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Using soil properties to indicate regulating ecosystem services in a Sudano-Sahelian agro-ecological landscape

Elinor Holén

Stockholm Resilience Centre
Kräftriket 2B, Stockholm University, SE 106 91
info@stockholmresilience.su.se
www.stockholmresilience.su.se

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Abstract

In semi-arid low yielding agro-ecological landscapes such as the Sahel both water and soil nutrients are limiting factors for crop growth. In addition to this there is a distinct difference in how well different land cover/land use types, so called ecotopes, perform in producing ecosystem services (ES) related to small-scale agriculture. This thesis seeks to explain differences in provisioning ES supply with the prevalence of regulating ES using indicators as proxies. The results show that the produced biomass is three times higher in the ecotope characterized as Depression than in Field. However, there are no or little significant differences between ecotopes regarding nutrients, organic matter and texture. In evaporation measurements the ecotope characterized as Fallow turned out to have the lowest evaporation rate, while there seemed to be little or no difference between Field and Depression. Water holding capacity, on the other hand, was slightly higher in Depression, which would mean that crops would manage a dry spell for between 6 to 10 days longer compared to other ecotopes. The absence of distinct differences in chemical and physical properties of the soil, even though this difference is evident in provisioning ES supply, shows that selecting relevant indicators is not easily done with available standard soil-plant systems indicators. Potential differences relating to water regulation could be further investigated by looking at factors that determine the direction of water flows and distance to ground water as a potential water supply for crops, e.g. topography, soil depth and the occurrence of crusts and hardpans as well as how they impact the patterns of runoff and runon in the landscape.

1. Introduction

People in the Sahel are dependent on the landscapes to provide them with certain goods and services for their livelihoods. The semi-arid landscapes of the Sahel are low-yielding and vulnerable to the natural changes in precipitation and droughts, changes that are potentially further enhanced by global climate change (Foley et al. 2003). However, since the mid 1980s researchers have seen an increase in seasonal vegetation, the so called re-greening (Hermann et al. 2005; Olsson et al. 2005). The factors behind this trend are still being investigated, but it can not be simply explained by only one factor (Olsson et al. 2005; Dardel et al. 2014; Brandt et al. 2015). This trend has also been debated. For example, UNEP (2012) showed that there has actually been a continuous degradation in land since the droughts of the 1960s and early 70s by using a different method than most previous studies of vegetation cover. According to the UNEP report land degradation in Burkina Faso is severe to very severe (UNEP 2012).

Landscape scale is *"the scale where nature and people interact and that affect and are most affected by human activities"* (Wu 2013, 1000). Through the interactions with and management by people, landscapes provide services and well-being that people benefit from. Land use in an agricultural landscape gives a straight forward example of the concept of ecosystem services (ES), as it includes both the ecological properties of the land and the social dimensions of management practices (Reyers et al. 2013). Sinare (2013) have identified landscape units that link to ES by being defined as a combination of land use and land cover, so called ecotopes. Ecotopes are functional units in a landscape that can be both structured by human activities and shaped by natural processes (Farina 2008).

Through change in land use or management of the landscape the provisioning of ES can change (de Groot et al. 2010), and climate change can in addition exacerbate or reduce these services. Ecosystems provide multiple services in tandem that interact in complex ways. Regulating ES affect landscape productivity as they underpin most provisioning services e.g. food, by maintaining soil fertility, water regulation, pollination etc. (MEA 2005; TEEB 2015; Raudsepp-Hearne et al. 2010). But even though a decline in regulating ES can reduce the resilience of an ecosystem the importance of them has been underappreciated (Bennett et al., 2009). These regulating services are important to sustain food security in regions like the Sudano-Sahel where people and economies are particularly closely connected to local landscapes and its provisional capacity. Regardless which of the debated vegetation trends are dominating it is of great interest to see the extent to which different services are generated in the landscape under certain land use conditions, to further understand how climate induced changes in the landscape can affect the livelihoods and well-being of small-scale farmers (Brauman et al. 2007). This knowledge can then be used to support sustainable development trajectories.

This study, as part of the overarching project *Adapting to changing climate in drylands: The re-greening in Sahel as a potential success case*, aims at assessing regulating ES in a village landscape in northern Burkina Faso. There has so far been little comprehensive work done on regulating ES compared to provisioning ES in these agro-ecological landscapes (e.g. Sinare 2013; Sinare and Gordon 2015).

1.2 Research question

This thesis aims to contribute to the understanding of what kind of regulating services are generated in different land use types in a micro scale landscape (<1 km^2) in the semi-arid Sahel. Specifically, *does the generation of regulating ecosystem services differ between ecotopes in a typical semi-arid low yielding agro-ecological landscape*? To elaborate on this I will investigate different factors representing the principal regulating services essential for agriculture and explain differences, or lack of differences, that ultimately sustains the provisioning capacity. It is of particular relevance to investigate these questions in the Sahel because people are closely dependent on local ES for their livelihoods. Both water and soil nutrients are limiting factors for crop growth, due to rainfall variability, limited irrigation and fertilization, and due to inherent nutrient poor, low organic matter erosion sensitive soils.

2. Conceptual framework

The conceptual framework for this study is illustrated in Figure 1. The box shows the focus of this study. Overarching the whole system are earth system processes including nutrient cycles, photosynthesis and climate circulation patterns. These processes have initially formed all landscape structures during millions of years, and recently (seen from a history of the earth perspective) anthropogenic activities have to a great extent shaped the landscapes to fit human purposes (see e.g. Steffen et al. 2011). This study is looking at the landscape as a social-ecological system by dividing the landscape into smaller units (section 2.1) and linking them to land use using the concept of ecosystem services (section 2.2).

2.1 Landscape approach

A landscape approach is a place-based approach to help investigate ecosystem's contribution to human well-being. A place-based approach provides the context where issues can be articulated and solved even when there are competing interests (Potschin and Haines-Young 2013; Sayer et al. 2013). The landscape approach is seen as appropriate for analysing synergies and trade-offs between conservation strategies and local livelihoods, and can therefore be a useful approach for creating management strategies for spatial planning and landscape sustainability (Sayer 2009; Potschin and Haines-Young 2013; Wu 2013). This study uses a sub-division of the landscape into eco-topes. Ecotopes are defined as *"the elementary unit of a landscape, homogenous for a particular pattern or function"* (Farina 2008, 395) and capture both the biophysical properties of the land and its resulting functionality. How to classify an ecotope is subjective and can be case specific (Farina 2008). In this case, ecotopes are classified from type of vegetation and land use (see Table 1 in section 3.2.) As part

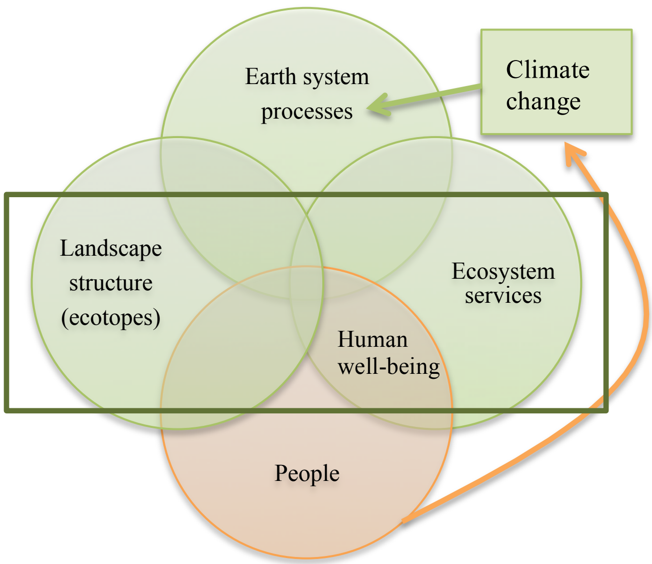

Figure 1. Conceptual framework for this study. The box shows the focus of this study. Earth system processes embed all ecosystems on earth and initially formed the landscapes around us. These processes now have good help from human activities as they change the landscape and larger scale processes by change in land cover. The landscape structure is made up by ecotopes, from which people obtain ecosystem services essential for their well-being. Another driver to this system is climate change, slowly changing the earth system processes. Adapted from Wu 2013.

of the landscape structure the ecotopes form a mosaic landscape, from which people obtain goods and services essential for their well-being. One driver and potential threat to this system is the human induced climate change, slowly changing the earth system processes affecting regional climate and precipitation.

