Biomass production and management practices in mixed crop-livestock systems in the west African Sahel: Opportunities and constraints

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Biomass production and management practices in mixed crop-livestock systems in the west African Sahel: Opportunities and constraints

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Summary

The Sahel is characterized by a marked inter-annual climate variability and has experienced a number of food security crises following the severe droughts during the 1970s and 1980s. Due to recent challenges such as rapid population growth, climate change, environmental concerns and market changes which cause major impacts to their production systems, the Sahelian people have been shifting and adapting their production systems and the way they live to cope with uncertainties. The objective of the present report is to review the various biomass production and management issues in the mixed crop-livestock systems in west African Sahel. An elaborated literature survey of peer reviewed papers mostly, was conducted. The studies were based on the Sahel scale research, more specifically research that had been published on the west African Sahel, including studies published between 1990s and 2016. Results show that many factors have contributed to the changes, among which, rainfall variability, population growth, human induced activities, land tenure systems and the effects of globalization. Various biomass production and management practices are employed in west African Sahel for both on-farm and off-farm biomass improvements. Some of the best practices are mulching, soil and water conservation techniques, composting, farmer managed natural regeneration (FMNR), agroforestry, etc. These practices have overall contributed to increase agricultural productivity, ecosystem services provisioning and have sometime deepened the difference between men and women, rich and poor, young and old people. Most of the constraints associated with large adoption of the best practices in the Sahel are land tenure systems, the huge gap between inputs and output investment costs but, the climate conventions are offering new opportunities that will ultimately contribute to positive changes. This will be possible only when land tenure systems in the region are reinforced, institutional linkages are strengthened and new information systems are used to inform farmers on climate issues and new agricultural practices.

Abbreviations and acronyms

FMNR	farmer managed natural regeneration
g	grams
GDP	gross domestic product
ha	hectare
Km	kilometre
Mg	magnesium
Mm	millimetre

1. Introduction

The Sahel is a semi-arid region extending from the southern border of the arid Sahara to the northern border of the subhumid tropical savannas (Charney 1975; Ouedraogo et al. 2014). The Sahel covers 3,053,200 kilometres $(km)^2$ and is concerned with parts of Senegal, Mauritania, Mali, Burkina Faso, Algeria, Niger, Nigeria, Chad, Sudan, South Sudan and Eritrea. This portion of the African continent is characterized by a marked inter-annual climate variability and has experienced a number of food security crises following the severe droughts during the 1970s and 1980s (Ali and Lebel 2009; Brandt et al. 2014; Meroni et al. 2014; Nicholson 2013).

The rainfall varies between 200 millimetres (mm) and 600 mm annually with a north-south positive gradient, mainly occurring between June and October. The majority of the population (about 80%) lives in rural areas practising agriculture and livestock farming (Ickowicz et al. 2012). Low and erratic precipitation in the Sahel is the most important factor limiting crop yield in the region. In addition, the unbalanced soil factors (texture and profile depth) with the prevailing precipitation has resulted in a crop yield (millet and sorghum, mainly) below the potential (Unger et al. 1991; Lal 1990). Livestock husbandry in the region has been a traditional activity built upon commonly organized use of resources such as water and pasture (Ancey et al. 2008).

Currently, due to recent challenges such as rapid population growth, climate change, environmental concerns and market changes which cause major impacts to their production systems, the Sahelian people have been changing and adapting their production systems and the way they live to cope with uncertainties. This change, although built upon their indigenous ingenuity to adapt to current situations, has however been favored by the introduction of external technologies and/or improvement of the existing ones by research and development institutions and nongovernment organizations (NGOs). These interventions are aimed at improving on-farm and/or off-farm biomass production for resilient household wellbeing in the Sahel. This present report reviews the various biomass production and management issues in the mixed crop-livestock systems in the west African Sahel.

The report mainly focuses on the drivers of changes, the production and management practices, the effects of the biomass production and management on agricultural productivities, gender and ecosystem services, some examples of best practices, trade-offs associated with the production, and the opportunities, constraints and lessons learned from biomass production. Some policy recommendations that can be used to improve biomass production and management practices are made.

2. Methodology

2.1 The region of interest

In this report, our region of interest is the west African Sahel with focus on Burkina Faso, Mali, Niger and Senegal (Figure 1). However, to enrich the data in the review, relevant information outside our region of interest but within west Africa have been included.

The population of the four countries has rapidly grown from 20 million people in 1960 to 80 million people in 2010 (Figure 2). More than 80% of the population are rural dwellers who practice small scale farming for their livelihoods of which 60% are involved in mixed crop-livestock systems (Ly et al. 2010). The crop-livestock systems play an important role for both agriculture and livestock as well as the maintenance of a good livelihood standard in west Africa. The majority of the livestock population depends on mobility and contribute 30% to the agricultural GDP. The farming system is oriented towards livestock and crop production that are more or less complementary in the land use system. The area being open, the access to natural resources is based on several usage rights to maintain their mobility and reciprocity (Ancey et al. 2008). A family organization governs the access to land and controls the production factors. Similar to the rapid increase of human population in the west African Sahel, the cultivated area and livestock populations have also increased between 1960 and 2010 (Figure 2). This may be an indicator of existence of conflicts linked to competition for natural resources between different land users which may sometimes result in migration of part of family members towards less crowded and more fertile zones in the south.

Figure 1. The Sahel zone and our region of interest

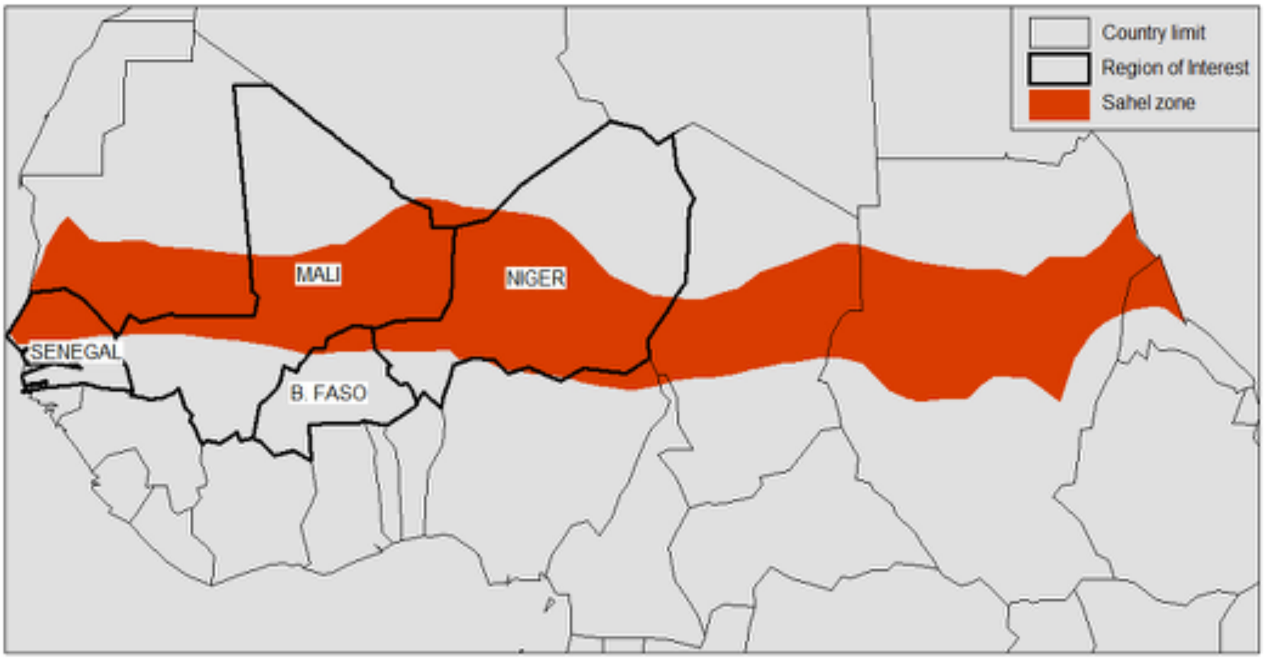
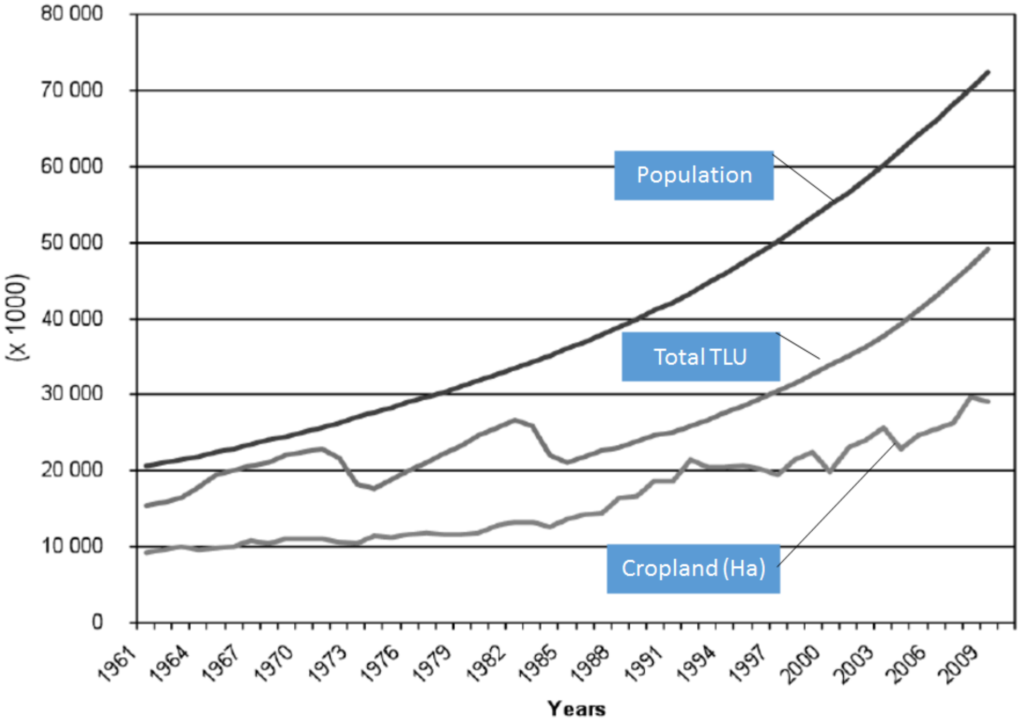


