Land degradation and agriculture in the Sahel of Africa: causes, impacts and recommendations

Stephen Doso Jnr

P.O. Box SA 199, Somanya, Ghana.
E-mail: paafioteye@yahoo.com. Tel: +233 0245135514.

Abstract: The Sahel region is largely dependent on agriculture as the main economic activity, with about 80-90% of the population actively engaged in agriculture. Land degradation is however a major environmental issue affecting the region, with negative consequences on agriculture. Unsustainable agricultural practices in the region in turn promote land degradation. This paper discusses the major environmental issues relating to land degradation and agriculture in the Sahel. It attempts to provide a descriptive report on the interactions between land degradation and agriculture based on a desk review of various scientific journals and reports on agriculture and land degradation in the Sahel region.

Land degradation in the Sahel is characterised by soil degradation, mainly due to wind erosion. This is favoured by climatic factors such as drought and diminishing rainfall, compounded by anthropogenic factors, including population growth, agricultural intensification and overgrazing. Climatic and anthropogenic factors may act independently or have effects on each other. These factors result in the reduction of vegetation cover, decrease in fallow periods and a reduction in the balance between fallow areas and cultivated fields, which are vital to maintaining soil fertility and reducing losses from erosion.

Agroforestry, integrated farming and practices that promote vegetation cover are proposed as sustainable land practices in the Sahel region. These will provide soil cover to protect soils against agents of erosion, increase agricultural productivity per unit land area and diversify farmers' sources of income, resulting in benefits for agricultural production and addressing land degradation.

Keywords: agriculture; agroforestry; anthropogenic factors; land degradation; integrated farming; Sahel.

1 Introduction

Land degradation is a major environmental issue affecting the Sahel region of Africa (UNEP, 2012). Land degradation has negative consequences on agriculture. Unsustainable agricultural practices in turn promote land degradation (Olsson et al., 2005). With agriculture being the main economic activity in the Sahel (Suttie et al., 2005), the effects of land degradation can be significant (UNEP, 2012). This paper discusses the major environmental issues relating to land degradation and agriculture in the Sahel. The next section describes the Sahel region and the subsequent sections discuss how agriculture and land degradation affect each other. The potential causes and their impacts are identified, and recommendations suggested.

2 The Sahel Region

The Sahel is a semi-arid grassland and shrubland transition zone stretching across the African continent between the Sahara desert to the north and the tropical savannas to the south (Herrmann, 2005). It covers parts of Senegal, Mauritania, Mali, Burkina Faso, Algeria, Niger, Chad, South Sudan, North Sudan and Eritrea (UNEP, 2012). The Sahel climate is characterised by a long dry season and a short humid season (Nicholson, 1995). The ecosystem is greatly controlled by rainfall, which is variable and unpredictable. The mean annual rainfall ranges from 200 mm in the north to 600 mm in the south (Visser and Sterk, 2007). The rainy season is intense and lasts for about 4 months with prolonged dry periods (Giannini et al., 2008). The vegetation cycle responds to the rainfall seasonality, with plant growth usually occurring in the humid months (Hulme, 2001). The vegetation is characterised by sparse vegetation cover from the Saharan biome which increases towards the Sudanian and Guinean biomes. The species consists of thorny shrubs interspersed between annual and perennial grasses at the north which changes to taller vegetation with more trees towards the south (Herrmann, 2005). Agriculture is the main backbone of the economies of the countries forming the Sahel region (UNEP, 2012). Figure 1 shows the Sahel region of Africa.

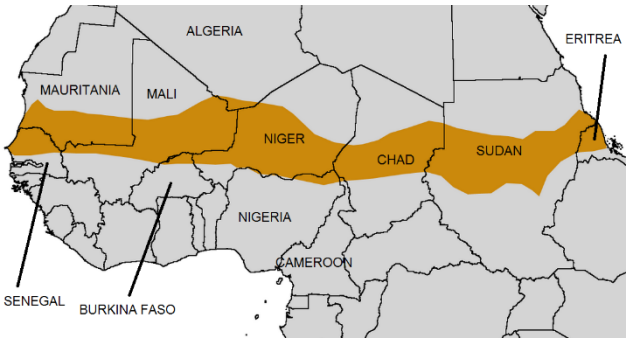

Figure 1. The Sahel region of Africa.