2.2 Ecosystem services

Agricultural activities depend on the function of ecosystems. The ecosystem perspective tries to bridge the gap between different disciplines through the concept of ecosystem services (Coates et al. 2013). There are several suggestions on how to define ES (see e.g. Fischer et al. 2009). This study uses the definition from the Millennium Ecosystem Assessment, suggesting that ES are defined as direct and indirect benefits that people obtain from ecosystems (MA 2003). The concept combines the biophysical landscape and the social landscape in a social-ecological system, where ES are created and impacted as people use them. ES are often divided into four categories; provisioning, regulating, cultural and supporting (Figure 1), where the last category is seen as fundamental for all the others (MA 2003). ES are not constant and they fluctuate in both space and time while also being utilized on a variety of scales (Fischer et al. 2009). People are to a greater or lesser extent directly dependent on ES for their well-being. In urban areas the equivalent to ES can be delivered by other facilities (grocery stores, air conditioning, waste-water treatment plants etc.), whereas in rural areas ES often are more closely linked in time and space to humans (Coates et al. 2013). Therefore landscapes need to be long-term provisioning of important ES (Wu 2013).

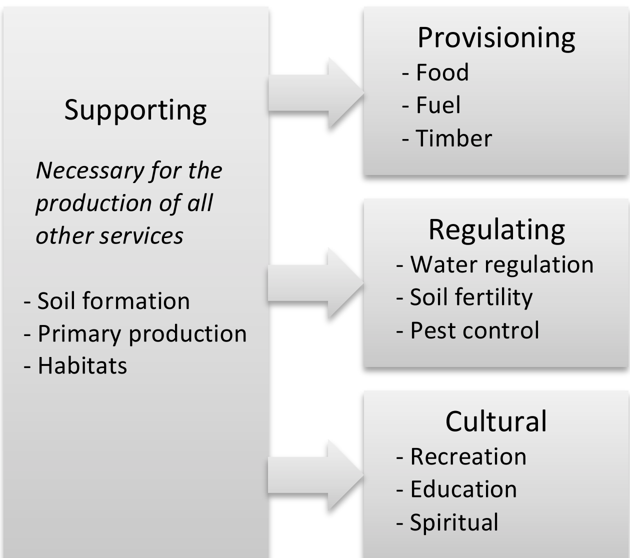

Figure 2. Categorisation of ecosystem services into supporting, provisioning, regulating and cultural, and examples thereof. Source: MA 2003; TEEB 2015.

Most areas have been managed for provisioning services, particularly food, although supporting, regulating and cultural services together generate a higher value (Coates et al. 2013). Regulating ES are the benefits obtained from the regulation of ecosystem processes (Figure 1; MA 2003) and they are essential for generating services with strong social involvement such as cultural services and food production (Reyers et al. 2013). This study focuses on regulating ES as they underpin the capacity to generate provisioning services such as staple crops, vegetables and pastures for livestock. In general, the capacity of regulating ES is said to be higher the more intact the ecosystem is, and that they decrease with intensity of land use (de Groot et al. 2010). Measuring ES can be complicated and therefore the use of proxies, or indicators, can be useful (Fischer et al. 2009; de Groot et al. 2010), especially when dealing with indirect services such as regulating ES. The indicators used in this study are described in section 3.1.

3. Methods

3.1 Selection of ecosystem services and indicators

Regulating ecosystem services are indirect benefits from biophysical and biochemical processes (Barrios, 2007), that underpin the capacity of delivering provisioning services such as crops, fodder and timber. The ES chosen for this study were soil productivity and water regulation using soil property parameters as indicators. An indicator is a measure that gives information about a feature beyond the indicator itself (e.g. Reyers et al. 2013). The indicators were chosen because they are associated with desirable conditions of the ES (Raudsepp-Hearne et al. 2010).

In an attempt to assess these services a number of indicators recognised by farmers as measures of soil productivity were identified (Belachew and Abera 2010), e.g. indicators relating to soil fertility, texture and water holding capacity. The services and indicators and their relationships are illustrated in Figure 3. It is debated whether soil productivity in this region is limited by nutrients in the soil (e.g. Bationo et al. 1998), or rainfall (e.g. Breman et al. 2001). The crop water uptake capacity is affected by the physical properties of the soil such as porosity and particle size that determine their rainfall infiltration and water holding capacity (Belachew and Abera 2010). Evaporation is also affected by texture, simply expressed because particle size and porosity determine how much water can be held in the pores of the soil, and the amount of water held in the soil determine how much can be evapotranspirated (Figure 4). Physical properties of the soil partly determine the amount of nutrients available for vegetation, together with other chemical properties such as pH. Carbon is stored in the soil as organic matter, which is decomposed matter from leaves and crop residues. Typically, carbon content is often lower on cultivated land than on naturally vegetated land because crops are taken from the fields leaving little or no

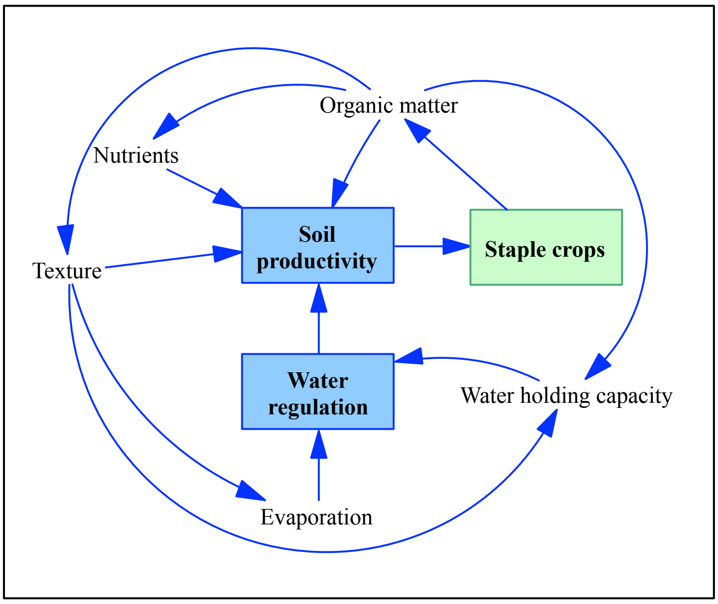

Figure 3. Ecosystem services (boxed) and indicators and how they relate to each other. Regulating services have blue boxes and provisioning have green.

residues for regeneration of organic matter (e.g. Post and Kwon 2000; Manlay et al. 2002). This is nicely summed up by Ouattara et al. (1999, 268): *"Soils constitute a kind of 'food storage' for plants, and their capacity and functioning are largely linked to their physical and hydrodynamic characteristics."*

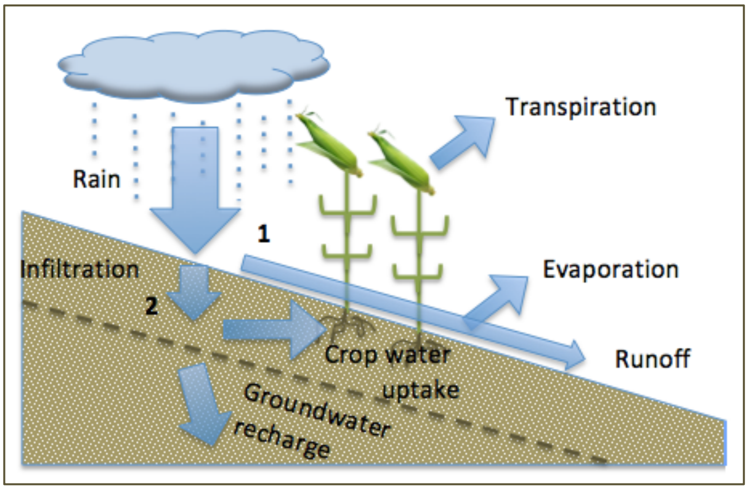

Figure 4. Figure showing partitioning points. 1) Rain hits soil surface, parting in runoff and infiltration. 2) In the soil, parting in crop water uptake and groundwater recharge. Crop water uptake is used by crops and transpired. Some soil moisture is lost as evaporation. Adapted from Rockström et al. 2003.

3.2 Case study description

The study area is Reko, a village in the Yatenga province in region Nord, Burkina Faso (see Figure 5) with a longterm annual rainfall of less than 600 mm y^{-1} during the rainy season from May-September (Sinare 2013) Most agricultural activity is made up of rain fed small-scale agriculture and a majority of the population has agriculture as key livelihood strategy alongside other sources of income. About 90 % of the population in region Nord is occupied in the agricultural sector (INSD 2009). The soils are generally highly degraded, prone to crusting and hence with low infiltration capacity resulting in low yielding (e.g. Bationo et al. 1998; Breman et al. 2001). Fields close to homesteads are cultivated more intensively and to a larger extent fertilised than fields farther away, which are sometimes left to rest (fallow). Agricultural practices have remained traditional and farmers till the soil by hand or sometimes with plough using oxen or horses. Burkina Faso is subject to a large population growth which further strains already stressed lands leading to shorter fallow periods (e.g. Mazzucato and Niemeijer 2000). The main crop is rainfed sorghum and millet that often is managed with low or no external input of nutrients (e.g. Ouattara et al. 1999).

Figure 5. Maps showing the location of the study site.

