure 4.7: Number of soils within the respective WRB soil reference group for the study site Mashare with the first preafix qualifier.

The vast area covered with Kalahari sands exhibits only low variability in soil properties. All soils are Arenosols of low pH (dystric), low topsoil SOC and low exchange capacity. On the slopes to the river, the sands are reddish with a slightly higher clay content (4.1 % in the subsoil) compared to the bright to grayish sands of the plateau areas further in the south (1.7 % clay in the subsoil). The relation of medium sand to fine sand (mS/fS) varies between 1.1 and 3.1 with a tendency to be wider in the topsoil than in the subsoil. Reserves of cations are large in the rubic Arenosols along the river. The soils of the dry riverbed are comparable to those of the old floodplains with high carbon contents and high amounts of bases.



Figure 4.8: The main WRB reference groups of the study site Mashare and location of the idealized catena (orange line). Areal picture by BingMaps.



Figure 4.9: Idealized catena for the study site Mashare with typical soil profiles: a) Gleyic Fluvisol; b) Petric Calcisol; c) Petric Calcisol; d) Cutanic Luvisol; e) Rubic Arenosol; f) Haplic Luvisol; g) Haplic Arenosol.

Chapter 4

corresponding to Figure 4.9.								
Profile number	a	b	с	d	e	f	g	
Height (m)	19	0	20	40	38	29	70	
Landscape unit	floodplain	old floodplain	old floodplain	old floodplain	Kalahari dunes	Kalahari dunes	Kalahari dunes	
Land use	grassland	bushveld	irrigation agr.	irrigation agr.	bushveld	bushveld	wood- land	
Classificati- on	Gleyic Fluvisol, Humic, Dystric, Clayic	Petri- Luvic Calcisol, Arenic	Petri-Luvic Calcisol	Cutanic Luvisol, Hypereut- ric	Rubic Arenosol, Eutric	Haplic Luvisol, Hypereut- ric, Arenic	Haplic Areno- sol, Eut- ric, Greyic	
Texture topsoil - subsoil	SiCL - SiL	SL - n.d.	SCL - CL	L - SL	S - S	LS - S	S - S	
pH_{CaCl}	4.3	6.4	6.7	7.4	5.4	5.8	4.4	
SOC $(g kg^{-1})$	22.82	15.44	11.94	4.21	4.23	8.14	3.81	
$TN (g kg^{-1})$	2.09	1.29	1.09	0.49	0.38	0.72	0.29	
C/N	10.9	12.0	11.0	8.6	11.1	11.3	13.1	
$P(mg kg^{-1})$	6.0	5.0	14.0	60.0	< 3	< 3	54.0	
K (mg kg ⁻¹)	52.0	144.0	285.0	174.0	26.0	78.0	9.0	
sum of bases (mmol eq/kg)	n.a.	65.6	135.9	247.3	9.3	45.7	9.3	

Table 4-3: Soil properties in the topsoil (0-10 cm) of the catena on the study site Mashare. The texture is indicated for the topsoil and subsoil if different from topsoil. Height = height above deepest soil profile; SOC = Soil organic carbon; P = plant available phosphorous; K = plant available potassium; Sum of bases = sum of exchangeable bases (Na, K, Mg, Ca). The profile number denotes the soil profile corresponding to Figure 4.9.

4.3.4 Soils of Seronga

In the study site of Seronga, the dominant soil types are Arenosols on the sandy plains (Figure 4.10). The soils within the floodplains are heterogeneous with regard to organic matter accumulation and the intensity of water influences. Riparian soils were all classified as Gleysols and composed of sandy fluvial sediments, however, without signs of fluvial deposition in the actual state. At these profiles, the accumulation of organic matter depends on the groundwater level and the density of the vegetation cover. We found topsoil SOC that reached 34 g kg^{-1} in a depression with grasses and only 2.4 g kg⁻¹ on a sandy levee (Table 4-4).



Figure 4.10: The main WRB reference groups of the study site Seronga and location of the idealized catena (orange line). Areal picture by BingMaps.



Figure 4.11: Idealized catena for the study site Seronga with typical soil profiles: a) Haplic Gleysol; b) Haplic Gleysol; c) Haplic Gleysol; d) Haplic Arenosol; e) Haplic Arenosol; f) Haplic Cambisol; g) Haplic Arenosol.



Figure 4.12: Number of soils within the respective WRB soil reference group for the study site Seronga with the first preafix qualifier.

Table 4-4: Soil properties in the topsoil (0-10 cm) of the catena on the study site Seronga. The texture is indicated for the topsoil and subsoil if different from topsoil. Height = height above deepest soil profile; SOC = Soil organic carbon; P = plant available phosphorous; K = plant available potassium; Sum of bases = sum of exchangeable bases (Na, K, Mg, Ca). The profile number denotes the soil profile corresponding to Figure 4.11.

Profile							
number	a	b	с	d	e	f	g
Height (m)	0	3	9	4	0	8	8
Landscape unit	floodplain	floodplain	floodplain	levelled kalahari dunes	levelled kalahari dunes	levelled kalahari dunes	levelled kalahari dunes
Land use	grassland	grassland	grassland	mopane bushveld	dryland agr.	mopane woodland	Baikiaea woodland
Classification	Haplic Gleysol, Dystric, Greyic, Arenic	Haplic Gleysol, Eutric, Hypero- chric, Arenic	Haplic Gleysol, Dystric, Greyic, Arenic	Haplic Areno- sol, Dystric	Haplic Arenosol, Eutric, Greyic	Haplic Cambisol, Eutric, Greyic	Haplic Arenosol, Dystric, Hyper- ochric
Texture topsoil - sub- soil	n.d LS	S - S	n.d S	S - S	LS - LS	SL - LS	S - S
pH_{CaCl}	4.5	4.9	4.5	4.8	5.9	5.1	3.9
SOC (g kg ⁻¹)	33.81	2.41	21.80	5.26	3.51	3.90	4.83
$TN (g kg^{-1})$	3.11	0.27	2.07	0.39	0.29	0.39	0.38
C/N	10.9	8.9	10.5	13.5	12.1	10.0	12.7
$P(mg kg^{-1})$	0.0	< 3	< 3	5.0	10.0	4.0	6.0
$K (mg kg^{-1})$	0.0	12.0	38.0	10.0	79.0	52.0	5.0
sum of bases (mmol eq/kg)	54.2	7.3	45.0	15.4	44.1	22.3	5.4

The dune sand area is located about 10 m above the floodplains. Here, in patchy distribution, two different soils occur with a third forming the direct boundary between both (Figure 4.11). The first type is a haplic Arenosol that is eutric and greyic. The second soil is also classified as Arenosol, however, it is different in terms of the two qualifiers dystric and hyperochric. The pH of both Arenosols are exclusive: The dark grayish to browngrayish Arensols depict a topsoil pH (in CaCl₂) between 5.3 and 7.1 (on average 5.9), whereas for the bright gray Arenosols the respective pH was found to be between 3.9 and 4.9 (on average 4.4).

Moreover, the topsoil SOC (eutric Arenosols on average 5.0 g kg⁻¹, dystric Arenosols on average 3.5 g kg⁻¹, see chapter 5), the sum of exchangeable bases and the P content. The distribution of both types of Arenosols is indicated by different vegetation: If undisturbed, the eutric Arenosols are covered with Mopane woodland and the dystric Arenosols with Terminalia woodland. Cropping is restricted to the eutric Arenosols.

The third soil between both units occurs as a slim strip of reddish colored Cambisols (slim red band in areal photograph, Figure 4.10). These soils exhibit an intermediate topsoil pH (4.6 - 5.6 in CaCl₂) and a slight increase in the clay content with depth. Also, the nutrient base is intermediate between both Arenosol units.

4.3.5 Soils under agricultural use

The analysis revealed the dependence of pedodiversity on the landscape unit. The slopes in the study site Cusseque and the floodplains in the three southern study sites were much more diverse, including Fluvisols, Calcisols, Arenosols, Luvisols and Cambisols, than the relatively homogenous hinterland and hilltops with dominating Arenosols. The land-use pattern is associated with the distribution of the fertile soils in most cases. In Cusseque and Caiundo, the prevailing land-use practice is slash and burn agriculture, which takes advantage of the nutrient flush after the burning of woodlands and only lasts for up to five years of continuous cultivation. Interestingly, the floodplains in Caiundo are only sporadically cultivated although the soil analysis indicated higher available nutrients contents for some of the soils in this landscape units suggesting a better suitability for cropping than the hilltops. A reason might be the cultural adaptation of the slash and burn practice which is restricted to woodlands. The staple crops in Cusseque and Caiundo are maize and cassava with intercropping of melons and beans. Additionally, in Cusseque horticulture is conducted in the wetlands on Histosols with potatoes and cabbage as the main crops. In Mashare the agriculture is focused on the loamier floodplains with permanent fields but extending to the nutrient-poor hinterland. The staple crop is Mahango (Pearl millet) and some intercropping vegetables like beans and ground nuts. In Seronga, agriculture concentrates on distinct areas which offer favorable conditions with elevated nutrient and carbon contents and p. The field are fenced against cattle and elephants and permanently cultivated with only occasional fellow periods.

4.4 Discussion on the soils of the Okavango Catchment

The soilscape in Cusseque was shown to be very diverse with particular soil types in the three different landscape units. Very little is published in the current scientific literature

Chapter 4

about the soil distribution on the landscape scale. Aside from the soil map of Angola from the Centro des Estudos Pedologicas (1961), the only recent study to my knowledge is from the Huambo region and aims at describing the soils with respect to their agricultural potential (Asanzi et al., 2006). They classified the soils according to the Soil Taxonomy (Soil Survey Staff, 1999), however, they found Alfisols and Ultisols, probably corresponding to the Luvisols and Acrisols described in this study. Even though they found some Oxisols (corresponding to Ferralsols in the WRB) in their study, they only appear in a few locations and were probably related to specific geology.

According to Jones et al. (2013), the vast northern part of the catchment is composed of Kalahari sands and covered with Ferralic Arenosols in the south-east and Haplic and Xanthic Ferralsols in the north-west. The Ferralsols are the result of intensive weathering of the bedrock, typical for the humid tropics (IUSS Working Group WRB, 2006). The proposed dominance of Ferralsols are depicted in the World Soil Map by Jones et al. (2013) further to the north west from the study site. On the study site, the dominant soil types were Arenosol, followed by Acrisols, which tends to be in line with Asanzi et al. (2006).

The soils in Caiundo are depicted as dominated by haplic Arenosols, with few inclusions of xanthic Ferralsols and carbic Podzols more in the eastern part of the middle reaches and with stretches of petric Calcisols along both main tributaries of the Okavango, the Cubango and the Cuito in the Soil Atlas of Africa (Jones et al., 2013). The dominance of Arenosols and the occurrence of Calcisols in the floodplains were confirmed by this study, however, as for the Cusseque site, no Ferralsols were found here.

The prevailing soil types in Mashare are Arenosols in the Kalahari dunes and Calcisols in the floodplains, which is in line with the findings of this study. South-west from the study site, the Kalahari sand still exists as well developed dunes and interdunes (Petersen, 2008). Calcisols are to found in the interdunes. The heavier textured soils found in the old floodplains and dry riverbeds at Mashare are confirmed by Strohbach and Petersen (2007) for a region about 100 km south-west from the study site Mashare. Likewise in our study, they can co-occur as Calcisols and Cambisols in the interdune areas of longitudinal dune-interdune systems and in omiramba (Petersen, 2008).

The study site Seronga was shown to be composed of two distinct landscape units: In the east the broadening river bed (Panhandle) with floodplains with several channels and lagoons and, in the west, the extending sandveld. This is in accordance with Jones et al. (2013), who show the soilscape to be composed solely of haplic Arenosols in the sandveld, whereas in the river bed a mixture of eutric Fluvisol and fibric Histosols occur.

The Seronga study site was found to be the least diverse site of the four. This may be caused by the concentration of sampling on the sandveld area, which is much lower structured than in Mashare and Caiundo. The diversity would be likely to increase if more sampling was conducted in the floodplains, which are characterized by a diverse pattern of levees, termite humps, peaty areas and depressions (Gröngröft et al., 2013b). Within the swamps, accumulation of organic substances may become very large and, at places, even large areas of peat accumulation was found by McCarthy (2013). The pH is slightly acid and lower than the respective pH-value in the open water of channels (pH 6.4) (Mosimane et al., 2017) which indicates the losses of base cations by leaching.

The distribution of the dominant soil types was found to be congruent with the world soil map by Jones et al. (2013) in most study sites. The dominance of Arenosols in the major parts of the Kalahari Basin is agreed upon by several authors (Hartemink and Huting, 2008; Jones et al., 2013; Simmonds, 1998; Strohbach and Petersen, 2007). The aeolian sands originate from the tertiary desert forming and were redistributed during the Holocene at dryer climates about 30,000 years ago when extensive sand drifts formed parallel dunes by easterly prevailing winds (Simmonds, 1998).

5 INFLUENCE OF CLIMATE, LANDSCAPE & LAND USE ON THE SOIL CARBON STOCKS

5.1 Background of SOC in southern Africa

Soil mining, low input farming systems and insufficient management of SOC is followed by the degradation of soils and a decline of the nutrient status by a negative nutrient balance (Bationo et al., 2007). This is of particular challenge for assuring the food security in Africa, especially with regard to the ongoing population growth (Tscharntke et al., 2012). It becomes obvious that soil management practices should be developed and adopted that help to maintain soil fertility, in particular for low input agricultural systems where natural soil fertility determines crop production (Lal, 2006). There are basic principles applying to the conservation of soil resources that are strongly linked to the management of SOM as indicated in Figure 5.1 (Lal, 2014). The influences that determine the amount, the stability and the quality of SOM are manifold and land use interferes at several stages with the formation of SOM and, therewith, the soil quality.



Figure 5.1: Basic principles of soil resource conservation. The figure indicates the central importance of SOM for soil quality. The Figure is from (Lal, 2014).

In nutrient-poor dryland soils, agricultural land use depends on the provision of nutrients during the decay of organic material but, at the same time, benefits from a high SOM sta-

Chapter 5

tus that aggregates soil particles, supports water holding capacity and buffers nutrient loss by leaching (FAO, 2017). The balance between input and outputs of SOM is thereby determining the SOC status of a soil (von Luetzow et al., 2006). The main inputs are plant roots and root exudates, plant litter and residues, and organic soil amendments like manure (Powlson et al., 2011). In conventional agricultural systems, the SOM-stock generally depletes during agricultural use because the feedback of organic material drops, while at the same time tillage practices support the soil respiration by exposing the protected SOM to the microbial access (McLauchlan, 2006). The loss of soil fertility by the depletion of SOM is particularly crucial in dry ecosystems that are known for their naturally low carbon contents being usually below 0.5 % (Lal, 2004). However the Kalahari soils are indicating a large relative variability with concentrations between 0.2 and 0.6 % on an overall low level (Perkins and Thomas, 1993).

Although it is known that soil carbon stocks are affected by land use, the magnitude of SOC decline attributed to different small holder land use practices in southern African semi-arid and semi-humid soils is little investigated. This chapter aims at contributing to the knowledge of these effects by investigating the SOC stocks in soils along the climatic gradient from semi-arid to semi-humid along the Okavango River and its tributaries. The need for suitable cropping land for the growing population leads to increasing conversion of natural woodlands to agricultural fields which increasingly endangers the soil functions (Kgathi et al., 2006; Mendelsohn and ElObeid, 2004). Land-use patterns suggest that the best soils for cropping are situated within certain landscape units as has been shown in the chapter The soils of the Okavango Catchment. In this chapter, it will be investigated, if the distribution of soil carbon stocks within the landscape follows the same pattern. This will be of main interest in order to develop future sustainable land-use strategies that incorporate active SOM management. Here, an assessment of soil carbon stocks is presented focusing on the following questions:

- How is soil carbon distributed within the different landscapes of the studied areas?
- Is the climatic gradient within the catchment influencing the pattern of SOC stocks?
- How does the conversion of woodlands to low input agriculture affect the SOC?

5.2 Sampling design

The sampling was stratified according to the dominant land-use and landscape structure as was explained in the chapter Design of the study and sampling. Afterwards, the field work aimed at sampling of all respective units of the combination of land-use and land-scape in land cover units (in the following referred to as LC-units). Overall, 26 LC-units were sampled with a total of 887 mixed soil samples from 267 soil pits. For details on soil sampling refer to chapter 3.1 Soil Sampling.

5.3 Results on SOC stocks in the Okavango Catchment

The variation of topsoil (30 cm depth) SOC stocks between the landscape units within one study site exceeds by far the variation of the sites (Figure 5.2). The highest SOC

stocks and, at the same time, the highest variability was found in the wetlands and wateraffected landscape units of each study site. Significantly higher SOC-stocks were measured in the old floodplains in Mashare compared to the adjacent Kalahari dunes. Also the soils under Mopane trees in Seronga exhibit significantly higher SOC-stocks than the surrounding soils with *Baikiaea* sp. dominated vegetation. The high variability within the wetlands Caiundo, Mashare and Seronga reflects the small-scale heterogeneity of the landscape units with clayey depressions and sandy levees. With increasing distance to the river, SOC stocks were found to be low, exceeding 3 kg m⁻² in dry riverbeds only (Table 5-1).

The overall highest contents were found in the peatlands in Cusseque. In Caiundo, Mashare and Seronga, highest contents were found in the regularly inundated recent floodplains (mean SOC contents of 27.2 g kg⁻¹, 15.2 g kg⁻¹ and 24.7 g kg⁻¹ respectively).

Median soil carbon stocks to 1 m depth on undisturbed plots was 4.09 kg m⁻²; the maximum of 49.6 kg m⁻² was found in Angolan peatlands and the minimum of 1.03 kg m⁻² in Arenosols of the pure sandy Kalahari dunes in Mashare. When restricted to the woodland sites on deep sandy Arenosols on Kalahari sands, the comparison of the four study sites reveals significantly higher SOC stocks in Cusseque compared to all other study sites (Figure 5.3a, Table 5-1). In these landscape units, the SOC stocks exceeded the aboveground woody biomass carbon on the three southern study sites (Caiundo, Mashare, Seronga) and was almost equally distributed in Cusseque (Figure 5.3b).



Figure 5.2: Topsoil (0-30 cm) organic carbon contents in the different landscape units. Letters indicate significantly different SOC stocks at p < 0.05 within the respective study site.



Figure 5.3: a) SOC stocks in woodlands of the study sites. Groups with significantly (p > 0.05) different carbon stocks are indicated by different letters. b) Average SOC stocks and estimated woody biomass carbon of woodlands in the study sites.

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Study site	Landscape unit	Z	C-stock, 0.3 m, woodland (kg m ⁻²)	Z	C-stock, 1 m, woodland (kg m ⁻²)	Z	0.3 m, dryland agri- culture (kg m ⁻²)	Z	1 m, dryland agri- culture (kg m ⁻²)
Cusseque	peaty wetlands	9	13.93 ± 4.31	0	42.5 ± 9.97				
	mineral wetlands	5	3.34 ± 1.96	4	12.67 ± 9.29				
	shallow slopes	17	2.17 ± 0.59	8	3.9 ± 0.87				
	deep sandy slopes	5	2.23 ± 0.46	5	3.93 ± 0.74				
	hilltops	27	2.69 ± 0.91	22	5.13 ± 1.24	5	2.25 ± 0.85	5	4.45 ± 1.13
Caiundo	recent floodplains	9	9.35 ± 2.67	9	16.74 ± 6.46				
	old floodplains levees	S	2.09 ± 0.37	5	4.76 ± 1.03				
	old floodplains depres- sions	٢	70 0 T 37 C	٢	C L C + CU Y				
	Kalahari dunes reddish	- c	2.+2 ± 0.8+	- c	21.2 ± 20.0	Y	1 11 ± 0 1	Y	7 18 ± 0 10
	Kalahari dunes yellow	1 4	1.63 ± 0.68	1 4	3.08 ± 1.01	0	1.0 - 11.1	þ	
Mashare	recent floodplains	6	3.92 ± 4.41	8	7.47 ± 8.15	-	1.53	1	4.41
	old floodplains	15	2.05 ± 1.32	10	4.5 ± 1.91	13	1.06 ± 0.43	10	3.51 ± 0.59
	Kalahari dunes	39	1.05 ± 0.27	11	2.62 ± 0.65	20	0.77 ± 0.29	14	2.33 ± 0.5
	omiramba	9	4.14 ± 2.48	S	8.26 ± 2.98	6	1.11 ± 0.47	6	2.95 ± 0.27
Seronga	recent floodplains	4	3.6 ± 3.57	m	2.86 ± 2.33				
	Kalahari sandveld, Mo-								
	pane	5	2.24 ± 0.38	5	5.13 ± 1.16	12	1.82 ± 0.43	12	4.42 ± 0.93
	Kalahari sandveld, transi-								
	tion	0	0.98 ± 0.4	1	3.14	1	1.21	1	3.26
	Kalahari sandveld, <i>Baikiaea</i>	C		C	1201220				
		0	1.22 ± 0.19	0	10.0 ± 0.07				

Table 5-1: SOC stocks estimated for two depths (0.3 m, 1 m) of the different landscape units in the study sites. Woodland sites



clay + silt (%)

Figure 5.4: Correlation between organic carbon and the sum of the clay and silt fraction of topsoils (010 cm) on all study sites (R2 = 0.483, n = 90, p < 0.001).