Figure 2. Dynamics of the human population, cropland and tropical livestock unit in the region of interest (Source: FAOSTAT 2012)



2.2 Definition of concepts

Biomass production practices

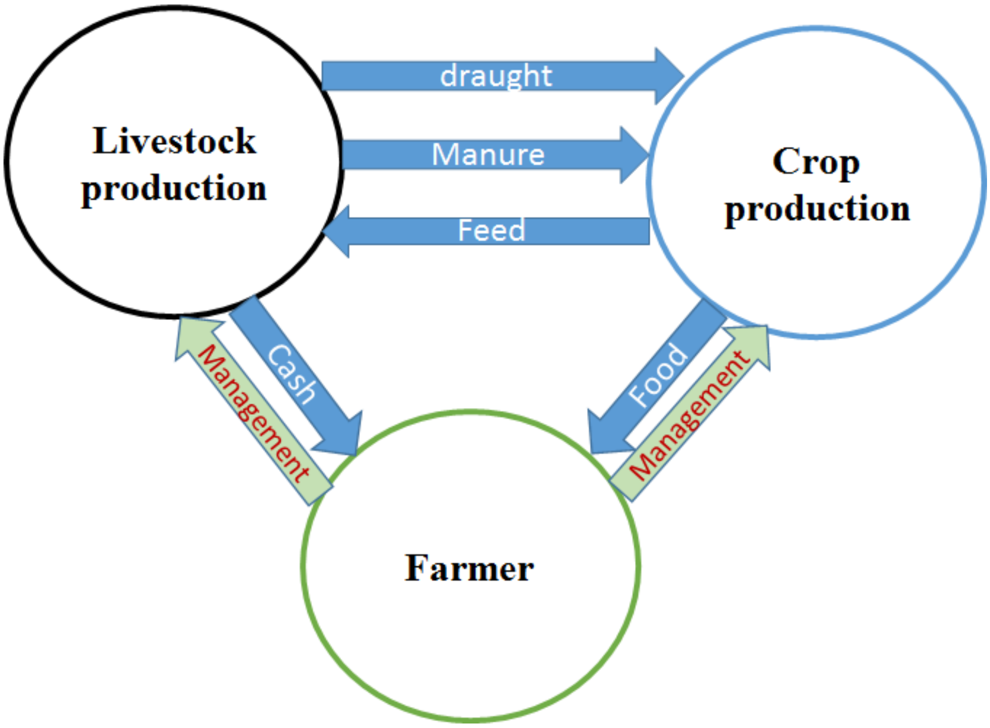
Biomass is concerned with all organic material that stems from plants produced by green plants converting sunlight into plant material through photosynthesis and includes all land and water based vegetation, as well as all organic wastes (McKendry 2002). Biomass production practices consist of all management strategies/interventions that aim to improve plant material production. In this report, for the sake of clarity we set apart two types of biomass production practices: on-farm biomass and off-farm biomass production. On-farm biomass production practices are all intervention/techniques that contribute to maximize crop yield while off-farm biomass production practices deal with any management technique aiming to enhance above ground plant production outside cultivated lands, considered as grazing land in the Sahel. This study specifically focuses on herbaceous and lignin biomass, and biomass from crop residues.

Mixed crop-livestock systems

Mixed crop-livestock or mixed farming systems are systems where crops and livestock are integrated on the same farm (Herrero et al. 2010; Thornton and Herrero 2014). Famers raise livestock in rural areas for many purposes including milk and meat production, traction, transport, manure production, as a store of wealth ('living saving account') and as a source of income to meet household needs. They plant grain crops to meet their consumption needs. Crop production provides feed (crop residues) to livestock while livestock production in turn provides draught, manure and traction to improve or facilitate crop production (Figure 3).

The mixed farming systems cover globally 2.5 million hectares (ha) of land and produce about 90% of the world milk supply and 80% of the meat from ruminants (Herrero et al. 2013). The system is particularly important for livestock and food security because it provides most of the staple food consumed by poor people.

Figure 3. Integrated crop-livestock production system in the west African Sahel



2.3 Review method

A systematic review of the literature published from the 1990s to 2016 on the west African Sahel was conducted. The following search engines were used: ISI Web of Science, ScienceDirect, Google Scholar, ResearchGate and Access to Global Online Research on Agriculture. The key search terms used were: biomass production in the Sahel, rangeland management practices in the Sahel drivers and impacts of change in the Sahel, and crop-livestock systems in the Sahel. All papers selected for review were written in English or French. The title and abstract were reviewed for relevance; if relevant, the papers were downloaded and read in full. Books chapters and conference proceedings meeting the key search terms were also included. The year of publication, the practice, the location and the key findings of literature selected for inclusion were recorded.

In terms of analysis, the literature was synthesized for general trends, the type and importance of the various practices, and the conclusions drawn. The practices identified in the selected literature have been grouped into sets of challenges addressed, the country and year the studies were conducted, their efficiency and constraints of adoption.

3. Results and discussion

3.1 Drivers of change in biomass production

Over the last three decades, the Sahel in general has experienced important and rapid changes in vegetation cover, plant community composition, hydrological conditions and soil properties (D'Odorico et al. 2013) which led to loss of ecosystem services and poses serious threats to sustainable livelihoods. This is referred to as desertification, resulting in an increase in barren lands, loss of soil nutrients and water holding capacity, increase in soil salinity and toxicity (D'Odorico et al. 2013; Martinez-Beltrán and Manzur 2005). For example, this process can create shifts in vegetation composition from perennial to annual species, palatable to unpalatable grasses or woodland to shrubland (Scholes and Archer 1997; Tarhouni et al. 2010; Todd 2006). In the west African Sahel, the impacts of increasing desertification are marked by erratic rainfall sequences within and between years coupled with recurrent desert locust invasion and the presence of large areas of inherently low fertility and crust prone soils, leading to high uncertainties in herbaceous and lignin biomass production, and biomass production from crop residues (Breman et al. 2001; Barry et al. 2008; Borona et al. 2015). Consequently, the west African Sahel today is suffering from an environmental and food crisis which sometimes leads to political instability. Among the driving forces of the change in biomass production are natural and human induced factors.

Climate change

Changes in the global and regional patterns of precipitation are the major drivers of the current Sahelian biomass status. According to Goudie (2006), many degraded zones were formed millions of years ago while the majority of them were affected by Pleistocene climate changes which extended at some points to currently much wetter zones. Lezine (1989) and Le Houerou (1997) identified two types of climate change in the Sahel: natural long-term fluctuations which altered the vegetation over the last centuries and short-term changes like the severe droughts that occurred in the1970s and 1980s.

Wind and water erosion

Sterk et al. (1996) and Middleton and Thomas (1997) have explored wind and water erosion systems in the Sahel and their effects on vegetation loss. It was revealed that one-third of the Sahel is affected by moderate to low wind erosion while one per cent of the Sahel (six million ha) are strongly affected by wind erosion. In this ecological zone, nutrients are stored within the few centimeters soil layer. As such, loss of topsoil material corresponds to loss of entire soil fertility. In the same way, water erosion frequently driven by heavy rainfall intensity washes away soil layers, resulting in extended lands with sparse vegetation cover and bare surfaces. Areas where wind and water erosion originate lose their soil nutrients while pooling areas benefit from deposited material, if not buried too deep.

Human activities

The degree of human impact on resources in the Sahel is strongly related to population growth (Wezel and Rath 2002). According to van Vliet et al. (2013) and Raynaut (2001), the Sahel region experienced one of the world's highest demographic growths from 1.5% per year in the 1950s to 3% per year in the 1990s, which has resulted in the threefold increase in the population. The west African Sahel population increased fourfold within a half of a century, from 20 million in 1960 to 80 million in 2010 (Figure 2). In the context of less developed countries, such as countries in the Sahel, population growth is always associated with biomass degradation through poor farming practices (Geist and Lambin 2002). In some cases (Burkina Faso and Senegal, mainly), biomass degradation is associated with in-migration of farmers fleeing drought affected zones and pulled by the fertile soil of the down south areas (Ouedraogo et al. 2009; Ouedraogo et al. 2012; Ouedraogo et al. 2015).

