Slash-and-mulch

Exploring the role of shrub-based agroforestry systems for smallholder farmers in the Sahel

Georges F. Félix Lancelloti

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This research was conducted under the auspices of the C.T. de Wit Graduate School of Production Ecology and Resource Conservation

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Georges F. Félix Lancelloti

Thesis
submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Tuesday 10th December 2019
at 4 p.m. in the Aula.

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184 pages

PhD thesis, Wageningen University, Wageningen, The Netherlands (2019)
With references, with summaries in English, Dutch, French and Spanish

ISBN: 978-94-6395-219-4
DOI: https://doi.org/10.18174/507362

En honor a las abuelas y abuelos
En gratitud con las madres y padres
Con cariño para las herederas y herederos

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List of abbreviations

ABACO	Agroecology-Based Conservation Agriculture (project)
CGIAR	Consultative Group on International Agricultural Research
CIRAD	Centre de coopération Internationale en Recherche Agronomique pour le Développement
ConneSSA	Connecting knowledge, scales and actors: an integrated framework for adaptive organic resource management targeting soil aggradation and agroecosystems' resilience in Sub Saharan Africa (project)
FAO	Food and Agriculture Organization, United Nations
FSE	Farming Systems Ecology Group, Wageningen University
GGWI	Great Green Wall Initiative
IRD	Institut de Recherche pour le Développement
NEWS	Native Evergreen Woody Shrubs
RW	Ramial Wood
RWA	Ramial Wood Amendments
SDG	Sustainable Development Goals
SOC	Soil Organic Carbon
SOCLA	Sociedad Científica Latinoamericana de Agroecología
SOM	Soil Organic Matter
SSA	Sub-Sahelian Africa
SWA	Semi-arid West Africa
WA	West Africa
WASSA	Woody Amendments for Sudano-Sahelian Africa (project)
WUR	Wageningen University & Research


MALI
NIGER
BURKINA FASO
OUAGADOUGOU
BOBO-DIOULASSO
GHANA
TOGO

Chapter 1 : General Introduction

1. Background

The African continent will likely be confronted to extended and more frequent drought periods, along with increased temperatures (IPCC, 2019). In the face of this pessimistic scenario, one would expect climate change to have severe impacts on the extension and intensity of degraded soils and biodiversity losses in Africa (Bai *et al*., 2008; Leroux *et al*., 2017). Plants can take advantage from periods with higher radiation but increased evaporation rates may reduce soil water content. Shorter or erratic rainy seasons would limit water availability for plant growth, decreasing vegetation stocks. Less vegetation would then lead to increased wind and water erosion. Sahelian soils are intensively weathered and poor (Bationo *et al*., 2007) which are characterized by shallow rooting, poor water infiltration, retention, and storage along with low SOM contents (Lahmar *et al*., 2012). Increasing population pressure in Sub Saharan Africa has resulted in more frequent cultivation of staple crops and reduced fallow periods (Wezel & Haigis, 2002; Hiernaux *et al*., 2009). Insufficient fallow periods have led to severe SOM depletion and subsequent soil degradation which undermines the livelihoods of local farm communities. Soil fertility regeneration cycles have consequently been cut short, with strong declines of soil quality (Kintché *et al*., 2015; Ripoche *et al*., 2015). With or without the application of mineral fertilizers, managing soil organic matter (SOM) is considered a cornerstone for sustainable farming and soil restoration (Masse *et al*., 2011).

In Burkina Faso, degraded soils where no crop production is possible affect more than 1 million farmers (Bai *et al*., 2008). If restored, these soils could potentially contribute to increased local food provision and to climate change mitigation via global carbon sequestration. Advancements toward the imitation of dryland forest floors to restore agricultural soils in the Sahel, a form of 'ecosystem mimicry' (Ewel, 1999), can be achieved via the intensive application of carbon-rich mulches. Therefore, strategies are needed to restore and maintain soil productivity via greater inputs of organic matter, greater water retention, reduced evaporation and runoff, increased soil biological diversity, and nutrient cycling and availability. Indigenous forms of agroforestry based on the use of local shrubs, as practiced by farmers, offer opportunities to design sustainable farming systems that are based on agroecological principles and can contribute to building resilience and adaptability in the face of climate changes.

1.1. Soil aggradation

Soils are major carbon sinks at the global level. Total carbon sequestered in African soils was estimated at 175 x 10^{15} g C, roughly 12% of world total soil C stocks (Batjes, 2001). Soil quality can be defined as "the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal [also human] health" (Doran & Parkin, 1996, cited by Bünemann *et al.*, 2018). Human activity influences soil quality by altering land-use and by management of natural resources. The ecosystem functions and services provided by soils are governed by degradation, mitigation and aggradation processes (Fig. 1.1; Karlen *et al.*, 2003; El Mujtar *et al.*, 2019). While undisturbed soils may be atmospheric C sinks, degraded and disturbed soils are more likely to be CO_2 sources, thereby increasing greenhouse gas (GHG) concentrations into the atmosphere (Lal, 2008).

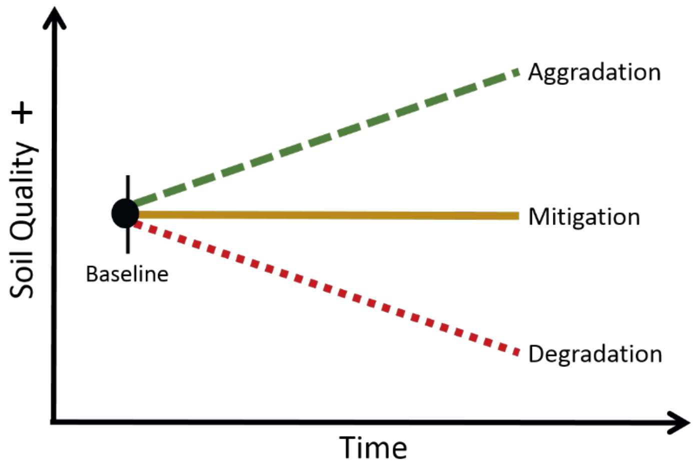


Figure 1.1. Dynamics in soil quality assessment. Adapted from: Karlen *et al.* (2003)

Prolonged soil mismanagement can cause irreversible soil degradation and formation of non-responsive soils (Tittonell & Giller, 2013). Conversely, SOM build-up and decay, could support sustained soil productive capacity (Janzen, 2006). SOM is closely linked to nutrient cycling and affects chemical, biological and physical fertility. There is a positive correlation between SOM, aggregate stability, water/nutrient-retention capacity, availability and crop yield (Bationo *et al.*, 2007). Increased biological respiration in the zone of influence of woody perennials releases C in a gaseous form (CO_2) back into the atmosphere, and in doing so, humification, aggregation and translocation of SOM and nutrients occurs and are recycled into the soil profile. This contributes to sequestering atmospheric C in soils and in plant biomass, including crops, trees, and shrubs. Therefore, sustainable farming systems require investing in SOM.

Organic amendments thus play a key role during the entire rehabilitation cycle. Roose *et al.* (1999) outlined practices for effective restoration of degraded soils, or *aggradation*, including reduced run-off/soil erosion, enhanced water infiltration/retention and root growth via incorporation of organic amendments, soil revitalization by surface-applied mulches, and balanced crop nutrition with effective use of available resources. Moreover, positive impacts of external inputs such as chemical fertilizers can only be attained when preceded by supportive measures including use of organic amendments (Tittonell & Giller, 2013; Kintché *et al.*, 2015). During soil aggradation, water productivity is enhanced due to increased soil water storage capacity/infiltration along with reduced runoff/evaporation losses. The application of organic mulches increases infiltration by up to 50% while reducing evapotranspiration losses by 25% (Tittonell *et al.*, 2012). Such increases in water utilization have tremendous impacts, especially in face of increased climatic risks in SSA since crop-water supply is greatly affected by the quality and quantity of soil cover (Barthès *et al.*, 2010).

Improved use of manure and composts are options to regenerate SOM-depleted soils in Sudano-Sahelian agroecosystems but the availability and quality of these organic materials is often limited (Erenstein *et al.*, 2015). Competing claims exist since crop residues are mainly used as livestock forage during the dry season, thereby limiting the availability of mulches to maintain or restore soil productive capacity. Woody residues (including small branches and leaves) from tree pruning or shrubs coppicing could represent a renewable organic resource with few alternative uses (other than fuelwood), and could constitute a viable option for sustaining soil quality and improving crop productivity. Indigenous farming families in the Sahel have long used native flora to restore soils as a standard farming practice (Wezel & Böcker, 1999; Roose & Barthès, 2001; Yélémou *et al.*, 2007). New socio-ecological constraints offer an opportunity to promote sustainable and ecological intensification for the use and management of this flora on agricultural lands through participatory re-design of these cropping and farming systems. Recognizing and effectively using existing local knowledge as complementary to science-based research innovations can contribute to upscale technical improvements and make innovations accessible to poorly-endowed farmers. Inventories of "existing local knowledge" can additionally provide insights during the analysis and exploration of ecologically-sound and socially-viable options.

1.2. Ecological theory and farming systems

The concept of 'ecology in agriculture' was coined by Hanson (1939) who established the need for 'ecologists' to broaden the spectrum of studies from wild native plants to domesticated (often exotic) plants, by also taking into account ecological processes within and around farming fields. Ecological concepts such as distribution and abundance of organisms, their activity and their diversity have been discussed in light of agricultural management practices, revealing processes such as nutrient cycling, competition, symbioses, succession, and mimicry (Kevan *et al.*, 1997; IPES, 2016). Ecological principles applied to agro-ecosystems, as bundled in *agroecology*, provides insights into the management and design of agro-ecosystems that are productive, environmentally-sound, and economically viable, and that are culturally adjusted and socially compatible to local farming families and communities (Altieri, 1983).

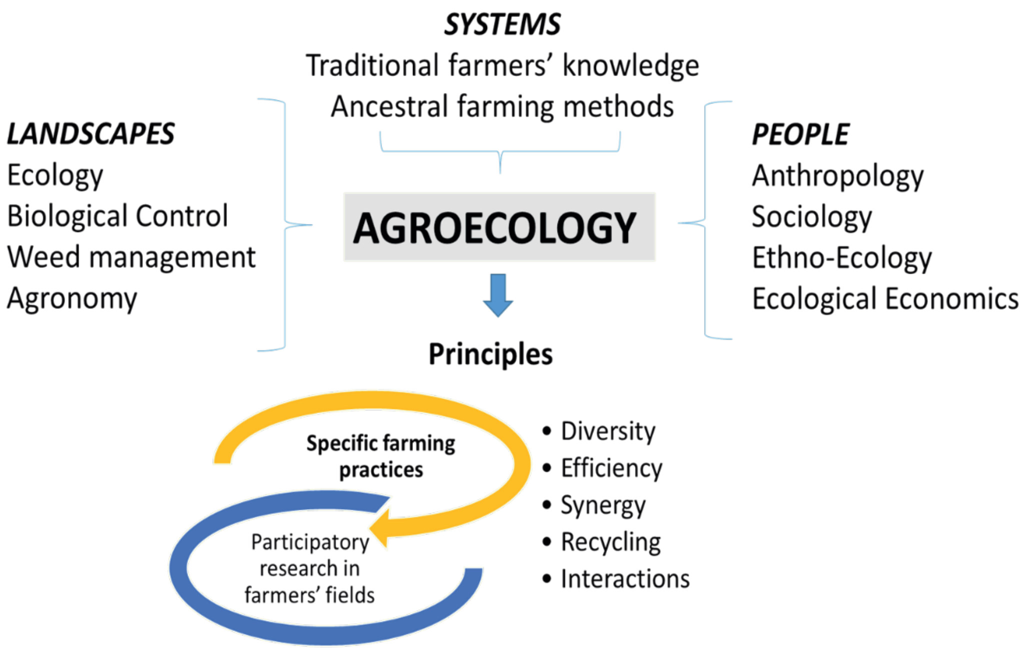


Figure 1.2. Schematic representation of the agroecology principles and the scientific fields that contribute to the analysis and design of sustainable and resilient food systems. Based on: Altieri (1983).

Agroecology draws from a diversity of knowledge bodies and provides tools and methodologies to assess the performance of agricultural systems in order to re-design sustainable and resilient food production schemes (Gliessman, 2002; Francis *et al.*, 2003; Wezel *et al.*, 2009; Tittonell, 2014; Altieri *et al.*, 2015; Nicholls *et al.*, 2016). The principles of agroecology (Fig. 1.2) have been compiled by scientists in contact with indigenous farming communities, particularly in Latin America, and based on two pillars: plant health and soil quality (Altieri, 1983; Reijntjes *et al.*, 1992; Ewel, 1999; Gliessman, 2002; Méndez *et al.*, 2013). The principle of *diversity* requires variety of species and genetic pools in space and time through crop rotations, crop associations and polycultures. The principle of *recycling* promotes nutrient flows and cycles of energy and matter by increasing capture, retention and recycling of resources (water, nutrients) through the utilization of organic biomasses to restore nutrients with practices like manuring, composting and waste-to-energy techniques (e.g. bio-digesters). The promotion of *interactions* through agroforestry, atmospheric N-fixation and crop-livestock integration will work towards improved biological relations, including the maximisation of intergenerational benefits (not only annual profits) as well as securing intergenerational knowledge transfers. *Synergies* between system components will likely secure favourable soil conditions and improve plant health via permanent soil cover, soil erosion control measures and crop associations in order to enhance ecosystem functioning, maintain community livelihoods and ensure quality of life for farm workers and family members. Finally, *efficiency* looks into achieving reasonable crop and animal productivity through minimizing internal losses, reducing external inputs and increasing external outputs. These five core agroecology principles have recently been endorsed and expanded by the FAO to include social and political elements that should guide the transition towards sustainable and resilient food systems (FAO, 2018). The practices that contribute to the implementation of each of these principles are site-specific.

In the case of the drylands of West Africa, the contributions made by Pierre Rabhi were central to the development of a “francophone” agroecology. In the early 1980s, this agronomist-philosopher born in Algeria, spent several years in Burkina Faso (ex-Higher Volta, *Haute Volta*) studying dryland farming systems and co-developing appropriate technologies alongside local farming families to increase food self-sufficiency drought-resistance capacity. Rabhi went to the Sahel to reinforce biological/organic farming by the *Centre de relations internationales entre agriculteurs pour le développement* (Criad), in the context of a solidarity treaty between France and Burkina Faso. Thomas Sankara, the President of Burkina Faso at the time, heard word from the successes of Rabhi in the countryside and appointed him in 1986 to lead the agrarian reforms based on agroecology. Unfortunately, Sankara was assassinated in 1987 and the scaling of agroecology under the revolutionary government never saw the light in Burkina Faso. Nevertheless, Rabhi’s legacy in Sahelian agroecology has persisted in villages of Burkina Faso, Mali, and Togo, amongst others, through the not-for-profit organisation he created 25 years ago, *Terre & Humanisme*. Other organisations such as CNABio, Groundswell International, and *TiiPaalga*, to cite a few, have followed Rabhi’s line of work and have been instrumental in the promotion, advocacy, and implementation of agroecology in Burkina Faso.

Especially in dryland regions, woody perennials (e.g. trees and shrubs) play an important role in the implementation of agroecological practices to sustain soil formation and food production through agroforestry systems (Bazié *et al.*, 2012; Bayala *et al.*, 2015; Zomer *et al.*, 2016). Integrated crop-perennial systems represent an intermediate between “no trees at all” and “too many trees for crop growth.” Whereas much has been studied about tree-based systems, shrub-based agroforestry systems have seldom been documented in view of intensifying the ecological relations between system components to increase drought-resistance.

1.3. Shrub-based agroforestry systems

Traditional shifting cultivation was based on slash-and-burn techniques, yet the practice has been hindered by the growing need for land in semi-arid West Africa (Diarisso *et al.*, 2015a). Historically, fallows have been central for soil fertility management in the Sahel, particularly in low-input cropping systems of West African drylands (Bonetti & Jouve, 1999; Wezel & Haigis, 2002). Woody biomass re-growth in fallows can locally improve soil physical, chemical and biological characteristics for crop cultivation (Manlay et al., 2004). Because of the urban sprawl and increasing population pressure, continuous cultivation is common nowadays, leaving little space for standing biomass regeneration. Reforestation efforts through farmer managed natural regeneration (FMNR) have successfully enhanced soil conditions, demonstrated increases in biodiversity, and had positive impacts on local livelihoods in environmentally-vulnerable areas such as drylands of the Sahel (van Walsum et al., 2014; Weston et al., 2015).

On the one hand, the ecological benefits of trees on croplands may interfere with crop developmental needs through competition for sunlight or water (Sanou *et al.*, 2011). On the other hand, shrub species provide similar services as trees to crop production depending on crown configuration, morphology and management (Pouliot *et al.*, 2011). Shrubs entrap run-off sediments (Wezel, 2000; Wezel *et al.*, 2000) and provide renewable organic biomass sources (Wezel & Böcker, 1999; Yélémou *et al.*, 2013a) for restoring soil productive capacity (Fig. 1.3). Additionally, shrubs have the capacity to bio-irrigate the crop in their vicinity via the hydraulic lift phenomenon (Kizito *et al.*, 2012; Bogie *et al.*, 2018a) and important topsoil additions of organic matter (Bright *et al.*, 2017). In Burkina Faso, Niger and Senegal, shrub-crop associations have been described on farmer fields as part of an integrated shrub-based agroforestry management system, featuring scattered species such as *Piliostigma reticulatum* (DC.) Hochst. and *Guiera senegalensis* J.F. Gmel. (Louppe, 1991; Gijsbers *et al.*, 1994; Wezel & Haigis, 2002; Wezel & Rath, 2002; Yélémou *et al.*, 2007; Lahmar *et al.*, 2012; Lahmar & Yacouba, 2012; Tittonell *et al.*, 2012; Yaméogo *et al.*, 2013; Hernandez *et al.*, 2015).

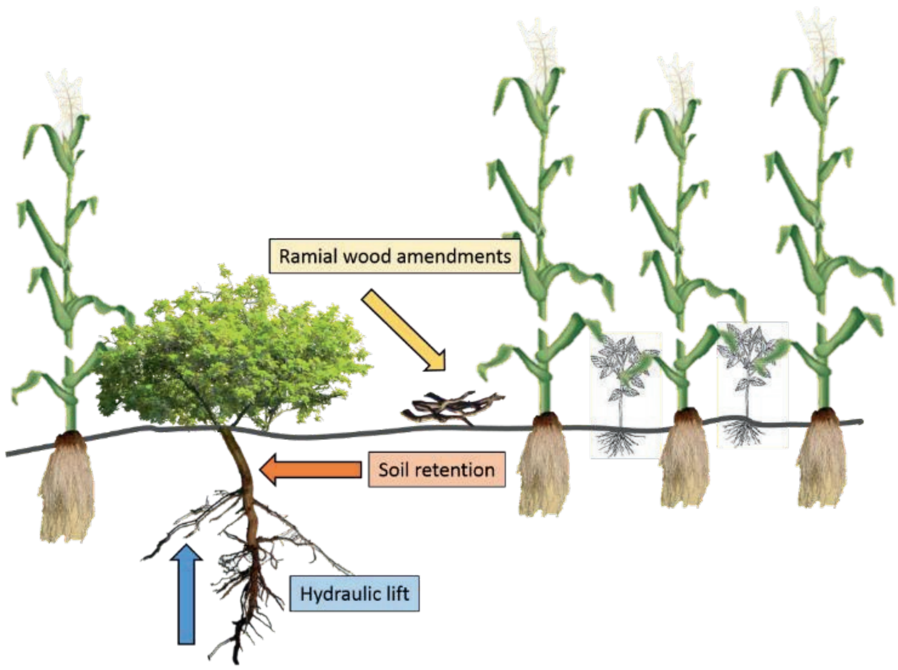


Figure 1.3. The management of *P. reticulatum* (Fabaceae - Caesalpinioideae) and *G. senegalensis* (Combretaceae) may sustain crop productivity via three main mechanisms: accessibility to organic material for mulching (i.e. aboveground biomass for use as ramial wood amendments), improvement of soil retention and formation (i.e. sediment entrapment), and increased soil moisture in the perennial's vicinity (i.e. hydraulic lift from belowground and increased topsoil organic matter contents).

P. reticulatum is native across West and Central Africa and its territory extends to Ethiopia and Sudan, following Sudano-Sahelian climates of 400-1000 mm rainfall per year (Arbonnier, 2002; Hernandez *et al.*, 2015). This woody legume species is usually structured as a shrub or a small tree (not exceeding 10 m height) that is known for its slow growth and multiple uses (medicinal, animal feed, construction material) in farming communities[1]. Characterized as an evergreen species, flowering and fructification of *P. reticulatum* usually take place by the end of the rainy season (Yélémou *et al.*, 2013c). Although it is in the Fabaceae family (ex-Cesalpinoideae), its nitrogen fixing capacity has not been demonstrated.

P. reticulatum has been studied in agroforestry parklands of Senegal where hydraulic lift and enhanced living conditions for soil biota constitute fundamental services of this (and other) woody shrub species (Kizito *et al.*, 2007; Lufafa *et al.*, 2008b; Dossa *et al.*, 2013). The capacity to re-sprout after slashing aboveground biomass has been described in Burkina Faso as a farmer-led innovation to support fertility restoration of degraded soils and improve growth conditions for crops on marginal agricultural lands (Yélémou *et al.*, 2007; Lahmar *et al.*, 2012; Lahmar & Yacouba, 2012; Yaméogo *et al.*, 2013). The use and management of its biomass (i.e. ramial wood amendments) has been identified as a promising farmer technique to restore soil productive capacity and improve crop productivity in drylands of West Africa (Yélémou *et al.*, 2014; Barthès *et al.*, 2015).