The focal scale of this study is micro scale landscapes (0-10 km^2), with a subdivision into ecotopes suggesting that ecotopes provide varied and different provisioning ES for local livelihoods and human wellbeing. Sinare (2013) have identified seven ecotopes in these villages: Depression, Homesteads, Fields, Fallow, Shrubland, and Forest (Table 1; Figure 6). As can be seen in Table 1 more than half of the village area consists of Fields. Adding to that almost 18 percent is Fallow, which makes almost 75 percent of the village cultivated land.

Bare soil and Forest are not included in this study on the underpinning regulating ES of ecotopes. Bare soils are not cultivated due to crust and low inherent fertility and do not provide any provisioning ES (Sinare 2013). Erosion is common during the rainy season. Forest is a very small part of the village and the forests present are sacred and therefore not used for other purposes than cultural/spiritual.

Table 1. Landscape subdivisions into ecotopes, classified from vegetation and land use. Distribution of ecotopes (% of village area) in 2012 and total village area (km^2) in Reko (from Sinare 2013).

Ecotope	Description	% of village area
Depression	Temporary water courses and their bordering fields. Topographically defined, clayey soil dominates. Often higher density of larger trees as compared to the other ecotopes, except Forest.	6
Homesteads	Land around homesteads, influenced by nutrient accumulation due to animal and human excreta. Also influenced by what humans plant, e.g trees for shade and vegetables.	3
Fields	Agricultural fields on different soil types. Trees and shrubs are present in a range of densities.	54
Fallow	Land that have been cultivated but left for fallow > 2 years. Shrubs have established, trees are present.	18
Shrubland	Non-cultivated land dominated by shrubs. Trees present in some cases, grass sprout around shrubs during the rainy season.	11
Bare soil	Land with no or very scarce vegetation.	7
Forest	Area with trees and shrubs in high density. Often but not always sacred.	1
Total village area		8.4 km^2

3.3 Data collection in the field

For an overview of the sampling and measurement protocol, see Appendix 1. All samples and measurements were made during fieldwork in Burkina Faso in October and November 2014.

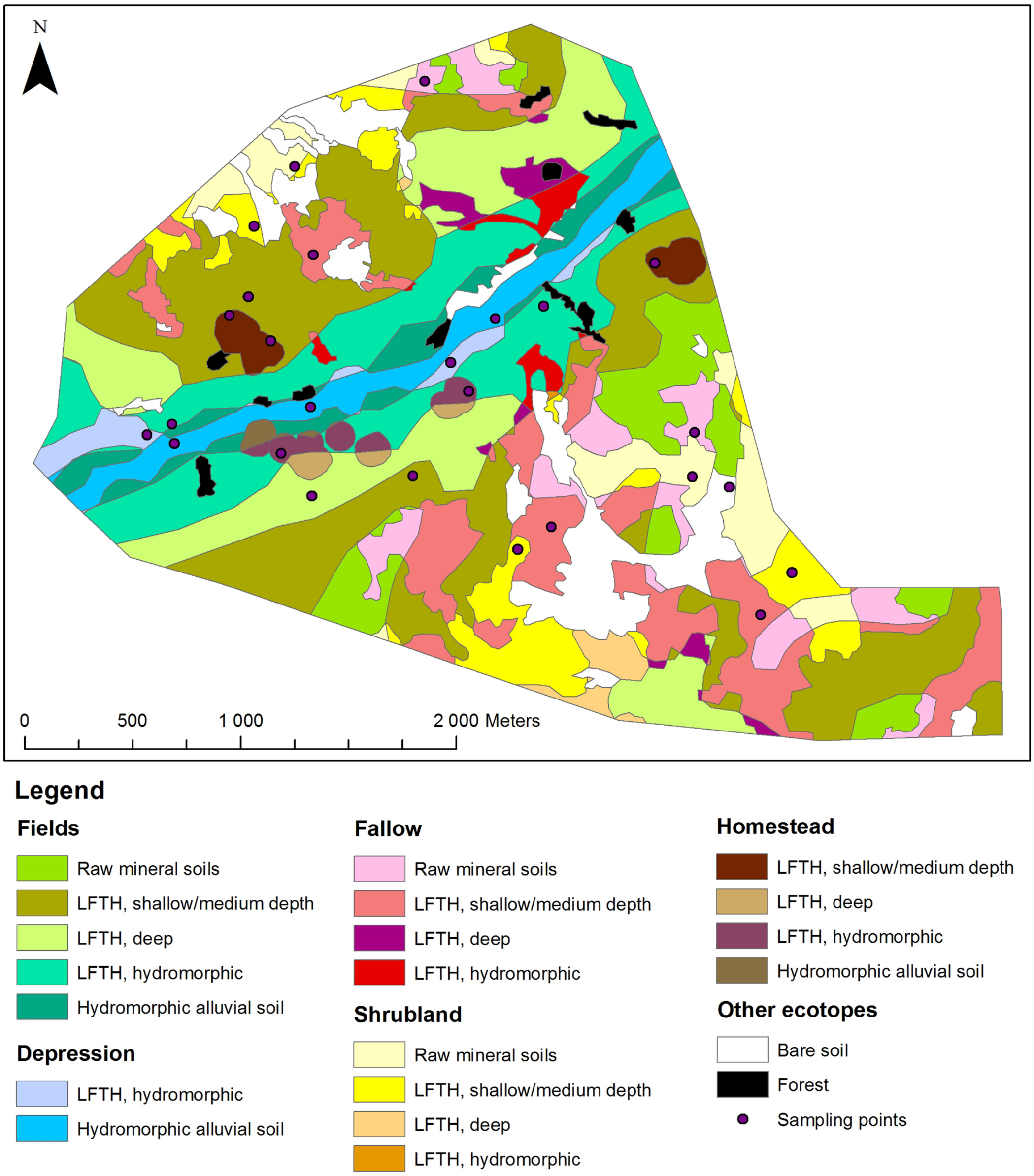

Figure 6. Combined ecotope and soil type map showing sample plots (Data sources: Sinare 2013; BUNASOL 2002). LFTH is an abbreviation for *leached ferruginous tropical soil with hardpan*. For full description of the soil types see Table 2.

3.3.1 Soil samples and analyses

Soil samples were taken to analyse organic matter, nutrients and soil texture. In total 77 soil samples were collected from 26 plots in three horizons (see Appendix 1). Five sampling points per ecotope were chosen from a combined ecotope and soil types map before going to the field (see Figure 6). The dominant soil types in each ecotope were sampled (see Table 2). An additional criterion for the field sampling points was that it had to be a sorghum field, since that is the dominant crop in Reko. The samples were taken from 0-10 cm, 10-20 cm and 20-30 cm depth to capture soil profile characteristics with depth. Each sample was a composite from four holes dug in the corners of a 2*2 m square, to get a representative sample from that point and avoid extreme values.

Table 2. Distribution of soil types in different ecotopes (%). Soil types with coverage >20% (in *italic*) were sampled.

	Raw mineral soils on ferralitic pans	Leached ferruginous tropical soil with hardpan, shallow or medium depth	Leached ferruginous tropical soil with hardpan, deep	Leached ferruginous tropical soil, hydromorphic or with spots and concretions	Poorly evolved hydromorphic alluvial soil
Fields	11	*41*	*21*	*21*	6
Depression	0	0	0	*27*	*73*
Homesteads	0	*44*	17	*32*	8
Fallow	*25*	*63*	6	6	0
Shrubland	*40*	*51*	9	0	0
Bare soil	*26*	*67*	7	0	0

Bulk density was measured using core sampling (Brown and Wherrett, n.d.). Bulk density was measured in three ecotopes (see Appendix 1) in two horizons, using four rings per horizon. Bunasol (Bureau National des Sols) in Ouagadougou conducted the chemical analyses and INERA soil physics lab in Saria analysed bulk density and particle size (granulometry).

The Walkley-Black procedure was used to analyse organic matter and total carbon content (Schulte 1995). Total nitrogen was analysed using mineralisation with sulphuric acid, selenium and salicylic acid, and available phosphorus was analysed using Bray no. 1 test (Bray and Kurtz 1945).

3.3.2 Land use

Harvest was estimated weighing biomass from three 5*5 m squares in four different sorghum fields, three within the Field ecotope and one in Depression. Semi-structured interviews regarding management of sampled ecotopes were conducted during the sampling to complement soil analyses data (see Appendix 4). Data gathered from the semi-structured interviews includes information about the management practices (fertilization etc.) for the last 5-10 years, years of fallow etc.

3.3.3 Evaporation

Soil microlysimeters were used to measure soil evaporation (Daamen et al. 1993; Wallace et al. 1999) in three ecotopes: Field, Fallow and Depression (see Appendix 1) during five days each using 16 lysimeters per ecotope. The lysimeters were weighed daily at sunrise and sunset to determine evaporation during the day (Burt et al. 2005; Jackson and Wallace 1999).