The overall average proportion of the SOC stock in the topsoil (0.3 m) to the total 1 m stock was found to be $50.1 \pm 10.8 \%$, indicating a relative concentration of SOC in the topsoil (Figure 5.5). A proportion of 33 % means that SOC is equally distributed in the first meter of soil depth. With as much as 51 %, 47 %, 45 % and 45 % of carbon within the first 0.3 m respectively from north to south, the average percentages for each study site did not differ greatly. The tendency to higher topsoil SOC stocks was found in all landscape units except for the peaty wetland in Cusseque, where the SOC was evenly distributed along the soil depth.

Relatively high topsoil contributions of SOC were found in the mineral soils of wetlands in all study sites and more even distributions were recorded on old floodplains. However, the variation within the landscape units was still high and no significant differences between them could be observed.

The effects of woodland conversion to acres with short periods of continuous cropping (2-3 years) did not change SOC stocks on slash and burn agricultural fields in Cusseque and Caiundo (Figure 5.6). On long-term agricultural fields (older than 20 years) in Mashare, however, significant losses were observed (Figure 5.6). Over all, for the five pairs of landscape units, mean values change between +0.24 and -2.12 kg m⁻² or +11 to - 39 % of the initial values.



Figure 5.5 Proportion of carbon in topsoil (0 -0.3 m) in relation to total SOC (0 – 1 m) in the different landscape units of the respective study sites. The 33 % line indicates an even distribution of SOC with soil depth.



Figure 5.6: SOC stocks in different woodland types (miombo in the study site of Cusseque, Baikiaea in the study sites of Caiundo and Mashare, Mopane in the study site of Seronga) and in corresponding acres. Note that conversion to agricultural use took place at different times (short period since wood-land conversion in Angola and Botswana (1-5 years), long term cultivation in Namibia (more than 20 years).

5.4 Discussion on carbon stocks

Carbon contents in the research area are generally rather low compared to more moist and temperate climates (Scharlemann et al., 2014). However, even lower values were found on a 1000 km transect in the Kalahari in Botswana where Wang et al. (2007) reported values of $1.8 - 6.3 \text{ g kg}^{-1}$ with a mean of 4.3 ± 1.5 in the topsoil (0 - 5 cm) and Ringrose et al. (1998) with 2.6 ± 1.9 in the topsoil (0 - 10 cm) on a similar transect. Soil carbon stocks for woodlands in this study are at the lower end of what is reported on other savanna woodland sites. Ryan et al. (2011) found soil carbon stocks of 76 ± 10 t ha⁻¹ within the first 0.5 m in Mozambique and Alam et al. (2013) report an average of 54 t ha⁻¹ in an Acacia-woodland savanna in Sudan. In contrast, the dimension of our findings is in good agreement with Post et al. (1982) who found carbon stocks on the Cusseque site are predominantly caused by the higher productive ecosystem in the more humid Angolan highlands which receives about 300 - 400 mm more precipitation than the other study sites. However, not only the input of organic material is larger, also the capacity of soils to stabilize SOC increases along the precipitation gradient.

The association of carbon to the mineral fraction and, in particular, to the clay fraction is reported by several authors for east and southern African soils (Bird et al., 2004; Walker and Desanker, 2004). Saiz et al. (2012) analyzed the variation of soil carbon stocks along a precipitation gradient in West Africa. They found available water and a negative relationship to sand content rather than clay to be the best predictive parameters for soil carbon stocks to 0.3 and 1 m depth respectively. The last finding could be confirmed by this analysis, where correlation to clay content only gave a lower $R^2 = 0.404$ compared to the clay + silt fraction (Figure 5.4). Carbon increase with increasing clay content can be explained by the physical protection of carbon from decomposition in small pores of inner silicate layers that are not accessible for microbes (Tisdall and Oades, 1982). Also, high water contents in water-saturated wetlands and peatlands are stabilizing SOM, leading to exceptionally high SOC stocks in these systems (Laiho, 2006).

We found a concentration of SOC in the topsoil of about 50 % with no explanatory power of climate. Jobbagy and Jackson (2000) described that, globally, the vertical distribution of carbon is slightly more associated with vegetation than with climate. However, they report a higher carbon content in the top 0.2 m in relation to the top 1 m of soil in moist climates (57 %) than in dry climates, where the relative amount averages at 29 %.

Our findings on the reduction of soil carbon due to agricultural use is common and often found in literature, whereby the losses by slash and burn agriculture are often less pronounced than those of permanent cultivation (Vashum and Jayakumar, 2016). This is attributed to long fallow periods and relatively short continuous periods of use suggesting that this practice can be regarded as sustainable as long as sufficient land is available for rotation (Vashum and Jayakumar, 2016). In contrast, the dimension of declining SOC stocks during permanent agricultural use is exceptionally high compared to other studies from tropical and subtropical regions. Touré et al. (2013) found 27 - 37 % lower carbon stocks on groundnut fields than in the respective savanna soils in a dryland study area in Senegal. Demessie et al. (2013) analyzed a chronosequence of fields at the age of 12, 20, 30, 40, 50 years in southern Ethiopia. They found 40 % lower carbon stocks up to the depth of 1 m in comparison to natural forests on crop fields used over a 12 year period already. Walker and Desanker (2004) reported a reduction of 40 % of soil carbon due to agricultural use in a study on miombo woodlands in Malawi. A probable reason for the high losses in this study are the long duration of agricultural use together with the high initial carbon stocks found in the woodlands of old floodplains.

In this chapter, the distribution of soil carbon stocks within relevant landscapes in the Okavango Catchment was asserted and by analyzing carbon stocks in soils with different climate conditions, in different landscapes and under different land use and land-use intensity, important controlling factors of SOM were identified. By comparing carbon stocks in pristine vegetated plots (woodland) and acres used over long period of time for food production, the decline of soil carbon stocks were confirmed which was most pronounced on dryland agricultural fields under use for some decades. Better estimations of the rate of carbon loss would be achieved by incorporating measurements of the loss of SOC by heterotrophic soil respiration. Gathering those data is possible by measuring the CO_2 fluxes from the soil to the atmosphere and by the quantification of contribution of the root respiration to the CO_2 flux. Knowing the input of organic material, the carbon budged could then be calculated and used to determine whether the area under interest is gaining or loosing SOC in its actual state (Urbaniak et al., 2016).

6 CO₂ FLUXES IN SUBTROPICAL DRYLAND SOILS: A COMPARISON OF THE GRADIENT & THE CLOSED CHAMBER METHOD

6.1 Methods for flux measurements

Trace gas exchange between soil and atmosphere with regard to global warming and the emission of greenhouse gases has become a focus of a large number of studies conducted in the fields of atmospheric and soil science (Schlesinger and Andrews, 2000). A wide range of methods are thereby used depending on the scale and process of interest. On the landscape scale, eddy covariance is the most widely applied technique that allows an integrated measurement of trace gas fluxes over large areas (Myklebust et al., 2008). This technique enables determination of net ecosystem fluxes but cannot distinguish directly between processes involved, such as CO_2 fluxes from soil respiration and photosynthesis. On the pedon scale, the most popular direct methods for measuring fluxes are based on closed chambers placed on the soil surface. The fluxes are measured by analyzing the increase of gas concentrations inside the chamber (closed dynamic chamber method, CDCM) or by controlling inlet and outlet gas concentrations continuously from the air stream through the chamber (Livingston and Hutchinson, 1995; Rolston, 1986).

A second indirect method for quantifying gas fluxes on the pedon scale is the gradient method (GM), which makes use of the concentration gradient of a specific gas species between the soil and the atmosphere. For the estimation of fluxes, the diffusion properties of the soil and concentration gradients of the gas within the soil must be known (De Jong and Schappert, 1972). Both methods have advantages and disadvantages concerning precision of flux estimates and applicability in the field.

The CDCM directly determines the flux from the soil surface to the atmosphere of the chamber irrespective of sources of the gas, transport mechanisms involved and the gas concentration within the soil. Possible sources of errors are underestimations due to a change in the concentration of the respective gas in the headspace which alters the gradient as driver of gas movement via diffusion (Kutzbach et al., 2007). Overestimations of soil respiration occur when mass flow is induced by pressure pumping under windy conditions (Davidson et al., 2002), during nighttime low turbulence conditions (Schneider et al., 2009) or while other abiotic geochemical processes are responsible for CO_2 release (Rey, 2015). Disturbance by the insertion of the collars into the soil may significantly affect the topsoil environment and the microclimate, the latter again affecting the CO_2 efflux (Heinemeyer et al., 2011). Serious disadvantages occur with regard to time series measurements in remote areas as the method cannot be operated for long periods without maintenance.

The GM is based on a CO_2 concentration gradient between soil and atmosphere that results from the CO_2 production within the soil, usually by soil respiration. The gradient can be used to determine fluxes that are driven exclusively by gas diffusion in the direc-

Chapter 6 _

tion of the lower gas concentration by using Fick's first law. Different methods exist to estimate the gas flux (for a review of methods, see Maier and Schack-Kirchner, 2014b). Compared to the CDCM, the GM possesses the advantage that it can operate independently from the observer by continuously logging the gas concentration in the soil (Tang et al., 2003). However, additional sources of errors may be introduced by the diversity of other variables that must be determined for the application of Fick's law such as diffusive properties of the soil, the concentration of the respective gas in a definite soil depth and the water content that changes air-filled porosity and therewith the diffusivity of the soil. Since the estimation of fluxes is very sensitive to changes of the soil gas diffusivity (D_s), attention must be given to its determination (Pingintha et al., 2010). Different models are available to infer D_s from the air-filled porosity alone (Buckingham, 1904; Marshall, 1959; Penman, 1940) or in combination with the total porosity to account for soil specific texture type and density effects (Millington and Quirk, 1961; Moldrup et al., 1997). A few other models additionally use specific soil water characteristics (Moldrup et al., 2013). However, model based estimates of D_s are unable to account for site specific variations, and predicted D_s values can themselves vary considerably between the methods (Pingintha et al., 2010). Measuring D_s in undisturbed soil cores might be laborious, but offers the possibility of obtaining data that comprises the actual site-specific environment.

Several studies have compared GM and CDCM. Most of them, however, were conducted in cold climates, for example, in Wolf et al. (2011) and in temperate forest soils, for example, in Maier et al. (2011) and Pihlatie et al. (2007). Very few are concerned with the special situations in hot semi-arid and arid environments with long dry periods (e.g. Fierer et al. 2005).

Due to logistic and financial restrictions, detailed CO_2 efflux measurements could be conducted during certain periods of the year only with manual gas sampling for the GM. The objectives of this chapter are:

- to compare the CDCM and GM for calculating a CO₂ efflux for subtropical soils,
- to evaluate the feasibility of the GM, particularly in order to gather future time series of continuous flux estimates in remote areas and
- to identify ways in which to attain precise estimates of the soil gas diffusivity.

6.2 Design of the study and sampling

The measurements took place in March/April 2012, in September 2012 and from February until May 2013, on seven plots in total (Table 6-1). Plots were chosen to represent a wide range of land-use and landscape units in order to gain a broad array of the behavior of soil CO₂ efflux and CO₂ gradients. Data are partly from diurnal time series (Kalinski, 2014). Names of the plots are given according to the combination of landscape unit (first letter: M = miombo woodland; F = former floodplain; K = Kalahari dune area) and land-use unit (second letter: D = dryland agriculture; B = bushveld; W = woodland).

6.3 Results on the GM and CDCM

6.3.1 Soil properties

The group of studied soils is relatively homogeneous in terms of soil type and soil texture with almost all plots being Arenosols or having a very sandy soil texture in the topsoil. Total porosity varied between the plots and was highest at the F-W and both M plots (Table 6-1). Soil texture of studied soils is very homogenous along the soil profile with only minor increase of clay in the subsoil (data not shown).

Overall, the soil organic carbon content within the profile is at a low level and varied in a minor range between 0.9 and 0.2 %, except for the topsoil horizon of F-W in which carbon concentration was about 3.6 % (Figure 6.1). Organic carbon accumulates in the upper 20 cm of the soil and rapidly decreases with soil depth to a level between 0.1 and 0.3 % in a depth of 60 cm. Topsoil was dry during most of the field measurements. For 76 % of the measurements, water contents were below field capacity. On the remaining measuring dates, water content varied between 0.0 and 51 % of the field capacity.

Table 6-1: Topsoil properties and the soil group of the plots. Coordinates are given in Gauß-Krüger / WGS84 projection and decimal degrees. Soil type and texture classes are classified according to IUSS Working Group WRB (2006); Tex = Texture; LS = loamy sand; S = sand; SOC = organic carbon stock, 0-30cm Φ = total porosity; BD = bulk density; AC = air capacity (air-filled porosity at pF = 1.8); FC = field capacity. Names of the plots are given according to the combination of landscape unit (first letter: M = miombo woodland; F = former floodplain; K = Kalahari dune area) and land-use unit (second letter: D = dryland agriculture; B = bushveld; W = woodland).

Plots	Site	Latitude	Longitu- de	Soil reference group	Tex	SOC	BD	Φ	AC	FC
				0		(kg m^{-2})	(g m ⁻³)	%	%	%
K-B	Na m	-17.9144	20.2079	Rubic Areno- sol	S	1.43	1.51	43.7	24.7	19.0
K-D	Na m	-17.9061	20.1466	Rubic Areno- sol	S	0.77	1.56	40.1	25.2	14.9
F-B	Na m	-17.8867	20.2131	Petri-Luvic Calcisol	LS	2.81	1.6	48.5	19.7	28.8
F-D	Na m	-17.8867	20.2128	Rubic Areno- sol	LS	1.46	1.56	41.9	19.6	22.3
F-W	Na m	-17.8925	20.2277	Hypoluvic Arenosol	LS	7.13	1.3	51.3	35.3	16.0
M-D	Ang	-13.6908	17.0633	Hypoluvi- Rubi-Brunic Arenosol	LS	2.01	1.36	50.1	30.9	19.2
M-W	Ang	-13.6896	17.0661	Rubic Areno- sol	LS	2.64	1.33	69.7	30.0	19.7



Figure 6.1: Depth distribution of soil organic carbon content [%]. Values refer to the center of the soil horizon.



Figure 6.2: Examples of CO₂ gradients: a) temporal variation (plot K-D, March – May 2013); b) spatial variation (date of driest topsoil moisture for all plots). Water content was about 1% for the plots at K and F and 2-3 % at the M plots. Data are means of the three parallel measurements (variation coefficient CV = 0.02 - 0.16).

6.3.2 Soil CO₂ gradients

For all plots and days, we found an increase in CO₂ concentration with depth. In the Arenosols of the Kalahari, the gradient is almost linear and gets lower during the changeover from the rainfall period to the dry period ranging from March to May 2013 (Figure 6.1a). Typically, the increase with depth is stronger in woodlands (F-W, M-W) compared to the bushveld and dryland agricultural plots (F-B, F-D, M-D) on the same landscape unit, found here in the miombo woodlands and on the old floodplains. Within the Kalahari Arenosols, differences between dryland agriculture and bushveld are insignificant (Figure 6.1b).



Figure 6.3: The diffusivity (D_s/D₀) versus air-filled porosity (ε) of all plots together with the fitting of the Troeh82 function. Additionally, all tested models that were used to drive D_s/D₀ with air-filled porosity (Buck04, Pen40, Mar56) and air-filled porosity together with total porosity (MQ61a, MQ61b, Mold97), assuming a mean total porosity of $\Phi = 0.46$ mm³ mm⁻³ as input parameters are plotted. The horizontal box-whisker plot denotes the range of air-filled porosity observed in the field.



Figure 6.4: Measured data of air-filled porosity (ε) in cm³ cm³, diffusion coefficients and fitting according to Troeh et al. (1982) for five plots. Horizontal bars indicate the range of air-filled porosity observed in the field; r = Pearson correlation coefficient; C, u and v = fitted model parameters. Each figure comprises data of three samples from the two uppermost horizons each of the respective plot. Data with air-filled porosity ε < 0.1 are eliminated, which led to the exclusion of six data points at F-D, F-B and five data points of the F-W plot from the wettest level. * mark the plots which were actually sampled.

6.3.3 Soil gas diffusivity

The range of air-filled porosity illustrates the dry topsoil conditions during the field campaigns with minimum values of $\varepsilon = 0.3$ on the K-B plot (Figure 6.4). For all plots, the observed range was significantly above the air capacity defined as air-filled porosity at pF = 1.8 or matric potential = 6 kPa (Table 6-1). Within the range of $\varepsilon = 0.3$ cm³ cm⁻³ and $\varepsilon = 0.45$ cm³ cm⁻³ the measured soil gas diffusivity varied by a factor of about two at the same air filled porosity (Figure 6.3). Compared to measured data, models tend to overestimate D_s/D₀ values, especially at high air-filled porosity. The Pen40 and Mar59 models completely failed to predict the measured D_s/D₀ values by strongly overestimating them over the entire range of air-filled porosity. The MQ61a-model gave reasonable values only at air-filled porosity $\varepsilon < 0.4$ and significantly underestimated D_s/D_0 at higher ε . The MQ61b and Mod97 models predicted relatively reasonable D_s/D_0 values at air-filled porosity $\varepsilon < 0.35$ but overestimated the values within the range of observed air-filled porosity at field measurements which were mainly above $\varepsilon = 0.3$. The Buck04 model fits the data well at $\varepsilon > 0.4$ but overestimated diffusion at low air-filled porosity.

6.3.4 CO₂ fluxes compared for CDCM and GM

For all plots and dates, the CDCM CO_2 effluxes varied between 0.27 and 6.21 µmol m-² s⁻¹, with higher values at the miombo woodlands (M) and lowest values at the dryland agricultural plots in Namibia (K-D, F-D). Resulting in an overall R² = 0.881 for the linear regression, the predicted and observed fluxes show a close relationship (Figure 6.5). Both the means of GM fluxes (1.99 ± 1.24 µmol m⁻² s⁻¹) and CDCM fluxes (1.72 ± 1.16 µmol m⁻² s⁻¹) and the regression line indicate a constant overestimation of fluxes measured by the GM. Taking a 10 % variation of the mean as confidence interval, there was a tendency of overestimation at 65 % and of underestimation at 17 % of the values, meaning that only 18 % of the modeled fluxes fit the measured fluxes. At plot F-D, systematic underestimations were detected whereas K-B and K-D showed a tendency of overestimation.

All GM fluxes calculated with model-derived diffusivities (Buck04, MQ61b and Mold97) overestimated the measured CDCM fluxes. The overestimation was strongest for the MQ61b and lowest for the Buck04 model, indicated by the low CRM (Table 6-2).



Figure 6.5: Comparison of fluxes using the CDCM and GM with diffusion coefficients adjusted according to Troeh et al. (1982) and calculated using the concentration gradient between the atmosphere and 10 cm soil depth.

Chapter 6

Table 6-2: Indices for model evaluation. Compared are the observed (CDCM) and predicted fluxes (N =
98). Slope = the slope of the linear regression; R^2 = the coefficient of determination; RMSE = the route
mean square error; NSE = Nash-Sutcliffe efficiency with values ranging from - ∞ and 1; CRM = Coeffi-
cient of Residual Mass.

	slope	\mathbb{R}^2	RMSE	NSE	CRM
Troeh82	1.004	0.884	0.457	0.814	-0.154
Buck04	1.256	0.869	0.608	0.671	-0.103
MQ61	1.650	0.869	1.454	-0.880	-0.681
Mold97	1.456	0.871	1.066	-0.011	-0.465



Figure 6.6: Comparison of predicted GM fluxes by using different approaches to attain the soil gas diffusivity and the measured fluxes by the CDCM. Lines denote linear regression lines between the different approaches and the CDCM fluxes.

Lowest RMSE and highest NSE obtained for the Troeh82 model indicate the overall best performance of this method. The negative Nash-Sutcliffe efficiency from the MQ61b and Mold97 predictions indicates that these models did not perform acceptably (Moriasi et al., 2007). Although R^2 is high and does not differ substantially between the methods, it is highest for Troeh82, indicating closest linear relationship of the CDCM and GM by use of the analytically determined diffusivities (Table 6-2, Figure 6.6). Slope and coefficient of residual mass indicate an overall overestimation of predicted fluxes. Whereas the overestimation with Troeh82 and Buck04 is only of minor importance, it is substantial when predicted by means of MQ61b and Mold92. Predictions by MQ61b and Mold97 led to severe overestimation of fluxes by almost doubling the values at high fluxes. Less pronounced overestimation occurred when using the Buck04 and Troeh82 models (Figure 6.6).

6.4 Discussion on the GM and CDCM

6.4.1 CO₂ fluxes

The magnitude of CO_2 fluxes and, correspondingly, the soil respiration varied between the plots as a function of soil moisture. This is supported by findings of eddy covariance measurements by Kutsch et al. (2008), who found nighttime fluxes are dependent on soil moisture and temperature in an *Acacia* savanna and a *Combretum* savanna in southern Africa. The range of flux variations lies within the range of fluxes reported for other moisture-limited environments, such as in Thomas et al. (2011) and Tang and Baldocchi (2005). However, other factors besides soil moisture, which influence soil respiration could not be detected by our study with infriquent measurements. This highlights the importance for continuos flux measurements to capture the site specific variation, which is introduced by other environmental factors than soil moisture, like land use, soil organic and inorganic carbon content, temperature and vegetation.