Ramial wood (RW) amendments (in the form of finely-chipped woody twigs) has been promoted in temperate areas such as Canada to restore soil functions on degraded lands, with application rates exceeding 20 Mg ha^{-1} (Lalande *et al.*, 2009; Barthès *et al.*, 2010). Sahelian agroecosystems feature dispersed and limited aboveground biomass stocks yet the RW amendments derived from native woody shrubs seem a promising option to restore SOM in these drylands. The recalcitrance to degradation of RW may be an advantage to build up topsoil carbon, but could reduce quick nutrient release. Additionally, RW amendments have low nutrient contents which could result in immobilisation of soil nutrients on dryland cropping systems (Barthès *et al.*, 2015). The question remains whether the effect of native *P. reticulatum* shrub biomass as soil amendments in Sudano-Sahelian cropping systems can effectively improve and sustain crop yields in time. Optimal shrub densities and agroecosystem designs to obtain beneficial effects to soil productive capacity also require further study.

[1] http://uses.plantnet-project.org/fr/Piliostigma_reticulatum_%28PROTA%29

1.4. Agricultural innovation

The Green Revolution after World War II re-shaped global agricultural landscapes and production systems (Mazoyer & Roudart, 2002). The advent of yield-enhancing and yield-protecting technologies gave way to the simplification of food production schemes, shifting away from traditional practices (i.e. labour- and knowledge-intensive) to promote space for modern technology-oriented strategies (i.e. high external inputs, improved varieties, heavy machinery). The reduction in the number of persons needed in food production triggered the idea that farmers would be at liberty to work in other sectors and spare more time enjoying recreational activities (Timmermann & Félix, 2015). High external input use, such as the wide application of agrochemicals has had a negative impact on human and environmental health that is difficult to oversee (IAASTD, 2009). Thus, the "modernization" of the rural workforce caused a general deskilling of farmers, focusing on technology rather than on biology. Furthermore, the successes of the Green Revolution have had consequences for the access to qualitative information by farmers, as the role of public extension services has declined in favour of other types of quantitative information provision, especially in regards to modern inputs (Theriault *et al.*, 2017; Timmermann *et al.*, 2017; Bentley *et al.*, 2019). Although this "agricultural revolution" enabled higher productivity in many regions of the world, as showcased initially in Asian communities, the proposed technological solutions came at a huge social and environmental cost for the rest of poor resource-endowed farmers in tropical areas of the Global South (Pielke & Linnér, 2019).

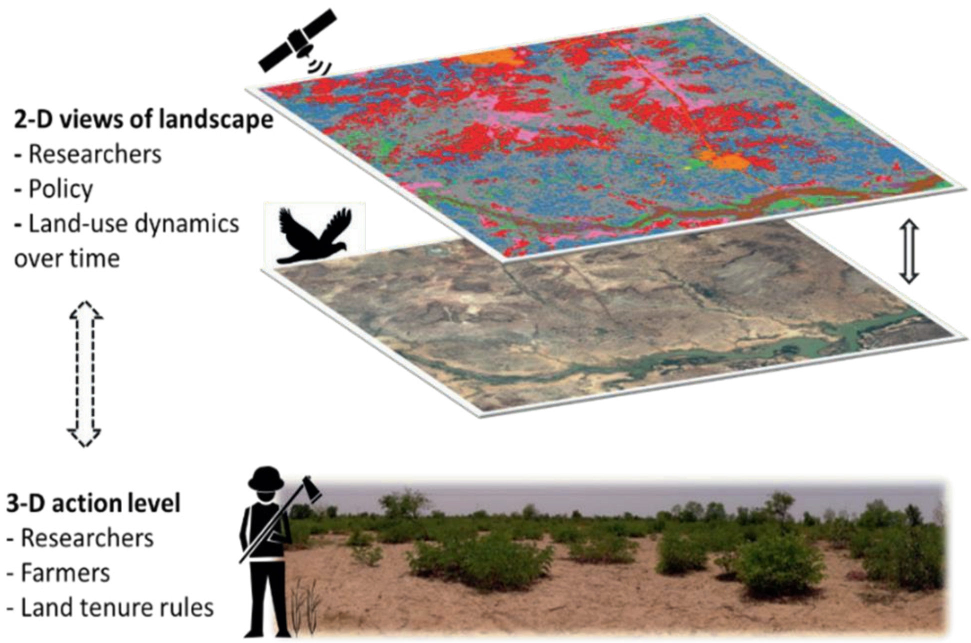


Figure 1.4. Schematic representation of landscape perceptions by different actors.While 2-D representations are useful for land-use diagnoses and planning, the 3-D perspective is where most landscape users can use and manage the natural resources.

To be socially, environmentally and economically sustainable, agricultural innovations need to be connected to the knowledge that users of the landscape have, their perceptions and the attitudes that human societies have of their environment (Fig. 1.4; Meijer *et al.*, 2014). If farmers do not have means to buy the products of agricultural innovations, these will hardly benefit from scientific advances (Timmermann, 2014). Agroecology, as a scientific discipline and practice oriented towards the reinforcement of autonomy in smallholder farming systems, is not delivered as top-down “silver-bullet solutions” but it is rather highly knowledge-intensive and it is rooted in farmer experimentation (Altieri & Toledo, 2011; Timmermann & Félix, 2015). Economic means thus, are not central in the adoption of novel practices. There are other traits that have a larger influence in the proper adoption (Meijer *et al.*, 2014), such as: (a) the farmer (e.g. personal, socioeconomic, personality, networks, status, information), (b) the external environment (e.g. geographical, culture, political), and (c) the technical efficiency of the practices (e.g. benefits, costs). These factors can be influenced without the use of much resources and supported by truly efficient and culturally-adapted research and extension services. The question remains whether farmer perceptions and practices in drylands of West Africa are in-tune with the acclaimed beneficial effects of technical options for restoration of soil productive capacity and improvement of crop productivity (i.e. shrub-based agroforestry systems).

2. Objectives

The objective of this thesis was to identify opportunities, trade-offs, and pathways to enhance resource-use efficiency of semi-arid agricultural landscapes through the use of an improved management of shrub-based woody amendments as a renewable source of organic matter to restore soil productive capacity and ensure food security, based on local farming families’ insights and priorities. The specific objectives were:

- To document and describe the diversity of management practices using woody perennials and their impact on crop performance and soil properties in semi-arid West Africa **(Chapter 2)**
- To evaluate the potential of ramial wood amendments to cope with agricultural soil degradation on topsoil organic carbon content, nutrient stocks and sorghum yields in a continuously cultivated system **(Chapter 3)**
- To explore the applicability and performance of ramial wood amendments on heterogeneous farmer fields by incorporating local ecological knowledge and perception **(Chapter 4)**
- To examine farmers’ use of biodiversity-mediated ecosystem services with emphasis on food production **(Chapter 5)**

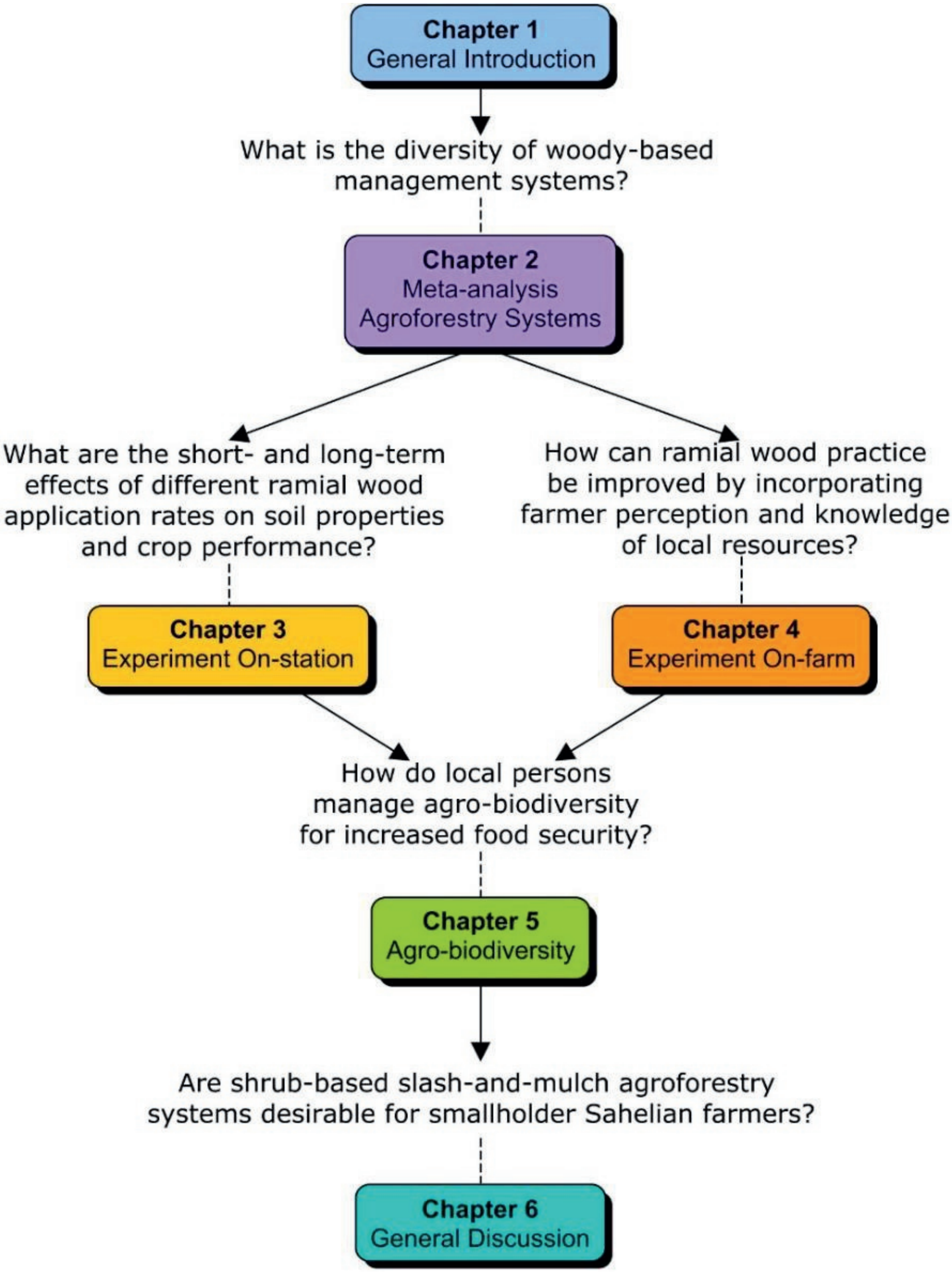


Figure 1.5. Schematic outline of thesis chapters and research questions.

3. Empirical data

The research questions were addressed through analysis of: (1) literature reviews, (2) field observations and farmer interviews, (3) on-station trials, and (4) on-farm experiments. Case-studies were conducted in three villages of the Sudano-Sahelian belt of Burkina Faso. The smallholder communities of Gampéla, Yilou and Kindi were specifically selected for their history in the use and management of shrub-based ramial wood amendments.

3.1. Case-study areas

Burkina Faso's climate ranges from Sahelian (250-500mm yearly precipitation) in the north over Sudano-Sahelian (500-900mm) in the center to Sudanian (900-1100mm) and exhibits dryness and intense heat for more than half the year with the months around July bringing the rainy season, when the intertropical convergence zone shifts northwards to the Sahel. Burkina Faso's mean annual temperature is 28°C, with the highest temperatures usually occurring by April (40–43°C), before the planting season starts, and the lowest temperatures occurring around December (18°C), after crop harvest. Rainfall is concentrated in one rainy season, ranging between 500 and 900 $mm \cdot yr^{-1}$, generally distributed from May through September.

The Gampéla Field Station is located in Gampéla (12° 24′ N, 01° 21′ W), at 15 km north-east of Ouagadougou, Burkina Faso's capital. The Field Station is co-managed by the French *Institut de Recherche pour le Développement* (IRD) and local *Université de Ouagadougou* to conduct agronomic trials in controlled conditions on dominant Acrisol soil types. The village of Yilou (13°01' N, 01°55' W) is located 80 km north of Ouagadougou on the N22 National Road where a local market takes place every three days. The village of Kindi (12°26′ N, 2°02′ W) is located 75 km to the west of Ouagadougou and on the lowest end of a watershed, where intermittent water-logging occurs on cropping fields during the rainy season. Dominant soil types in Yilou and Kindi are Lixisols, Plinthosols, and Cambisols. All villages are located on the Central Plateau of Burkina Faso, where the most important staple crop is sorghum (*Sorghum bicolor*) and the most prevalent cultural group are the *Mossé* (or Mossi).

3.2. Local land tenure rules

The relation between the Mossi people and their surrounding environment is quite unique. Farmers in the Mossi culture require permission from the local landlord in order to clear a field and exploit it for agricultural purposes. In every single village of the Mossi Plateau (Centre-North Burkina Faso), two political powers co-exist with well-defined responsibilities within local governance, independent from national level politics. The village chief (or *Teng-naaba*) is in charge of the political and human relations, while the members of the landlord family (or *Teng-soaba*) manage the access of all other villagers to land and tree resources (Paceré, 1994). These structures ensure the intergenerational knowledge transmission and guarantee social cohesion in collective decision-making. Under local tenure rules, farmers are allowed to take advantage of fruits and branches on remaining tree and shrub resources from the fields they use[2]. Farmers also have the right to plant annual crops for household consumption. In any given case, there are two prohibitions: farmers are not allowed (1) to either cut down legally- and culturally-protected species (i.e. *Vitellaria paradoxa, Parkia biglobosa*), nor (2) to plant new trees on communal lands used for agriculture (Yago, 2015). The non-respect of these communal land tenure rules would come upon as an infringement of cultural, social and legal values (Ouédraogo & Sorgho Millogo, 2007).

4. Thesis outline

This thesis is composed of six parts (Fig. 1.5): the General Introduction (**Chapter 1**), four core chapters (**Chapters 2-5**) and the General Discussion (**Chapter 6**). In **Chapter 2**, I provide an overview of the diversity of woody-based agricultural systems in the sub-region (semi-arid West Africa). In **Chapter 3**, I explore the potential of ramial wood (RW) amendments to mitigate soil degradation under continuously cultivated cereal cropping systems in controlled conditions. In **Chapter 4**, I test the applicability and performance of RW amendments on heterogeneous shrub-based agroforestry fields (with farmers), by incorporating local ecological knowledge and farmer perception of the practice into the analysis of agronomic observations. Finally, I examine in **Chapter 5** other farmer strategies that take advantage of biodiversity-mediated provision services, including the diversification of crop associations, the management of spatial heterogeneity around "fertility hotspots" and the role of perennials for improved household nutrition. In **Chapter 6** I critically analyse the "slash-and-mulch" practice and the role shrub-based agroforestry systems play for smallholder farmers in the Sahel.

[2] [*Les arbres*] : *"Il est interdit de les abattre de nos jours qu'ils soient fruitiers ou non. Ensuite, il n'est pas interdit de couper les bois raméaux : pour les arbres fruitiers cela n'est possible que lorsqu'ils sont vieux et les autres arbres non fruitiers, il faut le faire en début de saison des pluies. Enfin, dès les premières pluies les arbustes tels que les Bagana (*Piliostigma reticulatum*), Wilwiiga (*Guiera senegalensis*), et Randga (*Combretum micranthum*) sont coupées et servies de fertilisant aux sols arides. Ces espèces sont plus précieuses et utiles à Yilou qu'à Kindi."* (Yago, 2015)

Chapter 2 :Enhancing agroecosystem productivity with woody perennials in semi-arid West Africa. A meta-analysis

Abstract:
Soil degradation in semi-arid West Africa can be reversed through an intensified application of organic matter, especially on coarse soils. Woody perennials have been promoted in the region to secure organic matter sources and improve soil productive capacity, yet the mechanisms by which perennials provide benefits to soils and crops remain poorly understood, and no effective, generalizable agronomic recommendations exist. Here we reviewed the effects of trees and shrubs on soil properties and on crop yields in semi-arid West Africa (<1000 mm year^{-1}). Specific objectives of this meta-analysis were to (i) describe and (ii) quantify the effects of the presence of woody perennials and of ramial wood amendments on crop productivity and soil characteristics, and (iii) identify general recommendations on the integration of perennials with crops. An iterative keyword search was conducted to gather relevant literature. The search string consisted of four parts: source, practice, responses, and countries of interest. In total, 26 references on agroforestry parklands and 21 on woody amendments were included in the meta-database (314 entries, 155 for Parklands and 159 for ramial wood). We show that: (1) the presence of shrubs and trees on agricultural fields had an overall positive but variable effect on soil total C (i.e. +20 to 75%); (2) millet and sorghum yields were often higher in the presence of shrubs (-25 to +120%); (3) more variability was observed in presence of trees (-100 to +200%); and (4) the use of shrub- and tree-based ramial wood resulted in equal or higher cereal yields as compared to the control (-30 to +100%). Upscaling the use of biodiversity-driven processes in farming systems of West Africa may provide benefits to overall ecosystems but species' choice and trade-offs perceived at the farm level, including labour management and low ramial wood availability should be addressed through future research.

Keywords:
Agroforestry, Mulch, Sahel, Shrub-crop associations, Woody amendments

Published as: Félix GF, Scholberg JMS, Clermont-Dauphin C, Cournac L, & Tittonell P. 2018. Agronomy for Sustainable Development 38(6). DOI: 10.1007/s13593-018-0533-3l

1. Introduction

Agricultural-based economies prevail in semi-arid West Africa (SWA), yet harsh growing conditions such as extreme temperatures, erratic and low rainfall, and strong erosive winds on already nutrient-depleted soils, typically result in very low productivity or at times complete crop failure (Diarisso *et al.*, 2015a). Traditional agricultural areas near population centres are lost due to urban development, and agriculture is pushed onto both marginal land and forested areas (Reij *et al.*, 2005; Doso Jnr, 2014). The human population of West Africa (WA) has increased from 106 million in 1970 to 305 million in 2010, and the current annual growth rate of 2.78 % is one of the highest in the world (WorldBank, 2016). Population growth in rural areas intensifies pressure on land resources for subsistence farming (Andrieu *et al.*, 2015) by limiting the traditional practice of keeping fallow periods to restore soil fertility (Bonetti & Jouve, 1999).

Continuously cultivated crop fields and reduced fallow periods are short-chained soil restoration processes which do not compensate for the decline in soil organic matter in most soils used for agriculture in the region (Kintché *et al.*, 2015). Especially when coinciding with poor soil management and/or more extreme weather conditions, acute soil degradation may be the final outcome. This vicious circle of soil fertility decline (Lal, 2008) often results in the formation of non-responsive, degraded soils (Tittonell & Giller, 2013), represented on almost 600,000 km^2 of WA, half of which are featured by intensively weathered and inherently infertile soils in semi-arid environments (Bai *et al.*, 2008).

Concentrated efforts to reverse soil degradation by restoring soil productive capacity of marginal agricultural lands are essential to feed and sustain the livelihoods of a continuously growing population (Tittonell, 2016). SWA soils are coarse and intensively weathered, and this translates into limited capacity to store and protect soil organic matter (Bationo *et al.*, 2007). Organic matter accumulation in the soil can be achieved by increasing C-rich inputs and reducing C outputs from the soil. Organic inputs or amendments such as animal manure or crop residue mulches play a key role in soil restoration. Sources of organic matter in SWA landscapes are not so abundant and rather scattered (Gijsbers *et al.*, 1994; Sop *et al.*, 2011). Therefore, novel options to secure organic matter inputs to soil are required.

Crop residues are preferentially used to feed domestic ruminants or as fuel (de Ridder *et al.*, 2004; Giller *et al.*, 2009), so woody vegetation can provide an *in-situ* source of leaf and branch biomass for soil amendment (Bayala *et al.*, 2003; Diack *et al.*, 2010; Dossa *et al.*, 2012; Diedhiou-Sall *et al.*, 2013; Dossa *et al.*, 2013; Yélémou *et al.*, 2014). Ramial wood (RW) amendment availability relies on existing tree and shrub vegetation. The mechanisms by which woody amendments may provide benefits to soils and crops remain poorly understood, and no effective agronomic recommendations on the use of leaf and branch material currently exist in the SWA context (Bayala *et al.*, 2003; Barthès *et al.*, 2015; Félix *et al.*, 2018a).

The use of leaf and branch litter as soil amendments has been extensively evaluated in Canada and in temperate areas of Europe (Barthès *et al.*, 2010) where the application of large amounts of ramial chipped wood mulch (RCW; in French *bois raméal fragmenté,* BRF) improved soil structure, enhanced fungal activity (i.e. *Basidiomycetes*), and increased crop yields (i.e. +30% in potatoes, and +300% in strawberries) (Lemieux, 2001).

In semi-arid West Africa (SWA), the question remains as to whether biomass derived from trees and shrubs can provide an adequate soil amendment to improve soil quality and crop productivity, in a way that is sustainable and accessible to farmers. A systematic literature review was conducted to compile relevant case studies in SWA and elucidate the effects and corresponding mechanisms by which the woody perennials and the biomass they produce may help to regenerate or enhance soil productive capacity. Specific objectives of this meta-analysis were: (i) to describe interactions between agroecosystem components, (ii) to quantify the effects of the presence of woody perennials and the use of ramial wood amendments on crop productivity and soil characteristics, and (iii) to identify general recommendations on the integration of perennials with crops. Materials and methods for the selection of studies and indicators examined in this meta-analysis are described in the next section, followed by the results and discussion on the effects, feasibility, and trade-offs of scaling up the use of woody perennials in agricultural landscapes of SWA.