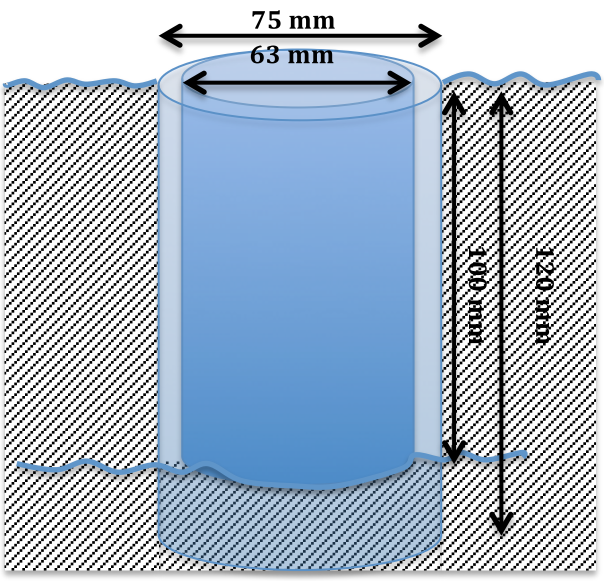

Figure 7. Construction of the microlysimeters using PVC pipes. The outside liner measures 75*120 mm and the inner lysimeter measures 63*100 mm. The top edge of both pipes are in level with the ground.

The lysimeters for the soil evaporation measurements were made out of PVC pipes 2 mm thick, with a diameter of 63 mm and height of 100 mm. They were installed in liners made out of PVC pipes with a diameter of 75 mm and a height of 120 mm, leaving a 4 mm gap between the liner and the lysimeter (see Figure 7). Since the measurements were made just after the rainy season rainfall was simulated by pouring water from an ewer until the soil was wet enough. After taking soil cores, the lysimeters were sealed with a cap made of aluminum foil (similar to the metal cap used by Daamen et al. 1993) and installed in the liner. The upper edge of both the liner and the lysimeter were in level with the ground when installed. To have conditions similar to the surrounding soil, new soil cores should be taken every day (see for example Daamen et al. 1993; Huixiao et al 1997). However, in this case the soil was too hard to enable this and the same soil cores were used for five days of measurements. The aluminium cap was removed every night to allow infiltration. In total 16 lysimeters in groups of 4 were installed in a sunny spot, except for in Field where they were installed with part time shadow to simulate the crop canopy cover (Figure 8). In Fallow, some of the soil cores were taken on such sandy soil that the soil cores would fall out when the cap was removed, and therefore half of the lysimeters were measured with their caps on for all five days. To weigh the lysimeters a portable battery powered electronic balance with a resolution of 0.1 g was used (as in e.g. Huixiao et al. 1997; Jackson and Wallace 1999).

Figure 8. Photo of soil microlysimeters in site. The fourth lysimeter group is out of picture.

3.4 Modelling water holding capacity

Soil hydraulic properties were calculated using neural network predictions in the Rosetta Lite plug-in in Hydrus-1D software. The Rosetta model uses soil texture and bulk density for estimating van Genuchten water retention parameters (Schaap et al. 2001). This is called pedostransfer functions (PTFs) because *"they translate existing surrogate data (e.g. particle-size distributions, bulk density and organic matter content) into soil hydraulic data"* (Schaap et al. 2001, 164). PTFs are hierarchical; meaning that predictions with more input parameters reduces uncertainty.

From the PTF curves produced in Hydrus-1D it was possible to get values for field capacity and wilting point. Field capacity is said to be the state in the soil that is ideal for plant growth (Brouwer et al. 1985). At field capacity infiltration has stopped and the pores in the soil is filled with air and water. As plant roots take up water and water evaporates from the soil surface the soil becomes dry. When the water content in the soil reaches the wilting point it becomes unavailable for the plants because the remaining water is tightly retained to the soil (Brouwer et al. 1985). Between field capacity and wilting point the soil water is available to plants. Field capacity is assumend to be -33 kPa and wilting point -1500 kPa (Brady and Weil 2008).

4. Results

All results from chemical and physical analyses can be found in Appendix 2.

4.1 Nutrient status in ecotopes

The regulating ES of soil fertility for the various ecotopes were indicated through the content of nitrogen (N), phosphours (P) and organic matter (OM). The general trend is that the content for all parameters decrease with depth. Total N concentrations range between 0.02-0.08 % of dry soil weight with Field having the lowest and Homestead and Depression having the highest concentration (see Figure 9). Statistical analysis shows a significant difference in total N between Field and Depression (p=0.027; 0.016; and 0.021 for the depths 0-10; 10-20 and 20-30 cm respectively). No differences were shown for available P ($p \geq 0.09$), where the results vary from 0.1-5.5 mg kg^{-1} in Field and 1.1-9.5 mg kg^{-1} in Homestead (see Figure 10). However, an outlier from Homestead was excluded in the analysis since it was seven times higher than the average for the other Homestead sampling points, hence deviated strongly from the normal range. Homestead is a very heterogenic ecotope (it being fields close to the houses), and there is no reason to suspect contamination of the sample or analysis error, but it would show an exaggerated p-value if included. OM concentrations range between 0.4-1.9 %, where the lowest concentrations were found in Field and the highest in Fallow (see Figure 11). The analysis shows a significant difference between Field (average 1.0 %) and Depression (average 1.6 %) for OM ($p \geq 0.033$) at 10-20 cm depth, but none on 0-10 and 20-30 cm ($p \geq 0.07$). In summary, the results show no or little significant differences between ecotopes both regarding nutrients, organic matter.

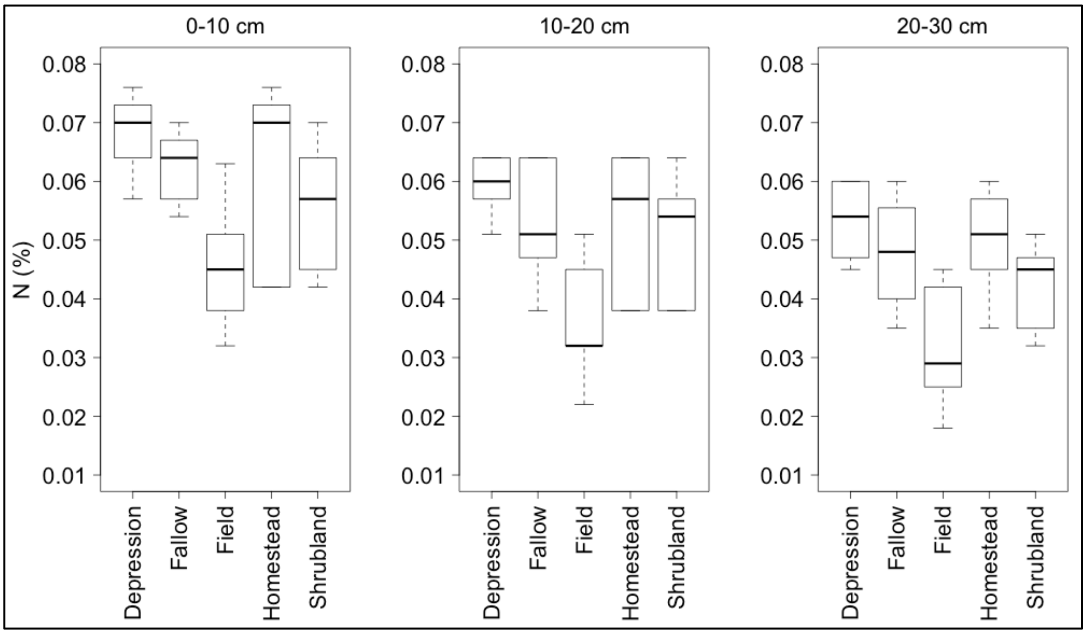

Figure 9. Nitrogen concentrations in different ecotopes for different depths.