3 Agriculture in the Sahel

The economies of the countries in the Sahel region are largely dependent on agriculture, with about 80-90% of the population actively engaged in agriculture (UNEP, 2012). Crop production and agropastoralism are the main economic activities in areas with rainfall of about 600 mm whiles in areas with rainfall of about 400 mm, rearing of livestock is the main economic activity (Mortimore and Turner, 2005). Rainfall variability increases as the total rainfall decreases, making agriculture in the low rainfall areas vulnerable to recurrent droughts. In areas with rainfall greater than 300 mm, the availability of nutrients, mainly nitrogen and phosphorus, are the limiting factors for biomass production (Aune and Bationo, 2008).

The Sahelian soils are mainly sandy (Bationo et al., 2014) with the dominant soil types being Entisols and Alfisols (Kang, 1985). Phosphorus and nitrogen are mostly deficient (Bationo et al., 2014; Breman et al., 2001). Table 1 shows some soil properties in the Sahel. In the southern part of the Sahel, agriculture is more diversified and includes subsistence crops such as cassava, sorghum and maize, and cash crops such as cowpeas, peanuts, wheat, sugar cane and cotton. In the northern portion, the subsistence crops are millet, sorghum and sometimes maize, with the main cash crop being cotton. In the parkland areas in the north, trees are also harvested for a variety of products (UNEP, 2012).

Agriculture is mainly rain fed, and the field sizes are usually small. Agriculture in the Sahel is characterised by extensification, labour intensification and capital intensification (Carswell, 2000). Extensification occurs where land is readily available and farmers expand their cultivated areas to increase production (Aune and Bationo, 2008). For example, pearl millet production increased in Niger and Mali due to extensification, as yields did not change for about 30 years. Land for pearl millet cultivation in Mali increased to 1.5 million hectares in 2005, from 0.54 million hectares in 1970. In Niger, millet lands increased from 2.3 million hectares in 1970 to 5.9 million hectares in 2005 (FAO stat, 2007). As land becomes limited as a result of population growth, fallow periods are decreased and labour increased to boost production. The labour per unit land area is increased for practices including land preparation, manure application and harvesting. For capital intensification, inputs such as agrochemicals, fertilizers and agricultural equipment are increased. Some farmers practice both capital and labour intensification on different portions of their farmlands (Aune and Bationo, 2008). A combination of extensification and intensification are also used, particularly for food crops (Aune and Bationo, 2008). Pearl millet yields in Burkina Faso increased from 500 kg ha^{-1} between 1976 and 1985 to 750 kg ha^{-1} between 1996 and 2005 whiles the cultivated land area increased by 41% during the same period (FAO stat, 2007). Generally, agriculture is becoming more market-oriented in the Sahel. The percentage of farm products brought and sold on markets rose from 20% in 1950 to about 50% in 2000 (Cour, 2001).

Table 1. General soil properties in the Sahel (Bationo and Mokwunye, 1991; Kang, 1985; Vanlauwe et al., 2014).

Property	Characteristic
Structural stability	Poor
Nutrient holding capacity	Low
Water retention capacity	Low
Organic matter content	Low
Effective cation exchange capacity	Low
Drought susceptibility	High
Texture	Coarse

Towards the northern part of the Sahel, pastorialism dominates, with about a quarter of the population engaged in animal husbandry. High stocking densities and overgrazing are common, which affects the growth pattern of grasses. The livestock varies among the ethnic groups, with the Tuareg favouring camels whiles the Fulani prefer cattle (UNEP, 2012). The Tuareg live at the fringe of the desert and are divided into many groups. The exclusive transhumant herders occupy lands not suitable for crops to the north of the agropastoralists, who live close to their fields. The agropastoralist Fulanis occupy the southern part of the Sahel, and rear small ruminants like sheep to provide meat for their families as the cattle are for capital, investment and prestige. The transhumant Fulanis travel through the lands of farming communities as their cattle feed on the stovers and fallows on farmlands (Suttie et al., 2005). The cattle help manure these farmlands through their droppings as they graze.