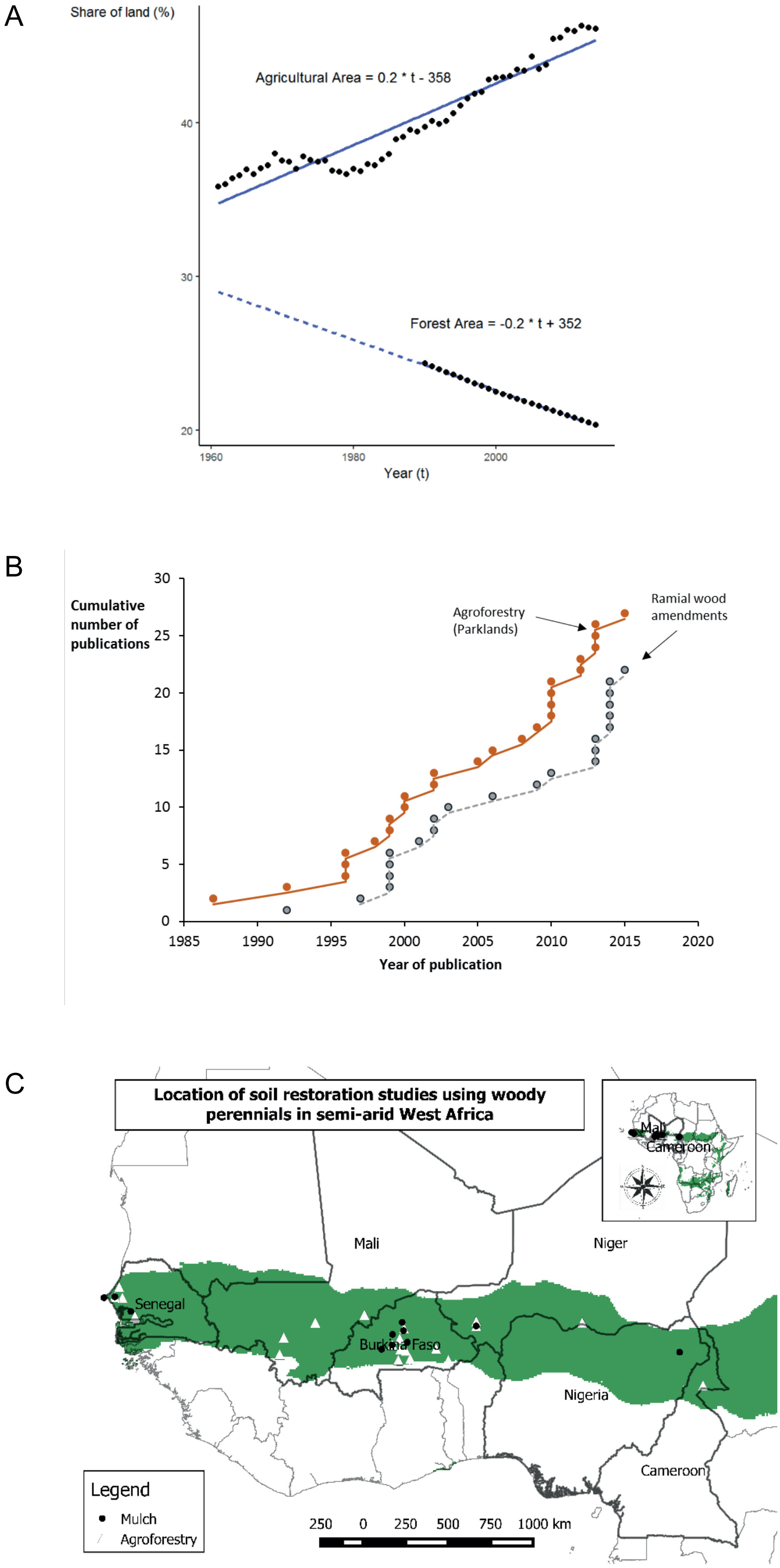
2. Materials & Methods

2.1. Geographical zone and farming systems

Agricultural landscapes of West Africa (WA) are heterogeneous (Fig. 2.1; Zorom *et al.*, 2013), ranging from deserts and semi-arid ecosystems to moist savannah, humid forests, and swamps (Jalloh *et al.*, 2012). Increasing rainfall from North to South drives an increasing complexity of land use in WA, including agro-pastoral systems in the driest areas and cropping or mixed farming systems in the wetter zones (Table 2.1). Agricultural areas have increased at the expense of forest areas (Fig. 2.2A). The geographical range of this meta-analysis covers SWA, including part of Senegal, The Gambia, Mauritania, Mali, Burkina Faso, Northern Benin, Niger, Northern Nigeria, and Northern Cameroon (Fig. 2.2C). This semi-arid 'belt' also corresponds partly to the location of the 'Great Green Wall' project, an international effort to counter the advancement of desertification (Dia & Duponnois, 2012). The region of study features a range of 300-1000 mm annual rainfall, concentrated in a single and relatively short period (unimodal rainfall pattern of 60 to 120 days) each year (Dixon *et al.*, 2001; West *et al.*, 2008). In the absence of irrigation it is possible to successfully cultivate millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*), as well as maize (*Zea mays*) towards the wetter southern parts of the rainfall gradient. Millet and sorghum crop yields (grain and biomass) were selected as indicators for our quantitative analysis.

Figure 2.1. Remnant woody perennials during dry season drive soil heterogeneity of agricultural fields via above- and below-ground interactions. Shea nut trees provide abundant leaf litter and support nutrient re-cycling (A). *Piliostigma* shrubs are managed as an off-season micro-fallowing system (B). Finally, bare fields will usually require more external inputs, including livestock manure, chemical fertilizer, or crop residues, to support nutrient balances (C). Photos: G. Félix, Yilou, Burkina Faso.

Figure 2.2. (right) Agricultural area (cropland) in West African countries increases at the expense of forest land; data source: FAOstats – Land Use Indicators, average share of land (%) for Benin, Burkina Faso, The Gambia, Mali, Mauritania, Niger, Nigeria, and Senegal (A). Cumulative number of publications on the impacts of agroforestry systems and woody much application on soil fertility and crop yields in semi-arid West Africa between 1987 and 2015 (B). Map of the region considered in this literature review (C).


A
Share of land (%)
Agricultural Area = 0.2 * t - 358
Forest Area = -0.2 * t + 352
40
30
20
1960
1980
2000
Year (t)
B
Cumulative number of publications
Agroforestry (Parklands)
Ramial wood amendments
30
25
20
15
10
5
0
1985
1990
1995
2000
2005
2010
2015
2020
Year of publication
C
Location of soil restoration studies using woody perennials in semi-arid West Africa
Mali
Cameroon
Mali
Niger
Senegal
Burkina Faso
Nigeria
Cameroon
Legend
Mulch
Agroforestry
250 0 250 500 750 1000 km

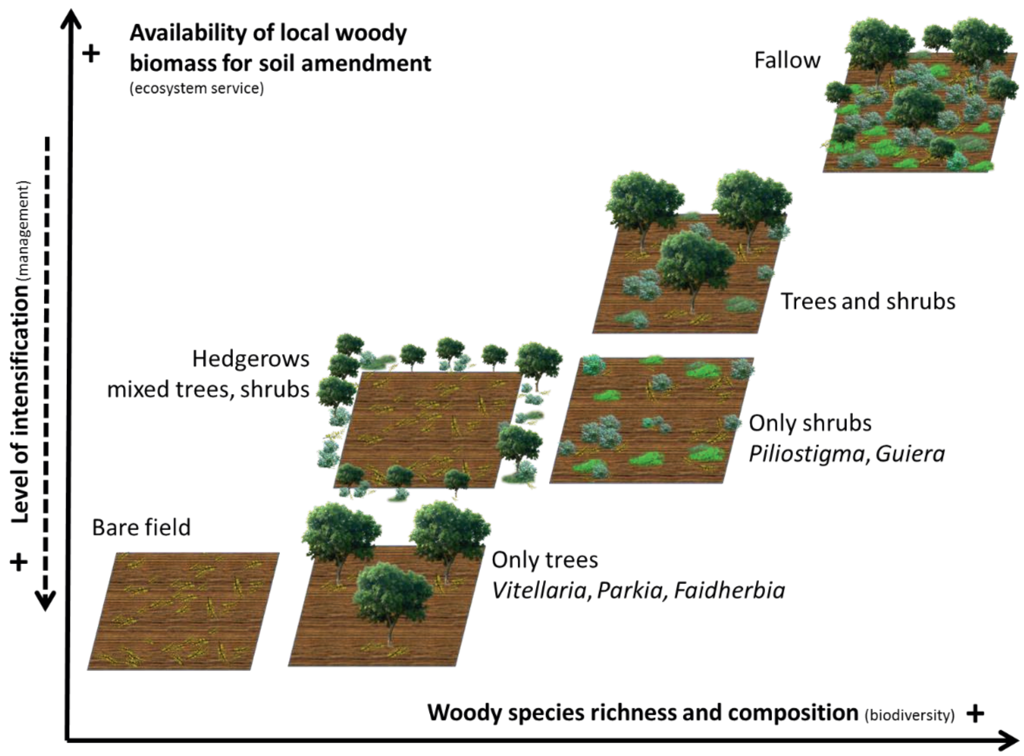


Figure 2.3. Conceptual agroecosystem designs for soil management with woody perennials, defined by local availability of woody species for soil amendment as a function of woody species diversity at field level. Intensification level refers to the degree of transformation of the original landscape (i.e. fallow).

Landscapes across SWA include trees and woody shrubs growing in or around the cropping fields, often reproducing the structure of an open savannah, or hereafter 'parklands' (Boffa, 1999). Trees are present in hedgerows or interspaced between crop plants within cropping fields, sometimes mixed with woody shrubs (Fig. 2.3). Potential *in situ* amounts of woody material available for soil amendment depend largely on agroecosystem design and woody perennial integration at the cropping system level (Sop & Oldeland, 2013; Feur, 2014; Cheriere, 2015).

2.2. Selection of criteria used for the literature review

A three-step procedure was employed to select papers related to woody perennial-based cropping systems in SWA. The first step was an iterative keyword search to capture relevant literature related to the effects of woody perennial species and associated leaf and branch material on restoration of soil productive capacity in semi-arid cropping systems. The search string consisted of four parts: the first search terms related to the source of the woody perennial ("tree" or "shrub"), the second to the management practice ("mulch" or "(inter)cropping"), the third to the response variables (e.g. soil properties and crop productivity), and the last one related to the specific environmental context (specific countries within SWA). The final combination of search keywords (Table 2.2) yielded 91 results in Scopus (based on titles, abstracts and keywords) and 267 results on ISI Web of Science (based on topic).

The second step consisted of manual screening of titles and abstracts of citations using the following criteria:

a. Studies that were conducted in the defined environmental context (rainfall <1000 mm yr^{-1} in semi-arid agroecosystems of Sudano-Sahelian Africa, including Senegal, The Gambia, Mauritania, Mali, Burkina Faso, Northern Benin, Niger, Nigeria, and Northern Cameroon).

b. Studies that included woody amendments as a management practice (surface-mulched or buried branches and/or leaves, but not biochar), and describing local uses of woody residues, or the presence of woody shrub or tree vegetation in farmers' fields, and reported effects on soil quality and/or crop productivity.

c. Studies conducted on either farmers' fields or experimental stations were typically included with corresponding field data; pure modelling results were excluded.

d. Literature reviews were excluded from the meta-analysis but were used to cross-check data, methods, and references.

From the total of 91 references of the Scopus search, 71 titles and abstracts did not meet one or more of the above listed criteria. Only 15% of the references were included in our database; these had clearly described treatments and experimental results. Additional references retrieved from ISI Web-of-Knowledge often concerned areas outside our study region (China or other parts of Africa). Thus, we only included those that were also present from the Scopus search and those relevant for the construction of our database (contributing with six additional references).

During a third step, papers were reviewed in full detail and key parameters and figures regarding production environment, management practices and response variables were compiled in a spreadsheet, checking for consistency in terms of scales and units and recalculating when necessary to obtain a common measure (and unit) for each target variable.

This information was complemented by grey literature, including one BSc thesis, three MSc theses, four PhD theses, and four reports by international organisations. Most of this literature was retrieved from the Wageningen University Library, The Netherlands, and from the library of *Centre d'Information Commun sur la Recherche et le Développment* (CICRD) located at the IRD/CIRAD campus in Ouagadougou, Burkina Faso. Supplementary data presented in the online version of a review paper by Bayala *et al.* (2014) were added to our dataset to analyse effects of trees in parklands, contributing 16 additional references. In total 47 references (Table 2.3) were included in the meta-database that was eventually analysed (26 references on parklands, 21 on ramial wood amendment applications).

In the selected studies, experimental treatments were located under tree canopy or, in the case of shrubs, within the vicinity of their canopy projection. Control data were from outside the area of canopy influence. Data concerning use of ramial wood (RW) amendments (mulched or buried) were considered with control treatments that did not apply RW as soil amendment.

2.3. Search metrics and overview

The earliest publication retrieved in our search on the effect of parkland agroforestry on soil and crop productivity was published in 1965 with the example of *Faidherbia albida* in Senegal (Charreau & Vidal, 1965). The oldest publication retrieved on ramial wood amendments in SWA is dated 1997 and was linked to keyword 'agroforestry mulches' (Tilander & Bonzi, 1997). The number of publications retrieved that reported on the use of biomass from woody perennials for soil amendment, whether through interactions in agroforestry parklands or as biomass transfer (cut and carry), plus the corresponding impacts on soil quality and crop yields in SWA, increased from less than ten prior to 1996 to about twenty between 1997 and 2005; another twenty publications appeared between 2005 and 2015 (Fig. 2.2B; Table 2.3). Most of the studies retrieved originated from Burkina Faso and Senegal, while Cameroon, Mali, Niger, and Nigeria were represented in a limited number of publications (Fig. 2.4A).

No homogenised term for ramial wood amendment practice exists. As a consequence, across the literature the following terms were identified as being similar or closely related to ramial wood amendments:

- agroforestry mulches (Tilander & Bonzi, 1997),
- prunings (Bayala *et al.*, 2003)
- leaf mulch (Bayala *et al.*, 2005),
- woody perennial leaf biomass (Yélémou *et al.*, 2014),
- woody biomass (Gruenewald *et al.*, 2007; Debela *et al.*, 2011),
- wood shavings (Chiroma *et al.*, 2006; Gajalakshmi & Abbasi, 2008),
- wood waste (Bulmer *et al.*, 2007; Andry *et al.*, 2011),
- woody debris (Brown & Naeth, 2014),
- wood (Bonanomi *et al.*, 2014),
- native agroforestry plant residues (Iyamuremye *et al.*, 2000),
- native shrub residues (Dossa *et al.*, 2009),
- branches of indigenous shrub (Wezel & Böcker, 1999),
- shrub material (Chapuis-Lardy *et al.*, 2015),
- ramial chipped wood (Gómez, 1997; Robert *et al.*, 2014),
- ramial wood amendments (Barthès *et al.*, 2015; Félix *et al.*, 2018a),

- chopped twig wood (Aman *et al.*, 1996),
- *rameaux ligneux* (Kabré, 2010),
- *bois raméal* (Barthès *et al.*, 2010), and
- *bois raméal fragmenté* (Zongo, 2009; Ba *et al.*, 2014; Somé, 2014)

A total of 19 woody species were documented in the literature reviewed (Table 2.4). *Faidherbia albida* (n=48) gathered the most entries in our agroforestry parkland database, followed by the tree species *Parkia biglobosa* (n=18) and *Vitellaria paradoxa* (n=17), and the shrub species *Piliostigma reticulatum* (n=25) and *Guiera senegalensis* (n=21). *P. reticulatum* (n = 52) and *G. senegalensis* (n=14) were the most represented species in experimental studies addressing the use of woody and leafy mulches as soil amendments in our database.

2.4. Data analysis

The dataset consisted of 314 entries (155 for agroforestry; 159 for RW) including information on treatments, rainfall, woody species, and crop yields (grain and biomass). When available, we recorded data on soil carbon and organic matter, soil nutrient availability, soil hydrological properties, and soil biological properties. The results were presented and discussed in light of relative effect size or response ratio (RR), calculated as the natural log (ln) difference between treatment and control (Eq. 1).

$$RR = \ln(\frac{Treatment\ yield}{Control\ yield})$$

An RR above zero denotes beneficial effects of treatment over control conditions.

3. Results & Discussion

Sudano-Sahelian landscapes include a variety of perennial woody species that grow spontaneously in farmed agroforestry parklands and provide different forms of organic material useful for soil amendment: (a) when this vegetation is coppiced, fresh branches and leaves are used either as surface mulching material or slightly buried (Louppe, 1991; Iyamuremye *et al.*, 2000; Yélémou *et al.*, 2007; Diack *et al.*, 2010; Lahmar *et al.*, 2012) and commonly combined with manure, crop residues, and/or compost prior to the growing season (Zongo, 2009; Kabré, 2010; Cabral, 2011). Tree or shrub litter can be deposited *in-situ* or transported (*ex-situ*) to neighbouring fields that require organic biomass input. Alternatively, (b) when that vegetation is (partly) burned, farmers can incorporate the resulting ashes into the soil (Lufafa *et al.*, 2008a; Lufafa *et al.*, 2009).

Various structures of agroforestry systems may be identified in SWA, including parklands, fallows, hedgerows, and alley cropping (Fig. 2.3). Although not specifically captured through our literature retrieval strings, the Farmer Managed Natural Regeneration (FMNR – or *Regénération Naturelle Assistée*) approach stands out in both the published and grey literature from West Africa as an agroforestry strategy based on higher tree and shrub densities per hectare than traditional parklands. FMNR entails intensive management of shrubs, pruning and coppicing by farmers, in order to achieve optimal synergies between crops and trees on farm land. There is considerable literature, notably by ICRAF and others on FMNR initiatives in the Sahel, claiming that farmers adopting FMNR since the 1990´s have "re-greened" millions of hectares through increases in tree/shrub densities (Weston *et al.*, 2015). It is therefore necessary to highlight that FMNR differs from more traditional, sparse-tree-density forms of parkland agroforestry. Yet most cases in our literature retrieval refer to traditional parkland agroforestry systems, and thus further distinction between these and FMNR was not possible in our analysis.

The influence of trees on crop yields and soil characteristics in parkland farming systems of SWA has been documented extensively (Fig. 2.4B), with largely positive effects on average (Sanou *et al.*, 2011; Bayala *et al.*, 2012; Sanou *et al.*, 2012; Coulibaly *et al.*, 2013; Sinare & Gordon, 2015a). Crop yield is a classical farmer indicator to assess the success of agricultural innovations, which is often documented in research papers as well. In the following section (3.1) we analyse effects of woody perennials on economic (grain) and biological (biomass) yields, followed by effects on soil properties (carbon, nutrients, water, and biology). Management options and resource limitations around the use of woody perennials in SWA are discussed in sections 3.2 and 3.3, respectively.

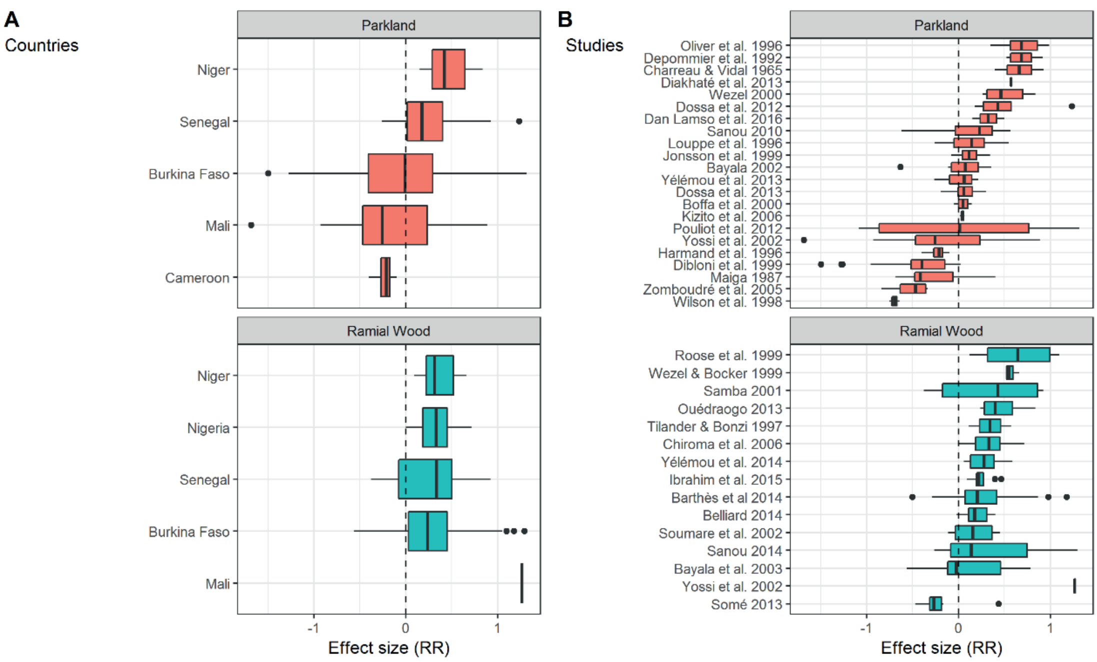


Figure 2.4. Variability of yield effect size per country (A) and per study (B).

3.1. Crop yields and soil properties under parklands

3.1.1. Crop yields

The phenomenon of *resource islands,* or *fertility hotspots,* has been documented with the use of *P. reticulatum* shrubs as nursing trees for young mango trees, which increased chances of fruit production in semi-arid to arid conditions in Senegal (Hernandez *et al.*, 2015). In a study from Niger, average grain yields reported in the vicinity of *G. senegalensis* shrubs were 773 kg ha^{-1} whereas yields in open fields (1.2 m-radius from shrub) were only 382 kg ha^{-1} (Wezel, 2000). Yield responses of sorghum and millet in parklands or with application of RW seem to be more important at low-rainfall sites, an effect that decreases with increasing rainfall (Fig. 2.5A). When environmental conditions for crop growth are not favourable (i.e. control yields are low), then sorghum and millet grain yields are less frequently affected next to the canopy of shrubs than under the canopy of trees (Fig. 2. 5B). Overall, crops performed best when grown nearby *F. albida,* and in the vicinity of shrubs such as *G. senegalensis* and *P. reticulatum*. Crops grown in the vicinity of species such as *Sclerocarya birrea, Albizzia lebbeck*, and *Balanites aegyptiaca* obtained less yields than those grown without the influence of these perennials (Fig. 2.6B).

In the vicinity of trees, taro and chili pepper performed better than maize and eggplant (Fig. 2.6A). Early studies on the effect of *F. albida* on groundnut productivity show no significant differences between the presence and the absence of trees (Louppe *et al.*, 1996). Data from a long-term experiment in Senegal show that groundnut response is not significantly different when intercropped with shrubs (*G. senegalensis*) as compared to no shrubs (Dossa *et al.*, 2013). Millet yields however, increased in presence of shrubs from the third to the eleventh year of intercropping in the same trial (Bright *et al.*, 2017).