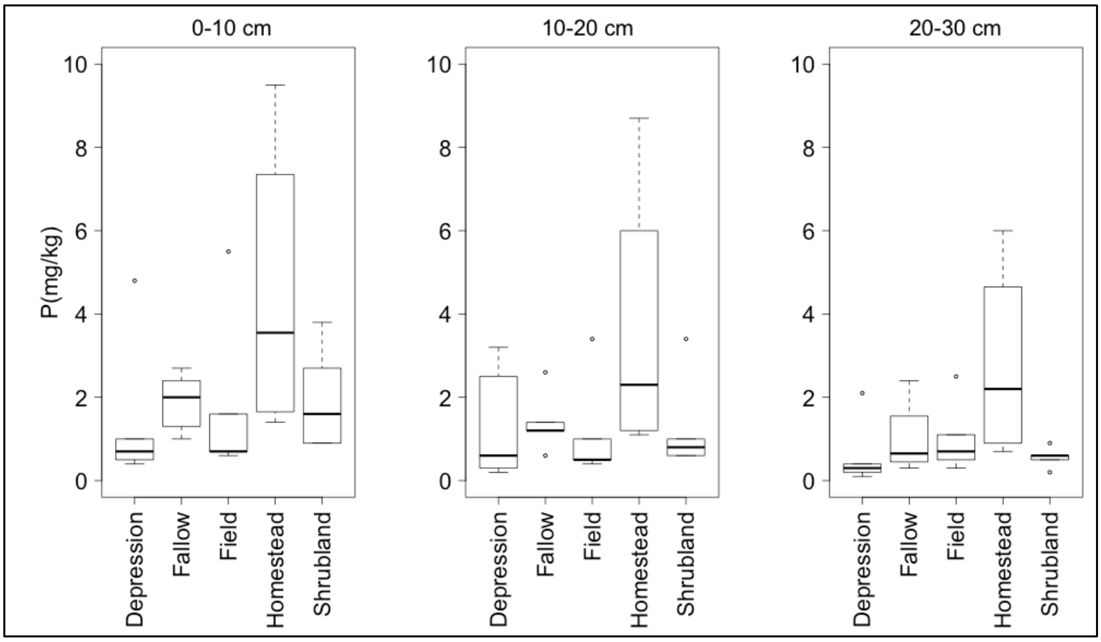

Figure 10. Available phosphorus in different ecotopes for different depths.

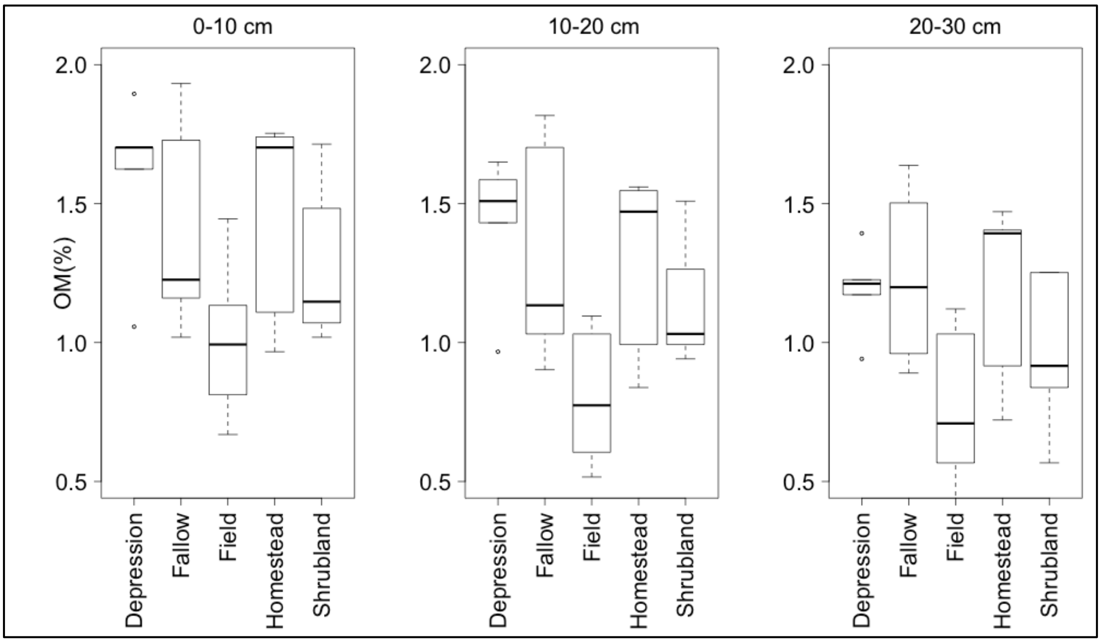

Figure 11. Concentration of organic matter in different ecotopes for different depths.

4.2 Soil physical properties of ecotopes

The physical properties of the soil have effects on both soil fertility and water holding capacity. There was no significant difference in texture (particle size) between the ecotopes. However, Depression seems to generally consist of a higher part of clay and silt than the others (see Figure 12). This corresponds to the fact that more than 70% of the soils in depression are alluvial soils (see Table 2), which in general are more fine-grained and fertile. All soils consisted mostly of fine sand, and in addition Field and Depression consisted of approximately 1/3 of clay. Particle size decreased with depth, i.e. higher amount of clay in the 20-30 cm layer whereas fine and coarse loam stays the same and the amount of fine and coarse sand decreased with depth.

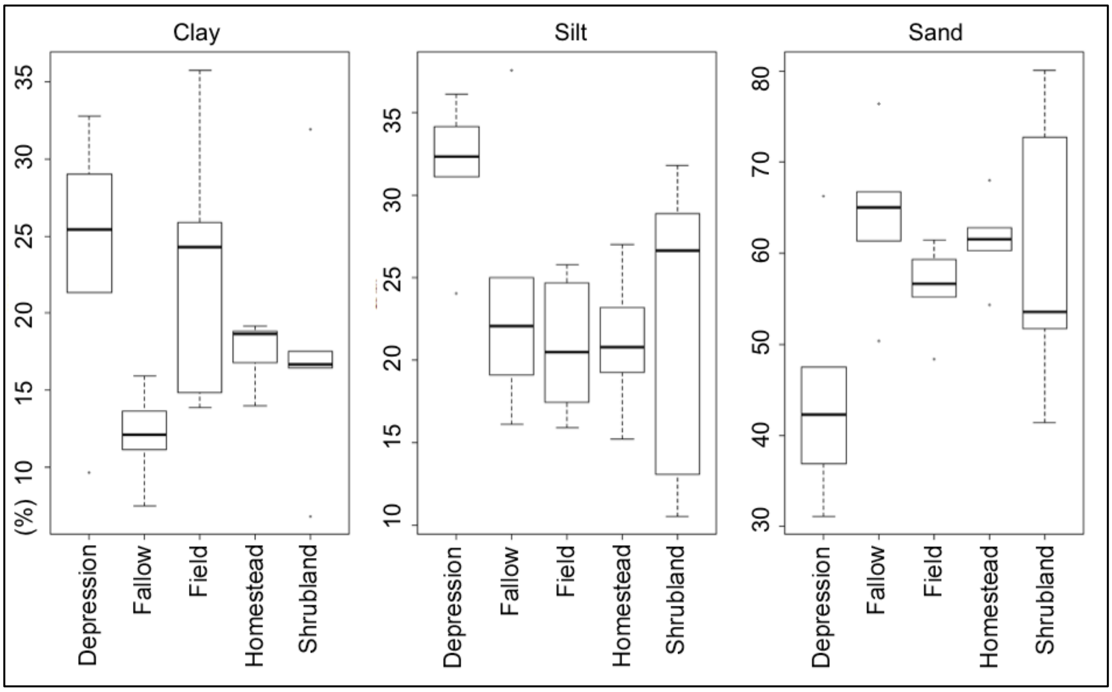

Figure 12. Particle size distribution in ecotopes.

4.3 Water regulating features in ecotopes

Fallow shows the lowest soil evaporation rate with the smallest variation, while there seems to be little or no difference between Field and Depression (Figure 13). Only eight lysimeters in Fallow are represented in the figure due to measurement errors (see section 3.3.3). The lysimeters excluded showed an overall higher evaporation rate but had a very small effect on the variation.

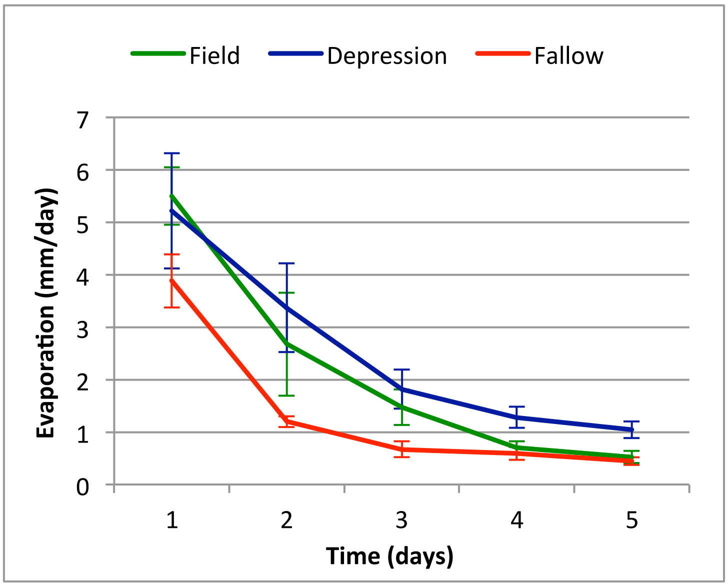

Figure 13. Average evaporation loss in the ecotopes field, depression and fallow. Error bars are showing standard variation from mean.