Wood energy requirement

About 80% of the population in the Sahel rely on traditional fuel use of wood and charcoal (Ouedraogo 2006; Ouedraogo et al. 2010; Ouedraogo et al. 2011) and this has led to an immense reduction of herbaceous and lignin biomass in the Sahel (Breman and Kessler 1995; Fontes and Guinko 1995; Wezel and Rath 2002; Tappan et al. 2004). In the past, only dead wood was collected for household energy requirements. Today, green wood is cut down by commercial traders to meet the energy need in the capital cities. In Senegal, similar to the other Sahel countries, cutting of trees for charcoal production was found to be the main factor that led to the disappearance of several tree species (Bergeret and Ribot 1990).

Grazing

Grazing areas in the Sahel include natural pasture, fallow land and harvested cropland (Wezel and Rath 2002). Grazing is among the factors of land degradation in some areas in the Sahel due to its high intensity and mobility and to the high sensitivity of most of the plant species to heavy grazing (Hiernaux 1998). Natural pasture is usually open to all users while fallow and post-harvest cropland can be used in mutual agreement with the owner.

Land tenure system

The lack of control over resources is one of the major reasons for the degradation of natural resources and this is exemplified by the Sahel case. As illustrated by Hardin (1968), in open access rangelands, the 'tragedy of the commons' paradigm holds that an individual behaving in his own self-interest will continue to exploit a common resource, even when it is being overused and degraded because the benefits from such behavior accrue to him alone, while the constraints are divided among members of the community as a whole.

Market orientation and globalization

In some remote areas of the Sahel, cash crops such as groundnut and cotton have been promoted during and after the colonial period (van Vliet et al. 2013). Intensive groundnut production was superimposed in Senegal in the 1840s while cotton production was introduced and maintained in Mali and Burkina Faso. The expansion of the cash crop production has resulted in decreased biomass with an important increase of bare lands. In the areas where cotton is currently produced, it is likely that the soil will become unfertile due to the overuse of chemical fertilizers.

In rural areas within the Sahel, the cost of living has risen greatly since the populations aspire to luxury as a spinoff of a new consumerism and market economy (Ouedraogo et al. 2015). They strive to meet the new living standards in terms of education, health, housing (metal and cement), transport (motorcycles) and communication (mobile phones). This can only be met by increasing the area of individual cash cropland. The artisanal gold mining boom in the

Sahel has led to mitigated impacts on the environment while huge areas have been destroyed for mining. In addition, important croplands in some localities have been abandoned because many young farmers converted to gold miners.

Faced with drought and declining crop yields in the 1980s, farmers in the Sahel began to experiment with various soil and water conservation and ecosystem restoration practices (Reij et al. 2005; Kabore and Reij 2004; Botoni and Reij 2009). The objectives were to rehabilitate the productive capacity of the land through better rainfall and runoff controls as well as to improve soil fertility management and reforestation.

3.2 Biomass production management practices in the Sahel and their main constraints

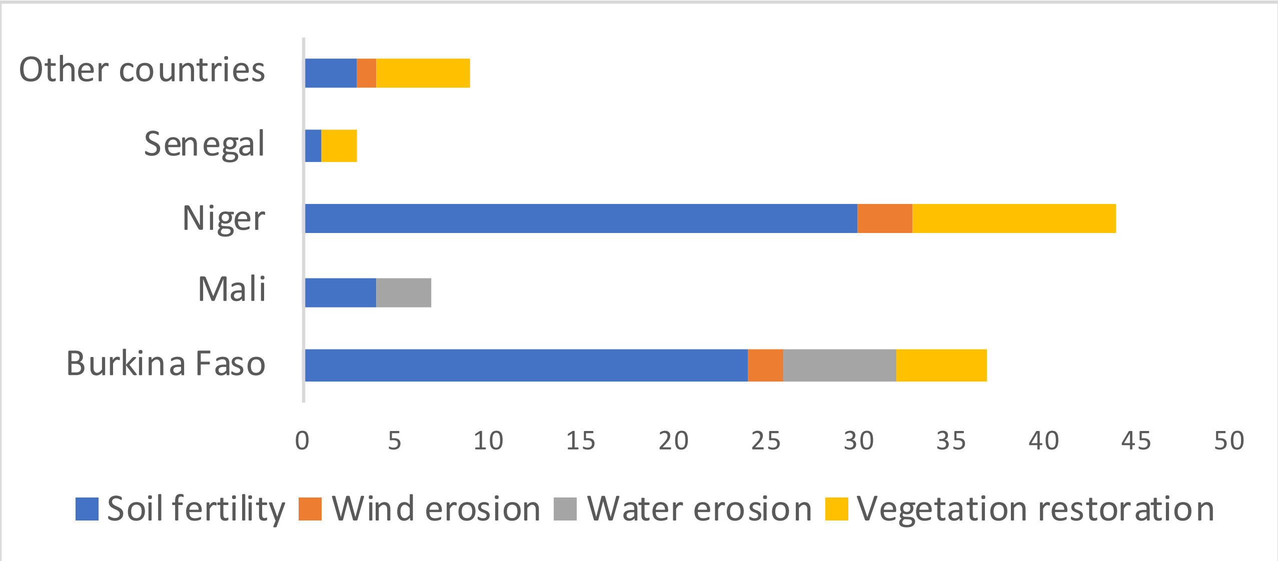
The results of the literature survey on biomass management practices are shown in Table 1. This table indicates the various practices, their efficiency and constraints and the publications on each practice since the 1990s as well as the countries where the studies were conducted.

Summary of the literature review

Figure 4 presents a simplified pictorial representation of the number of publications that address each of the four main challenges of the Sahel for each single west African Sahelian country. These challenges are: declining soil fertility, increasing wind erosion, increasing water erosion and decreasing vegetation cover. Niger has the highest number of publications (44) in general and particularly on soil fertility, wind erosion and vegetation degradation issues. It is followed by Burkina Faso (37) for the same issues. Few publications (three) were recorded for Senegal.

Among the Sahelian countries, Niger was the one that suffered the most from the severe droughts in the 1970s and 1980s. After the droughts, many researchers focused on Niger. Also, the presence of the headquarters of the International Crops Research Institute for the Semi-Arid Tropics and the AGRHYMET Regional Centre in Niamey may have contributed to the rise in the number of publications focused on this country. The few numbers of publications recorded for Mali and Senegal do not imply that important research has not been conducted in these countries but they might not have been published in English peer reviewed journals which we largely used for this study. We did not obtain access to publications that were not available on the web.

Figure 4. Number of publications dealing with the four main challenges in the west African Sahel (Source: literature review)



Soil fertility management practices

The literature survey revealed that in the west African Sahel, there are many management practices that aim to improve soil fertility for biomass and crop production in the mixed crop-livestock systems (Table 1 and Figure 5):

- On-farm crop residues management is a widespread practice in the Sahel. Crop residues management is defined as a technology whereby at the time of crop emergence at least 30% of the soil surface is covered by organic residue of the previous crop (Erenstein 2002). In addition to enhancing soil fertility, crop residues management can contribute to reduce wind and water erosion, improve the harvesting and conservation of the crop residues and can improve the nutritional quality of the crop residues as animal feed. The main challenges of this practice is that in the Sahel, crop residues have multiple uses that conflict with on-farm crop residues management: crop residues constitute important feeds for livestock and also a primary source of energy at the household level.

- Mulching consists of covering the ground with a layer of plant materials in order to conserve soil water, to stimulate the activity of soil biota (e.g. termites) and to reclaim degraded soil for crop production (Bayala et al. 2012; Ouedraogo et al. 2007). This is done using plant materials such as wild grass, crop residues or tree biomass, either leguminous or not. The main constraint of this practice is that it may not be applicable to a large-scale farming system due to limited availability of biomass and the conflicting use of crop residues as livestock feed, and use by households for other purposes such as fuel, for construction etc.

- Soil and water conservation techniques include traditional practices such as zai, half moon, stone and earth bunds and grass strips. These techniques are well adopted in the west African Sahel and aim at increasing infiltration, soil moisture retention, soil organic matter content and improving soil structure besides reducing soil erosion (Zougmore et al. 2000; 2003; 2004). Zai are planting pit systems where organic materials are deposited during the dry seasons (Photo 1). Crops (millet, sorghum etc.) are planted in it during the rainy season. On bare soils, pits are shown to increase the activities of termites which increase woody plants regeneration and speed up the restoration of degraded land (Mando and Stroosnijder 1999; Sileshi et al. 2010; Bayala et al. 2012). These techniques can also improve the vegetation cover. However, soil and water conservation techniques are labour intensive and time consuming.

- Manuring includes composting and green-manure management. Green manure is the biomass from herbaceous cover crops (***Crotolari***a spp, ***Mucuna cochincinensis*** (Lour.) A. Chev., ***Mucuna pruriens*** (L.) DC, ***Stylosanthes hamata*** (L.) Taub., ***Tephrosia vogelii*** Hook.f. etc.) grown to be turned under soil as a soil amendment and nutrient sources for subsequent crops (Bayala et al. 2012; Mabrouk et al. 1998). Usually the cover crop is established through relay cropping with the staple food crop. This works well if the farmer has his own livestock.