6.4.2 CO₂ concentration profiles

In contrast to studies on moist soils, which showed a pronounced zone of respiration activity primarily in the topsoil (Davidson et al., 2006; De Jong and Schappert, 1972; Fierer et al., 2005), our study revealed no evidence for increased activity in a specific horizon to a soil depth of 1 m. The linear shape of the CO_2 gradient in the soil indicates no distinct layers of pronounced CO_2 production or changes of diffusivity within the range of the measured profile. It can be presumed that the linearity is caused by a continuous source below the deepest measured point. This is likely because all plots showed very homogenous distribution of texture across soil depth with only minor increase of clay content in the subsoil (data not shown). However, accurate statements about the production profile are difficult, as precise knowledge about D_s and, in particular, its modification by soil moisture in the subsoil is lacking that would allow an estimate of depth dependent CO_2 production (Schack-Kirchner et al., 2011).

6.4.3 Soil gas diffusivity

The Troeh82 model worked well concerning the fitting of the $D_s/D_0 - \varepsilon$ relationship, which is not surprising because all three parameters can be flexibly adjusted. However, fitting was much less satisfactory if it was forced to meet the theoretical maximum of $D_s/D_0 = 1$ at $\varepsilon = 1$, which has been done by Troeh et al. (1982) and led to the simplification of the model by eliminating the parameter *C* in the form:

$$\frac{D_s}{D_0} = \left(\frac{\varepsilon - u}{1 - u}\right)^v \tag{15}$$

We did not use the simplified model as it is unreasonable to forecast the diffusivity above Φ and it is arguable whether the fitting that meets the data between $\varepsilon = 0.1$ and Φ will also be true for higher theoretical values > Φ . Well-aggregated soils, for example, may show gas diffusivity not as unimodal but rather having two or more functional pore regions, such as intra and extra-aggregate pore volume with the intra-aggregate pores normally finer than the extra-aggregate soil pores (Millington and Shearer, 1971).

The fitting parameters exhibit a pronounced variation between the plots. The parameter *u*, which may be interpreted as a fraction of isolated air-filled porosity at zero diffusion, was highest under dryland agriculture on Kalahari sand (K-D), which at the same time shows the lowest curvature parameter *v*, indicating almost linear relationship (Figure 6.4). The low values however are also associated with a lack of data points at low airfilled porosities. The sensitivity of model parameters to data at low ε is confirmed for plot F-W, where only one data point is responsible for higher *v* and low *u*. (Jin and Jury, 1996) applied the Troeh82 model in the form of equation 11 to a wide range of datasets, including repacked soils, natural soils and other porous media. They also found a high variability of the D_s/D₀ - ε relationship, particularly for natural soils.

As can be concluded from Figure 6.3 there was a significant variation of measured diffusivities at the same air-filled porosity. The curve fitting from Figure 6.4 revealed an overall higher diffusivity at the M-D plot. The F-W plot showed lower diffusivity at high air-filled porosity, which might indicate a lower connectivity of the pore space. This soil showed highest content of organic carbon in the topsoil which might affect the physical soil properties.

Although some models have computed reasonable D_s/D_0 values in a certain range of air-filled porosity the comparison of diffusivities attained by the models revealed relatively poor agreement with measured values when compared across the entire range of air-filled porosity. A similar pattern of modeled D_s/D_0 in comparison with measured data was observed by Jassal et al. (2005), who found strong overestimations of diffusivities for the Pan40 and Mar59 models and a very steep slope for the MQ61b model, leading to overestimations at high ϵ . It becomes obvious that with no (Buck04, Pen40, Mar59) or only one (MQ61a, MQ61b, Mold97) soil-specific parameter, it is hardly possible to cover the wide variety of diffusive properties in natural structured soil. This has been illustrated by Jin and Jury (1996), who compared the fitting of the Troeh82 model to a wide variety of soil with the MQ61a model adjusted to different total porosities.

6.4.4 Comparison of different methods for flux estimation

In general, the observed and predicted fluxes as calculated by use of the measured diffusivities were in strong agreement. The variation around the 1:1 line may be associated with inaccurate transfer of the measured diffusivity to the true water contents at field conditions. The individual measurements of the field water content varied about 10 %, which denotes a relative uncertainty of the field measurements compared to laboratory measurements, where the gravimetric adjustment of water content to soil cores can be done very precisely. The uncertainty of water content is compounded by the uncertainty introduced by the transfer of averaged laboratory measured D_s values to spatially varying field conditions.

On the other hand, the gas sampling procedure may introduce some methodological variation into the data. By removing gas trough tubes, the precise depth of the respective sample can only be estimated as the volume of soil from which the sample is taken strongly depends on the air-filled porosity and total amount of extracted soil gas (Maier and Schack-Kirchner, 2014b). This became obvious by looking at the implausible concentration measurements of the 5 cm soil depth and led to the exclusion of the respective data. The sources of error introduced by the sampling technique may be eliminated by installing CO₂ sensors directly into the soil which can also be installed in higher soil layers (Tang et al., 2003). As has been shown by Figure 6.5, the GM worked equally well for all measured plots. Under or overestimation could not be clearly associated with land use or landscape. Interpretation of site variability would be highly speculative, which is particularly associated with the manifold sources of errors in the GM compared to the direct measurement of fluxes by the CDCM. The calculation with modeled diffusivities led to very high flux estimates compared to the CDCM values for the MQ61b and the Mold97 models. Similar overestimations were reported by Pingintha et al. (2010). However, they found a relatively strong agreement of fluxes obtained from the Mold97 model.

Another problem for using the GM to calculate reasonable fluxes may arise from the increased soil respiration during wet conditions in the very shallow soil layer which alters the shape of the CO_2 gradient with soil depth. A large proportion of the soil respiration may occur in the first few centimeters of soil where soil carbon is concentrated (see Table 6-1, Figure 6.1) as has been reported by Davidson et al. (2006) and Jassal et al. (2005). Application of Fick's law neglects the input or output of gases within the studied domain, thus atmosphere fluxes cannot be detected sufficiently if significant topsoil CO_2 respiration occurs and gas concentration is measured in 10 cm soil depth.

7 LAND-USE IMPACTS ON THREE SOIL ORGANIC CARBON FRACTIONS IN TYPICAL SOILS OF THE OKAVANGO CATCHMENT IN ANGOLA & NAMIBIA

7.1 SOC fractions in dryland ecosystems

The decomposability of SOM of which SOC is the main constituent is a continuum from rapidly degradable compounds like carbohydrates and peptides to very recalcitrant and highly condensed aromatic organic compounds and stabilized organic matter via physical protection in conjunction with the mineral phase (Lehmann and Kleber, 2015). The ecosystem functions associated with SOC differ according to its stability. On the one hand, rapidly degradable SOC enhances soil fertility by improving the medium term nutrient storage and the release of nutrients during the decay of organic material by soil (micro)organisms. On the other hand, stabilized SOC fractions enhance the cation exchange capacity and support soil aggregation, which prevents nutrients from leaching and protects soils from wind and water erosion. The recalcitrant SOC fraction contributes to the long-term carbon sequestration (Lal et al., 2015). To describe the different fractions of SOC the continuum is often experimentally separated by chemical, physical and biological fractionation methods (McLauchlan and Hobbie, 2004).

There is large consensus that impacts of agricultural use on SOC depend on farming practices (McLauchlan, 2006). Soil carbon levels can either be enhanced or maintained by intensive input of organic material and reduced tillage or can be depleted during lowinput agriculture approaches in which the net balance between input and loss by heterotrophic respiration and removal of harvest residues is negative (McLauchlan, 2006). Contrarily to the general knowledge about the response of SOC to agriculture, the complex processes involved in the degradation of different carbon fractions particularly in southern African dryland soils are far less understood. Only few studies describing soil carbon stocks and microbial characteristics are available for southern African savannas and woodlands (e.g., Wichern and Joergensen, 2009; Woollen et al., 2012) and another few dealing with the effect of agriculture on soil microbial parameters in semi-arid ecosystems in eastern Africa (Pabst et al., 2016; Pabst et al., 2013). However, to my knowledge, no studies linking soil organic C fractions to land use in southern African savannas and woodlands have yet been published. These ecosystems are characterized by a pronounced climatic seasonality with associated high carbon turnover rates during the wet season and phases of carbon accumulation during the dry season with very limited soil respiration (Veenendaal et al., 2004). Subsistence farming is the prevailing agriculture practice in this region. It is characterized by very limited feedback of nutrients and organic matter by fertilizers, manure and crop residues making the naturally low productive soils even more prone to degradation. Depending on rainwater, it is only possible during the wet season.

The chapter focuses on the following open questions:

- How large is the potential carbon loss in the semi-arid and semi-humid area of southern Africa?
- Are total carbon stocks affected by agricultural land-use activity under the given climate?
- Is the effect of dryland and irrigation agriculture different for different carbon fractions?
- Does the climate have an influence on SOC fractions in the study area?

7.2 Design of the study and sampling

This analysis was conducted on two of the study sites, namely Mashare (Chapter 2.3) and Cusseque (Chapter 2.1). The aim was to analyze the impact of agricultural use on the size of three carbon fractions, stable C (C_{stable}), labile C (C_{labile}) and microbial C (C_{mic}). Thereby, the C_{labile} was defined as the amount of degradable carbon measured by soil incubation of 65-219 days followed by determining the saturation value of the respiration curve by model extrapolation. C_{stable} was calculated as the difference between total SOC and C_{labile} . A third fraction was defined as the microbial biomass (C_{mic}) by the fumigation-extraction method. To study the impact of land use, we compared agricultural fields with woodlands in three landscape units that differed in soil type, history of land use and mean annual precipitation (MAP) in Cusseque (semi-humid) and Mashare (semi-arid).

Soil sampling was focused on the three landscape units that are used for cropping: old floodplains and Kalahari dunes in Mashare and hilltops in Cusseque. Within these landscape units, we selected sampling plots in the land-use types rain-fed and irrigated agricultural fields and woodlands. The combination of landscape units and land-use types led to seven combined units, hereafter referred to as land cover units (LC-units), in which a total of 37 plots were sampled (Table 7-1). As in the studied soils most carbon is stored in the topsoil (Luther-Mosebach et al., 2016), we took soil subsamples from 0 to 10 cm depth from 13 locations on a cross of two diagonal lines of 30 m each at each plot. These subsamples were combined and mixed to get a representative topsoil sample.

The results on SOC in this chapter are comparable to chapter 5. However, they refer to the top 10 cm of soil to be congruent with the analysis of the carbon fractions. They are presented here as an important reference base for the interpretation of the carbon fractions.

7.3 Results on SOC and carbon fractions

7.3.1 Soil characteristics

The variation of soil properties between LC-units within the individual study sites was more pronounced than the variation along the climatic gradient between the Mashare and Cusseque sites (Table 7-1). The texture of all soils was dominated by sand (overall mean 88.4 %) in all landscape units, with some higher clay contents in the old floodplain soils, which come along with slightly higher values for exchangeable cations and electrical

conductivity. The old floodplain soils were unique in terms of their clay content, CEC, soil pH, inorganic carbon content, and salinity. The available phosphorus content was generally on a very low level (overall mean $7.1 \pm 6 \text{ mg kg}^{-1}$), yet between twofold and threefold higher contents were found on irrigated fields.

The mean pH (5.2 ± 0.6) was generally acidic on the very sandy Kalahari and hilltop soils, only the old floodplain soils varied around pH-neutrality (pH 6.4 ± 0.8) due to the presence of carbonates (data not shown).

Table 7-1: Means and standard deviations per LC-unit of important soil characteristics, N and C contents and C fractions at the two study sites Mashare and Cusseque. The designations of the LC-units are composed of a combination of the landscape unit: K = Kalahari dunes; F = old floodplain; H = hilltop and land-use type: D = dryland agriculture; I = irrigation agriculture; W = woodland. EC = salinity as electrical conductivity; SB = sum of exchangeable basic cations; BD = bulk density.

	KD	KW	FD	FI	FW	HD	HW
Number of							
plots (n)	4	4	6	3	5	8	7
Site / Country	Mashare/ Namibia	Mashare/ Namibia	Mashare/ Namibia	Mashare/ Namibia	Mashare/ Namibia	Cusseque/ Angola	Cusseque/ Angola
SOC (g kg ⁻¹)	2.02 ± 0.3	4.14 ± 0.53	3.27 ± 1.21	4.87 ± 0.61	14.6 ± 4.68	1.79	10.43 ± 1.52
N (g kg ⁻¹)	0.22 ± 0.03	0.39 ± 0.05	0.33 ± 0.11	0.45 ± 0.03	1.27 ± 0.46	0.62 ± 0.11	0.62 ± 0.06
CN	9.1 ± 0.1	10.7 ± 0.5	10 ± 1.8	10.7 ± 1.3	11.6 ± 1.3	16.8 ± 1.3	16.9 ± 1.9
SOC (g kg ⁻¹)	2.02 ± 0.3	4.14 ± 0.53	3.27 ± 1.21	4.87 ± 0.61	14.6 ± 4.68	10.33 ± 1.79	10.43 ± 1.52
C _{stable} (g kg ⁻¹)	1.87 ± 0.24	3.71 ± 0.45	2.94 ± 1.09	4.48 ± 0.58	13.01 ± 4.46	9.1 ± 1.8	8.52 ± 1.84
C _{labile} (g kg ⁻¹)	0.19 ± 0.11	0.48 ± 0.18	0.34 ± 0.16	0.39 ± 0.02	1.59 ± 0.26	1.23 ± 0.45	1.91 ± 0.57
$C_{mic} (g kg^{-1})$	0.1 ± 0.1	0.12 ± 0.12	0.12 ± 0.03	0.19 ± 0.11	0.59 ± 0.22	0.44 ± 0.12	0.49 ± 0.09
N _{mic} (mg kg ⁻¹)	6.45 ± 4.17	11.12 ± 5.5	16.13 ± 8.95	11.45 ± 7.09	69.06 ± 24.77	41.87 ± 22.99	45.48 ± 17.4
P _{av} (mg kg ⁻¹)	3.57 ± 2.06	8.21 ± 12.42	9.17 ± 6.79	19.67 ± 2.31	5.8 ± 2.77	5.94 ± 4.08	7.63 ± 5.41
BD (g cm ⁻³)	1.52 ± 0.04	1.51 ± 0.03	1.52 ± 0.07	1.41 ± 0.16	1.39 ± 0.13	1.43 ± 0.09	1.5 ± 0
Clay (%)	3.8 ± 1	3.2 ± 0.6	7.3 ± 2.6	13.6 ± 5.5	9.6 ± 3.5	6.9 ± 2.8	7.6 ± 0
Silt (%)	2.2 ± 1.2	2.5 ± 1.2	6.9 ± 5.9	3.6 ± 0.3	5.8 ± 2.6	3.6 ± 1	2.7 ± 0
Sand (%)	94 ± 2.2	94.3 ± 1.8	85.8 ± 7.8	82.8 ± 5.5	84.6 ± 4	89.5 ± 3.5	89.8 ± 0
pH	5.63 ± 0.63	5.61 ± 0.37	6.82 ± 0.87	5.8 ± 0.53	6.42 ± 0.52	5.31 ± 0.31	4.7 ± 0.55
EC (µS cm ⁻¹)	10.5 ± 2.6	12.3 ± 6.4	46.8 ± 18.5	39.3 ± 15	108.2 ± 47	35 ± 26.1	40.1 ± 9.8
SB (mmoleq. kg ⁻¹)	1.36 ± 0.8	0.86 ± 0.36	2.44 ± 1.64	7.94 ± 3.81	4.28 ± 0.53	0.76 ± 0.59	0.63 ± 0.17

7.3.2 SOC and its fractions

The SOC stocks (Figure 7.1a) as well as contents (Table 7-1) were highest in the woodlands on old floodplains in Mashare and lowest on agricultural fields on Kalahari dunes. With the exception of the old floodplains, all LC-units in Mashare were significantly lower in SOC than in Cusseque. The SOC stocks and contents tend to decrease on agricultural fields in Mashare, in Cusseque, however, no such effect could be observed. The overall
Chapter 7 _

mean of the stocks of the carbon fractions C_{stable} , C_{labile} , and C_{mic} were 1.05 ± 0.70 kg m⁻², 0.145 ± 0.105 kg m⁻² and 0.05 ± 0.037 kg m⁻² respectively (for contents refer to Table 7-1). The C_{stable} fraction dominated the SOC pool accounting for 82.8 - 97.5 % of total SOC depending on the LC-unit (Table 7-1). The C_{labile} -fraction and C_{mic} fraction are comparably small making up 2.5 - 17.2 % and 1.2 - 11.1 % of SOC, respectively.

In general, the pattern of the carbon contents (Table 7-1) and stocks (Figure 7.1b – d) of all carbon fractions was similar to that observed for SOC with higher values in Cusseque and the old floodplains than on the remaining LC-units in Mashare. On old floodplains in Mashare, we found significantly lower amounts of the carbon fractions on plots under both dryland and irrigation agriculture than under woodland. In Cusseque, the differences between the woodland and agricultural plots were statistically insignificant; however, C_{labile} in woodland tended to be lower compared to agriculture fields.

The relative loss compared to pristine woodlands has been found to be largest for $C_{la-bile}$ under irrigation agriculture and dryland agriculture on Kalahari dunes and on hilltops in Cusseque (Figure 7.2). The losses of total SOC and C_{stable} are closely related indicating the dominant contribution of the stable fraction in the FD, FI and KD unit. In the HD unit, however, the loss of C_{labile} seems to be primarily responsible for the overall loss of SOC. The carbon loss due to agriculture compared to the respective woodland plots was most pronounced on the Mashare old floodplains with about 80 % of C_{stable} and C_{labile} and 74 % of C_{mic} under dryland agriculture, and 68 %, 75 % and 58 % for C_{stable} , C_{labile} and C_{mic} respectively under irrigation agriculture (Figure 7.2). On Kalahari dunes, C_{mic} exhibits with 8 % much less decrease than C_{stable} and C_{labile} with 51 % and 70 % respectively. After the clearing of woodland, the C_{stable} fraction on soils on dryland agriculture fields in Cusseque does not change significantly. However, the mean C_{mic} with -5 % and C_{labile} with -27 % decreased on fields compared to woodlands, yet to a lower extent than in Mashare and not statistically significant.

Significant interdependencies were found between the carbon fractions C_{mic} and C_{labile} , with high correlations on the old floodplains and on the hilltops (Figure 7.3). The correlation was not significant on Kalahari dunes.

The CN ration was positively correlated with all carbon fractions and also with the initial respiration rate (Table 7-2). From the soil chemical parameters, electrical conductivity was positively correlated with the three carbon fractions. However, the positive correlation is caused by 4 plots from the woodlands on old floodplains, which exhibit significantly higher electrical conductivity than all other LC-units (Table 7-2). The sand content was negatively associated with N_{mic} at a significance level of p<0.05. C_{stable} was associated with the clay fraction, however, the correlation became only significant (r = 0.41, p<0.05) after exclusion of one outlier of very high clay content with high leverage. The relative amounts were not linearly related to any of the tested parameters.



Figure 7.1: Stocks of total carbon SOC (a), the carbon fractions C_{stable} , C_{labile} and C_{mic} (b-e), the initial mineralization rate (e) and the indices C_{labile} :SOC, C_{mic} :SOC, C_{mic} :C_{labile}, qCO₂ (f-j) compared for the LC-units. Vertical lines divide the respective landscape units. The designations of the LC-unit are composed of a combination of landscape unit: K = Kalahari sand; F = old floodplain; H = hilltop and land-use type: D = dryland agriculture; I = irrigation agriculture; W = woodland. Different letters denote significantly different groups at p = 0.01 according to one-way ANOVA with Tukey's HSD post-hoc test. No letters are shown in cases of statistical insignificance of ANOVA results.

Chapter 7



Figure 7.2: Median loss of carbon due to agricultural use relative to the median soil carbon amount in the corresponding woodland within the LC-units. The designations of the LC-units are composed of a combination of landscape unit: K = Kalahari dunes; F = old floodplain; H = hilltop and land-use type: D = dryland agriculture; I = irrigation agriculture; W = woodland.

7.3.3 Initial carbon mineralization rate

The overall average initial carbon mineralization rate was $10.35 \pm 8.98 \ \mu \text{gCO}_2\text{-C}$ g-soil¹ day⁻¹. Its variation between the LC-units was comparable to those found for the carbon fractions. The highest mineralization rates were found in the woodlands in the Mashare old floodplains, which were ten times higher than the lowest rates on dryland agriculture fields in the Kalahari dunes (Figure 7.1e). The average mineralization rate was always higher in woodlands than on the agricultural fields. However, the difference was only statistically significant on old floodplains.

7.3.4 Quality indices

The proportion of C_{labile} on total SOC (C_{labile} :SOC) was highest in the woodlands of Cusseque but was not significantly higher than on the dryland agriculture fields at this site (Figure 7.1g). The lowest C_{labile} :SOC was observed for irrigation agriculture. For all studied LC-units, the C_{labile} :SOC ratio was lower on agricultural fields compared to respective woodlands. The relation C_{mic} :SOC revealed a pronounced variability, which, however, was not related to the land-use type (Figure 7.1h). The average proportion of C_{mic} on the C_{labile} fraction (C_{mic} : C_{labile}) was highest in soils of irrigated fields and lowest in woodlands on Kalahari dunes (Figure 7.1i). In all cases, woodlands depicted smaller C_{mic} : C_{labile} ratios compared to the agricultural fields in the same LC-unit. However, none of the observed differences between relative proportions of C fractions was statistically significant according to ANOVA results. Although qCO_2 also did not significantly differ between landuse types, it appears that the energetic efficiency of microbial biomass to metabolize carbon tends to increases (lower qCO_2) with the impact of land use (Figure 7.1j).