In the southern, humid parts of West Africa, grazing is hindered by the presence of ticks and particularly tsetse flies, the vector for trypanosomiasis (Suttie et al., 2005). Transhumant Fulanis are increasingly settling in some of these areas by clearing trees and bushes to control the tsetse flies. Grazing lands have been damaged through human population increase, expansion of croplands into marginal areas, and deforestation for firewood. This has been aggravated by recurrent droughts, particularly in 1968 and in the early 1980s (Suttie et al., 2005). Fire is often used as a tool to promote palatable grasses for the grazing animals. The laterite plateaus are not cultivated; they are used for grazing and as sources of firewood (UNEP, 2012).

4 Land degradation in the Sahel

The Sahel is one of the most severely affected regions from land degradation and desertification in the world (UNEP, 1992). The region has experienced severe drought and increasing deterioration of soil quality and vegetation cover (Geist and Lambin, 2004). The United Nations Conference on Environment and Development defines desertification as land degradation in the arid, semiarid and dry sub humid areas due to various factors including climatic variations and human activities (UNCED,

1992/93). Land degradation is the reduction in the physical, chemical or biological status of land which may affect its productive capacity (Eswaran et al., 2001). Land degradation has adverse impacts on agricultural productivity, the environment and food security (Eswaran et al., 2001). Land degradation has resulted in the loss of the soil's productive capacity which is a great concern to the local people (Bielders et al., 2001) who are mainly subsistence farmers. Excessive exploitation of firewood and unsustainable agricultural practices including overgrazing and over-cultivation have in turn contributed to land degradation in the Sahel region (Olsson et al., 2005). The main form of land degradation in the Sahel is soil degradation through soil erosion and consequent nutrient loss, soil physical degradation through crust development, and salinization (UNEP, 2012).

4.1 Soil degradation

Soil degradation is the main form of land degradation in the Sahel (Niemeijer and Mazzucato, 2002). UNEP's "An Ecosystem Approach to Restoring West African Drylands and Improving Rural Livelihoods through Agroforestry based Land Management Interventions" project identified generally low soil organic carbon (SOC) content in the Segou region of Mali using infrared spectroscopy. SOC is a key indicator of soil condition in terms of nutrient status and availability, soil physical properties, and water holding capacity. The median SOC content was 3.12 g kg^{-1} in topsoils (0-20 cm) for all sites. Cultivated areas where found to have lower SOC in the topsoil compared to semi-natural areas which are not cultivated or managed. This was attributed to high sand content in the cultivated areas and also as a direct consequence of cultivation (UNEP, 2012).

Wind erosion is the main contributor to soil degradation in this region (Mainguet and Chemin, 1991). Wind erosion causes considerable loss of soil and nutrients in the Sahel, sometimes greater than the effect of water erosion (Visser et al., 2005a). The soil sediments are transported by wind through suspension, saltation and creep (Visser and Sterk, 2007). The finest soil particles are carried away as suspended dust which can travel for thousands of kilometres (Sterk et al., 1996). The finest soils contain relatively higher proportions of organic matter and nutrients in the topsoil, leading to considerable losses (Leys and McTainsh, 1994). Relatively larger particles are transported by saltation which bounces over the surface of the soil up to heights of about 2 meters. These also result in considerable nutrient losses as soil particles transported by saltation are usually aggregates of the finer nutrient-rich particles (Sterk et al., 1996). This however occurs over relatively shorter distances. Coarse sand particles bombarded by the saltating particles are transported by creep over distances ranging from centimetres to a few meters, keeping contact with the soil surface due to their size. Creep does not result in considerable nutrient losses as the coarse sand particles are poor in nutrients (Visser and Sterk, 2007).