In the case of *V. paradoxa*, Bazié *et al.* (2012) showed that chemical fertilisation on millet yields grown under the canopy of the tree would only show significantly higher results when the canopy of the tree was partially or totally pruned as compared to unpruned trees. Radiation is a major limiting factor to crop growth and development. When the crown is selectively pruned, then more light may be intercepted by crops growing underneath tree canopies. Pruning of tree crown is particularly beneficial to cereals (C_4 crops), yet growing shade-tolerant C_3 crops (i.e. taro) may help lift the labour constraint of pruning the trees (Pouliot *et al.*, 2011).

Coppiced material from woody perennials applied as mulch or buried ramial wood (RW) amendments had in most cases a positive effect on crop yields. As rainfall in the study area increased, the effect size of RW on crop yields decreased (Fig. 2.5A). In more than 70% of the cases, the yield responses were positive for cereal grain with the use of RW (Fig. 2.5B). Overall positive effects were noticeable for all crops (except peanut under RW Buried; see Fig. 2.6A). Beneficial effects were observed for any given source of woody material employed as RW (except for *P. biglobosa* ; see Fig. 2.6B).

Bayala *et al.* (2003) found that applying mulch of N-rich *P. biglobosa* leaves reduced millet grain and biomass yields while N-rich leaf material of *V. paradoxa* increased millet yield as compared to control conditions. This effect was linked to the recalcitrant nature of lignin (lig) and cellulose (cellu) composition of *P. biglobosa* leaves (C:N of 22, lig:cellu of 1.28) as compared to *V. paradoxa* leaves (C:N of 31, lig:cellu of 0.82).

P. reticulatum leaf biomass applied as a mulch at 1.25 or 2.25 t DM ha^{-1} on a tropical ferruginous soil (Lixisol) in Burkina Faso increased sorghum grain yields by 14 and 28 %, respectively, compared to a non-mulched control treatment (Yélémou *et al.*, 2014). A study in semi-arid Niger reported that applying 2 t DM ha^{-1} of *G. senegalensis* mulch during two consecutive years resulted in increased millet grain yields by 76% during the first year and by 94 % during the second year as compared to non-mulch control (Wezel & Böcker, 1999). Another experiment conducted on sandy-loam soils in Burkina Faso showed that yields decreased over the years on continuously cultivated plots, declining drastically during the 2nd and 3rd year for all treatments and control (Barthès *et al.*, 2015). In that experiment, the use of 1.5 t DM ha^{-1} of *P. reticulatum* leaf and branch material as mulch did not significantly increase sorghum yields as compared to control. The addition of RW does not automatically translate into increased crop yields, but the effects of RW use are rarely negative on crops (Fig. 2.5 and 2.6).

3.1.2. Soil carbon

Higher total soil C content (+20 to 75%) under canopies of woody perennials (Fig. 2.7A) is normally ascribed to litter deposition and sediment trapping. "Fertility" islands under perennial shrub canopies are also linked to fine root decay (Manlay *et al.*, 2004) and effective entrapment of wind-blown sediments (Wezel *et al.*, 2000; Leenders *et al.*, 2007), with sediment capture efficiency as a function of shrub density and canopy size (Mudrak *et al.*, 2014). This effect may also be related to the presence (and decomposition) of herbaceous plants whose growth is favoured underneath the shrub crown (Yélémou *et al.*, 2012). The presence of perennial species in agricultural fields may also create a microclimate due to shading and deposition of above- and below-ground organic material, resulting in pedospheres with increased capacity for C sequestration. Measurements of soil δ13C isotopic content in Burkina Faso showed that soil C in the vicinity of tree trunks was mainly from tree origin (C_3) and that C_4-derived soil C (from cereals) was similar in the open field and nearby the perennials (Jonsson *et al.*, 1999; Bayala *et al.*, 2006).

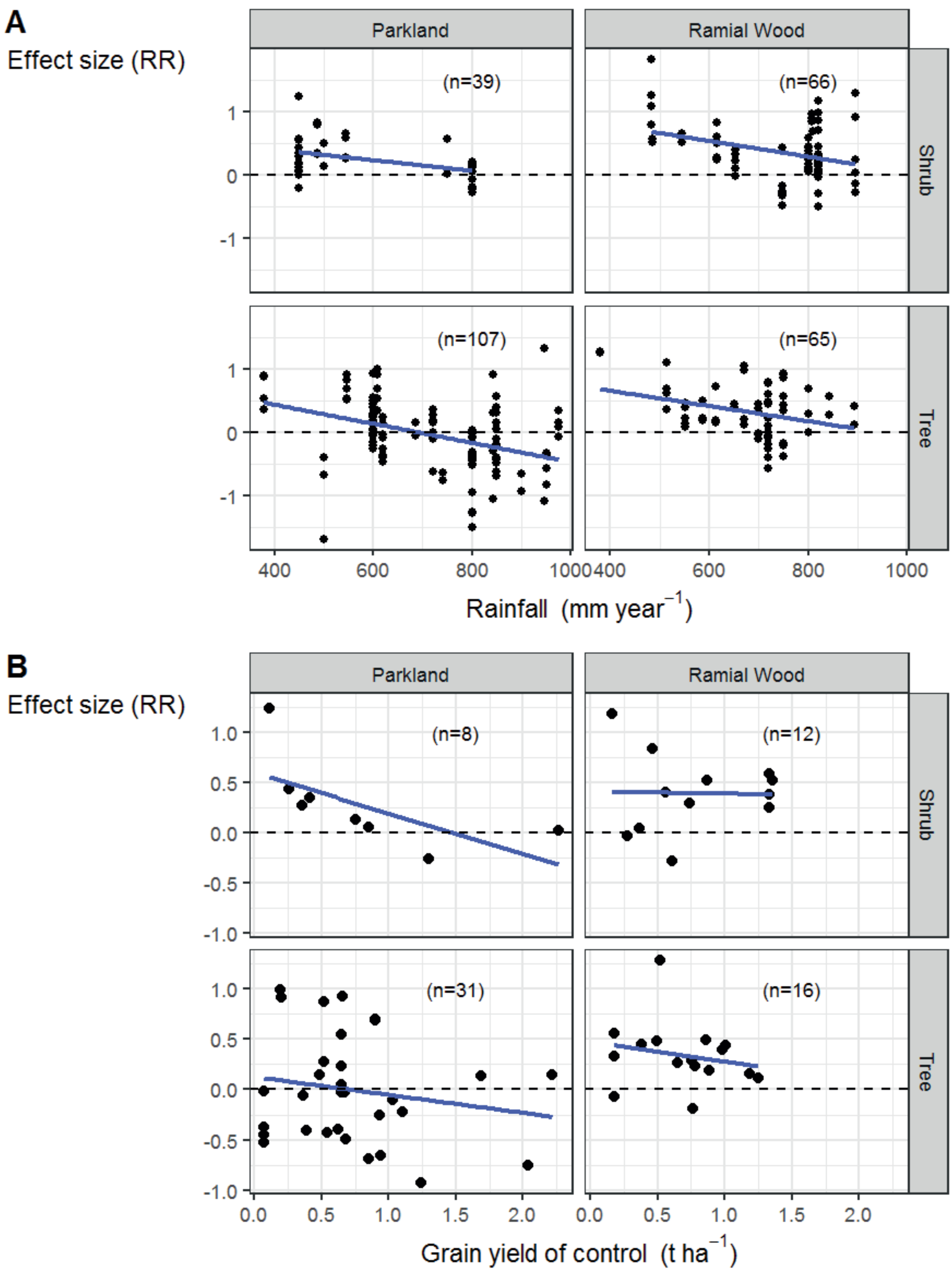


Figure 2.5. Effect size (response ratio) on yield over a rainfall gradient for all crops recorded in our meta-analysis (A), and effect size on millet and sorghum grain yields with treatments in function of the control grain yields (B).

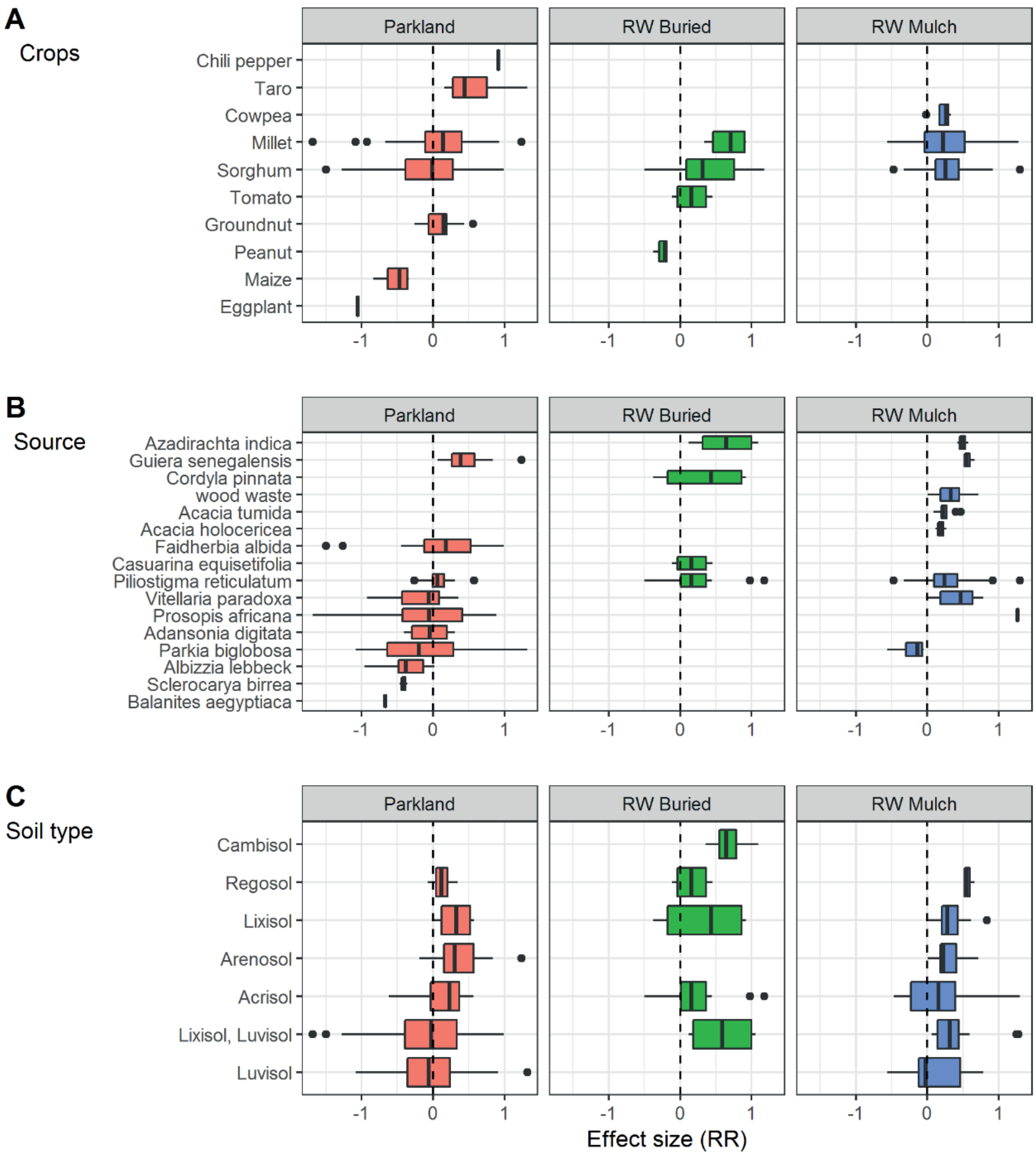


Figure 2.6. Effect size (RR) of yields per crop studied (A), per woody resource used (B), and per soil type (C).

In the vicinity of woody perennials there is both decomposed and non-decomposed organic material (including fine roots). This enhances soil moisture retention and reduces evaporation. Additionally, when livestock consume parts of a shrub plant (e.g. *P. reticulatum* fruits) or rest under the shade of woody perennials, nutrients tend to be concentrated via livestock depositions. Moreover, migratory and resident birds find refuge and food in perennial vegetation of agricultural zones of the Sahel (Stoate *et al.*, 2001) very likely further enriching soils in the vicinity of trees (i.e. *F. albida*) through deposition of organic droppings (Jonsson *et al.*, 1999; Sileshi, 2016).

Literature on soil C dynamics in response to woody biomass amendments reports different results. On the one hand, a study testing *P. reticulatum* shrub material as soil amendment in an experimental station reported slight (and non-significant) increases in soil C of less than 2% as compared to non-mulched conditions, and significantly lower with N addition, after three years (Barthès *et al.*, 2015). On the other hand, a study on the use of *Cordyla pinnata* at a rate of 156 kg t^{-1} of mulch reported extremely high increases of soil C of +600% in a timeframe of 120 days as compared to no mulch (Samba, 2001).

Soils amended with coppiced material as mulch tended to result in higher C contents than control soils that did not receive organic amendment, and higher than buried RW (Fig. 2.7A). As reported in the study of Bayala *et al.* (2003), *V. paradoxa* prunings increased soil C contents by 12% as compared to no-mulch conditions, while soils amended with *P. biglobosa* prunings enhanced soil C by 70% on average.

3.1.3. Soil nutrients

Soil total N and available P contents increased in the presence of woody perennials over situations without perennials, a probable indication of increased N and P deposition through litter, dust trapping, and potentially also in the case of N through some enhanced N_2 fixation and/or enhanced conditions for N retention in soil around these vegetation structures (Fig. 2.7B and 2.7C). Soil N and P concentrations underneath scattered shrubs in semi-arid Niger were indeed 38% and 51% higher than in open fields, respectively (Wezel *et al.*, 2000). In a study in Burkina Faso, total N was generally higher under *P. reticulatum* and *P. thonningii* than outside the shrub influence area (Yélémou *et al.*, 2012), an effect observed in Niger as well, where soil N content was significantly higher in the vicinity of shrubs compared to zones more than 2 m away from the shrubs (Wezel, 2000). This effect may be explained by greater nutrient input from organic material deposition, which itself can induce enhanced conditions for nitrifying bacteria. In a study in Senegal, soil total N, ammonium (NH_4^+) and total P contents in non-cropped areas were higher under canopies of *P. reticulatum* shrubs than on soils without shrubs, pointing towards enhanced nitrification processes nearby the perennials (Diakhaté *et al.*, 2013).

Application of RW mulch had beneficial effects on soil N overall, but this effect was not so clear for RW buried (Fig. 2.7B). *P. biglobosa, V. paradoxa* and *G. senegalensis* contributed

25 to 50% on average to soil N contents as compared to control treatments. *P. biglobosa* release of allelopathic components or lignin-to-N ratios may influence nutrient mineralization rates (Bayala *et al.*, 2005). Choice of species to use as RW amendments should be further explored in the light of C:N and lignin contents and the relation to N-immobilization, particularly when amendments are buried. Effects of RW on available P followed a similar trend as for soil N (Fig. 7C).

3.*1.4. .Soil water*

Systems with intercropped perennials show higher soil water content, making water more available for crop uptake. These results are largely due to belowground interactions, including (1) between roots and increased water infiltration that create preferential flows into deep layers of the soil (Bargués Tobella *et al.*, 2014), (2) a reduction in soil evaporation under tree canopies (Jonsson *et al.*, 1999), and (3) the hydraulic lift effect transporting deep-water and rewetting of surface soil water content, usually overnight (Bayala *et al.*, 2008; Kizito *et al.*, 2012).

In Burkina Faso, crops grown under *P. biglobosa* benefited from a 24% increase in soil water content as compared to control conditions (Wilson *et al.*, 1998). In Senegal, soil water content was higher by 20 and 28% in millet cropping systems with *P. reticulatum* and *G. senegalensis*, under shrub crown (i.e. soils were moister) (Kizito *et al.*, 2007). In this last study using neutron probes, the water balance for *P. reticulatum* and *G. senegalensis* shrubs intercropped with millet was superior to open-field observations, a difference explained by 'hydraulic lift.' This phenomenon implies that water is transferred from deeper subsoil layers to surface by deep-rooted perennials, and contributing to rewetting of upper soil horizons in the case of shrubs *P. reticulatum* and *G. senegalensis* (Kizito *et al.*, 2012) and trees *P. biglobosa* and *V. paradoxa* (Bayala *et al.*, 2008).

Enhanced infiltration rates may also result in higher water retention and storage in the upper layers of soil profiles underneath the canopy of the perennial species (Bargués Tobella *et al.*, 2014). Woody and herbaceous species co-exist in semi-arid landscapes and differences in root proliferation zones may be such that different vegetation components do not seem to compete for water resources (Seghieri, 1995).

V. paradoxa and *P. biglobosa* leaf applications as mulch in millet-based cropping systems were reported to decrease water ponding time in Burkina Faso (Bayala *et al.*, 2003), with more pronounced effects under *V. paradoxa* mulch than under that of *P. biglobosa*. RW applications increase soil organic matter content which likely result in enhanced soil water contents (Chiroma *et al.*, 2006). Moreover, organic matter additions will trigger termite activity, eventually leading to increased infiltration capacity (Mando, 1997b; Mando & Miedema, 1997; Ouédraogo *et al.*, 2004).

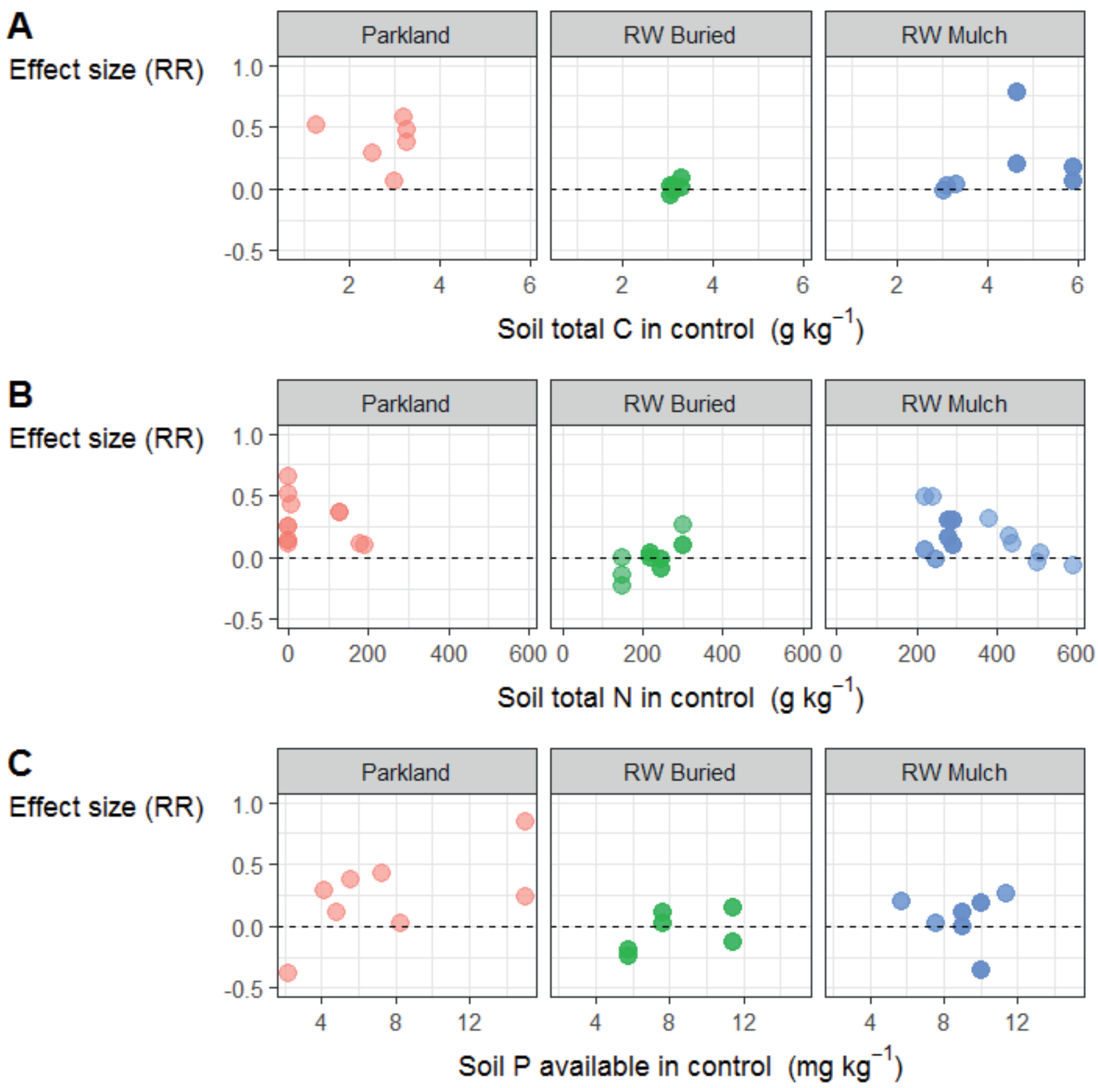


Figure 2.7. Effect size (RR) of treatments considered as a function of the value in control for soil total Carbon (A), total Nitrogen (B), and Phosphorus available (C).

3.1.5. Soil biology

Nutrient concentration in termite mounds as compared to adjacent soils may have both a biological origin from metabolic processes (saliva, faeces, plant debris), and a mineral origin from clay accumulation within nest structures (Sileshi *et al.*, 2010). Termite-mediated processes increased nutrient recycling, promoted soil formation, and enhanced soil moisture retention and infiltration in several trials conducted on drylands (Mando, 1997a, 1997b; Mando & Miedema, 1997; Mando, 1998; Léonard & Rajot, 2001; Laguemvare, 2003; Mando & Stroosnijder, 2006; Ouédraogo *et al.*, 2007). Some of the species of *Termitidae* in semi-arid Burkina Faso include *Odontotermes smeathmani, Microtermes lepidus,* and *Macrotermes bellicosus* (Ouédraogo *et al.*, 2004). Their diets include dry-wood, damp-wood, litter, and grass (Ouédraogo *et al.*, 2007; Kaiser *et al.*, 2015). There is a general consensus that termite foraging activity in SWA improves crop rainfall use efficiency when soils are mulched with either crop residues or ramial wood or with a combination of both (Léonard & Rajot, 2001; Brussaard *et al.*, 2007; Sileshi *et al.*, 2010). Water infiltration may be reduced in the presence of subterranean termites (*Odontotermes* genus) because water-repellent particles such as organic matter and silt are being transported towards the surface layer, making it more impermeable locally (Mettrop *et al.*, 2013). Termites in African savannahs contribute greatly to landscape heterogeneity (Davies *et al.*, 2016), but further study is required to understand the effect of particular termite species on soil nutrient dynamics at a landscape scale and their influence on the spatial distribution of perennials (Kaiser *et al.*, 2015).