Figure 7.3: Interdependence of C_{mic} and C_{labile} . Pearson correlation coefficients and significance levels are: Kalahari dunes: r = 0.34, p = 0.42; old floodplain r = 0.84, p < 0.001; hilltop r = 0.81, p < 0.001.

Table 7-2: Pearson correlation coefficients of the three carbon fractions, N_{mic} and the initial mineralization rate with important soil parameters for all samples. Levels of significance: *p<0.05; **p<0.01; ***p<0.001. SB = sum of extractable bases; EC = electrical conductivity.

	C _{stable}	C _{labile}	C _{mic}	N _{mic}	Initial respirati- on rate	C _{stab-} le:SOC	C _{labile} :SOC	C _{mic} :S OC
SOC	0.99***	0.71***	0.77***	0.82***	0.73***	-0.06	0.05	-0.19
Ν	0.9***	0.57***	0.61***	0.8***	0.67***	0.02	-0.03	-0.21
C/N	0.56***	0.6***	0.61***	0.39*	0.46**	-0.25	0.24	-0.06
pН	-0.16	-0.38*	-0.23	0.04	-0.14	0.23	-0.24	0.15
EC	0.62***	0.41*	0.49**	0.73***	0.61***	-0.01	0	-0.04
SB	-0.02	-0.2	-0.04	0	-0.01	0.28	-0.29	0.06
Kavailable	0.31	0.05	0.06	0.44**	0.26	0.14	-0.15	-0.14
$\mathbf{P}_{available}$	0.02	-0.03	-0.02	0.05	0.11	0.13	-0.15	-0.05
Sand	-0.39	-0.32	-0.26	-0.52*	-0.36	-0.02	0.05	0.04
Silt	0.21	0.08	0.07	0.26	0.15	0.15	-0.17	-0.05
Clay	0.34	0.29	0.19	0.39*	0.32	0.03	-0.06	-0.14

7.4 Discussion on the effect of land use on the carbon fractions

7.4.1 Total SOC

The differences between the topsoil SOC of the LC-units was comparable to those found for the 30 cm topsoil stocks in chapter 5.3.

The carbon stocks measured in the topsoil of the woodlands of Mashare on Kalahari dunes $(0.62 \pm 0.07 \text{ kg m}^{-2})$ were at the lower end of what was found in similar environments in northern Botswana (Bird et al., 2004; Ringrose et al., 1998; Wang et al., 2007) and Namibia (Wichern and Joergensen, 2009). Wang et al. (2007) recorded 0.9 kg m⁻² in a *Baikiaea*-woodland and Bird et al. (2004) found carbon stocks values between 0.35 and 0.45 kg m⁻² at a precipitation regime with mean annual precipitation being between 525 and 650 mm in Kalahari soils in northern Botswana, whereby both studies are referring to the top 5 cm of soil. In similar soils Ringrose (1998) and Wichern and Joergensen (2009) reported SOC contents of about 3.5 mg g⁻¹ and 5.6 mg g⁻¹ for the top 10 cm, which corresponds to 0.52 kg m⁻² and 0.8 kg m⁻² respectively, assuming a bulk density of 1.5 (± 0.1) g cm⁻³ as measured for the Kalahari dunes in this study.

The comparatively high SOC stocks in woodlands on old floodplains $(1.27\pm0.46 \text{ kg} \text{ m}^{-2})$ in this study may be attributed to high biomass productivity caused by nutrient enrichment indicated by the higher values of available P, exchangeable bases and EC in this LC-unit (Table 7-1). The relatively good water supply through shallow groundwater in the direct vicinity of the river may also support a higher primary productivity (Tsheboeng et al., 2016). Another contributing factor could be the clay and silt content which is high compared to the Kalahari dunes and the hilltops at the Cusseque site (Table 7-1) and may lead to the higher amounts of carbon found in the stable fraction (Fig 2b, 2f). This interpretation is supported by the positive correlation between C_{stable} and clay content (Table 7-2) suggesting a stabilizing effect of clay on organic matter. Clay and silt tend to stabilize SOC by physical protection in micro aggregates against microbial degradation and, therewith, lead to typically higher SOC contents (Six et al., 2002).

The higher carbon storage of the miombo woodland soils in Cusseque compared to the Kalahari dunes are in line with a study from Woollen et al. (2012) who reported 1.2 kg m^{-2} for the top 5 cm depth in a miombo woodland in Mozambique. In miombo woodlands the higher MAP supports higher ecosystem productivity (Revermann et al., submitted) which forms the basis of higher SOC stocks (Post et al., 1982).

7.4.2 Carbon fractions

The finding that 82.8 - 97.5 % of the total carbon is stored in the stable fraction is in line with the results from previous studies indicating that the pool sizes of fast and slow pools are inversely related, the smallest pool being the best decomposable and vice versa (Jen-kinson, 1990). Furthermore, our study showed that the higher the substrate availability (C_{labile}) the higher the amounts of C_{mic} (Figure 7.3) and the microbial activity (initial respiration rate), whereby C_{labile} is again correlated with total SOC (Table 7-2). Similar results were found by Wichern and Joergensen (2009), who reported a very close relationship between SOC and C_{mic}. Comparing C_{labile} to studies from comparable environments

is hardly possible as studies that estimate C_{labile} by incubation and model fitting are scarce. In a comparative study of different SOC fractionation methods, McLauchlan and Hobbie (2004) found the C_{labile} fraction calculated by model fitting to account for 4 % of total SOC from temperate soils. Tian et al. (2016) fitted an additive three pool model (fast, intermediate, and recalcitrant fraction) to cumulative CO_2 data from incubated samples from northern China. They found the C_{stable} fraction with as much as 79-90 % to account for the majority of SOC and the remaining labile part of 10-21 % being shared by a fast and an intermediate fraction, which is slightly more than was found for the respective fraction in this analysis. The relative amounts of C_{labile} observed (4.5 - 28.3 %) are on a slightly higher level as found by Zou et al. (2005) who reported C_{labile} fractions between 4.8 and 11.1 % for different tropical and subtropical forest soils by applying a sequential fumigation–incubation procedure to define the C_{labile} fraction.

The woodlands in Cusseque show high amounts of C_{mic} and C_{labile} . The small C_{mic} : C_{labile} ratio suggests that a large proportion of C_{labile} is apparently made of other SOM than C_{mic} , presumably plant-derived carbon sources like leaf litter, fine roots and root exudates. The C_{mic} in woodlands on Kalahari dunes was on a comparable level to findings by Wichern and Jörgensen (2009) who found mean values of $112 \pm 38 \ \mu g \ g^{-1}$ soil at a comparable precipitation regime of MAP > 400 mm in a tree savanna in northern Namibia. The total microbial cell numbers recorded by Huber (2016) for the same landscape units and landscape types in Mashare showed a similar pattern as was found in our study for the C_{mic} -fraction with much lower cell numbers on dryland and irrigated agricultural plots than in woodlands. Also, potential exoenzyme activities and nitrogen turnover rates measured by Huber (2016) were largely higher on woodlands confirming higher availability of the respective substrate at those plots.

The C_{mic} :SOC ratio is very high in our study (mean 4 % max 11.1 %, Figure 7.1h) with as much as 43 % of our samples exceeding the proposed upper limit of about 4.4 % according to Anderson (2003). Rates above 4.4 % are occasionally found in dryland soils but rarely exceed 5 % of SOC (Dlamini and Haynes, 2004; Khan and Joergensen, 2006). The high C_{mic} :SOC ratios observed in our study may be attributed to the adaptation of the soil microbial community to drought conditions (Huber 2016) by accelerating their substrate-use efficiency, which means that a higher percentage of carbon is incorporated into microbial biomass rather than catabolized to CO₂ (Wichern and Joergensen, 2009). The high C_{mic} : C_{labile} ratios support this interpretation suggesting that a high percentage of the C_{labile} is incorporated into the microbial biomass.

7.4.3 The effect of agriculture on C-fractions

The analysis shows that, while decades of agricultural use depleted all carbon fractions, the bulk losses are attributed to the stabilized carbon fraction. This indicates that the stable fraction analyzed in this study is still prone to remarkable degradation and a two-pool model may reveal a third pool of intermediate degradability (Schadel et al., 2013).

The finding that SOC decreases during agricultural use is widely recognized in literature (Don et al., 2011; McLauchlan, 2006). The dimension of SOC losses detected in this study on both old floodplains and Kalahari dunes are on the higher end of what was found by a meta-analysis of 56 studies dealing with tropical crop fields which found an average depletion of 25.2 % and a maximum 80 % (Don et al., 2011). However, Papst et al. (2013)

Chapter 7 ____

found with 76 % equally high relative losses in a semi-arid climate in the Mount Kilimanjaro ecosystem in Kenya. The high SOC losses may be associated with the long lasting settlement history and the continuous agricultural use with lacking fertility management in the close vicinity of the Okavango River. The observed decline in C_{mic} after the landuse change (Figure 7.1, Figure 7.2) has also been reported for soils in semi-arid climates in Kenya, and, comparable to our study, was affected by agricultural use (Pabst et al., 2016). The lower stocks of C_{mic} are probably caused by the lower substrate availability due to reduced organic matter input and the mechanical disturbance by tillage and digging (Dinesh et al., 2003).

We attribute the low decrease of SOC in agricultural fields compared to woodlands in Cusseque to the young age of the fields and the slash and burn practices that may have led to input of plant residues and fire products during the process of woodland clearing. Although most studies on the effect of slash and burn practices on SOC reported a significant decrease in SOC (Ribeiro et al., 2015), the opposite can be the case when burning residues are incorporated in the topsoil (Johnson and Curtis, 2001). For example, significant increases particularly in the highly pyrolyzed and recalcitrant fraction were found in dry Eucalyptus forests in Australia (Krishnaraj et al., 2016). In contrast to the SOC stocks, Clabile tends to decline soon after clearing of woodlands and during agricultural use in Cusseque (Figure 7.2) which is not surprising as it represents the best accessible carbon fraction. Ando et al. (2014) found that the initial microbial activity of burned sites was much higher than on undisturbed sites, indicating the immediate response of the microbial community to the push of nutrient release from burning residues. This positive priming effect was also found by Maestrini et al. (2015) who argued that the presence of labile organic matter in the pyrogenic organic residues may trigger the activity of soil organisms. This effect may also explain the very high outlier of the initial rate found on a plot cleared shortly before the time of sampling (Figure 7.1).

8 SYNTHESIS

Soils are essential for the provision of various ecosystem services and functions benefitting humankind (MEA 2005). Their significance, however, have long time been neglected in both environmental and socio-economic discourses. Initiatives in recent years like the Global Soil Week 2012 with the motto "Soils for Life" (Koch et al., 2012) or the International Year of Soils 2015 declared by the UN raised awareness of the value of soils and their contribution to peoples' livelihoods as well as the implementation of the Sustainable Development Goals (SDGs). To stress their beneficial role in soils, Rice et al. (2007) pictured SOM as "the backbone of soil productivity and a critical link between civilization and sustainable agriculture and productivity". SOM has high influence on soil quality and fertility. The maintenance of SOM at equilibrium in local soils and, thus, the preservation of current land-use conditions or an increase in SOM to an optimal level can significantly contribute to the SDGs (FAO, 2017).

Here, five goals are named which are indirectly influenced by SOM:

- SDG 2: "Zero hunger"
- SDG 3: "Good health and well-being"
- SDG 6: "Clean water and sanitation"
- SDG 13: "Climate action"
- SDG 15: "Life on land"

One prerequisite to reach the "zero hunger" goal is to maintain and optimize soil fertility for food production. Soil fertility, defined as the ability to support plant growth by supplying nutrients and water while securing the aeration of the root zone, is facilitated by the soil's SOM content and fluxes (Amberger, 2006). Within the SOM, nutrients are stored and made available by decomposition. Additionally, the SOM pool influences the physical and chemical processes controlling nutrient sorption and water storage and the soil's thermal properties (FAO, 2017). To better understand these circumstances, the following topics are discussed: first, the distribution of soil and associated land use in the landscape; second, the distribution of SOC within the natural environment landscapes and its shifts with the conversion of pristine vegetation to crop land; third, the possibilities to measure carbon fluxes as an indicator of soil respiration in remote areas; fourth, SOC fractions defined according to their degradability by incubation experiments and the microbial biomass in dependence on land use, climate and soil type; and, fifth, potentials and challenges to increase SOC, soil fertility and yields and the way ahead for soil fertility increase for the studied region.

8.1 Distribution of soil properties and land use

The analysis in chapter 4 of this study showed that the historic and recent influence of the Okavango River and its tributaries were the most important factors for the diversification of soil properties. The dynamic of the river has created a diverse pattern of soil types on the recent and old floodplains. Sandy levees and finer textured depressions developed

Chapter 8 _

during the sedimentation of fluviatile materials leading to a variation of soil types with very nutrient-poor Arenosols on levees and more nutrient-rich Calcisols, Cambisols, Luvisols, and Fluvisols and in depressions. The inhibition of carbon degradation in the permanent water-saturated milieu of wetlands led to the accumulation of organic material in Histosols. Moreover, the shallow groundwater led to the development of soils with typical hydromorphic features, like in Gleysols and Plintosols.

The most homogenous soil properties were found in the sand-dominated landscape units. The nutrient-poor and less developed Arenosols are present along the whole climatic gradient from south to north. They are typical for the Kalahari as has been reported by several authors (Hartemink and Huting, 2008; Petersen, 2008; Simmonds, 1998; Wang et al., 2007) and are typical for dryland areas worldwide (IUSS Working Group WRB, 2015). The prevailing type of Arenosols shifted along the gradient from haplic in the south, rubic in Mashare and Caiundo and hypoluvic in the north indicating the climatic influence by the stronger weathering of minerals and clay illuviation.

The mentioned large-scale maps indicate Arenosols as the prevailing soil type on the three southern study sites, suggesting that agriculture would be hardly possible on these soils which are characterized by their poor nutrient status (Hartemink and Huting, 2008). Even though this study confirmed the dominance of this soil type with the highest frequency of classified soil profiles at the respective study sites, it reveals a much higher pedodiversity accompanied by a diverse land-use pattern.

The hilltops in Cusseque and Caiundo as well as the old floodplains in Caiundo, the old floodplains and dry riverbeds in Mashare, and the patches of Mopane woodland in Seronga provide better soils in a matrix of nutrient-poor deep sandy Arenosols. In the Angolan part of the catchment the prevailing agricultural use was found to be slash and burn agriculture in the woodlands with maize and cassava as the staple crop. Suitable areas for this type of land use are widespread in Cusseque but are constrained to distinct areas in the semi-arid study site Caiundo. In Caiundo the floodplain soils actually indicate a better nutrient status as the soils on the hilltops but are only sporadically cultivated, whereas hilltops are intensively used. Histosols in the most northern site are used for dry-season horticulture producing cabbage, tomatoes, and potatoes.

In Mashare the permanent small-scale agriculture is concentrated on the more fertile soils in the old floodplains and omiramba, however, progressing into the unfavorable nutrient-poor Kalahari soils, probably due to the limited availability of fertile soils and high population growth (Pröpper 2015). The staple crop here is pearl millet, known for its relatively good ability to cope with erratic rainfall (Matanyair, 1996). On the other hand, large-scale irrigation agriculture schemes compete with small scale farms for the best soils in the floodplains. They produce maize and wheat in a seasonal crop rotation.

In Seronga, agriculture is concentrated on areas with elevated nutrient and carbon contents, favorable phosphorus content, and p. These soils promote very distinct vegetation compared to their surroundings, consisting of dominant stands of *Colophospermum mopane*. These patches are probably of fluviatile origin (Ringrose et al., 2008); however, up to now, their development has not yet been completely understood. Permanent rain-fed agriculture with maize as the staple crop is conducted on fields, which are fenced against elephants and cattle. Over all, it was observed, that people have a clear preference for certain soils for agricultural use, which is usually in accordance with the distribution of the highest soil fertility. An exception was found in the Caiundo area, where crop production was expanded on deep Arenosols whereas the more fertile soils of fluvial origin were predominantly fallows or secondary bushvelds. Most likely, this preference was established during civil war, as the area for crop is better protected. Here and in the northernmost site Cusseque, the driving factors for the use of the soil fertility function are the nutrient flushes after woodland clearing in the slash and burn agricultural systems. In contrast, with a dominance of permanent crop production systems, in the southern part the soil fertility function is associated with the parent material of the soil due to the accumulation of finer textured soils and nutrients in fluviatile sediments.

The small scale heterogeneity and the associated land-use options highlight the importance of knowledge about pedodiversity not only for its intrinsic values (Petersen, 2008) and relevance for the local biodiversity (Revermann et al., submitted) but also with respect to human well-being and ecosystem services. This study contributes to the needed knowledge base and newly describes the distribution of soils and their related land use in the Okavango Catchment. Thereby, characteristic patterns according to climate and land-scape became evident confirming the respective hypotheses that **the distribution of soils and pedodiversity in the Okavango Catchment shows characteristic patterns according to climate and landscape structure**. The study clearly discusses the agricultural land use in dependence of the available soil types, which, to my knowledge, is new for a gradient from sub-humid to semi-arid in southern Africa.

8.2 The distribution of SOC stocks

The diversity of the soils is accompanied by a high variability of SOC stocks resulting in a much higher within-site variability of SOC stocks compared to the variability between sites (Figure 5.2). In the soils of the Kalahari sands, which cover the largest proportion of the Okavango Catchment, the investigations revealed low SOC stocks (Chapter 5). These are typical for arid and semi-arid ecosystems and are caused by low primary production of the vegetation and simultaneous high temperatures supporting soil respiration during periods of optimal water availability (Lal, 2004; Post et al., 1982; Raich and Schlesinger, 1992).

In contrast to the low carbon storage of the Kalahari sands, the Okavango River with its unique ability of feeding a dry ecosystem reveals also special abilities to store soil carbon in its recent and also former wetland systems. The wetlands were found to store by far the largest amounts of carbon in the landscape in this study (Chapter 5). At the three southern sites (Caiundo, Mashare and Seronga) this is linked to the high biomass productivity caused by nutrient enrichment, indicated by the higher values of available P, sum of exchangeable bases, and EC in the floodplain soils (Chapter 4), and the good water supply by shallow groundwater in the direct vicinity of the river (Tsheboeng et al., 2016). Moreover, high activity clay minerals, which were found to be on average four times higher in floodplain soils than on Kalahari sands, are likely to effectively stabilize SOM by organo-mineral bonds (Baldock and Skjemstad, 2000). The grayish colored soils of the old floodplains, which may have an age of > 100 000 years (Ringrose et al. 2008) and which have lost their fluvial properties completely, have accumulated more SOC due to organo-mineral stabilization than the adjacent soils of the Kalahari sands. In Cusseque,

Chapter 8

the exceptionally high SOC stocks in the wetlands (Figure 5.2) are attributed to the permanently water-logged conditions that prevent aerobic soil respiration, thereby leading to a long-term accumulation of organic matter in peatlands (Urbaniak et al., 2016).

The high SOC stocks found in the wetlands are in accordance with the global soil carbon map by Hengl et al. (2014), in which parts of the Okavango Delta and some of the tributaries are distinguished from the surroundings by higher SOC contents. However, the highland of Bié in the northern part of the catchment is likely to store more SOC than is actually indicated by the global soil carbon map, particularly due to the presence of peatlands in the valleys. However, the dimension of higher SOC stocks has still to be validated by the spatial extrapolation of the findings of this study via GIS analysis. I can be concluded that the hypothesis that **the SOC stocks of the Okavango Catchment depend on the parent material of soils** is confirmed in this study.

I tested the influence of climate on SOC by comparing the soils of Kalahari sands between the four study sites (Figure 5.3a). It turned out that the southern three study sites did not differ in SOC and the climatic gradient was only evident from the higher SOC stocks in the most northern site, Cusseque. However, in Cusseque, some study plots had comparable small SOC stocks as in Seronga, the driest southernmost study site. The even distribution of SOC on the Kalahari soils is supported by Wang et al., (2007) who studied the dependencies between SOC contents in the topsoil and climate along a gradient from 365 mm to 879 mm mean annual precipitation in Botswana and Zambia. Dintwe et al. (2015) found an equally monotonic distribution of SOC stocks along a precipitation gradient in the Kalahari extending from the Okavango Catchment to southern Botswana.

In contrast to the relatively small variability in SOC between the sites (especially in the three southern sites), an increase in the aboveground carbon stocks of woody biomass in the Okavango Catchment along the climatic gradient from low to high precipitation could be observed (Figure 5.3b). These observations indicate that the importance of SOC for total ecosystem carbon stocks increases with decreasing precipitation. Even though the general trend is evident for the IPCC climatic regions (Scharlemann et al., 2014), I basically confirmed it in this case study within southern African woodland ecosystems.