Vegetation in bush fallows (Bielders et al., 2002) and valley sites (Visser et al., 2005b) adjacent to crop fields trap the saltation materials. With a balance between the fallow area and cultivated fields, saltation may result in local redistribution of nutrients and soil particles which remains

Figure 2. Laterite plateau in Segou town, Mali (UNEP, 2012).

in the system (Rajot, 2001). This may lead to declining fertility in the crop fields and build up of nutrients in the decrease of fallow periods and cultivation of new farm lands including marginal lands reduces vegetation cover leading the higher losses of saltation material. Farmers may benefit in the short term by cultivating these new sites but with time, these lands are also exposed to the forces of erosion. As more land gets under cultivation, the balance between fallow and cultivated area is reduced leading to net losses of saltation materials from the system (Rajot, 2001).

High evaporation rates in the Sahel causes surface crust development and the formation of laterites. These are sometimes several metres thick, or form lumps, resembling rocks. Water generally infiltrates poorly through these hardened soils resulting in high runoff during rainfall (UNEP, 2012). These laterite areas have high soil physical constraints, including restricting root penetration. The predominant vegetation in these areas is shrubby, distributed in dense thickets, as seen in Figure 2. The infiltration capacity on the laterites depends on the shrub cover densities. The high rate of evaporation is also promoted by the removal of vegetation cover which exposes the bare soil. Such exposed and frequently heated soils, with very little organic matter are also unfavourable for soil fauna. Soil fauna increase water percolation in soils through their movements. Crusts are also formed by

termites in high clay soils in the form of mounds. The activities of the termites results in localized improved rates of infiltration and higher soil nutrient content. This leads to the formation of fine-scale mosaics where more water demanding plants grow (UNEP, 2012).

Water erosion in the Sahel region occurs through splash, sheet, rill and gully erosion. This is influenced by the topography, mainly slope gradient and surface characteristics of the land, including the size of the soil particles, degree of particle cohesion and the nature of vegetation cover. Raindrops detach soil particles through splash erosion which are further transported through sheet erosion. Sheet erosion transports the fine nutrient-rich top soil particles and organic matter down slope which can be transported up to thousands of kilometres. The turbulence of sheet flow can be increased by wind driven rain drops falling into the flow. Clay, silt, nutrients and organic matter are selectively carried away by sheet erosion when runoff is low over gentle slopes, which is characteristic of the Sahel region (Roose and Barthes, 2001). Larger particles are transported by rolling or sliding over land surface due to the force of the running water. These are coarse sand particles which contain low nutrients. Saltation materials break up in the water and the fine particles are transported through suspension in sheet erosion (Visser and Sterk, 2007). Water erosion is limited in sediment transport off fields as compared to wind erosion. Pools form over the fields, reducing runoff and causing the soil sediments to settle. This results in local redistribution of sediments (Visser et al., 2005a).

4.2 Causes of land degradation in the Sahel

Land degradation in the Sahel is considered to be caused by climatic factors such as drought and diminishing rainfall, and human activities (Herrmann et al., 2005). The main human factors are pressure from population growth, agricultural intensification and to some extent migration. Though climatic and human factors may act independently, they can also have effects on each other. Recurrent droughts, together with low soil fertility are some of the main factors for people migrating from their villages. Droughts in the Sahel have sometimes been attributed to a response of the regional atmospheric circulation to anthropogenic factors such as overgrazing, over-exploitation of trees for fuel wood and expansion of agriculture to marginal lands, which have affected vegetation cover (Charney, 1975 as cited in Giannini et al., 2008).

4.2.1 Climate

Changes in climate may cause changes in land use practices (Mazzucato and Niemeijer, 2000) which may contribute to land degradation processes. Trends and variability in rainfall in the Sahel directly and indirectly affect crop production, vegetation, land degradation processes and the functions of the entire ecosystem (Boko et al., 2007). There has been an estimated reduction in rainfall of about 20 to 30% in the Sahel region in the second half of the 20th century (Batterbury and Warren, 2001). In Burkina Faso, it was found that farmers reallocated their fields from upland areas as an adaptation to declining rainfall. Some farmers abandoned farms in higher areas as yields where no longer adequate due to declining rainfall (Mazzucato and Niemeijer, 2000). The declining rainfall is also linked to a concentration of farming in sandy areas. Sandy soils have a relative advantage in dry areas (Reenberg, 1994). Lands have been extended through shifting farms from one type to the other compelled by climatic events (Mazzucato and Niemeijer, 2000).