- Rotation and crop association techniques improve food diversity. Legumes (e.g. cowpea, groundnut) are frequently intercropped or rotated with cereals. In order to improve soil fertility and animal nutrition, several cereal-legume associations and cover crops (e.g. mucuna, stylo, crotalaria etc.) are found in farmers' fields. Sorghum-cowpea millet-cowpea, maize-cowpea and sorghum-groundnuts associations are commonly found in the west African Sahel (Bado et al. 2006a,b; Bayala et al. 2012).

- The fallow system of farming is a practice dating from ancient times. Basically, the term fallow refers to land that is plowed and tilled but left unseeded during a growing season for a certain number of years to allow the soil to recover (Wezel 2000). The fallow system provides grazing lands for livestock. However, in the context of limited arable land due to population increase, the fallow system has almost been abandoned in many areas.

- The use of chemical fertilizers is not so well developed in the Sahel. This is because most of the farmers are unable to obtain inputs such as fertilizers and hybrid seeds due to the associated cost and fears of long-term soil and water pollution as is the case with most fertilizers (Epule et al. 2012; 2013; 2015).

Figure 5. Commonly used practices to enhance on-farm soil fertility and number of publications per country in the west African Sahel (Source: literature review)

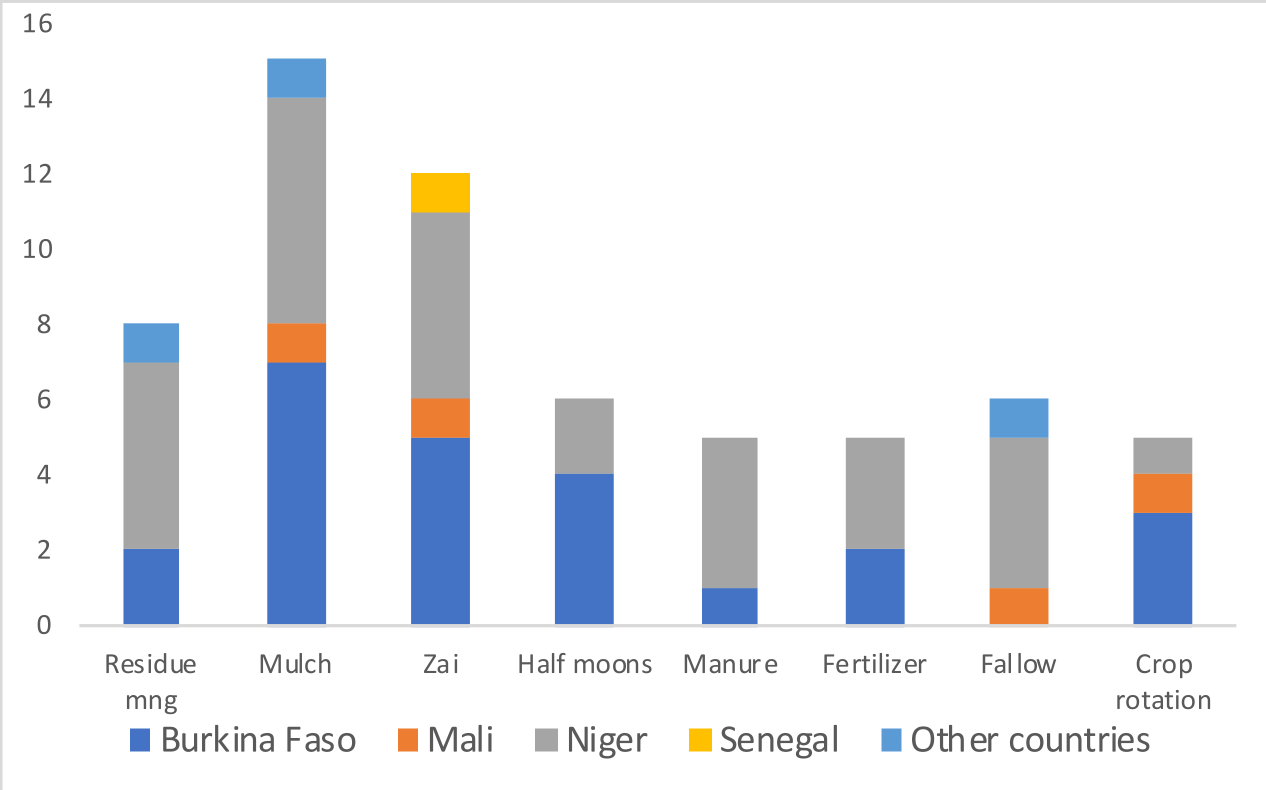


Photo 1. Zai pits (Thiou, Yatenga, March 2016)

Water and wind erosion controls

Practices such as wind breaks, grass strips, mulch lines, stone alignment/bunds and stone walls and terraces (Table 1 and Figures 6 and 7) are used to control water and wind erosion in the Sahel. The techniques contribute to biomass and crop production improvement as well (Zougmore et al. 2004; Kassogue et al. 1996). The limitation of these practices are that wind breaks and grass strips need to be protected from grazing and stone alignment, walls and terraces are labour intensive and time consuming.

Figure 6. Water erosion control techniques in the Sahel and number of publications per country (Source: literature review)

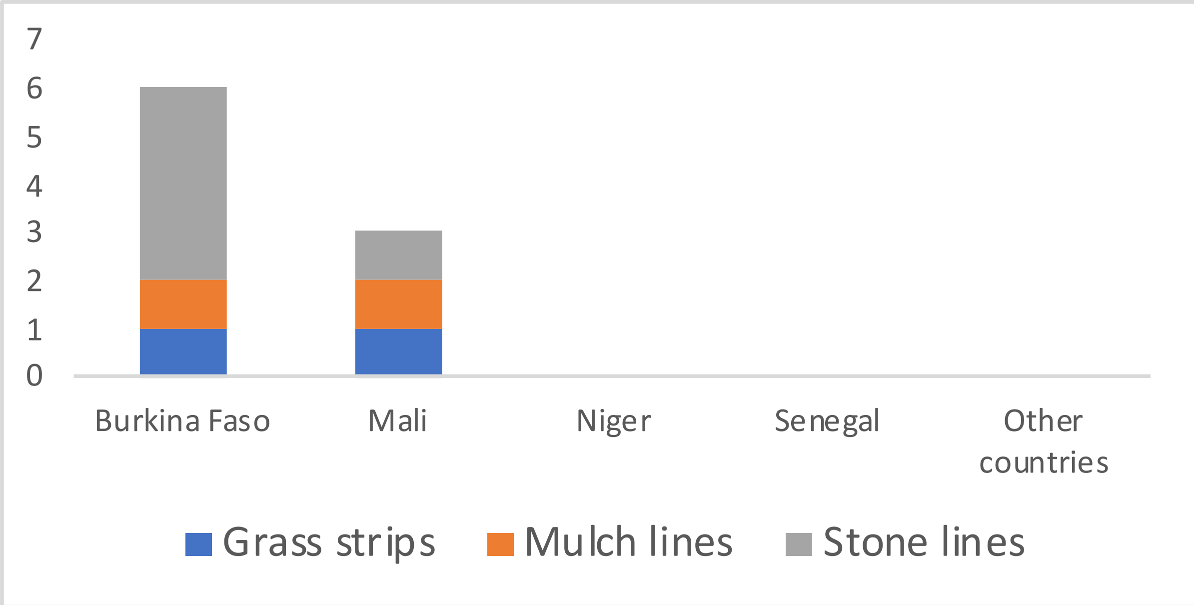
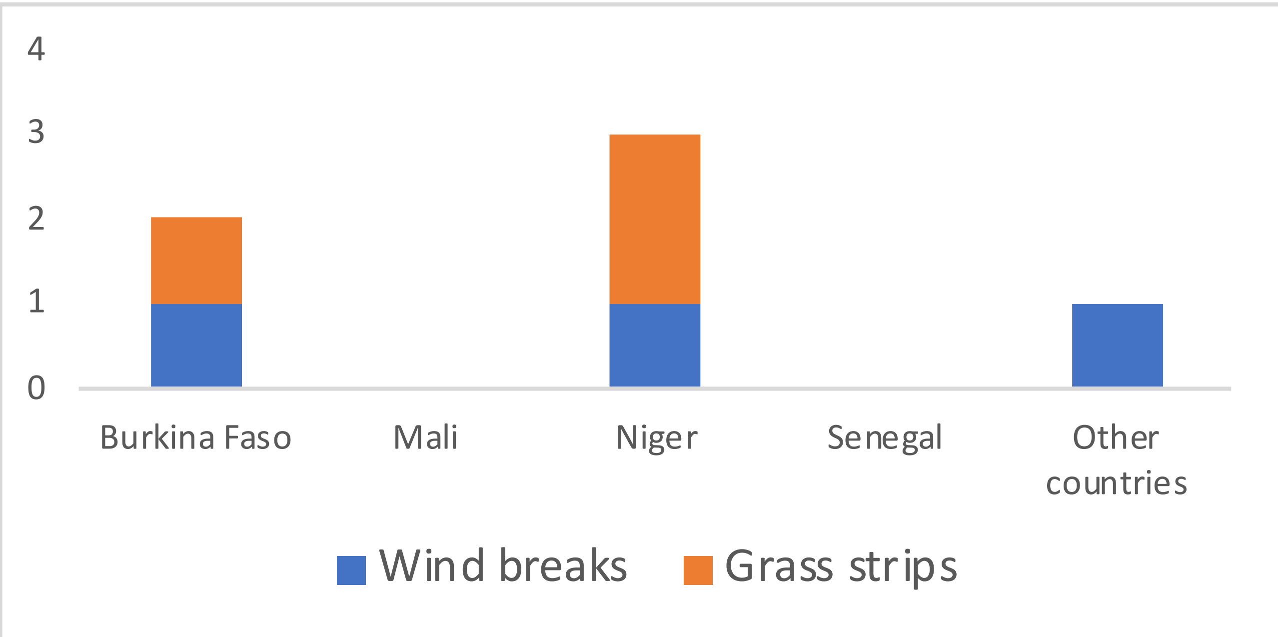