A possible explanation for the similar SOC stocks in the three southern study sites despite differences in aboveground carbon stocks may be found in the carbon balance. The carbon balance is strongly influenced by soil water availability, which differs substantially between the study sites. Microbial respiration has an optimum range regarding available soil water with water limitations at the dry end and oxygen limitations in watersaturated conditions. This is caused by the activity of exoenzymes, which depend on continues water films on the surfaces of soil particles and, at the same time, on the availability of oxygen, the diffusion of which is hindered by water-locked soil pores (Wood et al., 2013). The latter process is rarely the case in the studied soils as they are characterized by low a water-holding capacity due to their sandy soil texture. The predominantly low soil water availability at our sites may limit microbial respiration, as was evident from own results (Figure 8.1) and was also reported by various authors (Kutsch et al., 2008; Thomas et al., 2011; Veenendaal et al., 2004). The increasing length of dry soil conditions during the course of the year from north to south especially in the topsoil horizon may hamper degradation of litter and SOM during a larger number of days in which suboptimal water contents prevail. This reduced degradation may compensate for the reduced input of fresh

organic material. Campo and Merino (2016) also showed that higher SOC stocks are the effect of hindered turnover by drought.



Figure 8.1: a) decreasing CO_2 fluxes during the transition of the wet to the dry season 2013, measured at the Mashare and Cusseque study site. b) relationship between CO2 flux and soil moisture from the same data

The higher SOC stocks in the northernmost study site are most probably caused by the higher ecosystem productivity indicated by the higher aboveground biomass. The higher productivity may compensate for the likewise higher soil respiration (see discussion above), which was evident from the flux measurements (Figure 6.6). Furthermore, physical stabilization processes of clay may have contributed to the high SOC stocks. The clay content was slightly higher at this site and the clay content was generally positively correlated with the stable carbon fraction (Figure 7.1). Clay tends to stabilize SOM by physical protection in microaggregates against microbial degradation, which typically leads to higher SOC contents (Baldock and Skjemstad, 2000). However, the quality of clay minerals plays an important role on stabilization processes as well (Six et al., 2002; Tisdall and Oades, 1982). In contrast to the assumed high activity clay minerals from the floodplain soils at the other sites, the clay minerals at the Cusseque site are kaolinitic-dominated, indicated by the low amount of extractable cations. This type of clay minerals typically develops under tropical weathering. Despite the fact that the capacity of kaolinite to stabilize SOM is lower than that of smectite (Wattel-Koekkoek et al., 2003), the higher clay content at this site is likely to be responsible for SOM stabilization. To separate the influences of climate and the stabilization processes of clay on SOC stocks remains a challenge because often they tend to be strongly correlated. Even though the sand cover in the study is from the same geomorphological unit, the Kalahari Basin, higher precipitation in the north has promoted weathering of primary minerals and the formation of secondary (clay) minerals and, therewith, is correlated with precipitation, lower temperatures and higher ecosystem productivity. Under consideration of the identical parent material, I

Chapter 8

conclude, that the hypotheses that **the SOC stocks of the Okavango Catchment depend on climate** is not confirmed within the range of 450 < MAP < 750 mm. If there is an consistent increase in SOC to MAP of 1000 mm and more is, cannot be validated with my data.

The finding that SOC decreases during agricultural use is widely recognized in literature (Don et al., 2011; McLauchlan, 2006). However, SOC losses detected in this study on both old floodplains and Kalahari dunes, are exceptionally high and with its dimension newly described for the study region, compared to a meta-analysis of 56 studies dealing with tropical crop fields in which an average depletion of 25.2 % and a maximum 80 % was found (Don et al., 2011). The high SOC losses may be associated with the long lasting settlement history and the continuous agricultural use in the close vicinity of the Okavango River with the very low or even missing input of manure and fertilizers and the complete harvest of plant material reported by Kowalski et al. (2013).

In contrast to the exceptionally high losses, which were possible under permanent agricultural use, the effect of slash and burn agriculture on SOC stocks was much less pronounced. The low decrease of SOC in agricultural fields compared to woodlands in Cusseque can be attributed to the young age of the fields and the slash and burn practices that may have led to input of plant residues and fire products during the process of woodland clearing. Although most studies on the effect of slash and burn practices on SOC reported a significant decrease in SOC (Ribeiro et al., 2015), the opposite can be the case when burning residues are incorporated in the topsoil (Johnson and Curtis, 2001). For example, significant increases, particularly in the highly pyrolyzed and recalcitrant fraction, were found in dry Eucalyptus forests in Australia (Krishnaraj et al., 2016).

With this study I provide unique data on the distribution of carbon stocks in the Okavango Catchment and relate the findings to climate, soil type and land use. The introductory hypothesis that **the SOC stocks of the Okavango Catchment depend on climate**, **the parent material of soils and land-use type** could thereby be confirmed for the latter two but was refused for climate.

8.3 Method comparison for CO₂ flux measurements

The extent to which the application of manure and crop residues contributes to the provision of nutrients during their degradation or to the enhancement of the SOC level of the soils depends on the heterotrophic soil respiration. To quantify the soil respiration is crucial for the estimation of specific carbon budgets but can sometimes be a challenge, especially in remote areas. In this study, two measurement methods were compared, the gradient method and the closed dynamic chamber method for recording hourly CO₂ fluxes (chapter 6). The intention was to verify the suitability of the gradient method for the semiarid and semi-humid soils in order to generate long-time series of CO₂ flux measurements in future research. This would be desirable as only long-time series will provide the data needed for carbon balance estimations with sufficient accuracy to be meaningful (Smith et al., 2010). The measured fluxes of both methods were in reasonable agreement (Figure 6.5) suggesting that the GM offers a valuable tool for flux estimates on the pedon scale in dry ecosystems, which are characterized by high air-filled porosities and rarely occurring water logged soil conditions. A cost and time efficient method to gather continuous CO_2 flux estimates in high temporal resolution could be provided if the approach used permanently installed soil water content and CO_2 sensors. As the estimation of surface fluxes depends much on the precise determination of the soil gas diffusivity, it is important to spend effort in its estimation or measurement. The best results will be achieved by measuring the soil gas diffusivity through laboratory analysis, as was done in this study. Another possibility, however, would be to infer the diffusivity from air-filled and total porosity by using transfer models (Allaire et al., 2008).

In summary, it can be stated that by this study the introductory hypothesis that **the gradient method offers a useful tool to monitor CO₂ fluxes in remote areas under semiarid and semi-humid conditions** was confirmed for the first time in the southern African semi-arid and semi-humid regions with some restrictions concerning the estimation of the soil gas diffusivity. As the estimated diffusivities from transfer models can differ substantially (Figure 6.3), to the use of two models that serve as realistic upper and lower limit is recommended. To reduce the methodological bias, it is important to pay attention to the precise measurements of soil water content which is altering the soil pore space and, therewith, influences the diffusivity of the soil. The study showed that site-specific variations will otherwise be surpassed by methodological bias.

8.4 Carbon fractions

Soil heterotrophic respiration is not only dependent on environmental factors like soil moisture and temperature the influence of which can be measured by monitoring the CO_2 fluxes and subtracting the proportion of root respiration, but also on the degradability of the SOM. SOM is present as a continuum regarding degradability and can be experimentally divided into different pools. In this study, the separation of a labile and a stable carbon fraction by incubation experiments on different soils from different landscapes, land-use types and climatic regions aimed at identifying whether these factors have an influence on the relative proportions. Additionally, the microbial biomass as a third fraction was analyzed which represents an important indicator of SOM quality.

This study provides a first description of the distribution of carbon fractions in different landscape units under different climate regimes in southern Africa (chapter 7). Thereby, it was identified that the majority of SOC is stored in the stable fraction (82.8 - 97.5%), which is in accordance with the general assumption (Jenkinson, 1990), however, newly described for southern African soils.

Long-term agricultural use (> 25 years) was shown to significantly deplete total soil carbon stocks (Figure 7.1a) and all carbon fractions in the topsoil (Figure 7.1b-d). The stable fraction and the labile fraction were equally affected, whereas the microbial biomass showed comparably low decline in sandy soils. Short-term slash and burn agriculture (< 5 years) only affected the labile fraction but not the stable, suggesting that the labile fraction contributes to the peak of soil fertility after the burning of woodland. Besides the duration of land use, the magnitude of losses depended on the total soil carbon stock and is therewith linked to the soil type and parent material of the soil. The highest losses were associated with the highest organic carbon contents under natural conditions in mineral soils found on the old floodplain soils of Mashare.

Chapter 8

Contradictory to the widely accepted assumption that the energetic efficiency of the microbial community drops with the disturbances of ecosystems because more energy is needed for maintenance of the microbial community (Anderson, 2003), this study found no higher qCO_2 values on agricultural fields compared to woodlands. The presented results showed the clear tendency of higher qCO_2 on woodland plots in all landscape units. A similar effect was found by Dinesh et al. (2003) for Inceptisols in wet tropical soils in India. It is likely that the supply of readily decomposable organic material, which tends to be higher in the pristine woodlands, determines the microbial activity and overrides the effects of ecosystem stability, particularly in nutrient-limited systems (Joergensen and Castillo, 2001). In conclusion, the hypothesis that **the relative proportions of three different soil carbon fractions can be explained by the land-use type** was true for the labile and the stable fraction. The microbial biomass, however, was more associated with substrate availability indicated by high amounts of the labile fraction than with land use.

8.5 SOC for soil quality and soil fertility

The principal contribution of SOM to soil fertility has been known for long and, thus, the preservation and enhancement of SOM is one of the key principles in the recent incentives in sustainable intensification of agriculture (FAO, 2017). However, the role of SOM is ambiguous, as it improves soil chemical and physical properties with increasing content, while at the same time it supports plant growth by the release of plant available nutrients due to its microbial mineralization.

In sub-tropical regions with pronounced rainfall and dry seasons, the biophysical conditions to store SOM in the soil are restricted and low SOM contents are prevailing (Dixon and Turner, 1991; Lal, 2002; Post et al., 1982). However, this study shows that along with the distribution of soils, SOM and, thus, soil fertility in the landscape is scattered. The distribution of SOM varies on the small scale, e.g., under canopies of trees compared to intercanopy patches (Scholes and Archer, 1997) and on the meso scale, which means within and between the landscape units of the study sites. The SOM stocks and, thus, soil fertility is related to biomass production. Focusing on savannas with up to 600 mm annual rainfall, Scholes (1990) reported the effect of soil fertility on the ecosystems. The broad range in soil fertility influences the species composition, the physiognomy, the structure and the functioning of the savanna. Soil features of low fertility savannas comprise 0.2 -1.0 % SOC and a dominance of quarzitic and kaolinitic minerals with sum of bases < 20 cmoleg kg⁻¹. In contrast, nutrient-rich savannas feature 1.0 - 3.0 % SOC, smectitic minerals and sum of bases > 20 cmoleg kg⁻¹. For the studied sites, the dominance of SOC concentrations is < 1.0 % even in the Angolan highlands. Thus, the ecosystems should be related to low productivity savannas. However, in all landscapes soils with SOC > 1.0 %exist, concentrated in floodplains, omuramba, pans and other special landscape elements, supporting a vegetation of higher productivity. The patchiness of SOC distribution is, thus, a precondition for enlarged biodiversity but is - as the interaction with tree stands indicates – also caused by the distribution of plants and most likely by the activity of soil organisms, esp. termites.

The fertility of the studied soils was characterized by applying the QUEFTS model (Sattari et al. 2014), which was developed as a tool for land evaluation by combining the 80

assessments of soil properties and fertilizer requirements. The generic model simulates the steps from nutrient availability across nutrient uptake to final yields based on empirical observations and theoretical assumptions. Within the model, five soil properties have to be entered (pH, soil organic carbon, soil organic nitrogen, soil phosphorous (Olsen), soil exchangeable potassium) as well as the amounts of fertilizer applications. The model assumes a good crop management and sufficient rainfall. By application of the QUEFTS model to all soils of all studied landscape units, the high relevance of SOM as a critical variable for crop growth became evident (Pröpper et al. 2015). As in the actual smallholder production systems, the input of fertilizers is exceptional, the potential yield is predominantly controlled by the availability of nitrate, which is delivered by SOM during decomposition. For the fairly fertile soils of the old floodplains and omuramba, potential maize yields range between 800 and 1200 kg ha⁻¹ a⁻¹ for unused soils, whereas for the extended areas with Arenosol and Kalahari sands, the potential yields vary between 250 and 600 kg ha⁻¹ a⁻¹. These yield estimates are controlled by the SOC and – for the Angolan highland – by soil pH.

The patchy distribution of SOC in the landscape results in a specific land use, which is sometimes more, sometimes less adapted to the given conditions. The shifting cultivation practice in the north has been shown to have only minor effects on the soil carbon stocks and reveals to be a good option at present. The immediate flush of nutrients after burning the fields and the short duration of usage with periods maximum five years with subsequent fellow periods of at least ten years (Domptail et al., 2013) can be evaluated as being sustainable in the sense of maintaining soil fertility. However, if the current trend of expanding fields around settlements and along roads, which have been shown for parts of the catchment by Schneibel et al. (2016) will continue in future, land scarcity will probably result in shorter fellow periods and longer periods of continuous cultivation. Present population growth rates of 3 % for Angola let assume that these dynamics will further intensify (AfDB, 2015; Pröpper et al., 2015). Under these circumstances, it is likely that SOC and soil fertility drops and decreased crop yields will be attained under the current management system.

The exceptionally high losses of SOC under permanent dryland agriculture and the low crop yields under the current management system in Mashare (Gröngröft et al., 2013a) highlight the importance of soil carbon management strategies. The evaluation of the soil carbon dynamics, however, remains a challenge because the simple principle "the more, the better" does only apply occasionally, as some SOC bound ecosystem functions are strongly linked to the dynamics of the carbon degradation. On the one hand, a high SOC content supports the water holding capacity; on the other hand, the degradation of SOC is needed for the provision of nutrients. Both mechanisms are particularly important in weakly aggregated and nutrient-poor soils which are characteristic for large parts of southern Africa (Hartemink and Huting, 2008). The challenge in SOC management is to find good agreements with regard to these soil functions and more research regarding soil carbon dynamics would support the development of sustainable intensified smallholder agro-ecosystems (Powlson et al., 2016). Management techniques have been developed and explicitly adapted to dryland conditions and are summarized under the term Conservation Agriculture. These techniques stand for an sustainable intensification of land use, in the current literature also described as "ecologically intensified" (Tittonell, 2014) or, in

Chapter 8 ____

a wider context, "climate smart" agriculture (Lipper et al., 2014) and according to Pretty et al. (2011) broadly speaking means "producing more output from the same area while reducing the negative environmental impacts". Conservation Agriculture techniques include minimal soil disturbance, application of organic materials to the soil, mostly manure and crop residues, and mulching and intercropping with soil covering plants to reduce water loss by evaporation (Kassam et al., 2009). There is evidence that Conservation Agriculture can lead to the recovery of soil carbon contents and may improve soil quality in the long term (Thierfelder et al., 2016). However, there are also certain drawbacks including more need for weed and pest control, a lack of organic and mineral fertilizer inputs, and an increase in labor effort, which can lead to a low readiness by farmers to adopt such methods. This embraces the need for a diversification and local adaption of such methods (Tittonell et al., 2005; Vanlauwe et al., 2016).

Looking at the structured landscape with its pristine soil fertility distribution, the challenge is to use the ecosystem services in a sustainable way while satisfying the needs of the growing population. Here, the concentration of crop production and horticultural areas on the fertile parts of the landscape, a management of water resources for wise irrigation, the usage of recent floodplains and adjacent areas for grazing, and the use of goods from woodlands seems a realistic opportunity, which, however, needs further research and capacity building for farmers (Pröpper et al. 2015).

9 CONCLUSION & OUTLOOK

The study gave new insights into the distribution of soils and the associated land use in the Okavango Region, thereby identifying the close relationship between agricultural use and the variability of soil on the landscape scale. This highlights the importance of information about the small-scale heterogeneity of soils to support adapted and sustainable land use, and attempts in further research to preserve the diversity in the display of soil maps should be encouraged for land use-relevant soil mapping activities (Costantini and L'Abate, 2016).

Furthermore, the study provides new data on the distribution of carbon stocks, which were shown to be closely related to the heterogeneity of soil types and land use. For some landscape units, the findings corroborate current knowledge as for the extending Kalahari dune areas; for other parts of the catchment (in particular the Angolan part of the catchment) they, to my knowledge, provide the most detailed data available. It has been discussed in this study that the missing climatic effect on SOC stocks despite a positive effect of MAP on the above ground woody biomass carbon, may possibly be explained by the carbon balance. However, to prove this in detail, a complete budget calculation with incorporation of the CO_2 fluxes associated with photosynthesis and soil respiration would be desirable for future research.

The suitability of the gradient method for the measurement of CO_2 fluxes was approved for the first time on southern African soils by comparing the fluxes with measurements of the closed dynamic chamber method suggesting that the gradient method may be used to measure long-time series of CO_2 fluxes. However, its application over longer periods with solid state CO_2 sensors was not tested in this study and more research is recommended to further improve the method.

As the first study on carbon fraction for southern African soils of semi-arid and semihumid regions retrieved from incubation experiments, my results can contribute to the understanding of the composition of SOC in these regions. It was shown that the amount of each fraction is strongly determined by the total SOC and that permanent cultivation equally depleted the stable and the labile fraction. The data may be used for modeling carbon dynamics with carbon models that need to distinguish between different carbon pools (e.g., Andren et al., 2004; Falloon and Smith, 2002).

SOC as the main component of SOM is not only essential for fertile soils and thus for food production and human well-being, but also represent a massive source of greenhouse gas promoting climate change in case soils are not managed wisely. An improved understanding of the carbon stocks and dynamics are the basis for adapted management strategies (FAO, 2017). The new knowledge attained in the presented study aims at contributing to this knowledge base. As part of the ongoing research on the significance of SOM and SOC for fertility management, it will hopefully help to improve the sustainability of land management strategies and, therewith, minimize the human impact on soils while improving human well-being.

REFERENCES

А

- Abdelli, H. and Jouen, D., 2012. Diagnóstico Agrário Territorial da Província do Bie. Municipios do Andulo e Chitembo. GPC/ANG/045/SPA, FAO Angola Projecto TERRA, Rome.
- Ad-hoc-AG_Boden, 2005. Bodenkundliche Kartieranleitung, 5. Auflage. Schweizerbart'sche Verlagsbuchhandlung, Hannover.
- AfDB, A.D.B., 2015. African Statistical Yearbook.
- Alam, S.A., Starr, M. and Clark, B.J.F., 2013. Tree biomass and soil organic carbon densities across the Sudanese woodland savannah: A regional carbon sequestration study. Journal of Arid Environments, 89: 67-76.
- Allaire, S.E., Lafond, J.A., Cabral, A.R. and Lange, S.F., 2008. Measurement of gas diffusion through soils: comparison of laboratory methods. Journal of Environmental Monitoring, 10(11): 1326-1336.
- Amberger, A., 2006. Soil Fertility and Plant Nutrition in the Tropics ans Subtropics, Paris, 96 pp.
- Anderson, T.H., 2003. Microbial eco-physiological indicators to asses soil quality. Agriculture Ecosystems & Environment, 98(1-3): 285-293.
- Ando, K. et al., 2014. Short-term effects of fire intensity on soil organic matter and nutrient release after slash-and-burn in Eastern Province, Zambia. Soil Science and Plant Nutrition, 60(2): 173-182.
- Andren, O., Katterer, T. and Karlsson, T., 2004. ICBM regional model for estimations of dynamics of agricultural soil carbon pools. Nutrient Cycling in Agroecosystems, 70(2): 231-239.
- Asanzi, C. et al., 2006. Food production in the planalto of Southern Angola. Soil Science, 171(10): 810-820.

В

- Baldock, J.A. and Skjemstad, J.O., 2000. Role of the soil matrix and minerals in protecting natural organic materials against biological attack. Organic Geochemistry, 31(7–8): 697-710.
- Bastida, F., Barbera, G.G., Garcia, C. and Hernandez, T., 2008. Influence of orientation, vegetation and season on soil microbial and biochemical characteristics under semiarid conditions. Applied Soil Ecology, 38(1): 62-70.
- Bastida, F., Moreno, J.L., Hernandez, T. and Garcia, C., 2006. Microbiological degradation index of soils in a semiarid climate. Soil Biology & Biochemistry, 38(12): 3463-3473.
- Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B. and Kimetu, J., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agricultural Systems, 94(1): 13-25.
- Bird, M.I., Veenendaal, E.M. and Lloyd, J.J., 2004. Soil carbon inventories and delta C-13 along a moisture gradient in Botswana. Global Change Biology, 10(3): 342-349.
- Bojanowski, J.S., 2015. sirad: Functions for calculating daily solar radiation and evapotranspiration.
- Bombelli, A. et al., 2009. An outlook on the Sub-Saharan Africa carbon balance. Biogeosciences, 6(10): 2193-2205.
- Buckingham, E., 1904. Contributions to our knowledge of the aeration of soils, 25. U.S. Dept. of Agriculture, Bureau of Soils, Washington, D.C., 60 pp.