The drought in the late 20th century in the Sahel represents one of most striking shifts in climate (IPCC, 2007). Satellite imagery of the effects of the severe droughts in the Sahel between 1983 and 1984 showed a shift of the desert southward into the Sahel region (Olsson et al., 2005). Severe droughts affect the soil structure by causing the land to develop cracks and also affect crop production. The droughts also caused migration. Migrations in Burkina Faso commenced in the 1980 as a consequence of severe droughts which affected the central and northern portions of the country, resulting in considerable losses of crop and livestock to farmers. Since then, there has been increased migration to less drought areas in the south, west and east of the country as a livelihood diversification strategy. The size of crop land in the southern part of Burkina Faso has increased at annual rate greater than 1% since 1986 to 2006, caused mainly by population size and distribution of migrants (Quedraogo et al., 2009).

4.2.2 Anthropogenic factors

Pressure from population increase is considered to be the root cause of land degradation (Geist and Lambin, 2004). Demographic growth for the Sahel region increased from 1.5% per year to 3% per year between the 1950s to the 1990s resulting in a three-fold increase in population in the 20th century. This represents one of the highest demographic growths in the world (Raynaut, 2001). The total population for Burkina Faso for instance, increased from 5.6 million 1975 to 13.7 million in 2006 (INSD, 2007 as cited in Van Vliet et al., 2013). It is estimated that over 90% of Burkinabes are engaged in subsistence agriculture (Van Vliet et al., 2013). Population growth has resulted in the intensification of agriculture on existing farmlands and increased cultivation of marginal lands. The higher demand for food due to population growth has caused a decrease in fallow periods which declines the fertility of the soil, and consequently a decline in productivity (Mazzucato and Niemeijer, 2000). Farmers are then forced to cultivate new lands. Natural woody savannah lands have increasingly been converted to rain-fed cultivated lands due to this (Raynaut, 2001).

Expansion of cultivation to marginal lands increases degradation of upland field areas. These are then abandoned for new lands (Reenburg, 2001). Agricultural expansion, particularly groundnut cultivation, has resulted in the decline of fallow lands and savannah vegetation in

the Sahelian part of Senegal (Van Vliet et al., 2013). A trend spanning 40 years shows a steady increase in crop lands and eroded bare soils leading to a drastic decline in woody vegetation cover in Kouonkaba village in the Sahelian region of Mali (Ruelland et al., 2010). Increase in cultivated land area in the Sahelian portion of Niger between 1950 and 1998 also resulted in a 7 to 16% increase in eroded land at the detriment of the savannah (Seguis et al., 2004). Other human activities that have contributed to land degradation in the Sahel include excessive exploitation of firewood and overgrazing (Olsson et al., 2005).

4.3 Recommended sustainable agricultural and land management practices

Agroforestry can be practiced as a more sustainable land use practice in the Sahel compared to conventional agriculture. Agroforestry involves the deliberate use of trees in association with crops, pasture or livestock (Breman and Kessler, 1997). Agroforestry would be more beneficial in the Sahel as the use of external inputs in agriculture is relatively low. Productivity in agriculture can be increased by expanding the land area on which productivity depends or by increasing the yield per unit land area. In the Sahel where cropland is continuously becoming limited due to population increase and land degradation, the latter will be the favourable option. Agroforestry has an advantage over non-agroforestry land-use systems in achieving this goal by making more effective and efficient use of land resources. The different layers of trees and crops make more efficient use of above ground resources such as sunlight whiles the different rooting patterns of the trees and crops make more efficient use of below ground resources such as nutrients and water (Buck *et al*, 2010).