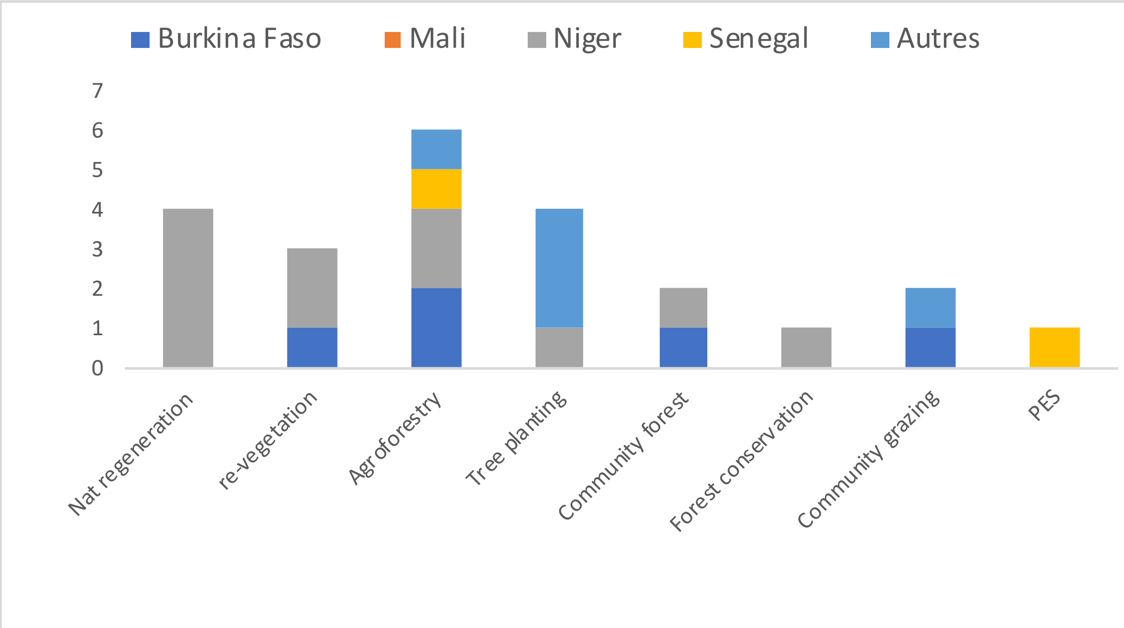
Figure 7. Wind erosion control techniques in the Sahel and number of publications per country (Source: literature review)



Improving tree biomass production

The literature survey reveals that various practices are used to improve off-farm biomass production in the Sahel (Table 1 and Figure 8):

Figure 8. Commonly used practices to improve off-farm vegetation cover and number of publications per country in the west African Sahel (Source: literature review)



- Farmer managed natural regeneration (FMNR) is a rapid, low cost and easily replicated approach to restoring and improving agricultural, forested and pasture lands. FMNR is based on encouraging the systematic regrowth of existing trees or self-sown seeds (World Vision 2012). It was begun in the 1980s and became increasingly popular in the west African Sahel. FMNR is based on the regeneration of native trees and shrubs from mature root systems of previously cleared desert shrubs and trees. Regeneration techniques are used in agricultural cropland and to manage trees as part of a farm enterprise. FMNR in the savannas is well adopted in southern Niger for instance and is known to produce continuous harvests of trees for fuel, building materials, food and fodder without the need for frequent, costly replanting (Joet et al. 1998). Trees are trimmed and pruned to maximize harvests while promoting optimal growing conditions.

- Revegetation of bare soil with mulch is similar to the mulching system with the only difference that it is used on bare soil on off-farm land. The principle is the same as the on-farm mulching techniques. This is an effective and rapid way to restore bare lands in the Sahel (Sterk and Haigis 1998).

- In the Sahel, vast tree planting programs usually take place during the rainy seasons, between July and August. Most of these programs are initiated by the government's institutions through their ministries of environment. NGOs and international development/research institutions also promote tree planting during that period. The success is however very limited due to lack of follow up and water stress resulting in high rate of mortality. Another factor limiting the success of tree planting in the Sahel is the weak land tenure system and the lack of property right over land. This discourages many people from planting trees on their farms and on the common rangelands.

- Forest conservation and/or protection consists of planning and maintaining forested areas for the benefit and sustainability of future generations. Forest conservation involves the upkeep of the natural resources within a forest that are beneficial to both humans and the ecosystem. Forest conservation acts to maintain, plan and improve forested areas. Forests provide wildlife with a suitable habitat for living along with filtering ground water and preventing runoff. In the Sahel however, due to the rapid population growth combined with the increasing demand for arable and wood materials, many conserved/protected forests have been cleared for agriculture and grazing.

- Community-based forest management is the management, by communities or smallholders, of forests and agroforests they own, as well as the management of state owned forests (some of which share customary tenure and rights under traditional laws and practice) by communities. The community forests in the Sahel are grazing lands where people collect wood materials for energy and domestic uses. In recent periods, some community forests are selected to benefit from the voluntary carbon market, where local communities are engaged in tree plantations, reforestation and afforestation.

3.3 Effects of biomass production and management practices on agricultural productivity

Mulching practices are proven to be very efficient and have a positive effect on crop productivity in the Sahel (Bayala et al. 2012; Klaij et al. 1993; Thornton and Herrero 2014; Erenstein 2003). It affects soil conservation, soil ecology, crop yield, labour and capital productivity and agricultural externalities (Erenstein 2003). A study in Nigeria by Carsky et al. (1998) revealed that when the mulch rate increases, the runoff and soil loss decrease substantially and the crop yield increases importantly. In zones outside the Sahel (e.g. Zimbabwe, China and USA), the use of mulching has significantly increased total soil organic carbon and three other active carbons (light fraction organic carbon, liable organic carbon and dissolved organic carbon) by 7.1–128.6% (Wang et al. 2015).

Years ago, farmers in the Sahel integrated trees in the farming system following the recognition that this practice offers them the opportunity to close yield gaps (Leakey 2012; Carsan et al. 2014). Practices such as evergreen agriculture that integrate ***Faiderbia albida*** and other trees are reported to increase groundnut yield by 37% in Senegal, sorghum by 115% in Burkina Faso and maize yield from 1 to 3 tonnes/ha in many countries in the Sahel (Sileshi et al. 2008; Garrity et al. 2010).

The use of compost significantly increases crop productivity and quality (Tables 2 and 3) with an increase rate of 45% (Ouedraogo et al. 2001).

Table 2. Effects of compost application on sorghum yield components (5 Mg* ha^{-1}) in Yatenga

Treatment	Grain yield (kg ha-1)	Number of grain/ panicle	1,000 grains weight (g)**	Straw day matter (kg ha-1)	Yield index
Compost (5 Mg ha-1)	1,698	4,213	25.5	5,145±777	0.3
No compost (0 Mg ha-1)	1,160	2,035	23.2	4,450±1415	0.3

Source: Ouedraogo et al. 2001
*Mg=magnesium
**g=grams

Table 3. Effects of compost application on sorghum yield components (10 Mg ha^{-1}) in Mediga

Treatment	Grain yield (kg ha-1)	Number of grain/ panicle	1,000 grains weight (g)	Straw day matter (kg ha-1)	Yield index
Compost (10 Mg ha-1)	1,380	4,071	30.04	3,285±614	0.4
No compost (0 Mg ha-1)	408	871	31.32	2,175±481	0.4

Source: Ouedraogo et al. 2001
*Mg=magnesium
**g=grams

FMNR increases the value or quantity of woody vegetation on farmland (Haglund et al. 2011). It involves the selection and pruning of stems growing from the stumps of previously felled trees to encourage the growth of single or multi stemmed trees. In some cases, farmers protect individual tree seedlings or whole plots of land by constructing makeshift fences. Studies from Haglund et al. (2011) revealed that FMNR adoption increases gross annual household income by between 22,805 and 27,950 Franc of the Financial Community of Africa per capita. The adoption significantly increases household income by 18–24%. Adopters grew an average of almost four crops on their farms while their matched nonadopters grew just over three, suggesting that adoption increases crop diversity. Adoption also appears to increase tree diversity by between one and three tree species per farm and increases tree density by between 12 and 16 trees per ha.