Higher microbial biomass activity may support a wider range of biogeochemical processes through faster decomposition rates of catabolites within the rhizosphere of *P. reticulatum*-millet intercrops (Diakhaté *et al.*, 2016). Yélémou *et al.* (2013a) found that microbial respiration increased by 13% and 266 % under the canopies of *P. reticulatum* and *P. thonningii* in agricultural fields. Diedhiou *et al.* (2009), showed that soil microbial communities from 'resource islands' exhibited higher biomass and greater diversity, and exhibited much more fungal flora as compared to outside of the woody perennials' area of influence (*G. senegalensis* and *P. reticulatum*). Their explanation of the process alludes to lower water stress and increased stimulation for litter decomposition processes. Diedhiou-Sall *et al.* (2013) studied, in controlled conditions, the effects of a composed substrate of *P. reticulatum* leaves and stems on soil microorganisms of Senegal that had never received woody amendments. The organic substrate input increased microbial biomass, as well as the levels of cellulase and β-glucosidase enzymes activities, which are closely related to C-mineralization.

Hernandez *et al.* (2015) confirmed observations regarding the abundance, diversity and higher activity of microorganisms within *P. reticulatum* resource islands in Senegal. Other studies have described microbial communities by focusing on the densities of predators, i.e. bacterivores, fungivores, others. The presence of shrubs in Senegal increased the abundance of bacteria-feeding nematodes over that of plant-feeding nematodes (Diakhaté *et al.*, 2013). This has important implications on nutrient cycling and availability since *P. reticulatum* influence tends to increase bacterivores and decrease plant-feeding nematodes (Diakhaté *et al.*, 2013).

3.2. Management options

The original forest landscape of SWA has been gradually cleared for crop cultivation at intensities that vary across the region (Fig. 2.1 and 2.2). The cutting of native trees and overstocking of transhumant cattle have contributed to desertification and degradation of fragile soils (Dongmo *et al.*, 2012b). Farming families in SWA have developed and/or adopted erosion and desertification control practices since the 1970s in order to counter drought (Critchley *et al.*, 1994; West *et al.*, 2008). This resulted in halting land degradation in SWA according to some views, which recognize a recent re-greening of the region thanks to soil restoration techniques (Mazzucato & Niemeijer, 1998; Niemeijer & Mazzucato, 2002; Farage *et al.*, 2007; van Walsum *et al.*, 2014). Tree-crop integrated systems, a form of agroforestry, occupy an increasingly important place in the development of sustainable farming systems in SWA (Gijsbers *et al.*, 1994; Ouédraogo & Alexandre, 1994; Yaméogo *et al.*, 2013). These systems have been shown to be resilient and adaptive despite the ecological and economic crises that have affected Sudano-Sahelian agriculture in the past four decades (de Ridder *et al.*, 2004; Aune & Bationo, 2008; Reij & Smaling, 2008; Hien *et al.*, 2010; Settle & Garba, 2011).

While woody perennials seem clearly linked to soil fertility hotspots, Bayala *et al.* (2015) advance that farming families would benefit more from the presence of trees on parklands by either: (a) pruning dense tree canopies to minimize light competition with cereals, or (b) maintaining the canopy but replacing cereals with shade-tolerant-species (i.e. taro). Identifying crop species and selection of woody perennials to associate with cereals will require mobilisation of ecological knowledge. Planting patterns that take into account environmental constraints (i.e. taro under *V. paradoxa* crown and cereals in the open fields) may further result in increased ecosystem service provision (i.e. biodiversity and improved household nutrition). Livestock breeders may also see yield benefits derived from tree- or shrub-based fodder as a complement to crop residues for animal nutrition. Woody perennials may furthermore provide renewable resources for fuelwood, construction material, and medicine (Yélémou *et al.*, 2007; Sop *et al.*, 2012). Applying FMNR is a low-investments method that can reconcile food production with reforestation and could furthermore improve economic and nutritional benefits from agriculture, including the improvement of health and psycho-social conditions (Weston *et al.*, 2015).

3.3. Resource limitations

Woody perennials prevailing in SWA tend to produce organic matter in the form of branches and leaves at relatively high rates despite being coppiced on a frequent basis. To illustrate woody and leafy biomass availability for soil amendments in a Sudano

Sahelian landscape, let us examine the example of a study led in Guié, a 47 km^2 village of Centre-North Burkina Faso (Kabré, 2010). In this locality, only six species were responsible for 63 % of the stems sampled in a systematic forestry inventory (Table 2.5). *Acacia macrostachya* was the most abundant species, representing 17 % of the sampled stems, yet this species has thorns and yields little leaf biomass. Therefore, when it occurs on the fields, it is usually slashed and burnt to ashes by farmers to clear cropping fields prior to the rainy season. *V. paradoxa* or shea butter tree, on the other hand, is abundant and accounts for higher biomass rates. Nevertheless, from the 829 kg DM ha^{-1} assessed in the study presented in Table 2.5, the biomass attributed to shea butter trees would be inaccessible as a source of soil amendments. This particular species is regulated in local and national policies since its products are consumed in local cuisine and exported as raw material for international cosmetics industry. *V. paradoxa* is deciduous. The leaf biomass is often burnt while it could be composted or used directly as mulch. As a result, the remaining 'available' woody and leafy biomass to apply on soils at Guié, Burkina Faso, includes three shrubs (*Combretum micranthum,. G. senegalensis,* and *P. reticulatum*) and one tree species (*Cassia sieberiana*), accounting for less than 250 kg DM ha^{-1} (Kabré, 2010).

In Senegal, *P. reticulatum* accounted for ca. 1 t ha^{-1} while *G. senegalensis* for 1-2 t ha^{-1} of C-rich biomass . Earlier studies in Senegal measured no more than 500 kg DM ha^{-1} of *G. senegalensis* (Louppe, 1991). These are rather low amounts as compared to the 1-6 t DM ha^{-1} that is applied in experiments documented in scientific literature. It is essential to take into account that the feasibility of RW use depends on:

- Effect of soil amendments on yield, nutrient cycling and soil C-sequestration rates,
- Richness and composition of woody perennials in ecosystem,
- Frequency of pruning, and
- Proximity between *source* and *sink* sites

The intrinsic capacity of a given species to re-sprout vigorously and produce large biomass, is a trait that is mediated by the environment and management. Identifying species with such trait is key and might be one of the future investigation areas. Transferring leaves and branches over long distances to apply on degraded soils represents an appreciable workload that may conflict with other on-farm or off-farm labour demands. Attention must also be given to local land tenure rules on the use, management, and plantation of trees and shrubs on agricultural fields, which may sometimes be disconnected from those promoted by institutions (Rousseau *et al.*, 2017).

4. Conclusion

The objective of this meta-analysis was to qualify and quantify the effects that woody perennials have on crop productivity and soil characteristics. We specifically studied the effects of woody perennials in agroforestry systems and the effects of coppiced material application as soil amendments (i.e. ramial wood, RW). Woody perennials in agroforestry systems locally create resource islands or fertility hotspots around their base, related to both aboveground (i.e. litter addition) and underground processes (i.e. hydraulic lift and root decay). From this meta-analysis, it is possible to advance that shrubs in cereal-based cropping systems render similar benefits as trees (i.e. and enhanced soil properties) with fewer trade-offs in terms of yield. These effects were more visible with low rainfall and at low site-productivity.

RW amendments had overall beneficial effects on crop yields and on soil C and N contents, independent of source material. Considerations on the resource availability and sustainability of the practice need to be further studied. Application of RW material from shrubs and trees may be an option to improve agricultural soils of semi-arid West Africa in perennial-annual crop systems. The results of this meta-analysis highlight the need for research on the use and management of perennials (especially of shrubs), on the synergies that occur amongst biodiversity components at the cropping system level, and on the trade-offs at the farming system level.

In the light of discussions about ´greening the Sahel´ through tree planting, or the establishment of a ´great green wall´ south of the Sahara, our meta-analysis indicates that great potential in terms of increasing and stabilising soil productivity can be derived from the intensive management of existing native woody vegetation, in multifunctional landscapes that combine food crop production with other tree-mediated ecosystem services.

5. Statement of data availability

The datasets generated during and/or analysed during the current study are available in the Wageningen University Library repository https://doi.org/10.4121/uuid:d60d11d6-cd5f-47b4-a5ad-4a4a97d41501.

Table 2.1. Sub-regions, ecosystems and farming systems of West Africa

Climatic sub-region	Months of rain	Annual rainfall (mm)	Average annual temperature (°C)	Land cover	Dominant Farming System
Saharo-Sahelian	1 – 2	250 – 500	24.4 – 28.5	Steppe with thorny bushes and annual grasses	Agropastoral – millet farming system. Mostly pastoral (transhumant herding) with pockets of subsistence farming based on millet, sorghum and cowpea
Sahelian	1 – 3	300 – 550	24.4 – 28.5	Steppe with thorny bushes and annual grasses	Agropastoral – millet/sorghum farming system. Mostly pastoral (transhumant herding) with pockets of subsistence farming based on millet, sorghum and cowpea
Sudano-Sahelian	2 – 3	350 – 600	23.7 – 25	Steppe with *Combretum* and annual grasses	Agropastoral – millet/sorghum farming system. Combination of transhumant herding and sedentary agropastoral agriculture. Subsistence farming based on millet, sorghum and cowpea
Sudanian	3 – 4	500 – 900	23.7 – 25	Savannahs with trees (*Balanites aegyptica, Acacia spp*) and shrubs	Cereal-root crop farming system. Mix of agricultural and agropastoral activities. Sedentary farming dominant, including sedentary village stock raising and permanent cropping of sorghum, millet, cowpea, cassava, cotton and groundnut, with transhumant pastoralism during the dry season.
Sudano-Guinean	4 – 5	750 – 1200	24.5 – 28.8	Savannah with trees or shrubs, sparse forests	Cereal-root crop farming system. Agricultural area characterized by perennial crops (mangos, citrus, cashew etc.), cotton, cassava, yam and cereals (sorghum, millet and maize). Sedentary village stock bull rearing, with transhumant grazing during the dry season.

Adapted from: (Arbonnier 2000; Dixon et al. 2001)

Table 2.2. Search terms and strings used during the literature retrieval

Search terms related to	Keywords	Scopus	Web of Science Core Collection
Source	(shrub* OR bush* OR wood* OR branch* OR leaf* OR tree* OR biomass)	91	267
Practice	AND (mulch* OR *crop*)		
Response	AND (soil fertility OR soil restoration OR soil quality OR productivity OR yield*)		
Context	AND(semi*arid OR arid OR sudan* OR soudan* OR sahel* OR senegal OR gambia OR mali OR mauritania OR burkina faso OR niger OR nigeria OR benin)		

Table 2.3. List of publications, the study locations within semi-arid West Africa, the woody species (or RW source), and the crop of study.

Authors	Source	Country of study	Woody species (or source)	Crop of study	Yield data rows
Agroforestry					
Bayala (2002)	PhD thesis	Burkina Faso	*Parkia biglobosa, Vitellaria paradoxa*	Sorghum, Millet	8
Boffa (1999)	Agroforestry Systems	Burkina Faso	*V. paradoxa*	Sorghum	2
Charreau and Vidal (1965)	Agronomie Tropicale	Senegal	*Faidherbia albida*	Millet	2
Depommier *et al.* (1992)	Proceedings	Burkina Faso	*F. albida*	Sorghum	6
Diakhaté *et al.* (2013)	European Journal of Agronomy	Senegal	*Piliostigma reticulatum*	Millet	1
Dibloni *et al.* (1999)	Report	Burkina Faso	*Albizzia lebbeck, F. albida, Prosopis africana*	Sorghum	18
Dossa *et al.* (2012)	Agronomy Journal	Senegal	*Guiera senegalensis*	Groundnut, Millet	7
Dossa *et al.* (2013)	Agronomy Journal	Senegal	*Piliostigma reticulatum*	Groundnut, Millet	7
Dan Lamso *et al.* (2016)	International Journal of Biological and Chemical Sciences	Niger	*G. senegalensis, Hyphaene thebaica*	Millet	4
Harmand *et al.* (1996)	Cahiers Scientifiques	Cameroon	*F. albida*	Sorghum	4
Jonsson *et al.* (1999)	Experimental Agriculture	Burkina Faso	*P. biglobosa, V. paradoxa*	Millet	4
Kizito *et al.* (2007)	Journal of Arid Environments	Senegal	*P. reticulatum, G. senegalensis*	Millet	2
Louppe *et al.* (1996)	Cahiers Scientifiques	Senegal	*F. albida*	Groundnut, Millet	18
Maiga (1987)	MSc thesis	Burkina Faso	*F. albida, P. biglobosa, V. paradoxa*	Millet, Sorghum	6
Oliver (1996)6	Cahiers Scientifiques	Burkina Faso	*F. albida*	Sorghum	6
Pouliot *et al.* (2011)	Agroforestry Systems	Burkina Faso	*P. biglobosa*	Chili pepper, Eggplant, Millet, Taro	6
Sanou *et al.* (2011)	PhD thesis	Burkina Faso	*Adansonia digitata, P. biglobosa*	Millet, Taro	4
Sidibe (2010)	PhD thesis	Mali	*Tamarindus indica*	Eggplant local, Sorghum	6
Wezel (2000)	Agroforestry Systems	Niger	*G. senegalensis*	Millet	8
Wilson *et al.* (1998)	Experimental Agriculture	Burkina Faso	*P. biglobosa*	Sorghum	2
Yaméogo (2008)	PhD thesis	Burkina Faso	*Borassus akeassii, F. albida*	Maize	2
Yélémou *et al.* (2013a)	Tropicultura	Burkina Faso	*P. reticulatum*	Sorghum	18
Zomboudré *et al.* (2005)	Biotechnol. Agron. Soc. Environ.	Burkina Faso	*V. paradoxa*	Maize	4

Table 2.3. *Continued*

Authors	Source	Country of study	Woody species (or source)	Crop of study	Yield data rows
Ramial Wood (Buried)					
Barthès *et al.* (2015)	Agroforestry Systems	Burkina Faso	*P. reticulatum*	Sorghum	12
Roose *et al.* (1999)	Arid Soil Research and Rehabilitation	Burkina Faso	*Azadirachta indica*	Sorghum	8
Samba (2001)	Annals of Forest Science	Senegal	*Cordyla pinnata*	Millet, Peanut	9
Soumare *et al.* (2002)	Biological Agriculture and Horticulture	Senegal	*Casuarina equisetifolia*	Tomato	6
Ramial Wood (Mulch)					
Barthès *et al.* (2015)	Agroforestry Systems	Burkina Faso	*P. reticulatum*	Sorghum	6
Bayala *et al.* (2003)	Arid Land Research and Management	Burkina Faso	*P. biglobosa, V. paradoxa*	Millet	16
Belliard (2014)	BSc thesis	Burkina Faso	*Piliostigma reticulatum*	Cowpea, Sorghum	6
Chiroma *et al.* (2006)	Experimental Agriculture	Nigeria	wood waste	Sorghum	12
Ibrahim *et al.* (2015)	Nutrient Cycling in Agroecosystems	Niger	*Acacia tumida*	Millet	12
Mando and Stroosnijder (2006)	Soil Use and Management	Burkina Faso	*Pterocarpus lucens*	Natural vegetation	8
Ouédraogo (2014)	MSc thesis	Burkina Faso	*P. reticulatum*	Cowpea	6
Salau *et al.* (1992)	Soil & Tillage Research	Nigeria	woodshavings	Plantain	1
Sanou (2015)	MSc Thesis	Burkina Faso	*P. reticulatum*	Sorghum	6
Shiyam *et al.* (2011)	World Journal of Agricultural Sciences	Nigeria	sawdust mulch	Cocoyam, Plantain	8
Somé (2014)	MSc Thesis	Burkina Faso	*P. reticulatum*	Sorghum	6
Tilander and Bonzi (1997)	Plant and Soil	Burkina Faso	*Acacia holocericea, A. indica*	Sorghum	6
Wezel and Böcker (1999)	Soil & Tillage Research	Niger	*G. senegalensis*	Millet	4
Yélémou *et al.* (2014)	Journal of Plant Studies	Burkina Faso	*P. reticulatum*	Sorghum	12
Yossi *et al.* (2002)	Report	Mali	*Prosopis africana*	Millet	2

Table 2.4. Botanical families, Latin, and English names of woody perennial species included in this meta-analysis.

Botanical family	Latin name	English name
Anacardiaceae	*Sclerocarya birrea* (A. Rich.) Hochst.	Marula nut
Arecaceae	*Borassus akeassii* Bayton, Ouédr. & Guinko	Palmyra palm
Arecaceae	*Hyphaene thebaica* L.	Doum palm
Bombacaceae	*Adansonia digitata* L.	Baobab
Casuarinaceae	*Casuarina equisetifolia* L.	Australian pine tree
Combretaceae	*Guiera senegalensis* J.F. Gmel.	Moshi medicine
Fabaceae - Cesalpinaceae	*Cordyla pinnata* Lepr. ex A. Rich.	Bush mango
	Piliostigma reticulatum (DC) Hochst	Camel's foot
	Tamarindus indica L.	Tamarind
Fabaceae - Mimosaceae	*Acacia holosericea* Cunn. ex G. Don	Fish poison/soapy wattle
	Acacia tumida F. Muell. ex Benth.	Pindan wattle
	Albizzia lebbeck (L.) Benth.	Koko
	Faidherbia albida Del.	Winter thorn
	Parkia biglobosa Jacq.	Néré, African locust tree
	Propsopis africana (Guill., Perrott. & Rich.) Taub.	Kirya, Ayan
Fabaceae - Papilionoideae	*Pterocarpus lucens* Lepr. ex Guill. et Perrott.	Barwood
Meliaceae	*Azaridachta indica* A. Juss.	Neem, Indian lilac
Sapotaceae	*Vitellaria paradoxa* C.F.Gaertn.	Karité, Shea nut tree
Zygophyllaceae	*Balanites aegyptiace* Del.	Desert date

Table 2.5. Potential woody biomass of three trees and three shrubs on a village territory of 47 km2 in Guié, Centre-North Burkina Faso. Data source: Kabré (2010).

Species	Woody plant type	% stems sampled	Woody branches biomass sampled <7 cm (kg DM.ha-1)	Woody twigs biomass sampled <2 cm (kg DM.ha-1)	Total Woody biomass sampled (kg DM.ha-1)
Acacia machrostachya	Tree	17	nd	nd	nd
Combretum micranthum	Shrub	13	32	18	50
Cassia sieberiana	Tree	13	61	38	99
Vitellaria paradoxa	Tree	11	356	290	646
Guiera senegalensis	Shrub	5	8	6	14
Piliostigma reticulatum	Shrub	4	10	10	20
Total		63	467	362	829

nd=no data

Chapter 3: Ramial wood amendments (*Piliostigma reticulatum*) mitigate degradation of tropical soils but do not replenish nutrient exports

Abstract:
Restoring degraded soils to support food production is a major challenge for West African smallholders, who have developed local innovations to counter further degradation. The objective of this study was to evaluate a local farmer's technique that uses ramial wood (RW) as soil amendment (*Piliostigma reticulatum* shrub species). Three treatments were applied in an experimental plot in Burkina Faso: control (no amendment), low-RW (3 Mg FM ha^{-1} yr^{-1}), and high-RW (12 Mg FM ha^{-1} yr^{-1}), RW was chipped to <5 cm pieces and either buried or mulched. Topsoil carbon (C), nitrogen (N) and phosphorus (P) in control and low-RW treatments declined after seven years of continuous sorghum cultivation . Use of high-RW amendment stabilized soil C content while N and P declined, thus not replenishing nutrient exports. Net contribution to soil C in the 0-15 cm layer was 15% of the applied C in the high-RW amendments. Although biomass and grain yields were higher in high-RW treatments, crop productivity declined throughout the experiment for all treatments. Termite casts on RW treatments evidenced the potential role of wood-foraging termites in diluting the impact of RW on soil fertility build-up and soil water content. We conclude that mitigating soil degradation under semi-arid conditions in Burkina Faso would require large amounts of woody amendments, particularly if the level of termite activity is high. Additional nutrient sources would be needed to compensate for removal in exported products so that biomass and grain production can be stabilized or increased.

Keywords:
Adaptation, Farmer innovation, Sahel, Shrub material, Termites

Published as: Félix GF, Clermont-Dauphin C, Hien E, Groot JCJ, Penche A, Barthès BG, Manlay RJ, Tittonell P, & Cournac L. 2018. Land Degradation & Development 29(8): 2694-2706. DOI: 10.1002/ldr.3033

1. Introduction

The majority of the rural population of West Africa cultivates the soil to produce crops for self-subsistence, using small amounts of external inputs and no irrigation (Masse *et al.*, 2011; Douxchamps *et al.*, 2015). Historically, these farming systems relied on fallow periods to restore soil fertility (Hiernaux *et al.*, 2009). The re-growth of native woody and herbaceous vegetation in fields left as fallow for 10 to 20 years would be eventually cut down, burnt on site, used as fuelwood, or more rarely, re-incorporated in the soil, restoring soil carbon and nutrients (Wezel & Haigis, 2002; Hiernaux *et al.*, 2009). Fallow and agricultural fields would alternate and rotate in time in these savanna ecosystems. Shortened fallow periods have been observed all over the region in the last few decades, associated with increased demographic pressure and the introduction of cash crops (CSFD, 2015; Diarisso *et al.*, 2015b). High demand for agricultural land has provoked a shift towards continuous cultivation, leading to severe soil degradation ranging from 2-3% (in Niger, Mali, Burkina Faso) and up to 9-17% (in Nigeria, Gambia, Senegal) of the agricultural soils in the region (Bai *et al.*, 2008).