By using paricle size distribution and bulk density in a neural network prediction model for pedotransfer functions, the results showed there were barely any differences except for the top 10 cm layer in Depression that showed a

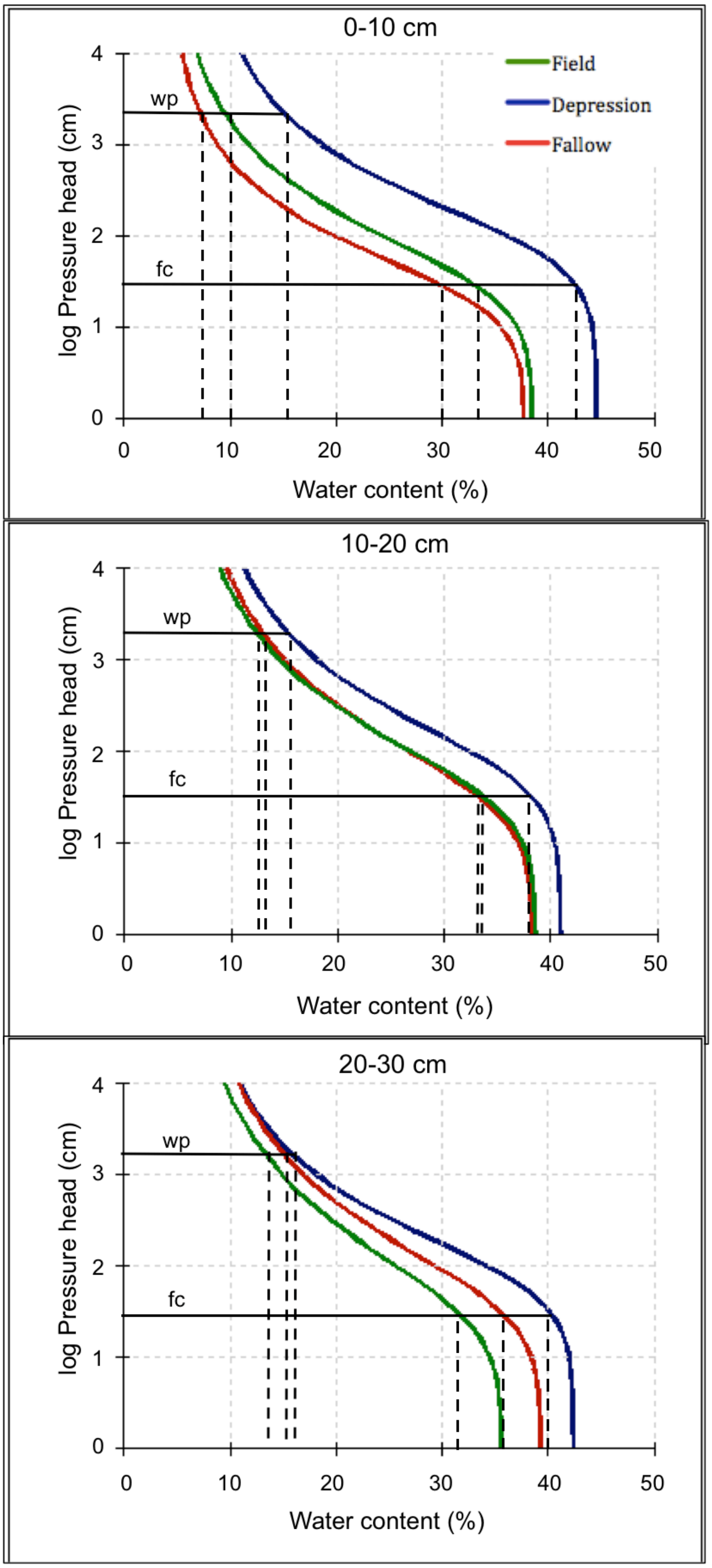

Figure 14. Pedotransfer function curves showing water content (x-axis) at a certain pressure (y-axis) at different soil depths. Field capacity (fc) and wilting point (wp) are marked out, between which water is available to plants. See also Table 3 for exact numbers.

slightly higher capacity in water retention (see Figure 14). For example, hydraulic conductivity was between two and three times higher for Field and Fallow respectively compared to Depression (see Table 3). The available water content for crops is on average 3 % higher for Depression. That gives 9 mm more available water in Depression compared to Field (and Fallow) for the upper 30 cm of soil at field capacity. The root depth of sorghum is 1.0-1.4 m (FAO 2013). Assuming the soil properties are similar down to 1.0 m it would mean an additional 30 mm of available water for crops in Depression at field capacity. The crop water need for sorghum is 3.6-5.2 mm per day (Critchley and Siegert 1991), which in this case would mean that crops in Depression would manage a dry spell between 6-10 days longer compared to crops in Field. In a report by the World Bank the actual crop evapotranspiration is said to be as low as 230-263 mm for sorghum in the central and southern parts of Burkina Faso, which would mean an even longer resistance to drought (Wahaj et al. 2007).

Table 3. Hydraulic properties of soils, where K_s is saturated hydraulic conductivity, θ_{wp} is wiliting point, θ_{fc} is field capacity, and θ_a is available water content. The column to the right shows average available water content for all three depths, while the number in brackets shows how many mm of water that equals for the upper 30 cm of soil.

Ecotope (depth)	K_s (cm day^{-1})	θ_{wp} (%)	θ_{fc} (%)	θ_a (%)	Avg. θ_a (%)
Field (0-10)	46.45	10%	33%	22%	21% (63 mm)
Field (10-20)	26.81	13%	34%	21%	
Field (20-30)	13.95	14%	32%	18%	
Depression (0-10)	18.63	17%	43%	26%	24% (72 mm)
Depression (10-20)	7.59	16%	38%	22%	
Depression (20-30)	12.87	16%	40%	24%	
Fallow (0-10)	61.63	8%	30%	22%	21% (63 mm)
Fallow (10-20)	24.85	14%	34%	20%	
Fallow (20-30)	16.63	15%	36%	20%	

4.4 Land use and management

Even though this study did not attempt to assess provisioning ES some biomass measurements were made for comparison. Biomass measurements show a two-threefold higher sorghum harvest in Depression compared to Field sites (Figure 15). Even though only one sorghum field in Depression was measured ocular observations showed that the biomass on fields in Depression were denser than on most fields in the Field ecotope. Out of the four sorghum fields where biomass measured, only Field 2 was fertilized with a few kg of fertilizers, while Field 1, 4 and Depression 5 was not fertilized (see Appendix 4).

All sampling points in Field were sorghum fields. Three out of five fields were fertilized with only “a few” kg of fertilizer. Three out of five fields in Depression were rice fields; the other two were sorghum fields. None of them were fertilized. The sampled points in Fallow had all been resting for more than 5 years. Most fields close to Homesteads were fertilized with manure and/or fertilizers. Pearl millet or maize was grown on these fields, which were never fallowed. Full notes from the interviews can be found in Appendix 4.

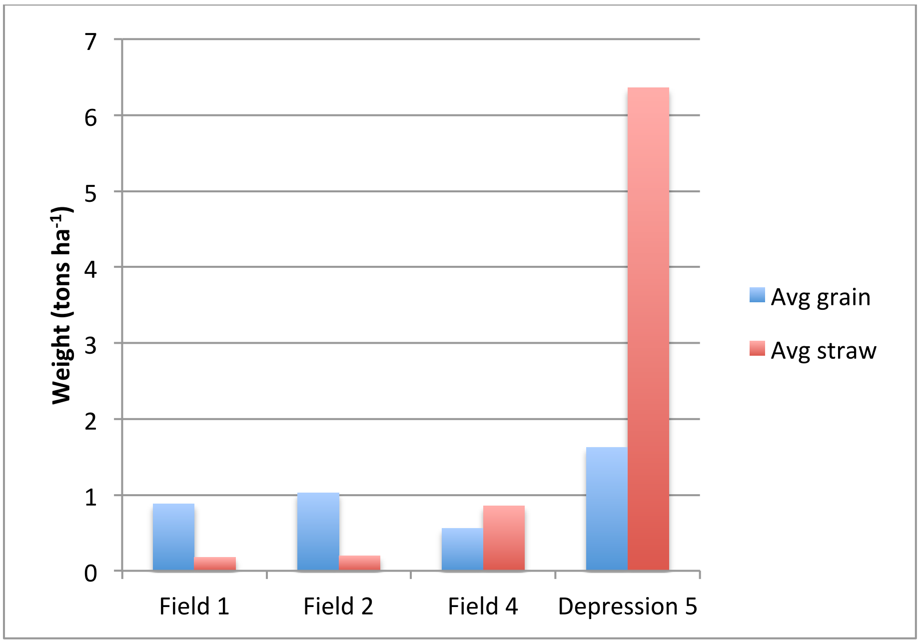

Figure 15. Harvest measurements extrapolated from sampling squares to kg ha^{-1}.