3.4 Effects of biomass production and management practices on gender

The Millennium Development Goals recognize the need to promote gender equality and empower women to participate in all facets of economic and social life with the aim of achieving sustainable development. In the mixed crop-livestock systems, the achievement of sustainable development for the rural poor, especially women, constitutes a real challenge. For decades, women in the Sahel have suffered from issues related to limited access to natural resources such as arable land, water, forest products, information, economic and social facilities etc., and this situation may be amplified as increasing climate variability shrinks resource availability.

Behavioural patterns of women and men, young and old, rich and poor differ greatly in the Sahel. In this context, the adoption rate of successful biomass production and management practices by men and women, rich and poor, young and old will differ significantly (Nampinga 2008). Practices that require financial resources, intensive labour and ownership of livestock such as chemical fertilizers, composting, and soil and water conservation techniques will be highly adopted among rich farmers while poor farmers will rely on low-cost practices with evident low outputs.

Improving biomass production practices and protecting the environment require reducing poverty and achieving livelihood and food security among rural women and men. There are many gender issues in the Sahel in relation to biomass production interventions in the Sahel (Ndungo et al. 2010). Rural women and men in the Sahel have different roles, responsibilities, and knowledge in managing natural resources. In crop production, for instance, men tend to focus on market-oriented or cash crop production, whereas women often work with subsistence crops, minor crops and vegetable gardens. Also, gender divisions of labour vary substantially by age, ethnicity and marital status. Consequently, the water use and management varies accordingly (Elmhirst and Resurreccion 2008). Around small reservoirs in the crop-livestock systems in the Sahel, men use water for irrigation systems and livestock watering, whereas women may not have access to irrigation systems for vegetable gardens and subsistence crops. Decreases in biomass and agricultural production and household food security create additional health problems related to increasing workload for women. Although both rural women and men play a critical role in natural resources management, women's use, conservation, and knowledge of resources play a key role in shaping local biodiversity. Also degradation of natural resources can alter gender responsibilities and relations in households and communities.

Access to new technology, information and training related to biomass production and management remains highly gendered, with most of the related initiatives targeted to men (Ndungo et al. 2010; Elmhirst and Resurreccion 2008). For instance, extension personnel in agriculture and natural resources frequently speak only to men, often erroneously expecting that the men will convey information to their wives (Agarwal 2003; Enarson and Meyreles 2004; Sachs 2007). Moreover, degradation of the natural resource base can result in new forms of cooperation, conflict or controversy between men and women or different ethnic groups: when natural resources become insufficient to support the livelihoods of the population, drastic measures result, such as men's or women's out-migration. Men's out-migration leaves women to assume men's traditional roles and responsibilities, increasing their work burden, but leaving them without equal or direct access to financial, social and technological resources (Lambrou and Laub 2004).

3.5 Effects of biomass production and management practices on ecosystem services

In general, the continuing efforts in rehabilitating the vegetation cover in the west African Sahel through wind and water erosion controls, agroforestry, FMNR, tree planting, community-based forest management and the pro-poor environmental service market may have already contributed to improving biomass production in this region. Many recent publications using large-scale analysis of the trend of vegetation cover in the west African Sahel based on Earth Observation Systems have revealed that there are important spots of re-greening (Herrmann et al. 2005; Anyamba and Tucker 2005; Hickler et al. 2005; Fensholt et al. 2012; Dardel et al. 2014). Despite the demonstration by these authors that rainfall improvement is the driving factor of the re-greening process of the Sahel, Herrmann and Tappan (2013), Olsson et al. (2005) Seaquist et al. (2008) Ouedraogo et al. (2014) argued that although rainfall has obviously increased during the last three decades, the state of greenness as observed from remotely sensed data (mostly National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer) could not have been reached without additional human factors. For Ahmedou et al. (2008), Botoni and Reij (2009), Kaboré and Reij (2004), Reij et al. (2009) and Sendzimir et al. (2011), the re-greening trend of the vegetation in the Sahel is mainly driven by the appropriate implementation of the biomass production practices by the population of the Sahel.

Good biomass production and management practices improve the provisioning, regulating and supporting services of the ecosystems. They improve the resilience and reduce the vulnerability of rural dwellers to diseases, drought and flood, resulting in enhanced food security and poverty alleviation. Management of natural resources such as pasture/range, woodlands, forest, wetlands and water resources results in a lower incidence of land use conflicts and improves wellbeing. Biomass production practices can have direct impacts on sediment transport, downstream water quality, flow patterns and groundwater recharge. A large range of ecosystem services are provided through sustainable biomass production interventions. These services include nutrient cycling, carbon sequestration, soil erosion control, maintenance of the hydrological regime, biological control of diseases, and pollution, waste and climate regulations.

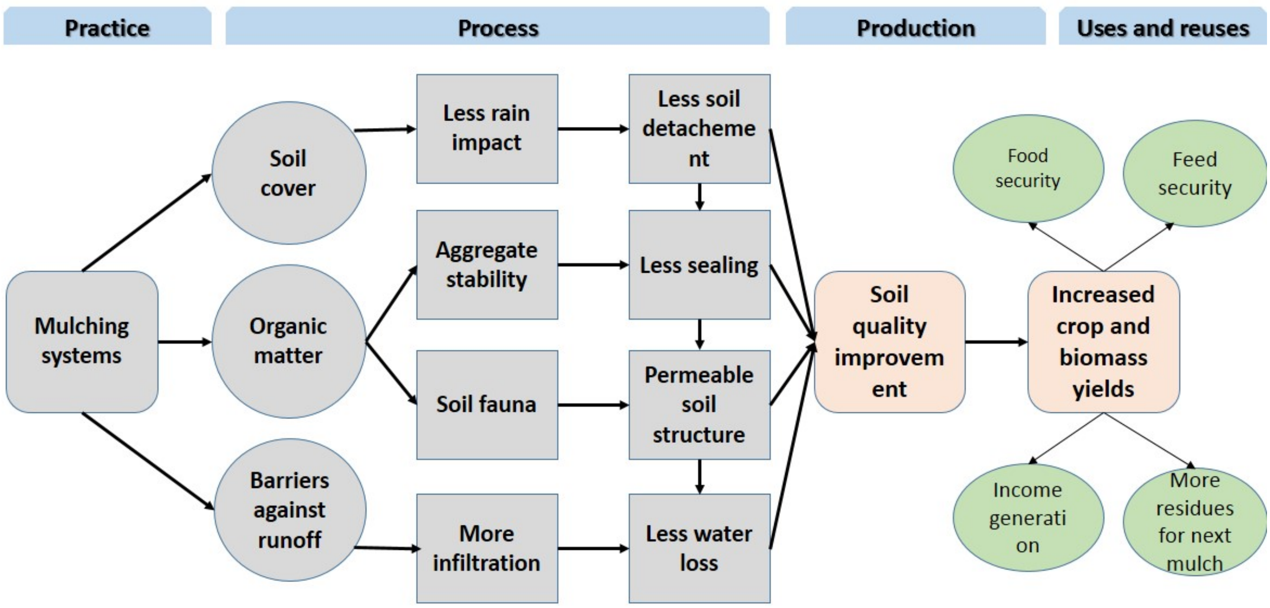
3.6 Examples of production, productivity and reuse capacity of biomass in crop livestock systems

Figure 9 is a pictorial representation of the mulching systems known as a successful biomass and crop management practice (Gicheru 1994). The mulching system halts soil erosion by providing a protective layer to the soil surface, increasing resistance against overland flow and enhancing soil surface aggregate stability and permeability through its combined physical and biological effects (Erenstein 2002). This results in soil quality improvement which in turn increases crop and biomass yields. Thus, mulching contributes to food security, poverty reduction (income generation), feed availability for livestock through abundant crop residues and provides more residues to be used for the next mulch.

Similarly, to the mulching techniques, the use of animal manure in crop production is widespread in the mixed crop-livestock systems in the Sahel for multiple reasons. Animal manure is used to improve soil quality on the farmlands. At harvest, crop residues are collected to feed animals during critical periods while livestock is grazed on harvested farms. In this context, the mulching techniques are not practiced. However, the digested crop residues (manure) are collected and spilled on the farms for the next cropping season.

Agroforestry and the use of legumes rotations or intercropping can positively influence the drivers of agricultural intensification such as nutrient cycling and water use and help close the yield gap in the Sahel (Carsan et al. 2014). Agroforestry systems using ***Faidherbia albida*** in maize fields are reported to improve water filtration and water use efficiency above sole maize treatments (Sileshi et al. 2008; Garrity et al. 2010). The use of legumes in rotation or as intercrops can restore soil nutrients by fixing nitrogen, improving soil organic matter and reducing reliance on fertilizer use. Practices involving species mixtures and intercropping can create diversified production systems yielding both staples and marketable tree products to improve livelihoods (Leakey 2012; Dawson 2013; Simons and Leakey 2004). The pods and leaves from ***Faidherbia albida*** are nutritious feeds and well appreciated by livestock which spend most of the time under these trees during dry seasons. While under these trees the livestock leave their manure which contributes to soil fertility under ***Faidherbia*** shade. The intercropping system with legumes has a double role for farmers. While legumes contribute to soil restoration, they also contribute to household food and nutritional security and improvement. Leaves and grains from beans, for instance, are valuable food as they are loaded with irons; their residues are also used for animal feeds.