When vegetation is cleared by people to address the need for land, scarce cover makes semi-arid West Africa (SWA) soils prone to degradation (Couteron & Kokou, 1997; Savadogo *et al.*, 2007; Sop & Oldeland, 2013). In particular, wind and water erosion and decreasing organic matter and nutrient contents in soils (Ganry *et al.*, 2001; Roose & Barthès, 2001), may lead to the formation of physical crusts on topsoil layers (Mando & Stroosnijder, 2006; Bationo *et al.*, 2007). Intensive plot-level management is required to counter land degradation at landscape level. Experience in the region indicates that soil structure and fertility could be rehabilitated by: (1) reducing water run-off and land erosion through creation of permeable micro-dykes (e.g. stone bunds or grass strips); (2) re-establishing macroporosity of soil and deep rooting capacity through localized tillage (e.g. *zaï* or half-moons); (3) stabilizing porosity by incorporation of organic matter; (4) revitalizing surface horizon by application of composted organic matter (e.g. domestic waste compost, animal manure); (5) increasing soil pH over 5 to reduce Al and Mg toxicity; and, finally (6) ensuring balanced crop nutrition by complementing organic amendments with nitrogen (N) and phosphorus (P) inputs (Roose *et al.*, 1999; Kathuli & Itabari, 2015).

Organic matter resources play a central role in soil rehabilitation (Mando, 1997a; Zougmoré *et al.*, 2003), as long as minimum effective doses are not in short supply. Organic resources traditionally used to restore soil fertility, such as crop residues, compost, and animal manure are subject to competing uses within smallholder farming systems (Erenstein *et al.*, 2015). Woody perennial species such as shrubs and trees are often present in these landscapes, providing numerous ecosystem services to farming families (Sop *et al.*, 2012; Bayala *et al.*, 2014; Sinare & Gordon, 2015b). In dryland agroecosystems, trees, and especially shrubs, may supply renewable quantities of branches and leaves useable to amend degraded soils (Lahmar & Yacouba, 2012; Breton *et al.*, 2016; Hueso-González *et al.*, 2016). Several studies on the use of such soil amendments, known as ramial chipped wood (RCW; in French, *bois raméal fragmenté*) were conducted in temperate regions, and they showed potential to restore soil functions, particularly of soil fungi and microbial communities (Barthès *et al.*, 2010; Breton *et al.*, 2015; Breton *et al.*, 2016). To what extent can soil productivity be restored in this way, how long will it take to rehabilitate severely degraded soils in a semi-arid tropical environment, and at what costs for farming families are questions that remain poorly explored in the context of SWA. In a study assessing effects of the native shrub amendments (*Piliostigma reticulatum* DC. Hoscht.) on soils and crops, Barthès *et al.* (2015) reported no significant yield differences with application of 3 Mg fresh mass (FM) ha^{-1} yr^{-1} of buried or mulched material on sorghum yields as compared to control or crop residue application. From that experience, conducted between 2007 and 2009 at Gampéla, Burkina Faso, the experiment described in this paper was partly modified by introducing higher rates of RW application in 2010 (12 Mg FM ha^{-1} yr^{-1}), incorporated or as mulch, and continued until 2013.

Here we present an analysis of the complete data series, from 2007 to 2013, to evaluate the potential of RW amendments to cope with agricultural soil degradation. RW consists of small branches and leaves of a native shrub species (*Piliostigma reticulatum* DC. Horscht.) as soil cover, at the on-set of rainy season. We hypothesised that application of RW as soil amendment has beneficial impacts on both soil quality and plant growth conditions, translating in crop yield increases, a necessary condition to ensure farmers´ adoption of this soil rehabilitation technique. Specifically, we studied the effect of two application rates (3 and 12 Mg ha^{-1}) with two modes of application (mulched or mixed in the soil profile) of woody amendments on topsoil organic matter and nutrient stocks and on sorghum yields in a continuously cultivated system (cereal monoculture).

2. Materials and methods

2.1. Study site

The experiment was conducted on the field station of Gampéla (12°24’35” N, 01°21’05” W), located 15 km North-East of Ouagadougou, Burkina Faso (Fig. 3.1a). Elevation is approximately 300 m.a.s.l., climate is of the Sudano-Sahelian type, with rainfall concentrated in one short rainy season, ranging between 700 and 1000 mm yr^{-1}, and generally distributed from May through October (Fig. 3.1b). The annual rainfall during the experimental period between 2007 and 2013 averaged 823 mm yr^{-1}, and was lowest in 2011 (728 mm) and highest in 2012 (973 mm). Mean annual temperature in the region is 28°C, with the highest temperature usually occurring by April (40-43°C), before the planting season starts, and the lowest temperatures occurring around December (18°C), when crops have already been harvested.

Gampéla field station is located in a slightly undulating landscape, with a slope steepness of on average 2%. Savanna type vegetation surrounds the experimental plot. Naturally-occurring species composition varies according to landscape features, as described in Table 3.1. Soils on the station are classified as endogleyic Acrisols, presenting silty sand texture in the topsoil and silty clay in the subsoil (FAO, 2015). A large proportion of the land area of Burkina Faso is characterized by this soil type (Hien *et al.*, 2010), which is generally suitable to grow crops like sorghum, millet, maize, cowpea, peanut, and groundnut, as evidenced on the neighbouring fields around Gampéla experimental field station.

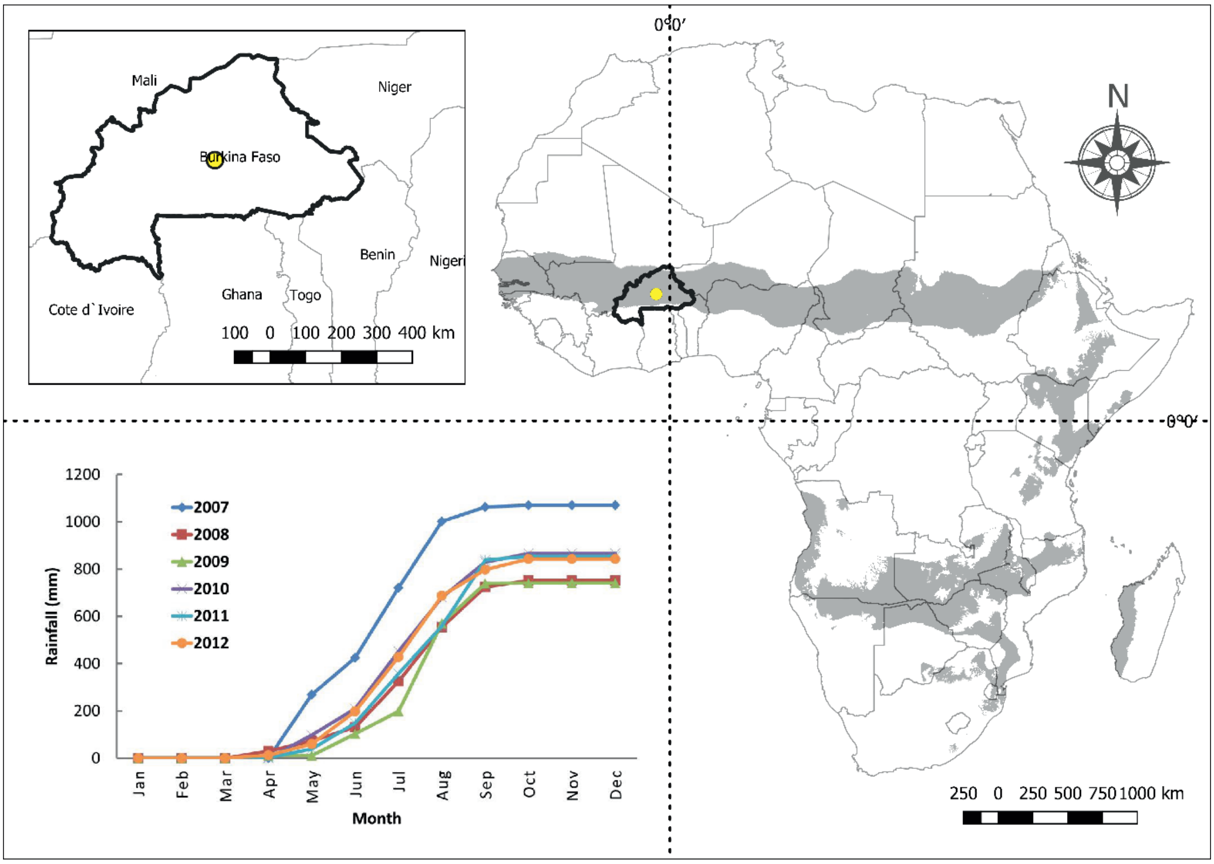


Figure 3.1. Geographical location and rainfall patterns (2007-2012) at Gampéla experimental field station (yellow dot), within semi-arid West Africa (shaded area). Agroecological zones available at: https://harvestchoice.org/data/aez5_clas. Rainfall data: Edmond Hien, IRD Ouagadougou.

2.2. Experimental design

The trial was implemented on a field that had been under natural herbaceous fallow during four years (2001 through 2005). In 2006, the field was uniformly sown with sorghum (manual cropping, no inputs). Experimental setup consisted of a randomized complete block design, with four blocks oriented perpendicularly to the main slope. Each block comprised six 6 × 5 m² plots, each separated by 1 m aisles, and the total experimental area covered 972 m^2. All treatments were homogeneously cropped with *Sorghum bicolor* L. Moench. (var. *Sariasso*) as sole crop with a row distance of 0.8 m, distance of 0.4 m within rows, and a plant density of 31,250 plants ha^{-1}.

Across the whole study, treatments that included woody amendments involved the application of *Piliostigma reticulatum* DC. Hoscht ramial wood as branches <2 cm in diameter, with their leaves, chipped with machete in pieces ≤5 cm long. This non nitrogen-fixing plant (*Fabaceae* family, formerly *Cesalpinaceae*) is common in Sudano-Sahelian areas (Arbonnier, 2002). *P. reticulatum* was selected as soil amendment for (a) its high abundance in the surrounding landscape (cf. Table 3.1) and (b) its characteristic fast renewal of vegetative organs upon land clearing even under continuous soil cultivation (Ky-Dembele *et al.*, 2007; Yélémou *et al.*, 2007). From 2007 through 2009, the experimental setup included treatments with the application of 3 Mg FM ha^{-1} yr^{-1} of woody shrub (*Piliostigma reticulatum* DC. Horscht.) material or sorghum (*Sorghum bicolor* L. Moench.) straw, either mulched (treatments WoMu3t and StMu) or buried (WoBu3t and StBu, see Table 3.2 for a detailed description of treatments, including fertilization).

Synthetic fertilizers were added to the straw treatments so that nutrient supply in wood and straw treatments was the same (2007-2009). One additional treatment with buried woody material received extra synthetic N (WoBu3t+N), and there was an untreated control plot (results reported in Barthès *et al.*, 2015). From 2010 through 2013, the experimental layout remained the same but the focus of the experiment shifted from an objective of comparing effects of two sources of organic amendments (straw vs. wood) to an objective of comparing two different rates of the same source of organic matter (only woody material), featuring a "low-RW" rate of 3 Mg FM ha^{-1} yr^{-1} (3t) *vs*. "high-RW" rate of 12 Mg FM ha^{-1} yr^{-1} (12t). Treatments with mulched or buried sorghum straw (StMu and StBu) were replaced in 2010 with high-RW mulched or buried (treatments WoMu12t and WoBu12t). The results of the experiment during the 2007-2009 period showed that the effects of RW and straw additions on topsoil properties and sorghum yields were similar (Barthès *et al.*, 2015). As, in addition, minerals added to straw (to provide similar amounts of N, P and K as RW) rendered comparison between both amendments difficult (because mineral N, P and K were in a much more available form), it was decided to address the question of amendment rate rather than continue studying the question of its woody vs. herbaceous nature. Thus, our analysis takes into account this shift as described in Table 3.2, by analysing two separate periods:

(1) A seven-year experiment (2007-2013) with four treatments conducted throughout the whole period (WoMu3t, WoBu3t, WoBu3t+N and Ctrl), and,

(2) A four-year experiment (2010-2013) including two new treatments (WoMu12t and WoBu12t) following practices of sorghum straw application (treatments StMu and StBu).Treatments tested from 2007 to 2009 had little significant effects on topsoil properties, especially the woody vs. herbaceous nature of the organic amendment (Barthès *et al.*, 2015): considering soil C, N and available P (P_{av})

concentrations at 0-5 and 5-15 cm depth at 2009 harvest, the only parameter significantly affected by the treatments was P_{av} at 0-5 cm, which was lower in WoBu, WoBuN and StBu than in WoMu and StMu (and intermediate in Ctrl), also as a significant result of initial P_{av} (2007) though it did not differ significantly between treatments to be set up. Thus we considered that the two new treatments and the four old ones had comparable backgrounds in 2010 and the analysis could be conductedover the following experimental period.

2.3. Data collection

2.3.1. Soil parameters

Soil samples were collected before the onset of this trial in April 2007 at 0-5 cm depth, and from 2008 through 2013 after harvest at 0-5 and 5-15 cm depths. Sampling depth corresponded to approximate soil disturbance depth in the region with the use of manual tools, at which most soil transformations occur. Each soil sample resulted from thoroughly mixing three subsamples diagonally distributed across each plot (e.g. near two corners of the plot and in the centre). After air-drying during 48 h, aggregates in soil samples were gently crushed using pestle and mortar, and sieved through 2 mm. Aliquots were then ground at 0.2 mm, packed in plastic jars and transported to Dakar, Senegal, for analysis at the LAMA facilities in *Laboratoire Mixte International IESOL* (LMI IESOL; http://lama.ird.sn/prestations/index.htm). Total soil C and N were measured by dry combustion using an elemental analyzer (CHN Fisons/Carlo Erba NA 2000, Milan, Italy). On carbonate-less soils, total C equals organic C. Soil mineral N (NO_3 and NH_4) was extracted by potassium chloride (KCl) then was measured by colorimetry. Total soil P was extracted by acid mineralization using a boiling mixture of chlorhydric (2/3) and nitric (1/3) acids, then was measured by colorimetry. Soil available P (P_{av}) concentration was determined on 0.2 mm-ground aliquots using the Olsen procedure for samples collected in 2007 and 2008 (extraction using sodium bicarbonate at pH 8.5), and the Olsen-Dabin procedure for samples collected from 2009 onwards (extraction using sodium bicarbonate and ammonium fluoride at pH 8.5), both with colorimetric assay.

2.3.2. Crop productivity

Sorghum grain and aboveground biomass weight were measured every year at harvest (October-November) on each plot by taking into account only the central zone of each plot, corresponding to 16.4 m^2 (out of 30 m^2). The sampling scheme intended to minimise possible border effects on outer rows of each plot. At harvest, grain and total aboveground biomass were weighed after air-drying in the shade for a period of at least 10 days. Mean yields (±SD) are provided in dry matter (DM) per hectare. Harvest data of 2013 was not included since drought and bird predation led to complete crop failure.

2.3.3. Termite foraging activity

As a proxy to termite activity, cast abundance was characterized at the beginning of planting seasons in 2010 and 2011. On each 30 m^2 plot (n=24), ten repetitions across the plot were conducted using a 1 m^2 square frame including a grid of 100 squares of 10 cm^2 each. The number of squares with cast presence was counted to determine the relative abundance, expressed as a percentage of total number of squares in the grid. Observations were averaged per plot and per year, one measure being conducted in 2010 and two in 2011, prior to planting but after RW application.

2.4. Data analyses

Statistical analyses were performed using the R software v3.3.2 (RCoreTeam, 2016). We conducted stepwise multiple regression and ANOVA analyses to assess effects of explanatory factors (block, year, treatment) on response variables (crop yields, soil carbon and nutrient contents). Grain, total aboveground biomass, and termite cast presence were considered response variables. Soil C, total N, mineral N, total P, and P_{av} (0-5 and 5-15 cm depths) were considered as response variables to treatments and as explanatory variables for crop productivity and termite cast presence. Possible interactions (Year:Treatment) and quadratic terms ($Year^2$) were additionally assessed for changes in residual sum of squares on individual response variables, using *AddTerm,* a forward model selection function in R (package MASS). Terms were added to the model provided they resulted in a significant ($p < 0.05$) reduction in the residual mean square.

3. . Results

3.1. Effect of ramial wood on topsoil carbon and nutrient content

Soil C content at 0-5 cm and 5-15 cm depths declined linearly when no (Ctrl) or low rates of RW (WoMu3t, WoBu3t, and WoBu3t+N) were applied during the 7-year period of the trial (Fig. 3.2a and 3.2b). Initial C content at 0-5 cm prior to planting in 2007 was on average 3.4±0.4 g kg^{-1}. After the seventh year of continuous sorghum cultivation, soil C content at harvest in 2013 had decreased to an average of 2.4±0.4 g kg^{-1}, with a significantly higher C content for treatment WoBu3t compared to other low-RW and control treatments (Fig. 3.2a). When high-RW treatments (WoMu12t and WoBu12t) were introduced in 2010, their effect resulted in stabilization of soil C content at 0-5 cm depth to 3.2±0.4 g kg^{-1} in average, over the last four-year period. Soil C content declined linearly at 5-15 cm depth and for all treatments, except for buried high-RW (WoBu12t), which maintained C contents over time (Fig. 3.2b; Table 3.3).

In the studied horizons (0-15 cm), total soil C stock (Mg ha^{-1}) declined by an estimate 5.3% per year for control and WoBu3t and WoMu3t treatments, by 2.7% for both WoBu3t+N and WoMu12t treatments, and by 0.7% for WoBu12t treatment. WoMu12t and

WoBu3t+N treatments were partly able to compensate the C degradation while WoBu12t treatment was able to compensate C loss almost completely, as compared to control. The net addition of buried high-RW rates (2.8 Mg C ha^{-1} yr^{-1}) is thus equal to the decline in C without any amendment. C loss in control was 0.4 Mg SOC ha^{-1} yr^{-1}, meaning that an equivalent 15% of buried C input at high-RW rates (WoBu12t) was remaining on the plot and was enough to compensate for soil C losses as observed in control plots for the 0-15 cm depth layer.

Total soil N (N_{tot}) content in both 0-5 and 5-15 cm-depths decreased over time and for all treatments (Fig.s 3.2c and 3.2d; Table 3.3). Soil N content at 0-5 cm-depth for low-RW treatments and control declined from 0.23±0.02 g kg^{-1} after second harvest to 0.16±0.03 g kg^{-1} after seventh harvest. Under high-RW application rates, soil N content was higher than under low-RW but declined linearly as well (Fig. 3.2c and 3.2d). The mode of RW application (buried or mulched) did not result in significant N differences at 0-5 cm depth. At 5-15 cm, the N_{tot} content for WoBu12t was higher than for the other treatments (R^2=0.1, $p<0.001$). Treatment WoMu12t N_{tot} contents was only slightly but significantly higher (R^2=0.4, $p<0.1$) than the control and low-RW treatments. Annual N_{tot} decline for the studied period and soil horizons (0-15 cm) was on average 4.7% (all treatments), with the lowest decline observed for WoBu3t+N (4%) and strongest for WoMu12t (5.5%).

Mineral N (N_{min}), measured at harvest, was variable between years with a tendency to slightly increase during the first years of the experiments and declined after the fourth year of measurement. N_{min} contents were homogeneous between all treatments, and at both studied depths (Fig. 3.2e and 3.2f; Table 3.3).

Variability in topsoil total P (P_{tot}) per treatment and per year content was observed (Fig. 3.3a and 3.3b). Nevertheless, at 0-5 cm depth P_{tot} declined for low-RW application and control while general stability was observed for high-RW application (Fig. 3.3a; Table 3.3). At 5-15 cm depth, high-RW application resulted in significant increase in time in soil P_{tot} content, while the mulched RW (WoMu12t) treatment showed higher P_{tot} contents than buried amendments (WoBu12t) (Fig. 3.3b; Table 3.3).

P_{av} content at 0-5 cm depth before planting in 2007 averaged 7.9±1.0 ppm, and declined strongly during the first years of the experiment but then stabilized at an average 4.9±3.6 ppm (Fig. 3c; Table 3.3). At both studied depths, P_{av} declined over time without significant differences between treatments (Fig. 3.3c and 3.3d).