5. Discussion

5.1 Homogeneity in soil chemical properties

A previous study by Sinare (2013) have identified and quantified provisioning ES in ecotopes in an agro-ecological landscape of Sudano-Sahel. The study showed a substantial difference in provisioning services between ecotopes. This study sought to explain the status of the regulating ES as underpinning and explaining the provisioning capacities of the ecotopes. Also, the biomass measurements in this study show a higher density in Depression compared to Field (Figure 15). However, basically no significant differences were shown neither for nutrients, organic matter or texture between ecotopes. In studies made on similar conditions N varies between 0.03-0.1 %; tot-P between 96-287 mg kg^{-1}; available P between 1.4-7.3 mg kg^{-1}; and organic C/organic matter between 0.3-2.1 % (Bationo et al. 1998; Mazzucato and Niemeijer 2000; Doamba et al. 2009; Belachew and Abera 2010). Traoré et al. (2014) showed that organic C was 0.4-0.6 % on degraded land and 0.8-1.1% in native land, while N was 0.03-0.05 % on degraded land and 0.07-0.09 % on native land in northern Burkina Faso. In a study by Mazzucato and Niemeijer (2000) farmers have valued different sites as "good" and "bad", and the amount of N ranged between 0.05-0.09 % and 0.03-0.05 % respectively. The results in this study ranges between 0.02-0.08 % with the lowest amount of N in Field, and the highest amount in Depression, both ecotopes used for crops (i.e. sites that should be considered as "better", at least). In a study by Belachew and Abera (2010) organic matter ranged between 1.3-2.9 %, which was valued as low to medium levels. This can be compared to the results in this study were organic matter ranged between 0.4-1.9 %. The ratio between total and available P can be very different, and the results from other studies shows a great variance in P levels, which is also the case in this study. Woody vegetation generally has a positive effect on nutrient and soil organic matter in soil (Sinare and Gordon 2015), but despite the mosaic landscape with trees and shrubs among the crops the amount of nutrients in the soil is low. Mazzucato and Niemeijer (2000) also concluded that low fertility is a natural state rather than the result of nutrient mining. However, nutrient mining also occurs further deteriorating the state of these low fertility soils. This indicates that there are other factors than nutrient levels determining whether a site is good for cropping or not. Of course, this is just a snapshot and more extensive sampling might have revealed some differences.

Farmers use indicators such as nutrient status, texture and water holding capacity to determine soil productivity (Belachew and Abera 2010). Darker soils indicate good soils, since they are rich in organic matter, which gives higher water holding capacity and available nutrients. Red soils, on the other hand, have low water holding capacity and nutrient status. The darker soils can be equivalent to the more clayey soils in Depression, while the soils in the other ecotopes are redder. But also, different soils are productive during different years, depending on the conditions. E.g. soils with high water holding capacity are good in years with low or moderate rainfall, while soils with better drainage are better in years with high rainfall (Belachew and Abera 2010), since water logging due to poor drainage can lead to insufficient air supply in the soil affecting e.g. soil chemical properties (van Breemen and Buurman 2002).

Another regulating ES provided (or not) by the different ecotopes is erosion control. Erosion removes topsoil and smaller particles, which contains most of the soil's nutrients and organic matter (Zougmoré et al. 2004; Pluske et al. 2015). Hence, bare soils are extra sensitive. Assessing erosion control have not been a part of this study, however, seeing the different types of landscapes one can have a rough apprehension/estimation of erosion control. E.g. Bare soil provides very little erosion control and deep grooves ran through the landscape, while Forest, Shrubland, Depression and the relatively vegetated Fields provide more erosion control through the vegetation cover both reducing water and wind impact on soils (Figure 16).

Figure 16. Bare soil.

5.2 Advantage in water holding capacity

Water holding capacity has shown to be underestimated in the pedotransfer function model (Schaap et al. 2001). The estimated hydraulic conductivity from the model (see Table 3) is 1-10 times lower than measurements on similar soils in Niger and Burkina Faso (Klaij and Vachaud 1992; Ouattara 1999). The available water content, on the other hand, is described to be 100 mm per meter in ferruginous soil (the majority of all soil in Reko; Ouattara 1999) while the model estimates it to be more than the double in Reko soils. These results indicate that the PTF model has some uncertainties but it can still be a useful indicator of differences when hydraulic data is lacking.

Both the PTFs and the evaporation measurements indicate that Depression has slightly higher water holding capacity (Figure 14; Table 3), giving crops in Depression 6-10 days of respite in case of dry spell. This parameter alone might explain some but not the entire difference in biomass production (see harvest measurements in Figure 15). Topography is another advantage for Depression, i.e. its lower altitude makes water flow towards Depressions and during the rainy season it is possible that crop roots can have access to groundwater supplies. Some (parts of) Depressions are even covered in water during the rainy season.

5.3 Reflections on methodology and limitations

Since regulating ES are difficult to measure directly the use of indicators is necessary. Both ES and indicators were chosen with regards to availability of proven measurement methods in combination with the time frame and resources of this study. N, P and C are common parameters for describing soil fertility, while evaporation (and infiltration) measurements are basic methods to create a simple water balance. The choice of indicators will be discussed further in section 5.4.

The Sudano-Sahelian soils are generally poor and low-yielding and in one sense relatively homogenous. As mentioned earlier more extensive sampling with focus on the most important ecotopes, with regards to provisioning ES, might have given a more nuanced picture when trying to distinguish them from each other.

The results from the Rosetta Lite model in Hydrus-1D are somewhat uncertain. Several studies have shown that the prediction of PTFs are more accurate the more input given, specifically if organic matter and soil moisture content is included in addition to particle size distribution (Schaap et al. 2001; Vereecken et al. 2010; Tóth et al. 2014). However, the software used only allowed calculations using particle size distribution and bulk density. Furthermore, the Hydrus-1D database is on European soils and can not be assumed to have the same properties as West African sandy soils. Even with European soils the model is modest in its predictions at best (Schaap et al. 2001), indicating that the results from this modelling are very uncertain.

5.4 Using indicators as proxies for ecosystem services

This study shows that investigating the most straightforward indicators for soil fertility does not reveal any obvious differences. So are these indicators good representatives for regulating ES? In this agro-ecological landscape more is needed to explain the capacity for provisioning ES in different ecotopes. The need of indicators as proxies for regulating ES is necessary, but the selection of them would have to be more sophisticated. A broader and more in depth analysis of soil chemical properties, including cation exchange capacity (CEC) that affect the availability of soil nutrients (e.g. Bationo et al. 1998; Gray and Morant 2002; Traoré et al. 2014), could be one approach. As seen in this study the biggest differences between ecotopes is indicators relating to water regulation. This could be further investigated by taking topography into consideration as well as depth of soil profile, since these two factors determine direction of water flows and distance to ground water as a potential water supply for crops. Related to this is the occurrence of crusts and hardpans and how they impact the patterns of runoff and runon in the landscape (Rockström et al. 1998). E.g. the runoff from Bare soil creates runon in neighbouring fields. This makes the spatial patterns of ecotopes and their location in relationship to each other an important factor. With this said, it is also important to bear in mind that the relationship between provisioning and regulating ES is interdependent, and that management for one can have impact on the other (Coates et al. 2013).

6. Conclusions

In spite of quite different averages, no statistical significant difference in nutrient content or texture could be shown. As the variance was large within ecotopes more samples would have been needed to statistically detect significant differences. However, it is also possible that other parameters or combination of parameters could be important for soil productivity that was not measured in this study.

A slightly higher water holding capacity in Depression gives an advantage for the fields located within that ecotope when there are days without precipitation.

Selecting relevant indicators for regulating ES to explain differences in provisioning ES is not easily done with standard soil-plant systems available indicators.