Figure 9. Mulching system and effects on soil fertility and crop production (modified from Erenstein 2002)



3.7 Adoption of best biomass enhancing practices in crop-livestock systems

FMNR appears to be one of the best biomass production and management practices in the mixed crop-livestock systems in Niger and Burkina Faso. Haglund et al. (2011), Abasse et al. (2009), Adam et al. (2006), Larwanou et al. (2006) and Reij et al. (2009) have strongly demonstrated that FMNR is widely practised in the region of Maradi and confers significant benefits at the household level (food, feed, fuel, housing material etc.). Extrapolating from their results, an estimated 62,000 households in the region of Maradi practise FMNR, raising the total gross income of the region by between USD17 and 21 million per year and contributing an additional 900,000 to 1 million trees to the local environment.

FMNR is a rapid, low cost and easily replicated approach to restoring and improving agricultural, forested and pasture lands. FMNR is based on encouraging the systematic regrowth of existing trees or self-sown seeds. The widespread adoption of FMNR is probably due to the fact that its benefits are obtainable at minimal costs to the farmer. The practice requires no expenditures beyond the farmer's additional labour. The annual benefit-cost ratio of practising FMNR is between 2.5 and 3.0 (Haglund et al. 2011).

According to literature cited above, FMNR has contributed to:

- expanding cultivation of cereals and vegetables, with harvests doubling in some areas;
- doubling or tripling producers' incomes through the sale of wood, seed pods and edible leaves in many rural areas in Niger;

- improving stocks of fuel wood and fodder;
- reducing average time spent by women collecting firewood from 2.5 hours to half an hour;
- an increase by 10- to 20-fold in tree and shrub cover on about five million ha of land, with approximately 200 million trees protected and managed;
- improving soil fertility as higher tree densities act as windbreaks to counter erosion, provide enriching mulch and fix nitrogen in root systems;
- increasing population of wild fauna, including hares, wild guinea fowls, squirrels and jackals;
- creating new food export markets, primarily to Nigeria; and
- creating a specialized local market in buying, rehabilitating and reselling degraded lands, with land values rising by 75–140% in some areas.

Mulching techniques (crop residues management and mulching using off-farm biomass) are proven to be the best practices for all the west African Sahel countries in general. Evidence from case studies are presented in section 3.3 and 3.6 of the present report.

3.8 Trade-offs and socioeconomic barriers associated with biomass production and management

Recent studies (Valbuena et al. 2015; Valbuena et al. 2012; Giller et al. 2009; Hiernaux and Ayatunde 2004) conducted at different sites with contrasting levels of agroecologies and crop intensity in sub-Saharan Africa have revealed that crop residues represent a fundamental resource for crop-livestock integration and intensification. Studies from Valbuena et al. (2015) and Valbuena et al. (2012) in sub-Saharan Africa and Asia revealed that crop residues provide livestock feed at sites with low crop intensity during dry season while at sites with high cereal intensity, crop residues are vital for fuel and construction. They concluded that the interaction between demand for biomass and access to alternative sources determine the intensity and diversity of crop residues use. It is important to note however, that the magnitude of crop residues as livestock feed does not necessarily depend on cropping intensity but on the availability of biomass from natural pasture which in turn is a function of the agroecological gradients. The studies by the authors cited above concluded that using crop residues for soil amendment is common in three cases: (i) moderate levels of cereal production, low demand for biomass and significant access to alternative feed resources; (ii) low demand for cereal production, high demand for biomass but access to better feed sources for dairy production and (iii) very high levels of crop production that satisfy high demand for biomass even if alternative resources are limited. In all cases, there are synergies between complementary roles of crop residues:

- Farmers use crop residues to feed power oxen at critical times of the year, thereby increasing the level of crop production, resulting in more crop residues for livestock feed.
- Farmers without livestock pay herders to graze the crop residues in their fields whereas in exchange, the livestock deposit manure on the crop field which improves the soil nutrient status and enhances crop yields.
- Farmers feed crop residues to their livestock in enclosures to improve feeding and manure production efficiency, thereby increasing the overall productivity of the farm.

When different uses of crop residues are not complementary, pressure on crop residues use can increase trade-offs. For instance, the removal of residues from the soil combined with the low use of inorganic fertilizers and animal manure increases erosions by water and wind and nutrient depletion of soils (Valbuena et al. 2015; Haileslassie et al. 2005). At this stage, to restore soil conditions, the mulching system can be promoted (Figure 9).

3.9 Opportunities and constraints for biomass production in the Sahel

The mixed crop-livestock system is affected by climate uncertainties and the entire system needs to cope with the changing situation. In the agricultural sector, the response to the threats posed by climate change may be technological such as the use of more drought tolerant crop varieties, behavioral such as shift in dietary regime, managerial such as implementing the different farm management practices, and political such as market and infrastructure development (Thornton and Herrero 2014; IPCC 2007).

One of the best adaptation options to changes in the Sahel is to increase the resilience of the mixed systems. This can be done through appropriate soil and integrated nutrient management (composting manure and crop residues, mulching, fertilizers etc.) and using legumes for natural nitrogen fixation to close yield gap (Wu and Ma 2015). There is also a need to improve water harvesting and retention to reduce the water shortage due to decreasing rainfall. The use of pools, ponds, dams, pits, retaining ridges and increasing soil organic matter will substantially raise the water retention capacity of the soil (Douxchamps et al. 2014; Lasage 2015). Efficient harvesting and early transformation of agricultural products can reduce post-harvest losses and preserve food security and quality. Another option is to deeply engage in crop-livestock farming when weather risks increase (Thornton and Herrero 2014). Livestock can be used as an asset to smooth income fluctuations and opportunistic cropping can provide dietary calories for households at critical times of shortage. The Early Warning System is an opportunity for the Sahel as it can be used for weather forecasting that could help the farming and risk management systems. Policy support and a secure land tenure system are essential for the implementation of the management practices. Poor performance of extension services or poor research extension linkages in the Sahel have sometimes been blamed for the limited spread of technologies (Thornton and Herrero 2014). Certain technologies such as soil and water conservation or rangeland restoration are inherently long term, requiring security of tenure over land for an extended period of time. Therefore, many farmers who lack land security are reluctant to invest in these technologies (Thornton and Herrero 2014; Giller et al. 2009).

Most of the biomass production interventions require technological appropriation and financial and institutional supports. However, in the Sahel, appropriate technical manuals for the best practices are lacking or when they exist, they are written in a language sometimes not accessible in most of the rural areas. In addition, the direct beneficiaries of the technologies often rely on financial assistance from NGOs/donors to be able to adopt the practices. Finally, despite the decentralization process started in the 2000s, many rural areas in the Sahel are still lacking institutional partners that would facilitate access and uptake of the management practices.

The payment for ecosystem services as vegetation conservation and restoration strategies is an important opportunity for the Sahel. It was poorly reported in the literature survey maybe because researchers have not yet investigated the outcomes of payment for ecosystem services. The voluntary carbon market such as Plan Vivo are oriented toward developing countries and contribute to diversifying local communities' income sources while engaging them in tree plantation, reforestation, afforestation and agroforestry. Between 2012 and 2016, 17 carbon sequestration projects from Africa were accepted in the Plan Vivo system, from which five belong to the west African Sahel (four for Burkina Faso and one for Senegal: http://www.planvivo.org/project-network/project-pipeline/). The main constraints for carbon project development in the Sahel is the recurrent one, land use right issues. For long-term investments through environmental service provision, secure tenure arrangements are absolutely capital (Tschakert 2007). In Senegal and Burkina Faso, there are coexisting and conflicting tenure systems between the state and the communities and this renders the success of the payment for ecosystem services projects very uncertain. As recommended by Tschakert (2004, 2007) for the flourishing pro-poor carbon market to succeed in the west African Sahel, flexible management plans, adequate payments and institutional strengthening appear to be the most critical elements to be integrated into pro-poor market-based mechanisms in order to address the needs and constraints of poor marginal smallholders.

Biomass production practices and management improve ecosystem services such as nutrient cycling, carbon sequestration, soil erosion control, maintenance of the hydrological regime, biological control of diseases and pollution reduction. It also contributes to close the yield gaps from 15% to 75% depending on areas and practices (Leakey 2012; Dawson 2013; Simons and Leakey 2004); thus contributing to income generation and diversification for the households.

3.10 Lessons learned and knowledge gaps

Smallholder farmers in the Sahel have a variety of technologies in both farming and grazing areas to adapt to their changing environment in a context of climate uncertainties and unprecedented population increase. Most of the practices in use are indigenous but have been improved by the research and development institutions. In the farming sector, practices such as crop residue mulching, mulching with use of wild grass combined with animal manure, weeds and tree biomass as well as the soil water conservation interventions (zai, half moon, stone alignments) and parkland systems are very promising. Combining all practices in a form of integrated nutrient management has been shown to considerably improve crop yields by minimizing nutrient losses in the environment and by managing the nutrient supply, and thereby results in high resource use efficiency, cost reductions and improved resistance to biotic and abiotic stresses (Wu and Ma 2015).

In the vegetation recovering management strategies, agroforestry, tree planting, FMNR, community forest management via a pro-poor service provision market have all been successful as they seem to have played a role in the slight vegetation recovery (the re-greening debate in the Sahel). However, scientific documentation of the extent to which those practices have contributed to the apparent re-greening is missing. Therefore, research activities that aim at quantifying the recovered areas due to each single practice will be very important. So far, there is no tool available that could facilitate targeting and scaling up such success stories throughout the west African Sahel. The development of such web-based tools will be a good contribution to re-greening the entire Sahel.