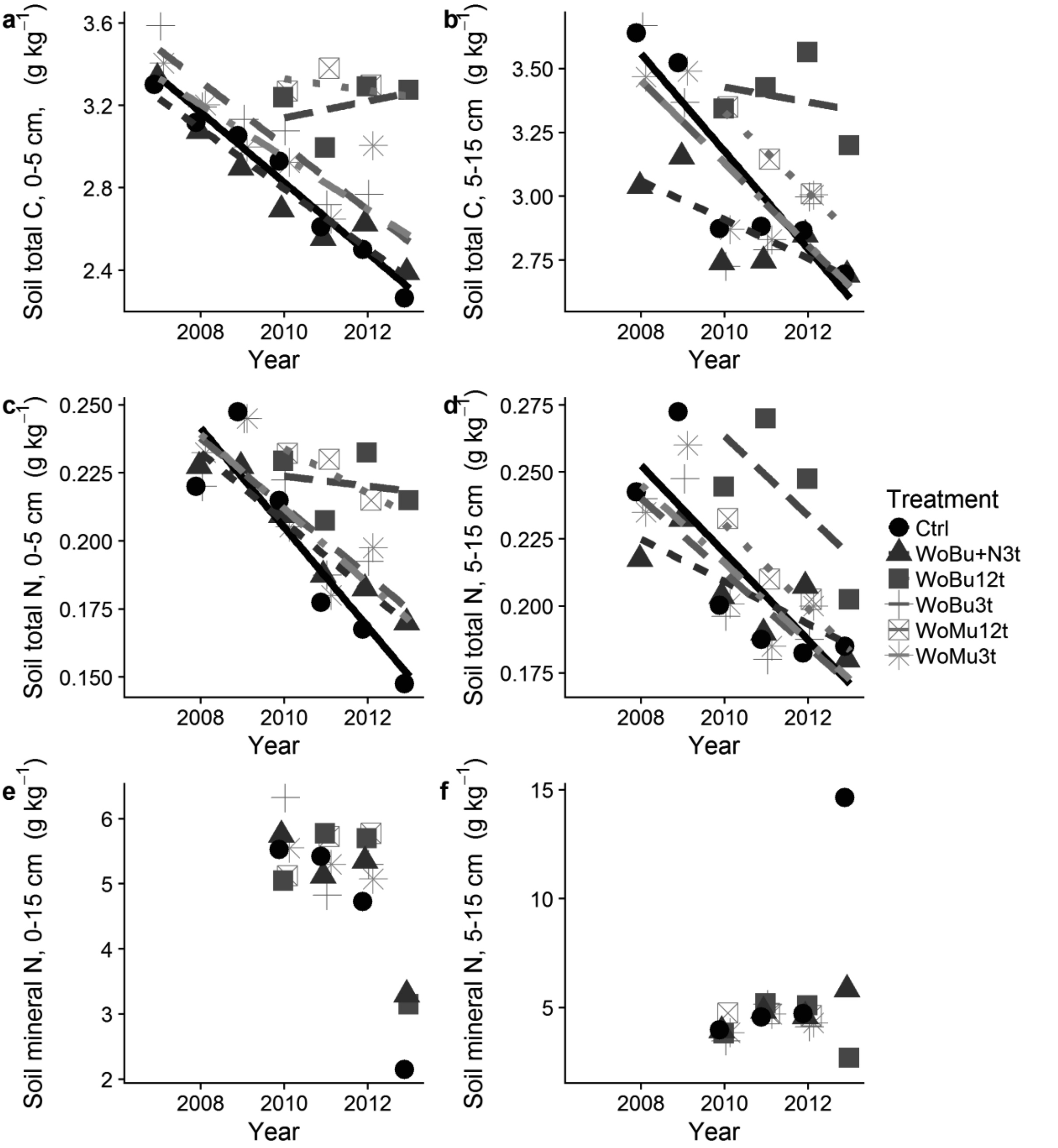


Figure 3.2. Topsoil content of carbon (C, a and b), total nitrogen (N, c and d), and mineral nitrogen (NO3 + NH4, e and f) as affected by absence (Ctrl) or low rates of woody amendment application (either mulched: WoMu3t or buried: WoBu3t, or buried with nitrogen fertilizer added: WoBu3t+N) from 2007 to 2013, and high rates of amendment application (WoMu12t and WoBu12t) from 2010 to 2013, at 0-5 cm (a, c, e) and 5-15 (b, d, f) cm depth. Lines indicate trends, details of the regression analysis are provided in Table 3.3.

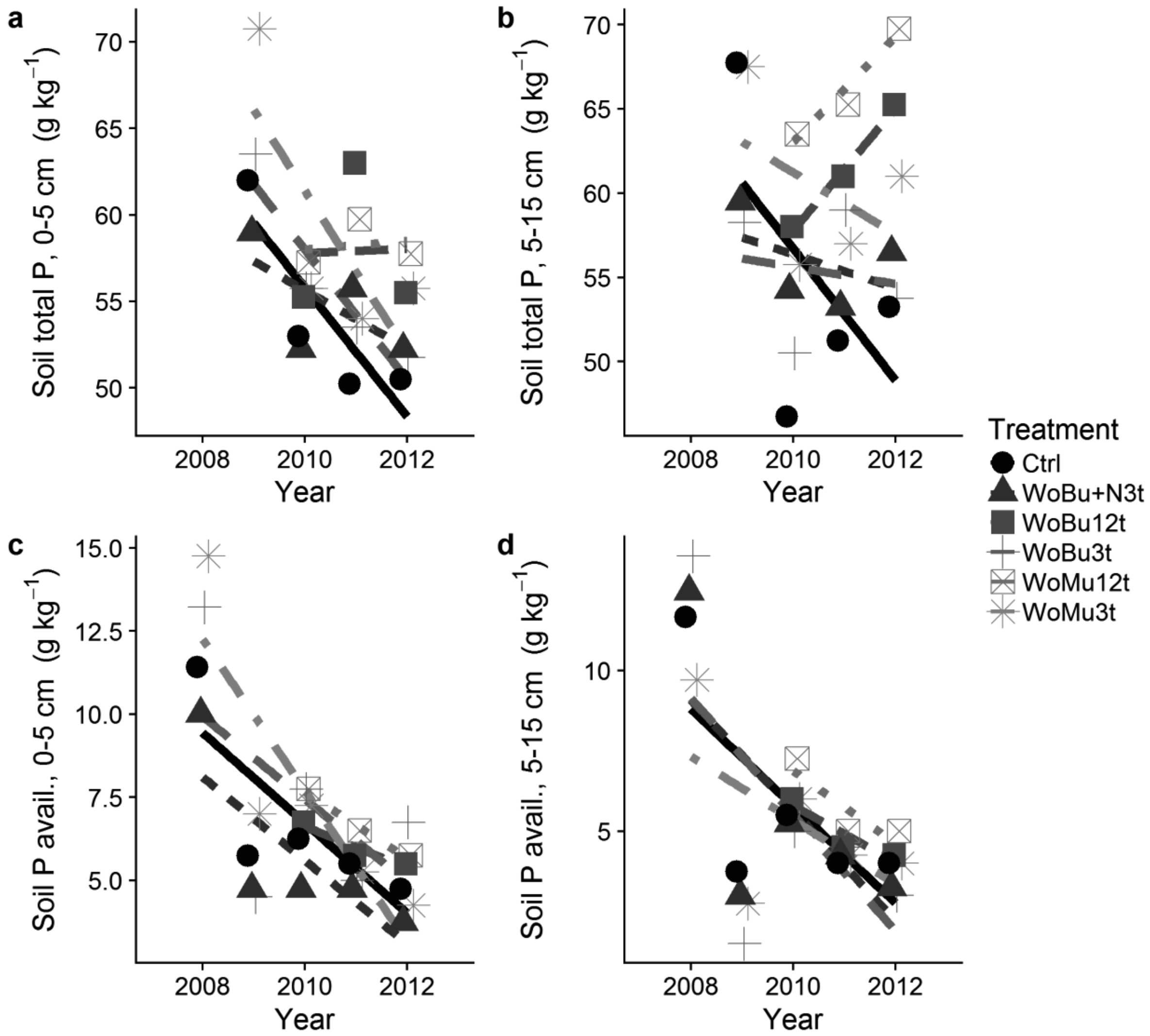


Figure 3.3. Trends for topsoil total phosphorus (P; a and b) and available P (Pav; c and d) as affected by no (Ctrl) or low rates of woody amendment application (WoMu3t, WoBu3t, or WoBu+N 3t) from 2007 to 2013, and high rates of amendment application (WoMu12t and WoBu12t; dash and dots line) from 2010 to 2013, at 0-5 cm (a, c) and 5-15 (b, d) cm depth. Lines indicate trends, details of the regression analysis are provided in Table 3.3.

3.2. Effect of ramial wood on crop productivity

Sorghum grain production declined for subsequent years, and for all treatments, although significant differences were found between treatments (Fig. 3.4a). Control and low-RW treatments yielded an average 0.8±0.3 Mg ha^{-1} at the first grain harvest and declined after six years of continuous cropping, to an average 0.2±0.2 Mg ha^{-1}, in 2012. Aboveground total biomass for control and low-RW followed a similar trend as grain yields, declining from 4.0±0.9 to 0.5±.04 Mg ha^{-1} (Fig. 3. 4b).

Treatment WoBu3t+N yielded slightly higher than other treatments during the period 2007 through 2012 (Table 3.4). When high-RW treatments were introduced in 2010, crop productivity with mulched RW (WoMu12t) yielded significantly more than control and low-RW treatments but less than buried RW (WoBu12t). In fact, high-RW treatments always yielded higher than the control, while low-RW treatments in some cases throughout the study yielded less than control plots (Fig. 3.4c and 3.4d).

3.3. Effect of ramial wood on termite activity

Termites and termite cast abundance was visible to the naked eye in the field (Fig. 5a through 5d). Observation of termite cast presence in 2010 was done after a short rain event, which partly 'erased' the casts from the surface, explaining the strong contrast between years (Fig. 3.6). Trends between termite cast presence and treatments were however clear in both years. Percentage of termite casts was significantly higher for high-RW treatments as compared to low-RW and to control, but was not significantly affected by RW mode of application (buried or mulched).

4. Discussion

In this study at Gampéla, Burkina Faso, a working hypothesis was that RW application as soil amendment would have beneficial short-term effects on both soil quality and plant growth conditions. The practice of mulching RW amendments from native woody shrubs is a farmer innovation (see Lahmar *et al.*, 2012), here tested during 7 years, in on-station field conditions, and featuring several treatments (i.e. control *vs.* high- or low-RW, and mulched *vs.* buried). Results show differences between treatments, featuring low and declining yields but consistently higher yields and enhanced soil conditions when high-RW rates were used (WoBu12t ≥ WoMu12t > WoBu3t+N > WoMu3t = WoBu3t = Ctrl). Treatment effects on soil C, soil nutrients, and crop productivity followed similar trends, suggesting that the highest yields obtained in the high-RW treatments may be partly due to increased nutrient input by high-RW (0.08 Mg N ha^{-1}; low-RW was 0.02 Mg N ha^{-1}). The fact that buried RW in some cases outperformed the effect of mulched RW deserves a closer look by taking into account decomposition dynamics of RW (i.e. by termites), in light of modifications to soil-water dynamics due to RW.

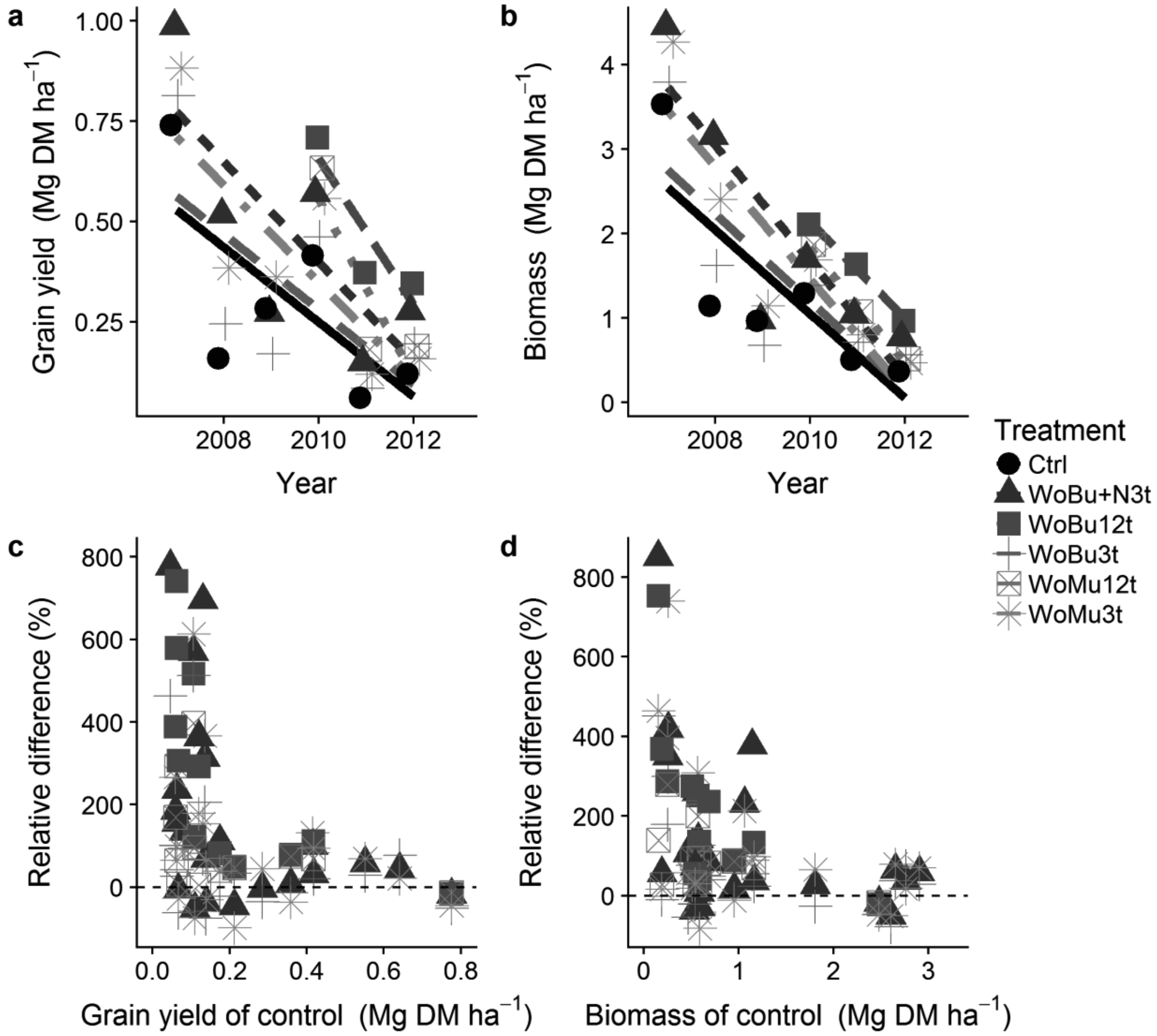


Figure 3.4. Average crop productivity results per treatment and year for sorghum grain yield (a) and total aboveground biomass (b) indicate a declining trend for all treatments and significantly higher yields with the use of high-RW rates (each data-point is the average of 4 observation per year). Treatments yield relative-to-control (in %) for sorghum grain (c) and total aboveground biomass (d) show that high-RW rates of application never yielded lower than control, while low-RW rates in some cases yielded less than control (each data-point is an observation as compared to the yield recorded for control of that block per year).

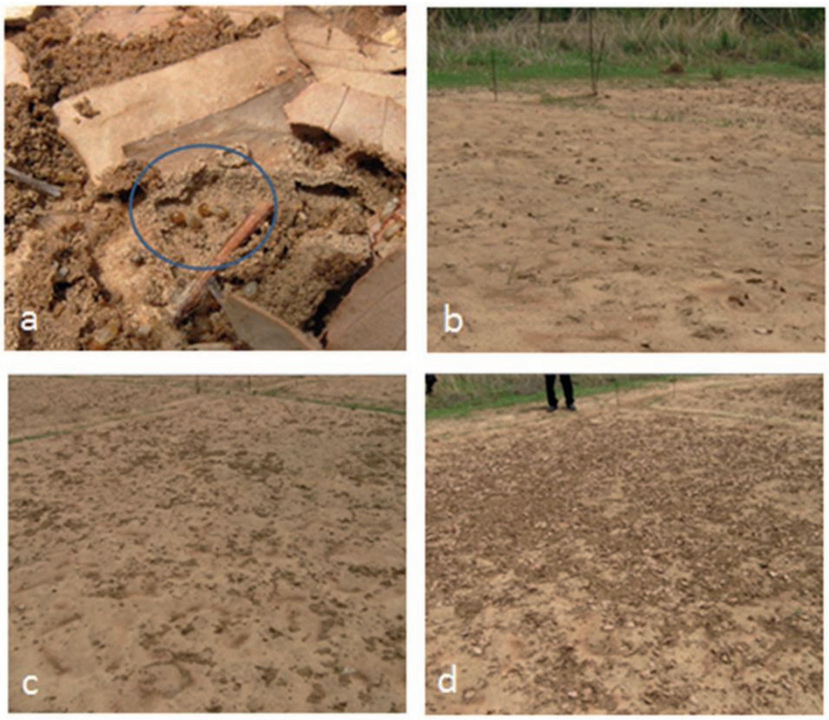


Figure 3.5. Termite cast abundance at Gampéla experimental station at the onset of planting season in 2010. A close-up on termites while foraging on ramial woody and leafy amendments (a) will allow the naked eye to observe low termite cast abundance when no RW mulch is applied (b), medium cast abundance with 3 Mg FM ha-1 year-1 (c), and high abundance of termite casts with 12 Mg FM ha-1 year-1 (d). Photos credit: Aurélien Penche.

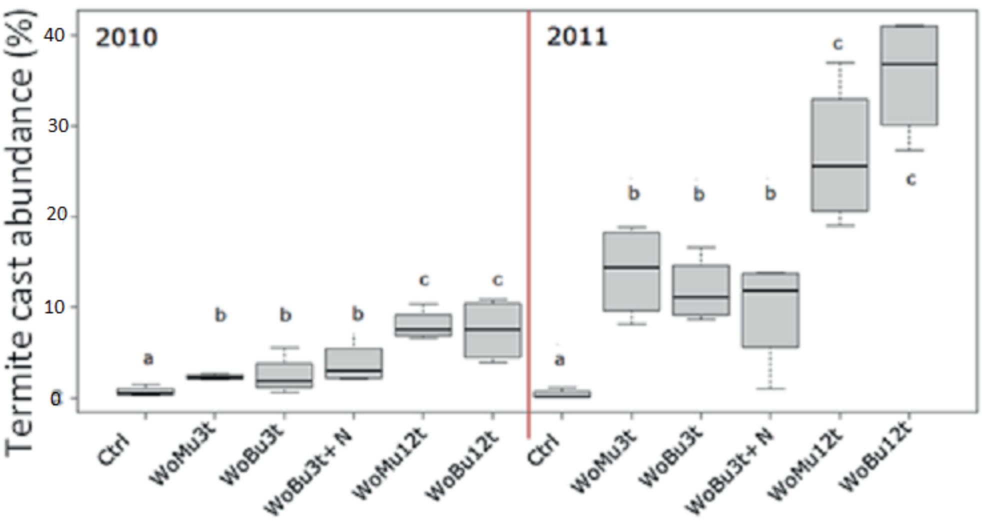


Figure 3.6. Termite cast abundance in % per treatment and per year measured (2010 and 2011), with different letters depicting statistical significant differences at $p<0.05$.

4.1. From local innovation to experimental agronomy

Studies in native agroforestry systems of Central America highlight the significant potential of slash-and-mulch practices on soil C storage (Fonte *et al.*, 2010). In semi-arid West Africa (SWA), mulching with small branches is a common technique to rehabilitate physically degraded soils by broadcasting branches and leaves on specific sectors of a field (CSFD, 2015). On low-fertility soils in farmer fields of Niger, 1-2 Mg DM ha^{-1} shrub material application (*Guiera senegalensis* J.F. Gmel.) had no significant effect on millet yield due to high variability of observed effects between farmer fields (Wezel & Böcker, 1999). On-station experimental studies using *Piliostigma*-based leaf material as soil amendment in Saria, Burkina Faso, showed that at rates of 2.4 Mg DM ha^{-1} in addition to NPK and urea, almost duplicated yields as compared no application (Yélémou *et al.*, 2014). In Gampéla, Burkina Faso, mixed branches and leaves at rates of 1.5 Mg DM ha^{-1} as soil amendments showed only small (and not statistically significant) increases in sorghum grain yields and soil C as compared to no application (Barthès *et al.*, 2015).

Our results over a seven-year trial at Gampéla, Burkina Faso, support the fact that RW applications, at rates of 1.5 Mg DM ha^{-1} (3t) do not allow to increase the sorghum yield, as compared to no-RW application. Higher rates of 6 Mg DM ha^{-1} (12t) allowed grain yield achievements of 0.4 Mg ha^{-1}, as compared 0.2 Mg ha^{-1} in the control, which is an average two-fold increase during the last four years of the study.

In addition to crop yields, our study revealed treatment effects on soil stocks of C, N, and P. Soil C (C_{tot}) content decreased over time despite yearly input of low-RW application (3 Mg FM ha^{-1} yr^{-1}) of woody shrub material, either mulch or buried. For the high-RW treatments (12 Mg FM ha^{-1} yr^{-1}), C_{tot} was maintained over the four-year period of application, especially when buried. Indeed, burying or mulching RW led to differences in soil C decline over time: burying high-RW rates quasi compensated C losses, with a decline of 0.7% yr^{-1}, while mulching the same amount of RW still led to a decline of 3-5% yr^{-1} in soil C content. Even though soil total N (N_{tot}) content was systematically higher with RW application rate, N_{tot} contents decreased for all treatments and at both studied depths (0-5 and 5-15 cm), at an average 5% yr^{-1}. Soil mineral N (N_{min}) was not affected by treatments, rather by rainfall, but general trend was towards decline in time. Soil total P (P_{tot}) decreased over time for low-RW and control treatments but was maintained at 0-5 cm depth and slightly increased at 5-15 cm depth for the high-RW treatments. Available P (P_{av}) decreased in time for all treatments.

In terms of nutrients, *Piliostigma* is a non N-fixing legume shrub with low N, P and K content (Table 3.2) thus, low soil nutrient content and declining yield data is expected under sole-RW input application. The limited capacity of *Piliostigma*-based RW input to replenish nutrient exports is a call for further field research with different sources of RW, as locally found in the regions (Table 3.1), and combination with other nutrient supply sources. Treatment effects on yields may also, be linked to modifications in soil-water dynamics – a known limiting factor for crop growth in the Sahelian region. Additional research with RW should include farmer knowledge through participatory techniques that have proven useful in better understanding soil dynamics while targeting for more efficient resource-allocation strategies (Barrios *et al.*, 2012).

4.2. Where did the carbon input go?

Added carbon could come from both the RW amendment and extra biomass production in the high-RW treatments, but the effect of treatments on belowground growth was limited (root estimation on the basis of 15% aboveground biomass, see Sher *et al.*, 2013). A comprehensive study for the Sahel showed that 0.8 Mg C ha^{-1} yr^{-1} is sufficient to maintain soil C stocks at ca. 5 Mg C ha^{-1} (Nakamura *et al.*, 2012). Accordingly, the $C_{leftover}/C_{input}$ ratio would be of 26% in the agroecosystems described by Nakamura *et al.* (2012). A similar line of reasoning leads to a ratio of 15% in our study, underlining low soil C stocks at Gampéla.