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Appendix 1

SAMPLING OVERVIEW						
	Soil **0-10** **10-20** **20-30 cm**	**Bulk** **0-10** **20-30 cm**	**Harvest**	**Evaporation**	**Infiltration**	**Particle size** **0-10** **10-20** **20-30 cm**
Field 1	x	x	x	x	x	x
Field 2	x		x			x
Field 3	x					x
Field 4	x		x			x
Field 5	x		-			x
Depression 1	x					x
Depression 2	x					x
Depression 3	x	x		x	x	x
Depression 4	x					x
Depression 5	x		x			x
Fallow 1	x	x		x	x	x
Fallow 2	x					x
Fallow 3	x					x
Fallow 4	x					x
Fallow 5	x					x
Shrubland 1	x					x
Shrubland 2	x					x
Shrubland 3	x					x
Shrubland 4	x					x
Shrubland 5	x					x
Homestead 1	x					x
Homestead 2	x					x
Homestead 3	x					x
Homestead 4	x					x
Homestead 5	x					x
Bare soil 1						
Bare soil 2						
Bare soil 3						
Bare soil 4						
Bare soil 5	x					x

Appendix 2

Parameter	Depth	Ecotope	(n)	Average	St Dev	Significant difference p<0.05)
Nitrogen (%)	0-10 cm	Field	5	0.046	0.012	No P=0.07
		Depression	5	0.068	0.008	
		Fallow	5	0.062	0.007	
		Shrubland	5	0.056	0.012	
		Homestead	5	0.061	0.017	
	10-20 cm	Field	5	0.036	0.012	**Yes** P=0.047
		Depression	5	0.059	0.005	
		Fallow	5	0.053	0.011	
		Shrubland	5	0.050	0.012	
		Homestead	5	0.052	0.013	
	20-30 cm	Field	5	0.032	0.011	**Yes** P=0.019
		Depression	5	0.053	0.007	
		Fallow	4	0.048	0.011	
		Shrubland	5	0.0.42	0.008	
		Homestead	5	0.050	0.010	
Available P (mg kg^{-1})	0-10 cm	Field	5	1.808	2.109	No P=0.253 (Anova) P=0.19 (Kruskal Wallis)
		Depression	5	1.480	1.887	
		Fallow	5	1.850	0.709	
		Shrubland	5	1.950	1.242	
		Homestead	4 (5)	4.5 (8.714)	3.74 (9.932)	
	10-20 cm	Field	5	1.166	1.270	No P=0.267 (Anova) P=0.264 (Kruskal Wallis)
		Depression	5	1.344	1.379	
		Fallow	5	1.418	0.743	
		Shrubland	5	1.282	1.212	
		Homestead	4 (5)	3.6 (7.864)	3.55 (10.018)	
	20-30 cm	Field	5	1.020	0.864	No P=0.093 (Anova) P=0.091 (Kruskal Wallis)
		Depression	5	0.616	0.822	
		Fallow	4	1.005	0.938	
		Shrubland	5	0.560	0.245	
		Homestead	4 (5)	2.8 (7.198)	2.43 (10.078)	
Organic matter (%)	0-10 cm	Field	5	1.011	0.300	No P=0.12
		Depression	5	1.596	0.317	
		Fallow	5	1.413	0.395	
		Shrubland	5	1.287	0.300	
		Homestead	5	1.454	0.384	
	10-20 cm	Field	5	0.804	0.255	**Yes** P=0.042
		Depression	5	1.429	0.271	
		Fallow	5	1.317	0.414	
		Shrubland	5	1.148	0.237	
		Homestead	5	1.282	0.340	
	20-30 cm	Field	5	0.763	0.309	No P=0.106
		Depression	5	1.189	0.162	
		Fallow	4	1.231	0.337	
		Shrubland	5	0.965	0.292	
		Homestead	5	1.181	0.340	
Sand (%)	0-30 cm	Field	5	56.21	6.89	No P=0.11
		Depression	5	51.39	12.61	
		Fallow	5	47.18	9.84	
		Shrubland	5	59.93	16.65	
		Homestead	5	61.42	6.59	

Silt (%)	0-30 cm	Field	5	20.87	5.35	No P=0.11
		Depression	5	24.49	4.48	
		Fallow	5	28.61	8.20	
		Shrubland	5	22.10	9.56	
		Homestead	5	21.10	4.45	
Clay (%)	0-30 cm	Field	5	22.91	9.20	No P=0.08
		Depression	5	24.13	8.41	
		Fallow	5	24.21	4.82	
		Shrubland	5	17.87	10.51	
		Homestead	5	17.48	4.69	

Appendix 3

Parameter	Depth (cm)	Anova test of significant difference between Ecotopes (0.05 significance level)	Specific differences between Ecotopes when Anova test positive (using Tukey's test, 0.05 significance level)	Comment
N	0-10	No P=0.07		
N	10-20	**Yes** P=0.047	Field - Depression P=0.027 Mean diff = -0.023%	
N	20-30	**Yes** P=0.019	Field - Depression P=0.016 Mean diff = - 0.021%	
Available P	0-10	No P=0.253 (Anova) P=0.19 (Kruskal Wallis)		Took away outlier (Homestead 3) Not normal/equal variance
Available P	10-20	No P=0.267 (Anova) P=0.264 (Kruskal Wallis)		Took away outlier (Homestead 3) Not normal/equal variance
Available P	20-30	No P=0.093 (Anova) P=0.091 (Kruskal Wallis)		Took away outlier (Homestead 3) Not normal/equal variance
OM	0-10	No P=0.12		
OM	10-20	**Yes** P=0.042	Field - Depression s P=0.33 Mean diff = 0.62%	
OM	20-30	No P=0.106		
Clay	Average	No P=0.11		
Silt	Average	No P=0.11		
Sand	Average	No P=0.08		

Appendix 4

Soil types:

Lithosol	- Raw mineral soils on ferralitic pans
Peu_moy-prof	- Leached ferruginous tropical soil with hardpan, shallow or medium depth
Profond	- Leached ferruginous tropical soil with hardpan, deep
Hydromorph	- Leached ferruginous tropical soil, hydromorphic or with spots and concretions
Alluvial	- Poorly evolved hydromorphic alluvial soil

	Soil type	Comments
Field 1	peu_moy-prof	Mixed sorghum and pearl millet. Variation in density, quite sparse in the "random" squares for harvest measurements.
Field 2	peu_moy-prof	Use of fertilizer, "a couple of kilos of NPK". Only sorghum have been grown for many years. In a small part of the field, around 10 m from the sampling point, there had been cow peas, already harvested.
Field 3	Profond	Sorghum, already harvested. Sorghum every year. "A little" NPK.
Field 4	Hydromorph	On this part of the field (hydromorphic) pretty sparse with sorghum, men south near the border to Depression and alluvial soil MUCH denser.
Field 5.2	Hydromorph	Sorghum field. NPK fertilizer. Sorghum every year. Clayey/sandy soil. Mixed sorghum and sesamy – beneficial mix. Mixed density. (The field next to this one is Fallow since two years, i.e. is Field on the map.)
Depression 1	Hydromorph	Pearl millet (and some sorghum). Every year the same, no fertilizers, no fallow. Very porous, more sand than last one (Depression 5).
Depression 2	Hydromorph	Rice field. No fertilizer.
Depression 3	Alluvial	Rice every year. No fertilizer. Covered (?) by water when raining the most, during rainy season.
Depression 4	Alluvial	Depression is mostly used for rice. This field is fertilized with NPK. Maize fields are fertilized with manure, sorghum and pearl millet fields not at all (Source: Maurice). More clayey soil here than earlier sampling points (Field, Homestead). Roots down to (at least) 30 cm.
Depression 5	Alluvial	Sorghum field, every year. No fertilizers. No fallow. Very compact clay.
Fallow 1	peu_moy-prof	Fallow more than 5 years, maybe more than 10.
Fallow 2	peu_moy-prof	Fallow more than 5 years, maybe more than 10.
Fallow 3	peu_moy-prof	Fallow more than 5 years, maybe more than 10.
Fallow 4	Lithosol	Very compact/hard soil. Hit rock/stone after 20-25 cm. Fallow at least two years, pretty big shrubs and some trees.
Fallow 5	Lithosol	Very distinct crust. Very hard to dig, hit rock/stone after 20 cm, only took 0-10 and 10-20 cm samples.
Shrubland 1	peu_moy-prof	A lot of bare soil and rocks nearby. Sparse with shrubs. Grass where we took samples, a lot of roots, mostly down to 15 cm but some also to 30 cm.
Shrubland 2	peu_moy-prof	Medium dense with shrubs, spots with bare soil.
Shrubland 3	peu_moy-prof	Roots down to 15-20 cm (pretty much). Relatively dense shrubs. A few trees.
Shrubland 4	Lithosol	Took samples where there were a small grassplot, next to a shrub. Roots down to at least 15 cm.
Shrubland 5	Lithosol	Roots down to 20 cm. Either very sandy or very gravelly (the four different pits). On the border to Bare soil. Sparse with shrubs.
Homestead 1	peu_moy-prof	Outskirts of Homestead, maize field. Roots down to at least 30 cm. Saw bugs in the soil, which I haven't done anywhere else. Possibly more porous?!

Homestead 2	peu_moy-prof	Outskirts of Homestead, border to Field. (Field, but within 50 m from houses = Homestead). Maize field surrounded by sorghum. Very hard/compact soil from 20 cm and further. Stone/rocks around 30 cm. The maize was harvested earlier in October (around three weeks before sampling). This year maize, past years sorghum. Fertilized with manure.
Homestead 3	peu_moy-prof	Pearl millet. Hard/compact soil, hard with both auger and broach(?). Fertilized with NPK and manure. Pearl millet every year.
Homestead 4	Hydromorph	Pearl millet field close to homesteads. Pearl millet every year. Manure from animals to fertilize. 4-5 "carts" on this field. Much more porous than other Homesteads.
Homestead 5	Hydromorph	Sorghum every year, no fertilizers, no fallow.