The inclusion of nitrogen fixing trees in agroforestry technologies adds nitrogen to the soil. Also, litterfall and the addition of prunings from the trees add organic matter to the soil. Organic matter improves soil physical conditions such as the soil structure, soil aeration and drainage. The tree canopy, in addition to the mulch layer of leaf litter and tree prunings can reduce soil erosion by reducing the impact of wind and rain drops on the soil ((Jose, 2009). The tree roots also reduce soil erosion by providing physical barriers which reduce run off and also by increasing infiltration of water into the soil (Buck et al., 2010). The shading effect of tree canopies and mulch provide a favourable microclimate for microbial activities in the soil which help in breaking down organic matter and improving soil physical conditions. Mulching also reduces weed proliferation. Agroforestry also provides cheap sources of fodder, fruits, fuelwood, poles, timber and medicinal herbs to the farmer depending on the trees used (Pimentel and Wightman, 2010).

Integrated farming involving mixed farming practices where the output from one farm component is used as an input for other components can help maximize land use per unit area. This is very vital in the Sahel where favourable croplands are limited. Integrated farming involving both crops and livestock can have both environmental and economic benefits. This can help improve soil fertility per unit land area through internal recycling of nutrients, and consequently improve crop yields. Livestock can either graze on crop residues or the residues can be collected and fed to the livestock in their housing. Manure from livestock housing can in turn be collected together with straw, feed left over and household waste and used on the crop fields. This can help improve soil organic matter and fertility and also serve as mulch. Mulch can help reduce soil erosion, conserve soil moisture and promote the activities of soil organisms. Livestock such as camels and cattle can further be used in land preparation and carting farm produce and fuelwood to homes. Integrated farming can also diversify farmers' sources of income and provide back up during crop failures.

Practices that promote vegetation cover such as the use of trees and hedges as windbreaks, the use of cover crops on slopes and green manuring can help protect soils from the agents of erosion. Vegetation increases the fluid drag on air stream which reduces the near surface wind velocity causing deposition of suspended dust particles. Vegetation has also been shown to reduce wind velocity gradient above the canopy which causes friction velocity to fall below the threshold for re-suspension of settling dust particles. A two-year study in New Zealand showed that dust deposition in vegetated areas was significantly improved by 199.86 kg ha-1 to 108.04 kg ha-1 in bare areas (McGowan and Ledgard, 2005). Vegetation can effectively trap large amounts of suspended soil particles. This dust when washed off by rains can return to the underneath soils with the accompanying nutrients and become available for plant use (Visser and Sterk, 2007).

5 Conclusions

Climatic factors such as declining rainfall and persistent droughts can have negative effects on agriculture and promote land degradation processes. In the Sahel, agricultural extensification and intensification due to population growth and unsustainable agricultural practices that reduce vegetation cover on lands have contributed to land degradation. Soil degradation through soil erosion is the main form of land degradation in the Sahel, resulting in nutrient loss, soil physical degradation and salinization and consequently reducing agricultural productivity. Extensification and the decrease of fallow periods may yield benefits for farmers in the short term. In the long term however, land degradation is exacerbated through exposing newly cultivated lands to the forces of erosion, a decline in soil fertility and the reduction in the balance between fallow and cultivated areas, leading to net losses of saltation material in the system.

With land degradation being a major problem in the Sahel, the use of sustainable agricultural and land use practices that promote vegetation cover on lands can help protect soils from erosion. These practices include agroforestry, growing of cover crops, grasses and drought resistant trees. Integrated farming is proposed to maximize land use per

unit area and diversify farmers' sources of income as favourable croplands are limited in the region. Practices that promote organic matter additions to soils such as mulching and addition of organic manure can also have positive benefits for both agricultural production and addressing land degradation.

References

Aune, J.B., Bationo, A. 2008. Agricultural intensification in the Sahel-the ladder approach. Agricultural Systems 98(2): 119-125.

Batterbury, S., Warren, A. 2001. The African Sahel 25 years after the great drought: assessing progress and moving towards new agendas and approaches. Global Environmental Change 11(1): 1-8.

Bationo A., Mokwunye A.U. 1991. Role of manures and crop reissued in alleviating soil fertility constraints to crop production with special reference to Sahelian zones of West Africa. Fertilizer Research 29: 125–177.

Bationo, A., Kihara, J., Waswa, B., Ouattara, B., Vanlauwe, B. 2014. Technologies for sustainable management of sandy Sahelian soils. In: Management of Tropical Sandy soils for sustainable agricultura. A holistic approach for sustainable development of problema soils in the tropics. FAO Regional Office for Asia and the Pacific. Bangkok. Pp.: 414-429.