- Campo, J. and Merino, A., 2016. Variations in soil carbon sequestration and their determinants along a precipitation gradient in seasonally dry tropical forest ecosystems. Global Change Biology, 22(5): 1942-1956.
- Ciais, P. et al., 2011. The carbon balance of Africa: synthesis of recent research studies, 369, 2038-2057 pp.
- Ciais, P. et al., 2013. Carbon and Other Biogeochemical Cycles. In: T.F. Stocker et al. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 465-570.
- Costantini, E.A.C. and L'Abate, G., 2016. Beyond the concept of dominant soil: Preserving pedodiversity in upscaling soil maps. Geoderma, 271: 243-253.

D

- Davidson, E.A., Savage, K., Verchot, L.V. and Navarro, R., 2002. Minimizing artifacts and biases in chamber-based measurements of soil respiration. Agricultural and Forest Meteorology, 113(1-4): 21-37.
- Davidson, E.A., Savage, K.E., Trumbore, S.E. and Borken, W., 2006. Vertical partitioning of CO2 production within a temperate forest soil. Global Change Biology, 12(6): 944-956.
- De Cauwer, V., 2013. Mashare Woody vegetation. In: Oldeland, J., Erb, C., Finckh, M., Jürgens, N. (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 117 - 119.
- De Jong, E. and Schappert, H.J.V., 1972. Calculation of soil respiration and activity fromCO2profiles in the soil. Soil Science, 113(5): 328-332.
- Demessie, A., Singh, B.R. and Lal, R., 2013. Soil carbon and nitrogen stocks under chronosequence of farm and traditional agroforestry land uses in Gambo District, Southern Ethiopia. Nutrient Cycling in Agroecosystems, 95(3): 365-375.
- Dinesh, R., Chaudhuri, S.G., Ganeshamurthy, A.N. and Dey, C., 2003. Changes in soil microbial indices and their relationships following deforestation and cultivation in wet tropical forests. Applied Soil Ecology, 24(1): 17-26.
- Diniz, A.C., 1973. Características Mesológicas de Angola. Descricao e correlacao dos aspectos fisiograficos, dos solos e da vegetacao das zonas agricolas Angolanas, Instituto de Investifacao Agronomica de Angola, Nova Lisboa.
- Dintwe, K. et al., 2015. Soil organic C and total N pools in the Kalahari: potential impacts of climate change on C sequestration in savannas. Plant and Soil, 396(1-2): 27-44.
- Dixon, R.K. and Turner, D.P., 1991. The Global Carbon-Cycle and Climate Change Responses and Feedbacks from Belowground Systems. Environmental Pollution, 73(3-4): 245-262.
- Dlamini, T.C. and Haynes, R.J., 2004. Influence of agricultural land use on the size and composition of earthworm communities in northern KwaZulu-Natal, South Africa. Applied Soil Ecology, 27(1): 77-88.
- Domptail, S.E., Große, L.M., Kowalski, B. and Baptista, J., 2013. Cusseque/Cacuchi The People. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 73-80.
- Don, A., Schumacher, J. and Freibauer, A., 2011. Impact of tropical land-use change on soil organic carbon stocks - a meta-analysis. Global Change Biology, 17(4): 1658-1670.

Elzhov, T.V., Mullen, M.K., Spiess, A.-N. and Bolker, B., 2016. minpack.lm: R interface to the Levenberg-Marquardt nonlinear least-squares algorithm found in MINPACK, plus support for bounds., R package.

F

- Falloon, P. and Smith, P., 2002. Simulating SOC changes in long-term experiments with RothC and CENTURY: model evaluation for a regional scale application. Soil Use and Management, 18(2): 101-111.
- FAO, 2017. Soil Organic Carbon: the hidden potential. Food and Agriculture Organization of the United Nations, Rome, Italy.
- FAO and ITPS, 2015. Status of the World's Soil Resources (SWSR) Main Report., Rome, Italy.
- Fierer, N., Chadwick, O.A. and Trumbore, S.E., 2005. Production of CO2 in soil profiles of a California annual grassland. Ecosystems, 8(4): 412-429.
- Finckh, M., Revermann, R. and Aidar, M.P.M., 2016. Climate refugees going underground a response to Maurin et al. (2014). New Phytologist, 209(3): 904-909.
- Frantz, D., Schneibel, A., Stellmes, M., Revermann, R. and Finckh, M., 2013. Caiundo Earth Observation. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 143-146.

G

- Gebert, J., Gröngröft, A. and Pfeiffer, E.-M., 2011. Relevance of soil physical properties for the microbial oxidation of methane in landfill covers. Soil Biology & Biochemistry, 43: 1759 – 1767.
- Grace, J., San Jose, J., Meir, P., Miranda, H.S. and Montes, R.A., 2006. Productivity and carbon fluxes of tropical savannas. Journal of Biogeography, 33(3): 387-400.
- Gröngröft, A., Luther-Mosebach, J., Landschreiber, L. and Kowalski, B., 2013a. A method for yield assessment on rainfed dryland agricultural fields. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 279–286.
- Gröngröft, A., Luther-Mosebach, J., Landschreiber, L., Revermann, R. and Eschenbach, A., 2013b. Seronga - Landscape. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 131-132.
- Große, L.M., Kowalski, B., Domptail, S.E. and Eigner, A., 2013. Seronga The People. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 147-158.

Η

- Haarmeyer, D.H. et al., 2010. The BIOTA Observatories. Klaus Hess Publishers, Göttingen & Windhoek.
- Hartemink, A.E. and Huting, J., 2008. Land cover, extent, and properties of arenosols in Southern Africa. Arid Land Research and Management, 22(2): 134-147.
- Heinemeyer, A. et al., 2011. Soil respiration: implications of the plant-soil continuum and respiration chamber collar-insertion depth on measurement and modelling of soil CO2 efflux rates in three ecosystems. European Journal of Soil Science, 62(1): 82-94.
- Hengl, T. et al., 2014. SoilGrids1km Global Soil Information Based on Automated Mapping. PLOS ONE, 9(8): e105992.

Ε

- Houghton, R.A., 2010. How well do we know the flux of CO2 from land-use change? Tellus Series B-Chemical and Physical Meteorology, 62(5): 337-351.
- Houghton, R.A. et al., 2012. Carbon emissions from land use and land-cover change. Biogeosciences, 9(12): 5125-5142.
- Huber, K., 2016. The role of microorganisms in the nutrient cycling of subtropical savannah soils, TU Braunschweig, Braunschweig, 136 pp.

- IUSS Working Group WRB, 2006. World Reference Base for soil resources 2006, FAO, Rome.
- IUSS Working Group WRB, 2015. World Reference Base for soil resources 2014, FAO, Rome.

J

- Jassal, R. et al., 2005. Relationship between soil CO2 concentrations and forest-floor CO2 effluxes. Agricultural and Forest Meteorology, 130(3-4): 176-192.
- Jassal, R.S. et al., 2004. A model of the production and transport of CO2 in soil: predicting soil CO2 concentrations and CO2 efflux from a forest floor. Agricultural and Forest Meteorology, 124(3-4): 219-236.
- Jenkinson, D.S., 1990. The Turnover of Organic Carbon and Nitrogen in Soil. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences, 329(1255): 361-368.
- Jin, Y. and Jury, W.A., 1996. Characterizing the dependence of gas diffusion coefficient on soil properties. Soil Science Society of America Journal, 60(1): 66-71.
- Jobbagy, E.G. and Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications, 10(2): 423-436.
- Joergensen, R.G. and Castillo, X., 2001. Interrelationships between microbial and soil properties in young volcanic ash soils of Nicaragua. Soil Biology & Biochemistry, 33(12-13): 1581-1589.
- Joergensen, R.G. and Mueller, T., 1996. The fumigation-extraction method to estimate soil microbial biomass: Calibration of the kEN value. Soil Biology and Biochemistry, 28(1): 33-37.
- Johnson, D.W. and Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management, 140(2-3): 227-238.
- Jones, A. et al., 2013. Soil Atlas of Africa, European Commission, Luxembourg.
- Jürgens, N., 2013. How can scientific information on the Okavango Region be made useful for decision making? – An integrated compilation of the first products of the project 'The Future Okavango'. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 7-8.

Κ

- Kalinski, K., 2014. Impact of land use on in situ soil respiration on savanna sites in northern namibia, University of Hamburg, Hamburg, 81 pp.
- Kallenbach, C.M., Frey, S.D. and Grandy, A.S., 2016. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nature Communications, 7: 10.
- Kassam, A., Friedrich, T., Shaxson, F. and Pretty, J., 2009. The spread of Conservation Agriculture: justification, sustainability and uptake. International Journal of Agricultural Sustainability, 7(4): 292-320.
- Kgathi, D.L. et al., 2006. The Okavango; a river supporting its people, environment and economic development. Journal of Hydrology, 331(1-2): 3-17.

- Khan, K.S. and Joergensen, R.G., 2006. Microbial C, N, and P relationships in moisture-stressed soils of Potohar, Pakistan. Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde, 169(4): 494-500.
- Kim, D.G., Thomas, A.D., Pelster, D., Rosenstock, T.S. and Sanz-Cobena, A., 2016. Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa: synthesis of available data and suggestions for further research. Biogeosciences, 13(16): 4789-4809.
- Koch, A., McBratney, A. and Lal, R., 2012. Global soil week: Put soil security on the global agenda. Nature, 492(7428): 186-186.
- Kowalski, B., Azebaze, N., Domptail, S.E., Große, L.M. and Pröpper, M., 2013. Mashare The People. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 121-128.
- Krishnaraj, S.J., Baker, T.G., Polglase, P.J., Volkova, L. and Weston, C.J., 2016. Prescribed fire increases pyrogenic carbon in litter and surface soil in lowland Eucalyptus forests of south-eastern Australia. Forest Ecology and Management, 366: 98-105.
- Kühne, A., Schack-Kirchner, H. and Hildebrand, E.E., 2012. Gas diffusivity in soils compared to ideal isotropic porous media. Journal of Plant Nutrition and Soil Science, 175(1): 34-45.
- Kutsch, W.L. et al., 2008. Response of carbon fluxes to water relations in a savanna ecosystem in South Africa. Biogeosciences, 5(6): 1797-1808.
- Kutzbach, L. et al., 2007. CO2 flux determination by closed-chamber methods can be seriously biased by inappropriate application of linear regression. Biogeosciences, 4(6): 1005-1025.

L

- Laiho, R., 2006. Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. Soil Biology & Biochemistry, 38(8): 2011-2024.
- Lal, R., 2002. Carbon sequestration in dryland ecosystems of West Asia and North Africa. Land Degradation & Development, 13(1): 45-59.
- Lal, R., 2004. Carbon sequestration in dryland ecosystems. Environmental Management, 33(4): 528-544.
- Lal, R., 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degradation & Development, 17(2): 197-209.
- Lal, R., 2014. Principles and Practices of Soil Resource Conservation, eLS. John Wiley & Sons, Chichester.
- Lal, R., Negassa, W. and Lorenz, K., 2015. Carbon sequestration in soil. Current Opinion in Environmental Sustainability, 15: 79-86.
- Lehmann, J. and Kleber, M., 2015. The contentious nature of soil organic matter. Nature, 528(7580): 60-68.
- Lipper, L. et al., 2014. Climate-smart agriculture for food security. Nature Climate Change, 4(12): 1068-1072.
- Livingston, G.P. and Hutchinson, G.L., 1995. Enclosure-based measurement of trace gas exchange: applications and sources of error. In: P.A. Matson and R.C. Harriss (Eds.), Biogenic Trace Gases: Measuring Emissions from Soil and Water. Blackwell Science. Blackwell Science, Cambridge, pp. 14–50.
- Luther-Mosebach, J., Kalinski, K., Gröngröft, A. and Eschenbach, A., 2016. CO2 fluxes in subtropical dryland soils—a comparison of the gradient and the closed chamber method. Journal of Plant Nutrition and Soil Science: n/a.

- Maestrini, B., Nannipieri, P. and Abiven, S., 2015. A meta-analysis on pyrogenic organic matter induced priming effect. Global Change Biology Bioenergy, 7(4): 577-590.
- Maier, M. and Schack-Kirchner, H., 2014a. Reply to comment on "Using the gradient method to determine soil gas flux: A review". Agricultural and Forest Meteorology, 197: 256-257.
- Maier, M. and Schack-Kirchner, H., 2014b. Using the gradient method to determine soil gas flux: A review. Agricultural and Forest Meteorology, 192: 78-95.
- Maier, M., Schack-Kirchner, H., Hildebrand, E.E. and Schindler, D., 2011. Soil CO2 efflux vs. soil respiration: Implications for flux models. Agricultural and Forest Meteorology, 151(12): 1723-1730.
- Marshall, T.J., 1959. The Diffusion of Gases Through Porous Media. Journal of Soil Science, 10(1): 79-82.
- Massman, W.J., 1998. A review of the molecular diffusivities of H2O, CO2, CH4, CO, O-3, SO2, NH3, N2O, NO, AND NO2 in air, O-2 AND N-2 near STP. Atmospheric Environment, 32(6): 1111-1127.
- Matanyair, C.M., 1996. Pearl Millet Production System(s) in the Communal Areas of Northern Namibia: Priority Research Foci Arising from a Diagnostic Study, International Crops Research Institute for Semi-Arid Topics, Gaborone.
- Maurin, O. et al., 2014. Savanna fire and the origins of the 'underground forests' of Africa. New Phytologist, 204(1): 201-214.
- McCarthy, T.S., 2013. The Okavango Delta and its Place in the Geomorphological Evolution of Southern Africa. South African Journal of Geology, 116(1): 3-54.
- McLauchlan, K., 2006. The nature and longevity of agricultural impacts on soil carbon and nutrients: A review. Ecosystems, 9(8): 1364-1382.
- McLauchlan, K.K. and Hobbie, S.E., 2004. Comparison of labile soil organic matter fractionation techniques. Soil Science Society of America Journal, 68(5): 1616-1625.
- MEA, Millenium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Synthesis, Washington, DC.
- Mendelsohn, J. and ElObeid, S., 2004. Okavango River The flow of a lifeline. Struik Publishers & Raison, Windhoek.
- Mendelsohn, J.M. et al., 2010. Okavango Delta: Floods of Life. RAISON, Windhoek.
- Millington, R.J. and Quirk, J.P., 1961. Permeability of porous solids. Transactions of the Faraday Society, 57: 1200 1207.
- Millington, R.J. and Shearer, R.C., 1971. Diffusion in Aggregated Porous Media. Soil Science, 111(6): 372-378.
- Ministry of Environment and Tourism, D.o.E.A., 2000. Natural Resource Mapping of the Kavango Region, Ministry of Environment and Tourism, Windhoek.
- Moldrup, P. et al., 2013. Structure-Dependent Water-Induced Linear Reduction Model for Predicting Gas Diffusivity and Tortuosity in Repacked and Intact Soil. Vadose Zone Journal, 12(3): 1-11.
- Moldrup, P., Olesen, T., Rolston, D.E. and Yamaguchi, T., 1997. Modeling diffusion and reaction in soils .7. Predicting gas and ion diffusivity in undisturbed and sieved soils. Soil Science, 162(9): 632-640.
- Moriasi, D.N. et al., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the Asabe, 50(3): 885-900.
- Mosimane, K. et al., 2017. Variability in chemistry of surface and soil waters of an evapotranspiration-dominated flood-pulsed wetland: solute processing in the Okavango Delta, Botswana. Water SA, 43(1): 104-115.

- Murray-Hudson, M., Finckh, M. and Revermann, R., 2013. Seronga- Vegetation. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 143-146.
- Myklebust, M.C., Hipps, L.E. and Ryel, R.J., 2008. Comparison of eddy covariance, chamber, and gradient methods of measuring soil CO2 efflux in an annual semi-arid grass, Bromus tectorum. Agricultural and Forest Meteorology, 148(11): 1894-1907.

0

Olson, D.M. et al., 2001. Terrestrial ecoregions of the worlds: A new map of life on Earth. Bioscience, 51(11): 933-938.

Ρ

- Pabst, H., Gerschlauer, F., Kiese, R. and Kuzyakov, Y., 2016. Land Use and Precipitation Affect Organic and Microbial Carbon Stocks and the Specific Metabolic Quotient in Soils of Eleven Ecosystems of Mt. Kilimanjaro, Tanzania. Land Degradation & Development, 27(3): 592-602.
- Pabst, H., Kuhnel, A. and Kuzyakov, Y., 2013. Effect of land-use and elevation on microbial biomass and water extractable carbon in soils of Mt. Kilimanjaro ecosystems. Applied Soil Ecology, 67: 10-19.
- Paul, E.A., 2016. The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. Soil Biology & Biochemistry, 98: 109-126.
- Pedologicas, C.d.E., 1961. Carta geral dos solos de Angola. Centro dos Estudos de Pedologia, Lisboa.
- Penman, H.L., 1940. Gas and vapour movements in the soil: I. The diffusion of vapours through porous solids. The Journal of Agricultural Science, 30(03): 437-462.
- Perkins, J.S. and Thomas, D.S.G., 1993. Spreading Deserts or Spatially Confined Environmental Impacts - Land Degradation and Cattle ranching the Kalahari Desert of Botswana. Land Degradation and Rehabilitation, 4(3): 179-194.
- Petersen, A., 2008. Pedodiversity of southern African drylands. PhD thesis at the University of Hamburg Thesis, Hamburg, 374 p and appendix pp.
- Pihlatie, M. et al., 2007. Gas concentration driven fluxes of nitrous oxide and carbon dioxide in boreal forest soil. Tellus Series B-Chemical and Physical Meteorology, 59(3): 458-469.
- Pingintha, N., Leclerc, M.Y., Beasley, J.P., Zhang, G. and Senthong, C., 2010. Assessment of the soil CO2 gradient method for soil CO2 efflux measurements: comparison of six models in the calculation of the relative gas diffusion coefficient. Tellus Series B-Chemical and Physical Meteorology, 63(3): 401-401.
- Post, W.M., Emanuel, W.R., Zinke, P.J. and Stangenberger, A.G., 1982. Soil Carbon Pools and World Life Zones. Nature, 298(5870): 156-159.
- Powlson, D.S. et al., 2011. Soil management in relation to sustainable agriculture and ecosystem services. Food Policy, 36: S72-S87.
- Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P. and Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agriculture Ecosystems & Environment, 220: 164-174.
- Preston, C.M. and Schmidt, M.W.I., 2006. Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions. Biogeosciences, 3(4): 397-420.
- Pretty, J., Toulmin, C. and Williams, S., 2011. Sustainable intensification in African agriculture. International Journal of Agricultural Sustainability, 9(1): 5-24.
- Pröpper, M., Gröngröft, A., Falk, T., Eschenbach, A., Fox, T., Gessner, U., Hecht, J., Hinz, M.O., Huettich, C., Hurek, T., Kangombe, F.N., Keil, M., Kirk, M., Mapaure, C., Mills, A.,

Mukuya, R., Namwoonde, N.E., Overmann, J., Petersen, A., Reinhold-Hurek, B., Schneiderat, U., Strohbach, B.J., Lück-Vogel, M., Wisch, U., 2010. Causes and perspectives of land-cover change through expanding cultivation in Kavango. In: M.T. Hoffman, U. Schmiedel and N. Jürgens (Eds.), Biodiversity in southern Africa. Volume 3: Implications for landuse and management. Klaus Hess Publishers, Göttingen & Windhoek.

Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., De Cauwer, V., Lages, F., Masamba, W., Murray-Hudson, M., Schmidt, L., Strohbach, B.J., Jürgens, N., 2015. The Future Okavango Findings, Scenarios and Recommendations for Action. Research Project Final Synthesis Report.

Q

Quinn, G.P. and Keough, M.J., 2002. Experimental Design and Data Analysis for Biologists. Cambridge University Press, Cambridge, 526 pp.

R

- Raich, J.W. and Schlesinger, W.H., 1992. The Global Carbon-Dioxide Flux in Soil Respiration and its Relationship to Vegetation and Climate. Tellus Series B-Chemical and Physical Meteorology, 44(2): 81-99.
- Revermann, R. and Finckh, M., 2013. Caiundo- Vegetation. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 91-96.
- Revermann, R., Maiato, F., Gomes, A., Lages, F. and Finckh, M., 2013. Cusseque Vegetation. In: Oldeland, J., Erb, C., Finckh, M., Jürgens, N. (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 59 - 63.
- Revermann, R. et al., submitted. Tropical dry forests and woodlands of the Cubango Basin in southern Africa A first classification and assessment of their woody species diversity. Phytocoenologia.
- Rey, A., 2015. Mind the gap: non-biological processes contributing to soil CO2 efflux. Global Change Biology, 21(5): 1752-1761.
- Ribeiro, A.A., Adams, C., Manfredini, S., Aguilar, R. and Neves, W.A., 2015. Dynamics of soil chemical properties in shifting cultivation systems in the tropics: a meta-analysis. Soil Use and Management, 31(4): 474-482.
- Rice, C.W., Fabrizzi, K. and White, P., 2007. Benefits of Soil Organic Carbon to Physical, Chemical and Biological Properties of Soil. In: J.M. Kimble et al. (Eds.), Soil Carbon Management: Economic, Environmental and Societal Benefits. CRC Press.
- Ringrose, S. et al., 2008. Diagenesis in Okavango fan and adjacent dune deposits with implications for the record of palaeo-environmental change in Makgadikgadi-Okavango-Zambezi basin, northern Botswana. Geomorphology, 101(4): 544-557.
- Ringrose, S., Matheson, W. and Vanderpost, C., 1998. Analysis of soil organic carbon and vegetation cover trends along the Botswana Kalahari Transect. Journal of Arid Environments, 38(3): 379-396.
- Rolston, D.E., 1986. Gas fluxes. In: A. Klute (Editor), Methods of Soil Analysis. American Society of Agronomy, Madison, pp. 1103 - 1119.
- Ryan, C.M., Williams, M. and Grace, J., 2011. Above- and Belowground Carbon Stocks in a Miombo Woodland Landscape of Mozambique. Biotropica, 43(4): 423-432.