4. Conclusion and institutional/policy recommendations

A considerable body of knowledge has been built up about biomass production practices as well as the drivers of change of the production systems in the Sahel. It can be argued that there are still gaps regarding practices performance and spatial extent but this should not deter further research, and refinement and promotion of these practices to combat hunger and poverty in the Sahel. Biomass production practices, when they are well performed, increase crop yield, provide abundant feed to livestock and moreover contribute to climate change mitigation. Biomass production ultimately depends on rainfall and human capacity to manipulate the production system. Therefore, in the light of climate change and increasing uncertainties for the future of the Sahel, effective biomass production practices that go beyond the conventional engineering concerns could be the best options for sustainable intensification production.

To develop a resilient biomass production system in the Sahel, more investments by governments, institutions and agencies are required. Within the framework of the regional Permanent Interstate Committee for Drought Control, the New Partnership for African Development and the international conventions namely the Convention of Biological Diversity, the United Nations Convention to Combat Desertification and the United Nations Framework Convention on Climate Change, African heads of state and governments have committed to investments to improve biomass production. Yet, many production and management practices are underutilized because there is a huge gap between the input prices (high) and the output prices (low) which is a result of under investments in market, infrastructures and upscaling techniques. We believe that the following recommendations can make biomass production in the west African Sahel more efficient and resilient to the various shocks for the benefit of agricultural and livestock productivity.

- Strengthen land tenure systems to give property rights to land users. In most countries in the Sahel, clear land use policy is lacking and this discourages farmers from adopting land management options on lands that do not belong to them. As all practices require investments (financial, labour and time), farmers will not assume investment risks on a piece of land where there is no guarantee of a return on investment.
- Foster institutional linkages to create better conditions for a large diffusion of best practices. Extension services should be strengthened and their agents should be trained and well equipped so that they can reach farmers more easily. Good collaboration between extension services, NGOs and community-based organizations such as youth associations and women's groups are essential.
- Foster the use of climate information to inform decision-making. Because high intensity rainfall variability is the main concern for biomass production in the Sahel, the use of seasonal climate forecasts to inform farmers, herders and other users will be necessary to inform and guide management decisions in the case of an impending drought.
- Promote improved biomass production and management practices such as mulching, crop residues management, agroforestry, soil water conservation, composting/manuring, agricultural rainwater harvesting, drought tolerant crop varieties, crop diversification and small scale irrigation.

- Develop special rural micro credit schemes for small scale farmers. Farmers in the Sahel have often been bypassed by new technologies because the rural financial facilities are poor or lacking in sufficient resources. Micro credit schemes in the form of rural finance should be promoted.

Table 1. Biomass production publications in the west African Sahel (* means low efficiency; ** high efficiency)

Reference	Country	Intervention	Additional advantages	Efficiency	Constraints for adoption
Addressing degraded soil fertility issues					
Bationo and Mokwunye 1991 Buerkert 1995 Muehlig-Versen et al. 1998 Haigis and Heidhues 1998 Lamers and Feil 1995 Michels 1994 Sterk and Spaan 1997	Burkina Faso Niger Niger Niger Niger Sahel in general Niger Niger Niger	On-farm crop residues management	Reduced wind and water erosion	**	Crop residues used for livestock and household energy
Lamers and Feil 1995 Slingerland and Masdewel 1996 Hien et al. 1998 Tilander 1993 Haigis and Heidhues 1998 Wezel and Boecker 1999 Mabrouk et al. 1998 Bado et al. 2006a Bationo et al. 2007 Bayala et al. 2003 Boffa et al. 2000 Buerkert and Lamers 1999 Coulibaly et al. 2000 Ouedraogo et al. 2007 Giller et al. 2009	Niger Burkina Faso Burkina Faso Burkina Faso Niger Niger Niger Burkina Faso Niger Burkina Faso Burkina Faso Niger Mali Burkina Faso Sahel in general	Mulching	Reduced wind and water erosion	**	Only applicable in small areas
Ouedraogo and Kabore 1996 Wedum et al. 1996 Hasan 1996 Rinaudo 1996 Mabrouk et al. 1998 Hassane et al. 2000 Ambouta and Amadou 2000 Baro and Zougmore 2005 Diatta et al. 2001 Zougmore et al. 2000 Zougmore et al. 2003 Zougmore et al. 2004	Burkina Faso Mali Niger Niger Niger Niger Niger and Burkina Faso Senegal Burkina Faso Burkina Faso Burkina Faso Burkina Faso	Planting pits (zai)	Revegetation	**	Labour intensive and time consuming
Hassane et al. 2000 Ambouta and Amadou 2000 Baro and Zougmore 2005 Zougmore et al. 2000 Zougmore et al. 2003 Zougmore et al. 2004	Niger Niger Burkina Faso Burkina Faso Burkina Faso Burkina Faso	Half moons	Revegetation	**	Labour intensive and time consuming
Lamers and Feil 1995 Mabrouk et al. 1998, Neef 1998 Ouedraogo et al. 2006 Akponikpe et al. 2008	Niger Niger Niger Burkina Faso Niger	Manuring (composting, corralling)	Revegetation	**	Need of own livestock

Reference	Country	Intervention	Additional advantages	Efficiency	Constraints for adoption
Bationo and Mokwunye 1991 Buerkert 1995 Lamers and Feil 1995 Ouedraogo et al. 2006 Akponikpe et al. 2008	Burkina Faso Niger Niger Burkina Faso Niger Niger	Mineral fertilizers		*	Cost intensive, misused by poor farmers
Cissoko 1993 Floret et al. 1993 Wezel 2000 Lamers and Feil 1995 Haigis 2000 Wezel and Boecker 1998	Mali Sahel in general Niger Niger Niger Niger	Fallow	Reduced wind and water erosion, revegetation	*	Declining fallow period
Bado et al. 2006a Bado et al. 2006b Bagayogo et al. 2000 Kouyaté et al. 2000	Burkina Faso Burkina Faso Mali Burkina Faso and Niger Mali	Rotation and association	Improve food diversity		
Addressing wind erosion issues					
Michels 1994 Michels et al. 1998 Leenders et al. 2005	Sahel in general Niger Burkina Faso	Wind breaks	Reduced water erosion	*	Need to be protected from grazing
Renard and Vandenbeldt 1990 Michels et al. 1998 Leenders et al. 2005	Niger Niger Burkina Faso	Grass strips	Reduced water erosion	*	Need to be protected from grazing
Addressing water erosion issues					
Kassogue et al. 1996 Slingerland and Masdewel 1996	Mali Burkina Faso	Grass strips	Reduced wind erosion	**	Need to be protected from grazing
Kassogue et al. 1996 Slingerland and Masdewel 1996	Mali Burkina Faso	Mulch lines	Reduced wind erosion	*	Other uses of mulch material
Kassogue et al. 1996 Slingerland and Masdewel 1996 Zougmore et al. 2000 Zougmore et al. 2003 Zougmore et al. 2004	Mali Burkina Faso Burkina Faso Burkina Faso Burkina Faso Burkina Faso	Stone lines and bunds	Increased soil fertility	**	Labour intensive
Kassogue et al. 1996	Mali	Stone walls and terraces	Increased soil fertility	**	Labour intensive
Restoring vegetation cover					
Taylor and Rands 1992 Rinaudo 1996 Sterk and Haigis 1998 Joet et al. 1998	Niger Niger Niger Niger	FMNR	Reduced wind and water erosion, increased soil fertility		Cropland expansion
Chase and Boudouresque 1987 Kessler et al. 1998 Sterk and Haigis 1998	Niger Burkina Faso Niger	Revegetation of bare soil with mulch	Reduced wind and water erosion, increased soil fertility	**	Only on small areas
Kessler et al. 1998	Burkina Faso	Land rehabilitation with light grazing	Reduced wind and water erosion	*	Uncontrolled grazing intensity

Reference	Country	Intervention	Additional advantages	Efficiency	Constraints for adoption
Sturm 1998 Kho et al. 2001 Louppe et al. 1996 Wilson et al. 1998 Zougmore et al. 2005 Badejo 1998	Niger Niger Senegal Burkina Faso Burkina Faso Sahel in general	Agroforestry-parkland	Reduced wind and water erosion, increased soil fertility	**	Tree density control according to selected species
LeHouerou 1989 Kerkhof 1990 Orr (1995) Wickens 1997	Sahel in general Sahel in general Niger Sahel in general	Tree planting	Reduced wind and water erosion, increased soil fertility	**	Limited success
Peltier et al. 1995 Kessler et al. 1998	Niger Burkina Faso	Community-based forest management	Reduced wind and water erosion, increased soil fertility	*	Institutional barriers
Neef 1999	Niger	Conservation of natural vegetation	Reduced wind and water erosion, increased soil fertility	*	Institutional barriers
Wickens 1997 Kessler et al. 1998	Sahel in general Burkina Faso	Management of communal grazing land	Reduced wind and water erosion	*	Institutional barriers
Tschakert 2007	Senegal	Payment for ecosystem services	Increased vegetation cover Alternative source of revenue	**	Institutional barriers

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