Bielders, C.L., Alvey, S., Cronyn, N. 2001. Wind erosion: the perspective of grass-roots communities in the Sahel. Land Degradation & Development 12(1): 57-70.

Bielders, C.L, Rajot, J.L., Amadou, M. 2002. Transport of soil and nutrients by wind in bush fallow land and traditionally managed cultivated fields in the Sahel. Geoderma 109: 19-39.

Boko, A., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman, Elasha, B., Tabo, R., Yanda, P. 2007. Africa. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. Pp.: 433-467.

Breman, H., Kessler, J.J. 1997. The potential benefits of agroforestry in the Sahel and other semi-arid regions. Developments in Crop Science 25: 39-47.

Breman, H., Groot, J.J., van, Keulen, H. 2001. Resource limitations in Sahelian agriculture. Global Environmental Change 11(1): 59-68.

Buck, L.E., Lassoie, J.P., Fernandes, E.C. (Eds.). 2010. Agroforestry in Sustainable Agricultural Systems. CRC Press. Boca Raton, FL.

Carswell, G. 2000. Agricultural intensification in Ethiopia and Mali. IDS Report 48. Institute of Development Studies, University of Sussex. Brighton. Pp.: 46.

Cour, J.M. 2001. The Sahel in West Africa: Countries in transition to a full market economy. Global Environmental Change 11(1): 31-47.

Eswaran, H., Lal, R., Reich, P.F. 2001. Land degradation: an overview. In: Bridges, E.M., Hannam, I.D., Oldeman, L.R., Pening de Vries, F.W.T., Scherr, S.J., Sompatpanit, S. (Eds.). Responses to Land Degradation. Proc. 2nd. International Conference on Land Degradation and Desertification, Khon Kaen, Thailand. Oxford Press. New Delhi. Pp.: 20-35.

Geist, H.J., Lambin, E.F. 2004. Dynamic causal patterns of desertification. Bioscience 54(9): 817-829.

Giannini, A., Biasutti, M., Verstraete, M.M. 2008. A climate model-based review of drought in the Sahel: Desertification, the re-greening and climate change. Global and planetary Change 64(3): 119-128.

FAO stat. 2007. http://faostat.fao.org/ (accessed 6 August 2014).

Herrmann, S.M., Anyamba, A. and Tucker, C.J. (2005). Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. Global Environmental Change 15(4): 394-404.

Hulme, M. 2001. Climatic perspectives on Sahelian desiccation: 1973-1998. Global Environmental Change 11(1): 19-29.

IPCC, 2007. Summary for policymakers. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge.

Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: an overview. Agroforestry Systems, 76(1): 1-10.

Leys, J.F., McTainsh, G. 1994. Soil loss and nutrient decline by wind erosion-cause for concern. Australian Journal for Soil and Water Conservation 7: 30-35.

Kang, B.T. 1985. Cropping systems and soil fertility management in the humid and subhumid tropics with special reference to West Africa. In: Mokwunye, U., Vlek, P.L.G. (Eds.), Management of nitrogen and phosphorus fertilizers in sub-Saharan Africa. Developments in Plant and Soil Sciences 24: 83-94.

Mainguet, M., Chemin, M., C. 1991. Wind degradation on the sandy soils of the Sahel of Mali and Niger and its part in desertification. In: Aeolian Grain Transport. Acta Mechanica Supplementum, Vol. 2. Springer. Vienna. Pp.: 113-130.

McGowan, H., Ledgard, N. 2005. Enhanced dust deposition by trees recently established on degraded rangeland. Journal of the Royal Society of New Zealand 35(3): 269-277.

Mazzucato, V., Niemeijer, D. 2000. Rethinking soil and water conservation in a changing society. A case study in eastern Burkina Faso. Tropical Resource Management Papers, Vol. 32. Wageningen University. Wageningen.

Mortimore, M., Turner, B. 2005. Does the Sahelian smallholder's management of woodland, farm trees, rangeland support the hypothesis of human-induced desertification? Journal of Arid Environments 63(3): 567-595.