S

Saiz, G. et al., 2012. Variation in soil carbon stocks and their determinants across a precipitation gradient in West Africa. Global Change Biology, 18(5): 1670-1683.

- Sanchez-Canete, E.P. and Kowalski, A.S., 2014. Comment on "Using the gradient method to determine soil gas flux: A review" by M. Maier and H. Schack-Kirchner. Agricultural and Forest Meteorology, 197: 254-255.
- Schack-Kirchner, H., Kublin, E. and Hildebrand, E.E., 2011. Finite-Element Regression to Estimate Production Profiles of Greenhouse Gases in Soils. Vadose Zone Journal, 10(1): 169-183.
- Schadel, C., Luo, Y.Q., Evans, R.D., Fei, S.F. and Schaeffer, S.M., 2013. Separating soil CO2 efflux into C-pool-specific decay rates via inverse analysis of soil incubation data. Oecologia, 171(3): 721-732.
- Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R. and Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Management, 5(1): 81-91.
- Schjonning, P., Eden, M., Moldrup, P. and de Jonge, L.W., 2013. Two-Chamber, Two-Gas and One-Chamber, One-Gas Methods for Measuring the Soil-Gas Diffusion Coefficient: Validation and Inter-calibration. Soil Science Society of America Journal, 77(3): 729-740.
- Schlesinger, W.H. and Andrews, J.A., 2000. Soil respiration and the global carbon cycle. Biogeochemistry, 48(1): 7-20.
- Schmidt, M.W.I. et al., 2011. Persistence of soil organic matter as an ecosystem property. Nature, 478(7367): 49-56.
- Schneibel, A., Stellmes, M., Roder, A., Finckh, M., Revermann, R., Frantz, D., Hill, J., 2016. Evaluating the trade-off between food and timber resulting from the conversion of Miombo forests to agricultural land in Angola using multi-temporal Landsat data. Science of the Total Environment, 548: 390-401.
- Schneider, J., Kutzbach, L., Schulz, S. and Wilmking, M., 2009. Overestimation of CO2 respiration fluxes by the closed chamber method in low-turbulence nighttime conditions. Journal of Geophysical Research-Biogeosciences, 114: 1-10.
- Scholes, R.J., 1990. The influence of soil fertility on the ecology of southern African dry savannas. Journal of Biogeography, 17: 415 - 419.
- Scholes, R.J. and Archer, S.R., 1997. Tree-grass interactions in savannas. Annual Review of Ecology and Systematics, 28: 517-544.
- Simmonds, E.B., 1998. Soils of the Okavango River Basin, Windhoek.
- Simmonds, E.B., 2000. Soils of the Kavango Region, Republic of Namibia. Directorate of Environmental Affairs. Ministry of Environment and Tourism, Windhoek.
- Six, J., Conant, R.T., Paul, E.A. and Paustian, K., 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant and Soil, 241(2): 155-176.
- Sleutel, S., De Neve, S., Roibas, M.R.P. and Hofman, G., 2005. The influence of model type and incubation time on the estimation of stable organic carbon in organic materials. European Journal of Soil Science, 56(4): 505-514.
- Smith, P. et al., 2010. Measurements necessary for assessing the net ecosystem carbon budget of croplands. Agriculture Ecosystems & Environment, 139(3): 302-315.
- Staff, S.S., 1999. Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys. United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC.
- Steudl, T., Göhmann, H., Flügel, W.-A. and Helmschrot, J., 2013. Hydrological assessment of hydrological dynamics in the upper Okavango. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 247–261.
- Strohbach, B.J. and Petersen, A., 2007. Vegetation of the central Kavango woodlands in Namibia: An example from the Mile 46 Livestock Development Centre. South African Journal of Botany, 73: 391 - 401.

- Tang, J.W. and Baldocchi, D.D., 2005. Spatial-temporal variation in soil respiration in an oakgrass savanna ecosystem in California and its partitioning into autotrophic and heterotrophic components. Biogeochemistry, 73(1): 183-207.
- Tang, J.W., Baldocchi, D.D., Qi, Y. and Xu, L.K., 2003. Assessing soil CO2 efflux using continuous measurements of CO2 profiles in soils with small solid-state sensors. Agricultural and Forest Meteorology, 118(3-4): 207-220.
- Team, R.C., 2016. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
- Thierfelder, C. et al., 2016. Evaluating manual conservation agriculture systems in southern Africa. Agriculture Ecosystems & Environment, 222: 112-124.
- Thomas, A.D., Hoon, S.R. and Dougill, A.J., 2011. Soil respiration at five sites along the Kalahari Transect: Effects of temperature, precipitation pulses and biological soil crust cover. Geoderma, 167-68: 284-294.
- Tian, Q.X. et al., 2016. Factors controlling soil organic carbon stability along a temperate forest altitudinal gradient. Scientific Reports, 6.
- Tisdall, J.M. and Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science, 33(2): 141-163.
- Tittonell, P., 2014. Ecological intensification of agriculture—sustainable by nature. Current Opinion in Environmental Sustainability, 8: 53-61.
- Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Shepherd, K.D. and Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya II. Withinfarm variability in resource allocation, nutrient flows and soil fertility status. Agriculture Ecosystems & Environment, 110(3-4): 166-184.
- Touré, A., Temgoua, E., Guenat, C. and Eberling, B., 2013. Land Use and Soil Texture Effects on Organic Carbon Change in Dryland Soils, Senegal. Open Journal of Soil Science, 3(6).
- Troeh, F.R., Jabro, J.D. and Kirkham, D., 1982. Gaseous-Diffusion Equations for Porous Materials. Geoderma, 27(3): 239-253.
- Tscharntke, T. et al., 2012. Global food security, biodiversity conservation and the future of agricultural intensification. Biological Conservation, 151(1): 53-59.
- Tsheboeng, G., Murray-Hudson, M. and Kashe, K., 2016. Response of riparian plant communities to distance from surface water in the Okavango Delta, Botswana. African Journal of Ecology: n/a.

U

Urbaniak, M. et al., 2016. Measuring Major Components of the Terrestrial Carbon Balance. In: L. Mueller, A.K. Sheudshen and F. Eulenstein (Eds.), Novel Methods for Monitoring and Managing Land and Water Resources in Siberia. Springer Water. Springer Int Publishing Ag, Cham, pp. 401-423.

V

- Valentini, R. et al., 2014. A full greenhouse gases budget of Africa: synthesis, uncertainties, and vulnerabilities. Biogeosciences, 11(2): 381-407.
- Vance, E.D., Brookes, P.C. and Jenkinson, D.S., 1987. An Extraction Method for Measuring Soil Microbial Biomass-C. Soil Biology & Biochemistry, 19(6): 703-707.
- Vanlauwe, B., Coe, R. and Giller, K., 2016. Beyond averages: new approaches to understand heterogeneity and risk of technology success or failure in smallholder farming. Experimental Agriculture.

- Vashum, K.T. and Jayakumar, S., 2016. Soil organic carbon status and sustainability of slash-andburn cultivation in India. Journal of Sustainable Forestry, 35(8): 591-603.
- VDLUFA, 1991. Methodenhandbuch. Band 1. Die Untersuchung von Böden.
- Veenendaal, E.M., Kolle, O. and Lloyd, J., 2004. Seasonal variation in energy fluxes and carbon dioxide exchange for a broad-leaved semi-arid savanna (Mopane woodland) in Southern Africa. Global Change Biology, 10(3): 318-328.
- von Luetzow, M. et al., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions a review. European Journal of Soil Science, 57(4): 426-445.
- von Luetzow, M. et al., 2007. SOM fractionation methods: Relevance to functional pools and to stabilization mechanisms. Soil Biology & Biochemistry, 39(9): 2183-2207.

W

- Walker, S.M. and Desanker, P.V., 2004. The impact of land use on soil carbon in Miombo Woodlands of Malawi. Forest Ecology and Management, 203(1-3): 345-360.
- Wang, L., D'Odorico, P., Ringrose, S., Coetzee, S. and Macka, S.A., 2007. Biogeochemistry of Kalahari sands. Journal of Arid Environments, 71(3): 259-279.
- Wattel-Koekkoek, E.J.W., Buurman, P., van der Plicht, J., Wattel, E. and van Breemen, N., 2003. Mean residence time of soil organic matter associated with kaolinite and smectite. European Journal of Soil Science, 54(2): 269-278.
- Weber, A., 2013a. Caiundo- Climate. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 85-86.
- Weber, A., 2013b. Cusseque Climate. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 45-46.
- Weber, A., 2013c. Mashare Climate. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 103-104.
- Weber, A., 2013d. Seronga Climate. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 133-134.
- Wehberg, J. and Weinzierl, T., 2013. Okavango Basin Physicogeographical setting. In: J. Oldeland, C. Erb, M. Finckh and N. Jürgens (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 3.
- White, F., 1977. The underground forests of Africa: a preliminary review. The Gardens' Bulletin, 29.
- Whitmore, A.P., 1996. Describing the mineralization of carbon added to soil in crop residues using second-order kinetics. Soil Biology & Biochemistry, 28(10-11): 1435-1442.
- Wichern, F. and Joergensen, R.G., 2009. Soil Microbial Properties Along a Precipitation Transect in Southern Africa. Arid Land Research and Management, 23(2): 115-126.
- Williams, C.A. et al., 2007. Africa and the global carbon cycle. Carbon balance and management, 2: 3.
- Wolf, B. et al., 2011. Applicability of the soil gradient method for estimating soil-atmosphere CO(2), CH(4), and N(2)O fluxes for steppe soils in Inner Mongolia. Journal of Plant Nutrition and Soil Science, 174(3): 359-372.
- Wood, T.E., Detto, M. and Silver, W.L., 2013. Sensitivity of Soil Respiration to Variability in Soil Moisture and Temperature in a Humid Tropical Forest. Plos One, 8(12): 7.
- Woollen, E., Ryan, C.M. and Williams, M., 2012. Carbon Stocks in an African Woodland Landscape: Spatial Distributions and Scales of Variation. Ecosystems, 15(5): 804-818.

Zou, X.M., Ruan, H.H., Fu, Y., Yang, X.D. and Sha, L.Q., 2005. Estimating soil labile organic carbon and potential turnover rates using a sequential fumigation-incubation procedure. Soil Biology & Biochemistry, 37(10): 1923-1928.

SUMMARY

Global land-use conversions are accompanied with the loss of soil organic carbon (SOC) and soil nutrients and are, as a consequence, threatening soil bound ecosystem functions like soil fertility, carbon sequestration, and ecosystem resilience. These ecosystem functions are strongly linked to soil organic matter (SOM), from which SOC is the main constituent. On the one hand, SOM enhances soil fertility by improving the soil nutrient level as well as the cation exchange capacity, which prevents nutrients from being leached. SOM is responsible for a medium term storage and release of nitrogen that is provided during the decay of organic material by soil microorganisms. Additionally, SOM plays a major role in aggregating soil particles and thus supports the soil water holding capacity and protects the soil from wind and water erosion. On the other hand, SOC being part of the terrestrial carbon pool has a high significance in the global carbon cycle by contributing to the exchange of carbon between terrestrial ecosystems and the atmosphere. The pictured significance of SOM highlights the importance of a profound understanding of the factors and processes that determine the development and dynamics of SOC stocks.

The present study aims at contributing to an improved understanding of the impact of land use on SOC, investigated at four study sites in the Okavango Catchment, situated in southern Africa. The focus of the study lies on four topics concerning the distribution of soils in the landscape and aspects of SOM: (I) a detailed description of the soil types with identification of the WRB soil reference groups, their properties and formation; (II) the distribution of SOC-stocks in the landscape and their response to agriculture; (III) the process of soil respiration addressed by testing two methodological approaches to quantify the CO_2 fluxes in order to verify the suitability for the application in remote areas; (IV) the SOC-fractions, defined according to their degradability by incubation experiments and microbial biomass, both in their dependence on land use, climate and soil type.

The research sites are located in the Okavango Catchment which stretches from the sources of the Okavango River in the central Angolan highlands to the Okavango Delta in Botswana. All sites encompass the Okavango River or its tributaries and all relevant land-scape units. All together, they cover a climatic gradient with falling precipitation from north to south. The northern most site, Cusseque in central Angola in the highlands of Bié at the Cusseque River and receives a mean annual precipitation (MAP) of about 987 mm. The study sites of Caiundo and Mashare are situated along the midstream of the river with a MAP of 732 mm and 571 mm, respectively. The southernmost site, Seronga, lies at the so-called "Panhandle", a broad wetland forming the transition of the Okavango River to its Delta in north-western Botswana. This represents the driest study site with a MAP of 478 mm.

(I) The study newly describes the distribution of soils and pedodiversity in the Okavango Catchment (chapter 4). Thereby, the characteristic patterns according to climate and landscape structure became evident. Moreover, the study identified the dependence of pedodiversity on the landscape unit. The slopes in the study site Cusseque and floodplains in the three southern study sites were much more diverse – including Fluvisols, Calcisols, Arenosols, Luvisols and Cambisols – than the relatively homogenous hilltops and hinterland respectively with dominating Arenosols. The allocation of agricultural land use has been found to follow the distribution of the fertile soils in most cases, and was always concentrated on specific landscape units. An exception was found in the Caiundo area, where crop production has been expanded on deep Arenosols whereas the more fertile soils of fluvial origin were predominantly unused.

(II) The diversity of soil types is accompanied by a high variability of carbon stocks within the landscape (chapter 5). The results show that the variability of SOC stocks between the landscape units highly exceeds the differences between the four study sites. The floodplains and the wetlands store the largest amounts of SOC whereas the areas of sand dunes were found to be poor in SOC. Median SOC stocks to 1 m depth were 37 t ha⁻¹ with a maximum of 46.5 kg m⁻² in Angolan peatlands and a minimum of 2.4 kg m⁻² in Arenosols of natural pure sandy levees near the river at the study site of Mashare. The climate effect on SOC stocks has been shown only by the northernmost site with significantly higher SOC stocks. The vertical distribution of SOC varies between landscape units. A concentration in the topsoil is mostly pronounced in Arenosols with the lowest nutrient status. Woodland conversion and dryland agriculture leads to a change in SOC between +11 and -39 % of initial values. SOC loss was strongest on fields with ongoing crop production; short-term rotation within shift and burn agricultural had no significant impact on SOC.

(III) The extent to which the application of manure and crop residues contributes to the provision of nutrients during the degradation process of SOM or to the enhancement of the SOC level depends on the heterotrophic soil respiration. It can be measured by the CO_2 fluxes from the soil to the atmosphere, including the identification of the heterotrophic part of the CO_2 flux. Flux measurements are crucial for the estimation of specific carbon budgets, but can sometimes be challenging, especially in remote areas. In this study, two measurement methods, the gradient method and the closed dynamic chamber method, for recording CO_2 fluxes were compared (chapter 6). The aim was to verify the suitability of the gradient method for the semi-arid and semi-humid soils in order to generate long time series of CO_2 flux measurements in future research. This would be desirable as only long time series will provide the data needed for carbon balance estimations with sufficient accuracy to be meaningful.

The closed dynamic chamber method directly measures the CO_2 flux by measuring the rise in CO_2 concentration in a closed chamber that is connected to the soil surface and sealed against the atmosphere. The gradient method is based on Fick's law and requires knowledge on diffusion properties of the soil, concentration gradients between soil and atmosphere and the air-filled porosity. The CO_2 concentration profile in this study was determined by collecting soil gas samples from different soil depths. The study was conducted on two sites, Mashare (semi-arid) and Cusseque (semi-humid) with comparable sandy soil texture. Soil gas diffusivities were measured in lab experiments using diffusion chambers and undisturbed soil cores. Modeled diffusivities were predicted according to six popular models based on air-filled porosity and total porosity as input parameters. Results show strong agreement between both methods based on measured diffusivities. However, with modeled diffusivities overestimations of fluxes for most of the tested models, especially at high air-filled porosity, were detected. In conclusion, the investigation indicates that the gradient method offers a valuable tool for flux estimates on the pedon scale in dry ecosystems particularly in combination with measured diffusivities and includes the possibility for investigating subsurface processes involved in the CO_2 production. However, if diffusivities were modeled using two models that serve as realistic upper and lower limit as the estimated diffusivities from transfer models can differ substantially is recommended. To reduce the methodological bias, it is important to pay attention to the precise measurements of soil water content which is altering the soil pore space and therewith are influencing the diffusivity of the soil. The study showed that sitespecific variations will otherwise be surpassed by methodological bias.

(IV) Soil heterotrophic respiration not only depends on environmental factors, like soil moisture and temperature whose influence can be measured by monitoring the CO₂ fluxes, but also on the degradability of the SOM. The SOM is present as a continuum regarding degradability and can be experimentally divided into different pools. In this study, a labile (C_{labile}) and a stable (C_{stable}) carbon fraction was separated by incubation experiments on different soils from different landscapes, land-use types and climatic regions to see, whether these factors have an influence on the relative proportions (Chapter 7). Additionally, the microbial biomass carbon (C_{mic}) as a third fraction was analyzed, as it is an important indicator of SOM quality. Investigations on the effect of long-term dryland and irrigation agriculture as well as on the short-term effect of slash and burn practices on the stocks of C_{stable} and C_{labile} and the C_{mic} were carried out by comparing agricultural fields to unused woodlands in the same landscape units. C_{labile} was defined as the degradable fraction of carbon during incubation and quantified by fitting a decomposition model to the cumulative respired CO₂ Carbon of incubated soil samples. C_{mic} was quantified using the fumigation-extraction method.

The results indicate that the stocks of all fractions significantly decreased during longlasting agricultural use on plots with potentially high carbon stocks on old floodplains with about 80 % of C_{stable} and C_{labile}-fraction and 74 % of C_{mic}. Also poorer sandy Kalahari soils exhibit decreases of the C_{stable}, C_{labile} and C_{mic} fraction of 51 %, 70 % and 8 % respectively, however, only the decrease of C_{labile} was significant. The findings indicate that all three fractions were strongly interrelated suggesting that total organic carbon determines the size of all carbon fractions. Long-term agricultural use did not change the relative proportions of C_{labile} and C_{stable} significantly, suggesting, that a modified SOC balance of input and output evenly affects both fractions over time. Under slash and burn agriculture, however, the labile fraction is the first to be depleted indicating a probable contribution of C_{labile} to the expected peak of soil fertility after the burning of woodlands. Furthermore, the microbial activity tended to be predominantly driven by the availability of labile organic carbon.

The present study provides a wide range of new data and knowledge on soil carbon stocks and dynamics in a so far poorly explored region of southern Africa. It gave new insights into the distribution of soils and carbon stocks and their link to agricultural land use in the Okavango Region, and highlights the importance of a profound understanding of SOC for soil fertility in semi-arid and semi humid regions As part of the ongoing research on the meaning of SOM and SOC for fertility management, it add on the data basis for at supporting improved and sustainable land management strategies and therewith minimize the human impact on soils while improving human wellbeing.

ZUSAMMENFASSUNG

Die weltweite Umwandlung von Wald zu ackerbaulich genutzten Flächen geht nicht nur mit dem Verlust von organischen Bodenkohlenstoff (soil organic carbon, SOC) und Nährstoffen einher, sondern bedroht damit auch die bodengebundenen Ökosystemfunktionen wie Bodenfruchtbarkeit, Kohlenstoff-Sequestrierung und Ökosystem-Resilienz. Diese Ökosystemfunktionen stehen in engem Zusammenhang mit der organischen Bodensubstanz (soil organic matter, SOM), deren Hauptbestandteil SOC darstellt. Durch die Erhöhung des Bodennährstoffniveaus sowie die Verbesserung der Kationenaustauschkapazität, die verhindert, dass Nährstoffe ausgewaschen werden, verbessert die SOM einerseits die Bodenfruchtbarkeit. SOM ist auch verantwortlich für die mittelfristige Lagerung und Freisetzung von Stickstoff und anderer Nährstoffe, die während des Abbaus von organischem Material durch Bodenmikroorganismen zur Verfügung gestellt werden. Darüber hinaus spielt SOM eine wichtige Rolle bei der Aggregation von Bodenpartikeln und unterstützt so die Bodenwasserhaltekapazität und schützt den Boden vor Wind- und Wassererosion. Auf der anderen Seite hat der Kohlenstoffanteil der SOM als Teil des terrestrischen Kohlenstoff-Pools eine hohe Bedeutung im globalen Kohlenstoffzyklus, indem er große Mengen an potentiell umsetzbarem Kohlenstoff speichert und durch Festlegungsund Umsetzungsprozesse zum Austausch von Kohlenstoff zwischen terrestrischen Ökosystemen und der Atmosphäre beiträgt. Die dargestellte bedeutende Rolle von SOM macht die Notwendigkeit deutlich, die Faktoren und Prozesse, die die Entwicklung von organischen Kohlenstoffbeständen des Bodens bestimmen tiefgreifend zu verstehen.

Die vorliegende Studie zielt darauf ab, einen Beitrag zum besseren Verständnis des Einflusses der Landnutzung auf SOC zu leisten. Dieser wurde an vier Untersuchungsstandorten im Okavango Einzugsgebiet im südlichen Afrika näher betrachtet. Im Mittelpunkt der Studie stehen vier Themen rund um die Verteilung von Böden in der Landschaft und Aspekte des Kohlenstoffzyklus: (I) eine detaillierte Beschreibung der Bodentypen mit Identifizierung der WRB-Bodenreferenzgruppen, ihren Eigenschaften und ihrer Genese, sowie ihrer Nutzung; (II) die Verteilung der SOC-Vorräte in der Landschaft und der Einfluss landwirtschaftlicher Aktivitäten, des Ausgangsgesteins, und des Klimas; (III) der Prozess der Bodenatmung durch die Prüfung zweier methodischer Ansätze zur Quantifizierung der CO_2 -Flüsseund deren Eignung für die Anwendung in abgelegenen Gebieten; (IV) die experimentell bestimmten, nach ihrer Abbaubarkeit definierten SOC-Fraktionen und die mikrobielle Biomasse, beides in ihrer Abhängigkeit von Landnutzung, Klima und Bodentyp.

Das Okavango Einzugsgebiet erstreckt sich von den Quellen des Okavango im angolanischen Hochland bis zum Okavango Delta in Botsuana. Alle Standorte umfassen den Okavango-Fluss oder seine Nebenflüsse und decken einen klimatischen Gradienten mit fallenden jährlichen Niederschlägen und steigenden mittleren Jahrestemperaturen von Norden nach Süden ab. Der nördlichste Untersuchungsstandort, Cusseque, liegt im Zentrum von Angola, im Hochland von Bié, und erhält einen durchschnittlichen jährlichen Niederschlag von etwa 987 mm. Die Standorte Caiundo und Mashare befinden sich ent-
lang des Mittellaufes des Okavango und erhalten einen mittleren Jahresniederschlag von 732 mm bzw. 571 mm. Der südlichste Standort, Seronga, liegt am sogenannten "Panhandle", einem breiten Feuchtgebiet, das den Übergang des Okavango-Flusses zum Delta im nordwestlichen Botswana bildet. Dies ist der trockenste Standort mit einem mittleren Jahresniederschlag von 478 mm.

(I) Die Studie beschreibt erstmals die Verteilung von Böden und Pedodiversität im Einzugsgebiet des Okavango (Kapitel 4). Dabei wurden die charakteristischen Muster in Bezug auf Klima- und Landschaftsstruktur deutlich. Darüber hinaus wurde in der Arbeit die Abhängigkeit der Pedodiversität von der Landschaftseinheit identifiziert. Die Hänge im Untersuchungsgebiet Cusseque und die Auen an den drei südlichen Untersuchungsstandorten waren viel diverser – darunter Fluvisols, Calcisole, Arenosole, Luvisols und Cambisols – als die relativ homogenen Hügelkuppen und das Hinterland mit dominierenden Arenosolen. Die Verteilung der landwirtschaftlichen Nutzung hat sich in den meisten Fällen der Verteilung der fruchtbaren Böden angepasst und war immer auf bestimmte Landschaftseinheiten konzentriert. Eine Ausnahme davon bildet der Ackerbau in Caiuno, der auf tiefen, von Natur aus nährstoffarmen Aerosolen stattfindet, während die fruchtbaren Böden fluvialen Ursprungs in den Flussauen überwiegend ungenutzt blieben.

(II) Die Vielfalt der Bodentypen ist von einer hohen Variabilität der Kohlenstoffvorräte innerhalb der Landschaft begleitet (Kapitel 5). Die Ergebnisse zeigen, dass die Variabilität der SOC-Vorräte zwischen den Landschaftseinheiten bei weitem die Unterschiede zwischen den vier Untersuchungsstandorten übersteigt. Die Flussauen und die Feuchtgebiete speichern die größten Mengen an SOC, während die Gebiete der Sanddünen niedrige SOC-Vorräte aufwiesen. Die medianen SOC-Vorräte auf 1 m Tiefe betrugen 37 t ha⁻¹, mit einem Maximum von 46.5 kg m⁻² in angolanischen Torfgebieten und einem Minimum von 2.4 kg m⁻² in reinsandigen jungen Arenosolen an sandigen Uferwällen in der Nähe des Flusses in Mashare. Die Auswirkung des Klimas auf SOC-Vorräte wurde nur durch den Vergleich des nördlichsten Standorts zu den drei südlichen deutlich, da hier im Mittel höhere Werte festgesellt wurden. Die vertikale Verteilung von SOC variiert zwischen den Landschaftseinheiten. Eine Konzentration im Oberboden ist am stärksten bei Arenosolen mit dem niedrigsten Nährstoffstatus ausgeprägt. Die Umwandlung von Waldflächen hin zu Trockenfeldbau führt zu einer Veränderung der SOC-Vorräte zwischen +11 und -39% gegenüber den Ausgangswerten. Der SOC-Verlust war am stärksten auf den Feldern unter kontinuierlicher Bewirtschaftung, kurzfristige Rotation im Zuge von "slash and burn"-Landwirtschaft hatte keine signifikanten Auswirkungen auf SOC.

(III) Das Ausmaß, in dem die Anwendung von Dünger- und die Rückführung von Ernterückständen zur Bereitstellung von Nährstoffen während ihres Abbaus oder zur Erhöhung der SOC-Ebene der Böden beitragen, hängt von der heterotrophen Bodenatmung ab. Diese kann durch die Erfassung von CO₂-Gasflüssen vom Boden zur Atmosphäre (unter Berücksichtigung der der autotrophen Wurzelatmung) gemessen werden. Gasflußmessungen sind entscheidend für die Schätzung der spezifischen Kohlenstoffbudgets, können aber vor allem in abgelegenen Gebieten manchmal problematisch sein, da sie z.T. sehr wartungsintensiv sind. In dieser Studie wurden zwei Messmethoden zur Aufzeichnung von CO₂-Flüssen verglichen, das Gradientenverfahren und ein System mit geschlossenen dynamischen Hauben (Kapitel 6). Ziel war es, die Eignung der Gradientenmethode für die halbtrockenen und halbfeuchten Böden zu verifizieren, um künftig Langzeitreihen von CO₂-Flussen messen zu können. Dies ist erstrebenswert, da nur lange Zeitreihen die ausreichende Genauigkeit liefern können, die für die Carbon-Balance-Schätzungen benötigt werden.

Das geschlossene dynamische Haubenverfahren misst direkt den CO₂-Fluss durch Messung des Anstiegs der CO2-Konzentration in einer geschlossenen Haube, die mit der Bodenoberfläche verbunden und gegen die Atmosphäre abgedichtet ist. Die Gradientenmethode basiert auf dem Fickschen Gesetz und erfordert Kenntnisse der Diffusionseigenschaften des Bodens, die Konzentrationsgradienten zwischen Boden und Atmosphäre und das luftgefüllte Porenvolumen. Das CO₂-Konzentrationsprofil in dieser Studie wurde durch das Messen von Bodengasproben aus unterschiedlichen Bodentiefen bestimmt, die mittels Gaslanzen entnommen wurden. Die Studie wurde an zwei Standorten durchgeführt, Masahre (semi-arid) und Cusseque (semi-humid) mit vergleichbarer sandiger Bodenbeschaffenheit. Die Bodengasdiffusivität wurde in Laborexperimenten unter Verwendung von Diffusionskammern und ungestörten Bodenkernen gemessen. Die modellierten Diffusivitäten wurden anhand von sechs gängienModellen, die auf der Grundlage der luftgefüllten Porosität und der Gesamtporosität als Eingangsparameter die Diffusivität modellieren, bestimmt. Die Ergebnisse zeigen eine gute Übereinstimmung zwischen den ermittelten Flüssen, beider Messverfahren auf der Grundlage der gemessenen Diffusivitäten. Jedoch wurden mit modellierten Diffusivitäten eine Überschätzung der Flüsse für die meisten der getesteten Modelle, insbesondere bei hoher luftgefüllter Porosität, erzeugt. Die Untersuchung zeigte, dass die Gradientenmethode ein wertvolles Instrument für Gasflussmessung auf der Pedon-Skala in trockenen Ökosystemen bietet, vor allem in Kombination mit gemessenen Diffusivitäten. Sie bietet zudem die Möglichkeit, unterirdische Prozesse in der CO₂-Produktion zu untersuchen, da Verläufe der CO₂ Gradienten mit der Bodentiefe untersucht werden können. Bei der Modellierung von Diffusivitäten empfiehlt sich jedoch die Verwendung von zwei Modellen, die als realistische Ober- und Untergrenze dienen, da die geschätzten Diffusivitäten von Transfermodellen erheblich voneinander abweichen können. Um eine methodische Verzerrung zu reduzieren ist es wichtig, auf die genauen Messungen des Bodenwassergehalts zu achten, die den Bodenporenraum verändern und damit die Diffusivität des Bodens beeinflussen. Die Studie zeigte, dass ortsspezifische Unterschiede ansonsten durch methodisch bedingte Variabilität überlagert werden können.

(IV) Die heterotrophe Bodenatmung hängt nicht nur von Umweltfaktoren wie Bodenfeuchte und Temperatur ab, deren Einfluss durch die Erfassung der CO₂-Flüsse identifiziert werden kann, sondern auch von der Abbaubarkeit der SOM. Die SOM liegt als Kontinuum in Bezug auf seine Abbaubarkeit vor und kann experimentell in verschiedene Pools aufgeteilt werden. In dieser Studie wurde eine labile (C_{labile}) und eine stabile (C_{stable}) Kohlenstofffraktion durch Inkubationsexperimente getrennt. Die Untersuchung wurde an Proben aus verschiedenen Böden verschiedener Landschaften, Landnutzungsarten und Klimazonen durchgeführt, um zu sehen, ob die genannten Faktoren einen Einfluss auf die relativen Anteile der Fraktionen haben (Kapitel 7). Zusätzlich wurde der Kohlenstoff der mikrobiellen Biomasse (C_{mic}) als dritte Fraktion bestimmt, da diese ein wichtiger Indikator für SOM-Qualität darstellt. Für die Auswertung wurden jeweils Proben von landwirtschaftlich genutzten Flächen mit natürlichen Standorten aus der gleichen Landschaftseinheit verglichen. C_{labile} wurde als die abbaubare Kohlenstofffraktion definiert, indem ein Kohlenstoffabbaumodel an die kumulative CO_2 -Produktion der inkubierten Bodenproben angepasst und extrapoliert wurde. C_{mic} wurde mittels der Fumigations-Extraktions-Methode quantifiziert.

Im Ergebnis haben die Vorräte aller Fraktionen bei langjähriger landwirtschaftlicher Nutzung auf Standorten mit potenziell hohen Kohlenstoffbeständen mit etwa 80% der C_{stable}- und C_{labile}-Fraktion und 74% der C_{mic} Fraktion deutliche Abnahmen verzeichnet. Auch SOC-ärmere, sandige Kalahari-Böden zeigen eine Abnahme der C_{stable}-, C_{labile}- und C_{mic}-Fraktion von 51%, 70% bzw. 8%, wobei nur die Abnahme von C_{labile} statistisch signifikant war. Die Ergebnisse zeigen, dass alle drei Fraktionen stark miteinander verknüpft in Beziehung stehen, was darauf hindeutet, dass die Menge des gesamten SOC die Höhe der einzelnen Kohlenstofffraktionen bestimmt. Langfristige landwirtschaftliche Nutzung veränderte die relativen Proportionen von C_{labile} und C_{stable} signifikant, was darauf hindeutet, dass eine modifizierte SOC-Bilanz von Input und Output gleichmäßig beide Fraktionen im Laufe der Zeit verringert. Unter "slash and burn" Landwirtschaft jedoch ist die C_{labile} Fraktion die erste, die abgebaut wird und damit vermutlich mitverantwortlich für den Peak an Bodenfruchtbarkeit nach dem Abbrennen von Wäldern ist.

Die vorliegende Arbeit stellt eine Vielzahl neuer Daten über Kohlenstoffvorräte und ihrer Dynamiken in einer bisher wenig erforschten Region zur Verfügung. Die neu generierte Wissensbasis zu SOC-gebundener Prozesse in semi-ariden und semi-humiden Gebieten der Okavango Region können als Basis dienen für neue Forschung dabei könnte der Fokus auf die Generierung langer zeitreichen zur Bodenrespirationsmessungen von Feldern liegen, oder der Erfassung weiter Daten zur Berechnung von Kohlenstoff Budgets. Solche Daten können im Rahmen der aktuellen Forschung über die Bedeutung von SOM und SOC für das Fruchtbarkeitsmanagement dabei helfen, die Nachhaltigkeit von Landmanagementstrategien zu evaluieren und zu verbessern und damit die menschlichen Auswirkungen auf Böden zu minimieren und gleichzeitig zur Verbesserung des menschlichen Wohlergehens beizutragen.

LIST OF FIGURES

Figure 2.1:	The Future Okavango (TFO) research area with the four study sites Cu = Cusseque, Ca = Caiundo, Ma = Mashare, Se = Seronga. The TFO-Research Area comprises the active catchment from the highland of Bié in central Angola to the Okavango Delta in Botswana (map is from Pröpper et al., 2015)
Figure 2.2:	Study site Cusseque in the highland of Bié in central Angola and the positions of soil profiles. The colors schematically indicate the landscape units within the area. Areal picture by BingMaps
Figure 2.3:	Walter-Lieth climate diagram of Cusseque (Weber, 2013b). The x-axis starts with July and ends in June9
Figure 2.4:	Study site Caiundo at the Cubango River in south Angola and the positions of soil profiles. The colors schematically indicate the landscape units within the area. Areal picture by BingMaps
Figure 2.5:	Walter-Lieth climate diagram of Caiundo (Weber, 2013). The x-axis starts with July and ends in June
Figure 2.6:	Study site Mashare at the Okavango River in northern Namibia and the positions of soil profiles. The colors schematically indicate the landscape units within the area. Areal picture by BingMaps
Figure 2.7:	Walter-Lieth climate diagram of Mashare (Weber, 2013b). The x-axis starts with July and ends in June
Figure 2.8	Study site Seronga at the transition of the "Panhandle" to the Okavango Delta in Botswana and the positions of soil profiles. The colors schematically indicate the landscape units within the area. Areal picture by BingMaps
Figure 2.9:	Walter-Lieth climate diagram of Seronga (Weber, 2013b). The x-axis starts with July and ends in June
Figure 4.1:	Number of soils within the respective WRB soil reference group for the study site Cusseque with the first preafix qualifier
Figure 4.2	: The main WRB reference groups in the study site Cusseque and location of the idealized catena (orange line). Areal picture by BingMaps
Figure 4.3:	Idealized catena for the study site Cusseque with typical soil profiles: a) Hypoluvic Arenosol; b) Rubic Arenosol; c) Pisoplinthic Plinthosol; d) Haplic Gleysol; e) Sapric Histosol; f) Pisoplinthic Acrisol; g) Haplic Cambisol; h) Rubic Arenosol
Figure 4.4	Number of soils within the respective WRB soil reference group for the study site Caiundo with the first preafix qualifier
Figure 4.5	: The main WRB reference groups of the study site Caiundo and location of the idealized catena (orange line). Areal picture by BingMaps

Figure 5.2: Topsoil (0-30 cm) organic carbon contents in the different landscape units. Letters indicate significantly different SOC stocks at p < 0.05 within the respective study site.

Figure 6.2: Examples of CO2 gradients: a) temporal variation (plot K-D, March – May 2013); b) spatial variation (date of driest topsoil moisture for all plots). Water content was about

- Figure 7.1: Stocks of total carbon SOC (a), the carbon fractions Cstable, Clabile and Cmic (b-e), the initial mineralization rate (e) and the indices Clabile:SOC, Cmic:SOC, Cmic:Clabile, qCO2 (f-j) compared for the LC-units. Vertical lines divide the respective landscape units. The designations of the LC-unit are composed of a combination of landscape unit: K = Kalahari sand; F = old floodplain; H = hilltop and land-use type: D = dryland agriculture; I = irrigation agriculture; W = woodland. Different letters denote significantly different groups at p = 0.01 according to one-way ANOVA with Tukey's HSD post-hoc test. No letters are shown in cases of statistical insignificance of ANOVA results.

LIST OF TABLES

- Table 5-1: SOC stocks estimated for two depths (0.3 m, 1 m) of the different landscape units in
the study sites. Woodland sites and dryland agricultural sites on the respective
landscape unit are indicated.45
- Table 6-2: Indices for model evaluation. Compared are the observed (CDCM) and predicted fluxes (N = 98). Slope = the slope of the linear regression; R^2 = the coefficient of

LIST OF PUBLICATIONS

Journal Articles

- Luther-Mosebach, J., Gröngröft, A., Eschenbach, A., 2015. Influence of Landscape and Land-use on the Soil Carbon Stocks in the Okavango Catchment, In: Knoblauch, C., Fiencke, C., Berger, K. (Eds.), Böden im Wandel, 77. Hamburger Bodenkundliche Arbeiten, 77, Verein zur Förderung der Bodenkunde Hamburg, Hamburg, pp. 155-166.
- (2) Luther-Mosebach, J., Kalinski, K., Gröngröft, A., Eschenbach, A., 2016. CO2 fluxes in subtropical dryland soils—a comparison of the gradient and the closed chamber method. Journal of Plant Nutrition and Soil Science, n/a-n/a. doi: 10.1002/jpln.201600137.
- (3) **Luther-Mosebach, J.**, Gröngröft, A., Eschenbach, A., (in prep.). Land-use impacts on three functional organic carbon fractions in soils of the Okavango Catchment. Journal of Arid Environments.
- (4) Gröngröft, A., Luther-Mosebach, J., Landschreiber, L., Kowalski, B., 2013. A method for yield assessment on rainfed dryland agricultural fields, In: Oldeland, J., Erb, C., Finckh, M., Jürgens, N. (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology, 5, pp. 279–286.
- (5) Revermann, R., Oldeland, J., Goncalves, I.C.R., Luther-Mosebach, J., Gomes, A., Jürgens, N., Finckh, M., submitted. Tropical dry forests and woodlands of the Cubango Basin in southern Africa - A first classification and assessment of their woody species diversity. Phytocoenologia.

Fact sheets

- (6) Gröngröft, A., Luther-Mosebach, J., Landschreiber, L., Eschenbach, A., 2013. Cusseque - Soils, In: Oldeland, J., Erb, C., Finckh, M., Jürgens, N. (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology 5, pp. 51-54.
- (7) Gröngröft, A., Luther-Mosebach, J., Landschreiber, L., Eschenbach, A., 2013. Mashare - Soils, In: Oldeland, J., Erb, C., Finckh, M., Jürgens, N. (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology 5, pp. 105-108.
- (8) Gröngröft, A., Luther-Mosebach, J., Landschreiber, L., Eschenbach, A., 2013. Seronga - Soils, In: Oldeland, J., Erb, C., Finckh, M., Jürgens, N. (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology 5, pp. 135-137.
- (9) Gröngröft, A., Luther-Mosebach, J., Landschreiber, L., Revermann, R., Eschenbach, A., 2013. Seronga - Landscape, In: Oldeland, J., Erb, C., Finckh, M., Jürgens, N. (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology 5, pp. 131-132.

- (10) Gröngröft, A., Luther-Mosebach, J., Landschreiber, L., Revermann, R., Finckh, M., Eschenbach, A., 2013. Cusseque - Landscape, In: Oldeland, J., Erb, C., Finckh, M., Jürgens, N. (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology 5, pp. 43-44.
- (11) Gröngröft, A., Luther-Mosebach, J., Landschreiber, L., Revermann, R., Finckh, M., Eschenbach, A., 2013. Caiundo - Landscape, In: Oldeland, J., Erb, C., Finckh, M., Jürgens, N. (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology 5, pp. 83–84.
- (12) Gröngröft, A., Luther-Mosebach, J., Landschreiber, L., Revermann, R., Finckh, M., Eschenbach, A., 2013. Mashare - Landscape, In: Oldeland, J., Erb, C., Finckh, M., Jürgens, N. (Eds.), Environmental Assessments in the Okavango Region. Biodiversity & Ecology 5, pp. 101-102.

Books

- (13) Pröpper, M., Gröngröft, A., Finckh, M., Stirn, S., De Cauwer, V., Lages, F., Masamba, W., Murray-Hudson, M., Schmidt, L., Strohbach, B.J., Jürgens, N., 2015. The Future Okavango Findings, Scenarios and Recommendations for Action. Research Project Final Synthesis Report, p. 190. - - contributing author: Luther-Mosebach, J.
- (14) Liniger, H., Mekdaschi Studer, R., Moll, P., Zander, U., 2017. Making sense of research for sustainable land management. Centre for Development and Environment (CDE), University of Bern, Switzerland and Helmholtz-Centre for Environmental Research GmbH – UFZ, Leipzig, Germany, 304 pp. - contributing author: Luther-Mosebach, J.

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- Band 55: **Gebert, J.**: Mikrobielle Methanoxidation im Biofilter zur Behandlung von Rest-Emissionen bei der passiven Deponieentgasung. 2004. 235 S.