Niemeijer, D., Mazzucato, V. 2002. Soil degradation in the West African Sahel: how serious is it? Environment: Science and Policy for Sustainable Development 44(2): 20-31.

Nicholson, S. 1995. Sahel, West Africa. In: Nierenberg, W. A. (Ed.), Encyclopedia of Environmental Biology, Vol. 3. Academic Press. San Diego, CA. Pp.: 261-275.

Olsson, L., Eklundh, L., Ardö, J. 2005. A recent greening of the Sahel—trends, patterns and potential causes. Journal of Arid Environments 63(3): 556-566.

Ouedraogo, I., Savadogo, P., Tigabu, M., Cole, R., Odén, P.C., Ouadba, J.M. 2009. Is rural migration a threat to environmental sustainability in Southern Burkina Faso? Land Degradation & Development 20(2): 217-230.

Pimentel, D., Wightman, A. 1999. Economic and Environmental Benefits of Agroforestry in Food and Fuelwood

Production. In: Buck, L.E., Lassoie, J.P., Fernandes, E.C.M. (Eds.), Agroforestry in Sustainable Agricultural Systems. CRC Press. Boca Raton, FL. Pp.: 295-317.

Rajot, J.L. 2001. Wind blown sediment mass budget of Sahelian village land units in Niger. Bulletin de la Société Géologique de France 172(5): 523-531.

Raynaut, C. 2001. Societies and nature in the Sahel: Ecological diversity and social dynamics. Global Environmental Change 11(1): 9-18.

Reenberg, A. 2001. Agricultural land use pattern dynamics in the Sudan-Sahel—towards an event-driven framework. Land Use Policy 18(4): 309-319.

Roose, E., Barthes, B. 2001. Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. Nutrient Cycling in Agroecosystems 61(1-2): 159-170.

Ruelland, D., Tribotte, A., Puech, C., Dieulin, C. 2011. Comparison of methods for LUCC monitoring over 50 years from aerial photographs and satellite images in a Sahelian catchment. International Journal of Remote Sensing 32(6): 1747-1777.

Seguis, L., Cappelaere, B., Milési, G., Peugeot, C., Massuel, S., Favreau, G. 2004. Simulated impacts of climate change and land-clearing on runoff from a small Sahelian catchment. Hydrological Processes 18(17): 3401-3413.

Sterk, G., Herrmann, L., Bationo, A. 1996. Wind-blown nutrient transport and soil productivity changes in Southwest Niger. Land Degradation & Development 7: 325-335.

Sterk, G, Stein, A., Stroosnijder, L. 2004. Wind effects on spatial variability in pearl millet yields in the Sahel. Soil & Tillage Research 76: 25-37.

Suttie, J.M., Reynolds, S.G., Batello, C. (Eds.). 2005. Grasslands of the world. Plant Production and Protection Series, No. 34. Food and Agriculture Organization of the United Nations (FAO). Rome.

UNEP. 2012. Sahel Atlas of Changing Landscapes: Tracing trends and variations in vegetation cover and soil condition. United Nations Environment Programme. Nairobi.

UNCED. 1992/93. Agenda 2. United Nations. Rio de Janeiro.

UNEP. 1992. World Atlas of Desertification. Edward Arnold. London.

Van Vliet, N., Reenberg, A., Rasmussen, L.V. 2013. Scientific documentation of crop land changes in the Sahel: A half empty box of knowledge to support policy? Journal of Arid Environments 95: 1-13.

Visser, S.M., Sterk, G. 2007. Nutrient dynamics—wind and water erosion at the village scale in the Sahel. Land Degradation & Development 18(5): 578-588.

Visser, S.M., Sterk, G., Karssenberg, D. 2005a. Modelling water erosion in the Sahel: application of a physically based soil erosion model in a gentle sloping environment. Earth Surface Processes and Landforms 30(12): 1547-1566.

Visser, S.M., Sterk, G., Karssenberg, D. 2005b. Wind erosion modelling in a Sahelian environment. Journal of Environmental Modelling and Software 20: 69-84.