In our experiment, the estimated decline rate in the control treatment was higher (0.42 Mg ha^{-1} yr^{-1}) and the leftover carbon of amendments was lower (15.2% of buried RW), so that a larger amount of 2.8 Mg C ha^{-1} yr^{-1} input required for balancing degradation. This is an unexpected outcome since lignin-rich RW inputs should be prone to slower C mineralisation rates than the crop residues and the manure considered in the study by Nakamura *et al.* (2012). This leaves us with the question: "where did the carbon input go?" The most probable hypothesis to explain the high degradation rates in this experiment is that C was mostly exported in the form of organic particles via termite foraging (Orgiazzi *et al.*, 2016). This hypothesis is coherent with results that show increased termite activity when organic matter inputs are applied, and modelling studies that show termite activity as a non-negligible source of error in soil C prediction models (e.g. Shirato *et al.*, 2005). This also highlights the link between termite activity, organic matter inputs, and soil physical properties, including water dynamics.

Termite casts were monitored only during two years in our study, but there was a clear treatment effect, with significantly higher termite activity as RW application rates increased (12t > 3t > Ctrl). At Gampéla, Barthès *et al.* (2015) found that RW attracted more termite activity than sorghum crop residues in 2008, possibly due to the nature of organic matter (e.g. cellulose in sorghum stalks, lignin in RW). When this experimental setup shifted from crop residue application to higher doses of RW, we observed enhanced termite activity, along with enhanced crop productivity, an element often described in SWA (Sileshi *et al.*, 2009). Whereas termites increase crop growth conditions via enhanced soil physical structure (e.g. increased porosity leading to enhanced water infiltration, upper soil fertilization by nutrient-rich casts), an additional effect of RW could be attributed to organic amendment effects on water dynamics, more likely for high RW application (Barthès *et al.*, 2010): higher infiltration and lower evaporation (especially when mulched), and higher soil water content retention (especially when buried). Interpretation of our data may however, be limited by lack of soil water content data.

Future studies should consider isotopic techniques to trace the magnitude of movement of organic input by termites from experimental plots, jointly with soil water studies.

4.3. Woody resource availability - bottleneck and opportunity

Aboveground standing woody biomass estimates in semi-arid Burkina Faso are low and highly variable, ranging from to 5-7 Mg DM ha^{-1} (Fischer *et al.*, 2011) but rarely exceeding 10 Mg DM ha^{-1} (Cabral, 2011; Feur, 2014). On the one hand, *Vitellaria paradoxa* C.F. Gaertn. constitutes an important share of this biomass, but its use is highly regulated by local and national laws (Elias, 2012; Gallagher *et al.*, 2016), and it is therefore usually inaccessible for farmers as a viable source of RW. On the other hand, shrub species such as *P. reticulatum* and *G. senegalensis* are more abundant in SWA landscapes and accessible as RW but represent less than 1 Mg DM ha^{-1} (Lufafa *et al.*, 2008b; Kabré, 2010), and are, in theory, also subject to national forest regulation. Nevertheless, applying 12 Mg ha^{-1} of fresh wood and leaf material as soil amendment seems unrealistic, or would require considerable concentration of nutrients from larger areas. Alternative ways of increasing the resource should be explored.

Increasingly, the effect of woody shrubs and trees is studied and documented, especially in light of ecosystems services provision in SWA (Dossa *et al.*, 2013; Bayala *et al.*, 2015). More rarely studied is the effect of *in situ* production of agroforestry mulches on crop productivity and soil quality. Farmers from across semi-arid Africa (Fig. 3.1a) can rely on a variety of services from surrounding vegetation by combining soil amendments from a diversity of sources, including trees and shrubs (Table 3.1), and provided little or no trade-offs exist between possible uses (e.g. amendment *vs.* fuelwood or medicine needs). The agronomic minimum crop requirement in light of the landscape constraints on the availability of RW are issues fairly unexplored in the context of semi-arid West Africa.

Farmer-managed natural regeneration (FMNR) could be a feasible and low-investment strategy to increase woody resources locally, and has already been implemented in many drylands of Africa with impressive results (Haglund *et al.*, 2011; Dia & Duponnois, 2012; Bayen *et al.*, 2015). Even though soil and water conservation systems such as stone bunds, *zaï*, half-moons, grass strips, mulching, manuring, and hedgerows are widely accepted in Burkina Faso, planting trees still remains a source of possible conflict between landowners and land users (Ouédraogo & Sorgho Millogo, 2007). When the re-greening occurred in the South of Niger, partly due to a recovery of rainfall after the dry episodes of the 1970s and 80s, it is important to highlight that restrictions on use of tree products were lifted (Reij *et al.*, 2005). In other areas, national forest regulations can be a serious limitation to the motivation of farmers to plant or protect native species. Design options at the plot level should probably be explored at plot and community levels. The adequacy of woody resource availability to attain the desired agronomic effect needs to be tackled from an integrated perspective where RW is not just an input, but also valued for other services rendered by shrub woody perennials. This would additionally support processes such as capture of wind-driven particles (Leenders *et al.*, 2007), hydraulic and nutrient uplift from deeper soil layers (Kizito *et al.*, 2012), and securing of forage provision during the dry season (Schlecht *et al.*, 2006; Zampaligré *et al.*, 2013).

5. Conclusion

Soil carbon (C), soil nutrients (N_{tot}, $N_{mineral}$, P_{tot}, and P_{av}), and sorghum yields declined throughout the duration of the experiment. Sorghum productivity was low in all treatments. Nevertheless yields were stimulated by treatments featuring buried high-RW rates and to some extent by mulched high-RW without fertilization and by buried low-RW rates combined with N fertilization. These findings highlight the fact that ramial wood amendments may mitigate tropical soil degradation but cannot replenish soil nutrient exports. In fact, a technique that is interesting from a certain point of view might not be so performant from another point of view. Our study analysed various crop performance criteria during several years, allowing for an assessment of trade-offs at plot level of RW technology (i.e. soil C stocks *vs.* yield improvements). Enhancing the technology of RW application should take into account these performance criteria and be reasoned in terms of trade-offs and opportunities. Future research efforts should also focus on the effects of RW on water use efficiency by crops. This criterion is likely to be important in a context of climate change, where decreases are foreseen in the periodicity and intensity of rainfall events in semi-arid West Africa.

Our results also show that buried high-RW application rates of 12 Mg FM ha^{-1} yr^{-1} of *Piliostigma* shrub-based material allowed to sustain topsoil C in Acrisols of Burkina Faso, while lower RW application rates resulted in decline of C content throughout the seven-year period of study. We noticed that C leftover in the soil was much lower than expected with high-RW annual rates of C input. The limited capacity of high-RW treatments to increase soil C stocks may be linked to enhanced degradation of C input through termite foraging activity. Employing isotopic techniques to trace the magnitude of movement of organic input by termites from experimental plots, jointly with soil water studies, would greatly contribute in better understanding C dynamics in the region.

From a farmer's perspective the amount of shrub material needed to sustain crop yields with RW seems unrealistic given current biomass availability in the landscape. Reforestation strategies with woody perennials, including shrubs and trees, could however represent opportunities for farming families to further support development of RW technology in SWA, in light of local needs and labour allocation possibilities.

Table 3.1. Vegetation types surrounding Gampéla experimental field station and key species.

Landscape feature	Trees	Shrubs	Herbaceous
Lowland and riverbed	*Anogeissus leiocarpus* (DC.) Guill. & Perr. *Mytragina inermis* (Willd.) K. Schum.		*Vetiveria nigritana* Retz.
Open savanna	*Balanites aegyptiaca* (L.) Del. *Combretum glutinosum* Perr. *Parkia biglobosa* (Jacq.) R.Br. *Sclerocarya birrea* (A. Rich.) Hochst. *Vitellaria paradoxa* C.F.Gaertn.	*Acacia gourmaensis* A. Chev. *Acacia macrostachya* Reichenb. *Balanites aegyptiaca* (L.) Del. *Combretum glutinosum* Perr. *Guiera senegalensis* J.F.Gmel. *Pilostigma reticulatum* (DC.) Hochst. *Ziziphus mauritiana* Lam.	*Andropogon gayanus* Kunth. *Ctenium elegans* Kunth. *Eragrostis tremula* (L.) Hochst. *Loudetia togoensis* (Pilg.) C.E.Hubb. *Pennisetum pedicellatum* Trin.
Close to household compounds	*Azadirachta indica* A.Juss., *Eucalyptus* sp. L'Hér. *Mangifera indica* L.	*Cassia sieberiana* DC. *Combretum micranthum* G. Don. *Pilostigma reticulatum* (DC.) Hochst.	*Andropogon gayanus* Kunth.

Table 3.2. Description of experimental treatments. Average dry matter wood input (Wo) quality was 46.2 % of C, 1.31 % of N, 0.088 % of P, 0.88 % of K, a C:N ratio of 35, and a water content of 49% (years 2007-2013). Average sorghum biomass (St) tissue quality was 43.2% of C, 0.59% of N, 0.042% of P, 0.82% of K, a C:N ratio of 73, and a water content of 2% (years 2007-2009).

Treatment	Cropping system description
Ctrl	2007-2013 (*control*) Cropping system mimicking local farming practices, without any inputs and manually operated. Soils were hoed at 5 cm depth early June and sown uniformly with sorghum (*Sorghum bicolor*) three to four weeks later, when rains were providing enough water to revive adequate soil moisture content for plant growth. Plots were then manually weeded using a hoe, and harvested in October or November, when grain was mature.
WoMu 3t	2007-2013 (*3t ha^{-1} wood mulched, without N*) Similar to Ctrl with addition of 1.5 Mg DM ha^{-1} yr^{-1} ramial woody shrub material (*Piliostigma reticulatum*), manually chipped with machete, mulched on surface and covered with small amounts of soil to prevent biomass dispersal by wind or water runoff.
WoBu 3t	2007-2013 (*3t ha^{-1} wood buried, without N*) Similar to WoMu3t with incorporation of woody shrub material (small branches and leaves) at a rate of 1.5 Mg DM ha^{-1} yr^{-1}, and manually buried at 5 cm depth using a hand hoe.
WoBu 3t +N	2007-2013 (*3 t ha^{-1} wood buried, with N*) Similar to WoBu3t with addition of 9.6 kg N ha^{-1} yr^{-1} as urea, applied two weeks after emergence of sorghum seedlings, in one time.
WoMu 12t	2010-2013 (*12 t ha^{-1} wood mulched*) Similar to WoMu3t with instead, four times the amount of fresh woody shrub material, an equivalent of 6 Mg DM ha^{-1} [previous treatment] 2007-2009 *(*StMu*; straw mulched, with NPK*) Mulched straw from sorghum crop residues at a rate of 1.6 Mg DM ha^{-1} yr^{-1}, covered with small amounts of soil to prevent biomass dispersal by wind or water runoff, and completed with mineral fertilizer (14-23-14) and urea, two weeks after emergence of sorghum seedlings. This fertilization aimed at achieving similar C, N, P, and K applications in both Wood and Straw treatments. Thus, N, P, and K doses under straw treatments were close to 10.47, 0.65, and 0.75 kg ha^{-1}.yr^{-1}, respectively.
WoBu 12t	2010-2013 (*12 t ha^{-1} wood buried)* Similar to WoBu3t with instead, four times the amount of fresh woody shrub material, an equivalent of 6 Mg DM ha^{-1} [previous treatment] 2007-2009 (StBu; *straw buried, with NPK*) Similar to StMu with a modification: crop residues were incorporated into topsoil at 5 cm depth using a hand hoe.

Table 3.3. Contributions to the variance and R2 (%) explained in the multiple regression analysis for soil attributes as affected by blocks, year, treatment effects, rainfall, year quadratic, and year-to-treatment interactions (significance: *** p<0.001, ** p<0.01, * p<0.05, . p<0.1). Treatments with low amendment applications (2007 through 2013): control (Ctrl), ramial wood (RW) mulched 3 Mg ha^{-1} (WoMu3t), RW buried 3 Mg ha^{-1} (WoBu3t), and RW buried 3 Mg ha^{-1} with synthetic fertilizer (WoBu3t+N). Treatments featuring high amendment applications (from 2010 through 3013): RW mulched 12 Mg ha^{-1} (WoMu12t) and RW buried 12 Mg ha^{-1} (WoBu12t).

Soil attribute	Total C		Total N		Mineral N		Total P		Available P	
Sampling depth (cm)	0-5	5-15	0-5	5-15	0-5	5-15	0-5	5-15	0-5	5-15
2007-2013: Treatments with low amendment applications (Ctrl, WoMu3t, WoBu3t, WoBu3t+N)										
Block	0.12***		0.11***							
Year (Y)	0.43***	0.36***	0.43***	0.40***	0.41***		0.16**		0.35***	0.31***
Treatment (T)	0.04*									
Y^2		0.04**			0.08**	0.13**	0.05 .	0.10**	0.12***	0.16***
Y:T										
Rainfall		0.14***	0.08**	0.16***	0.12**	0.13*		0.14**	0.23***	0.41***
Total (R^2_{adj})	0.59	0.54	0.62	0.56	0.60	0.25	0.21	0.25	0.70	0.88
2010-2013: RW treatments (i.e. with high amendment applications WoMu12t and WoBu12t)										
Block	0.15***	0.09**	0.13***	0.06 .			0.10 .			
Year (Y)	0.04**		0.12***	0.07**	0.35***	0.06*		0.04 .	0.08*	0.20***
Treatment (T)	0.36***	0.30***	0.23***	0.27***				0.22**		
Y^2		0.02 .			0.14***	0.18***				
Y:T						0.10 .				
Rainfall		0.03 .			0.17***	0.18***				
Total (R^2_{adj})	0.56	0.44	0.48	0.39	0.67	0.53	0.10	0.25	0.08	0.20

Table 3.4. Contributions to the variance and R^2 (%) explained in the multiple regression analysis for crop productivity parameters as affected by block, year, treatment, rainfall effects, soil attributes (total C, total N, mineral N, total P, and available P) at 0-5 and 5-15 cm depths, and year quadratic and year-to-treatment effects (significance: *** p<0.001, ** p<0.01, * p<0.05, . p<0.1). Treatments with low amendment applications (2007 through 2013): control (Ctrl), ramial wood (RW) mulched 3 Mg ha^{-1} (WoMu3t), RW buried 3 Mg ha^{-1} (WoBu3t), and RW buried 3 Mg ha^{-1} with synthetic fertilizer (WoBu3t+N). Treatments featuring high amendment applications (from 2010 through 3013): RW mulched 12 Mg ha^{-1} (WoMu12t) and RW buried 12 Mg ha^{-1} (WoBu12t).

Sorghum crop productivity	Grain yield	Aboveground biomass
2007-2012: Treatments with low amendment applications (Ctrl, WoMu3t, WoBu3t, WoBu3t+N)		
Block	0.07*	0.05**
Year (Y)	0.34***	0.55***
Treatment (T)	0.05 .	0.05*
Y^2		
Y:T		
Rainfall		0.013 .
Ctot 0-5 cm		
Ctot 5-15 cm		
Ntot 0-5 cm		
Ntot 5-15 cm	0.009*	0.005**
Nmin 0-5 cm	0.004 .	0.004*
Nmin 5-15 cm		
Ptot 0-5 cm	0.009*	0.003 .
Ptot 5-15 cm	0.015**	0.009***
Pav 0-5 cm	0.009*	0.005**
Pav 5-15 cm	0.006*	
Total (R^2_{adj})	0.50	0.69
2010-2012: RW treatments (i.e. with high amendment applications WoMu12t and WoBu12t)		
Block		0.05*
Year (Y)	0.32***	0.46***
Treatment (T)	0.15***	0.17***
Y^2		
Y:T		
Rainfall	0.19***	
Ctot 0-5 cm		
Ctot 5-15 cm		
Ntot 0-5 cm		
Ntot 5-15 cm		
Nmin 0-5 cm		0.02 .
Nmin 5-15 cm		
Ptot 0-5 cm	0.02*	
Ptot 5-15 cm		0.015 .
Pav 0-5 cm		0.015 .
Pav 5-15 cm		
Total (R^2_{adj})	0.68	0.73

Chapter 4: On-farm experimentation with shrub-based agroforestry mulches in dryland Burkina Faso: Making sense of heterogeneity

Abstract:
To assess the impact of ramial wood (RW) amendments on crop yields in Piliostigma reticulatum shrub-based agroforestry parklands in semi-arid Burkina Faso, varying amounts of shrub material were compared on eight farmer-led experimental plots. Soil properties and crop productivity were monitored during three consecutive years. Participatory methods allowed characterizing three "local soil classes" that characterise spatial heterogeneity. Local soil knowledge allowed to make sense of observed heterogeneous effects of mulch on crop performance. Shrub-based mulches improved crop productivity on "shallow" and "sandy" soils, but their use is not recommended on "clayey" soils as the extra labour investments are not compensated by short to medium-term crop yield benefits. Rarely has research targeted the re-design of agricultural management practices based on indigenous soil knowledge.

Keywords:
Indigenous ecological knowledge, land degradation, *Piliostigma reticulatum*, soil restoration, woody perennials

Submitted as: Félix GF, Clermont-Dauphin C, Douzet J-M, Hien E, Saunier-Zoltobroda T, Groot JCJ, Cournac L, Tittonell P. 2019. Agroecology and Sustainable Food Systems (Under review)

1. Introduction

Population growth in West Africa has intensified pressure on land resources for subsistence farming (Cilliers, 2009; Doso Jnr, 2014). Consequently, continuous cereal cultivation in smallholder agriculture reduces the implementation and length of traditional woody-based fallows to restore soil productive capacity via organic matter accruement (Diarisso *et al.*, 2015a). Underpinned by the principle that soil organic matter is central to sustainable crop production (Bationo *et al.*, 2007), keeping the soil covered with organic mulches is a strategy to recycle carbon and nutrients into soil profile and maintain soil moisture for plant growth (Altieri *et al.*, 2015). Crop residues are a locally-produced source of organic matter. However, trade-offs appear when farming families have to choose between protecting their soils or feeding their livestock with crop residues (Tittonell *et al.*, 2015a).

In drylands of West Africa, woody perennials have been promoted as a reliable source of organic amendments for soil restoration and for their positive effects on local soil conditions and local livelihoods (Barthès *et al.*, 2010; Haglund *et al.*, 2011; Weston *et al.*, 2015). Agronomic research in Burkina Faso (Yélémou *et al.*, 2013a), Niger (Wezel, 2000), and Senegal (Bright *et al.*, 2017; Bogie *et al.*, 2018b) shows that spatial and temporal arrangements to grow crops associated with native evergreen woody shrubs (i.e. *Piliostigma reticulatum* and *Guiera senegalensis*) improve crop performance and soil conditions locally. The presence of woody shrubs in parklands reduces water run-off, intercepts wind-driven residues and surface soil sediments and accumulates nutrients around their base (Wezel *et al.*, 2000; Félix *et al.*, 2018b). Innovative farmers are also keeping a part of the soil covered with branches and leaves of coppiced native shrubs that spontaneously grow on their fields (Lahmar *et al.*, 2012).

Few studies have been conducted for more than two years on farmer fields and with farmers on the shrub-crop system in the Sahel. The need for farmer participation in research to design more sustainable natural resources management systems has become increasingly acknowledged (Holt-Giménez, 2002; Stoate & Jarju, 2008; Bezner Kerr *et al.*, 2018). Participatory approaches include participatory action-research, farmer experimentation, and farmer-to-farmer trainings, amongst others (Khumairoh *et al.*, 2019). Particularly, the 'sharing of wisdoms' between indigenous and academic knowledge has proven useful to assess and optimize efficiencies of low-resource endowed farming systems (Nicholls & Altieri, 2018; Šūmane *et al.*, 2018; Teixeira *et al.*, 2018). Recognizing that rain-fed cereal cropping systems in the Sahel require low-resource investment management practices to increase soil moisture, improve water infiltration, and ensure soil water retention, the question remains whether the intensified use and management of native shrub material is a viable practice for local farming families to face recurrent drought periods and changing rainfall patterns.

The objective of this study was to assess, together with local rain-fed family farmers in Burkina Faso, the impact of different application rates of shrub material as soil amendments on associated cereal-legume crops. We evaluated the performance of shrub-based agroforestry parklands, using *Piliostigma reticulatum* leaf and branch material as ramial wood (RW) mulch on soils. The working hypothesis of the on-farm experiment was that the application of coarse *Piliostigma*-based RW as mulch can improve crop performance as compared to no-mulch situations. We expected that the positive effects of RW on crops would be boosted by simply increasing mulch application rates, via concentration of shrub biomass and litter.

2. Materials and methods

2.1. Study area

The present study was conducted in Yilou (13°01' N, 01°55' W), a village in the Central Plateau of Burkina Faso (Fig. 4.1). The study area is part of the semi-arid belt of Sudano-Sahelian West Africa, with average temperatures of 24°C and annual rainfall of 550 mm yr^{-1} (400-700) on dominant soil types Lixisols, Plinthosols, and Cambisols (Diarisso *et al.*, 2015a). The village of Yilou was founded over 100 years ago (Fig. 4.2), and in the last 25 years, at least four key projects around sustainable land management and agriculture have been implemented: PATECORE (1988), ABACO (2010), WASSA (2013), and ConneSSA (2016). The PATECORE[3] project was responsible for the widespread establishment of contour stone lines in Northern Burkina Faso to protect soil resources and counter land degradation. he ABACO[4] project revolved around the use of sorghum crop residues to restore soil organic matter contents and improve yields; an important learning outcome from the research conducted with ABACO was that crop residues are a major favourite to feed livestock and farmers rarely invest it for mulching soils (Tittonell *et al.*, 2012). The WASSA[5] and the ConneSSA[6] projects aimed to understand trade-offs at landscape scale in order to optimize soil organic matter recycling. Research projects have brought infrastructure improvements and capacity-building opportunities to local farmers (e.g. the construction of a weather station via ABACO and field visits to experimental stations via WASSA).

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[3] Projet Amenagement des Terroirs et Conservation des Ressources dans le Plateau Central, http://www.fao.org/3/X5301E/x5301e05.htm

[4] Agroecology-Based Conservation Agriculture

[5] Woody Amendments for Sudano-Sahelian Africa, www.wassa-eu.org

[6] Connecting knowledge, scales and actors: an integrated framework for adaptive organic resource management targeting soil aggradation and agroecosystems' resilience in SubSaharan Africa, https://connessa.uni-hohenheim.de/en/112332

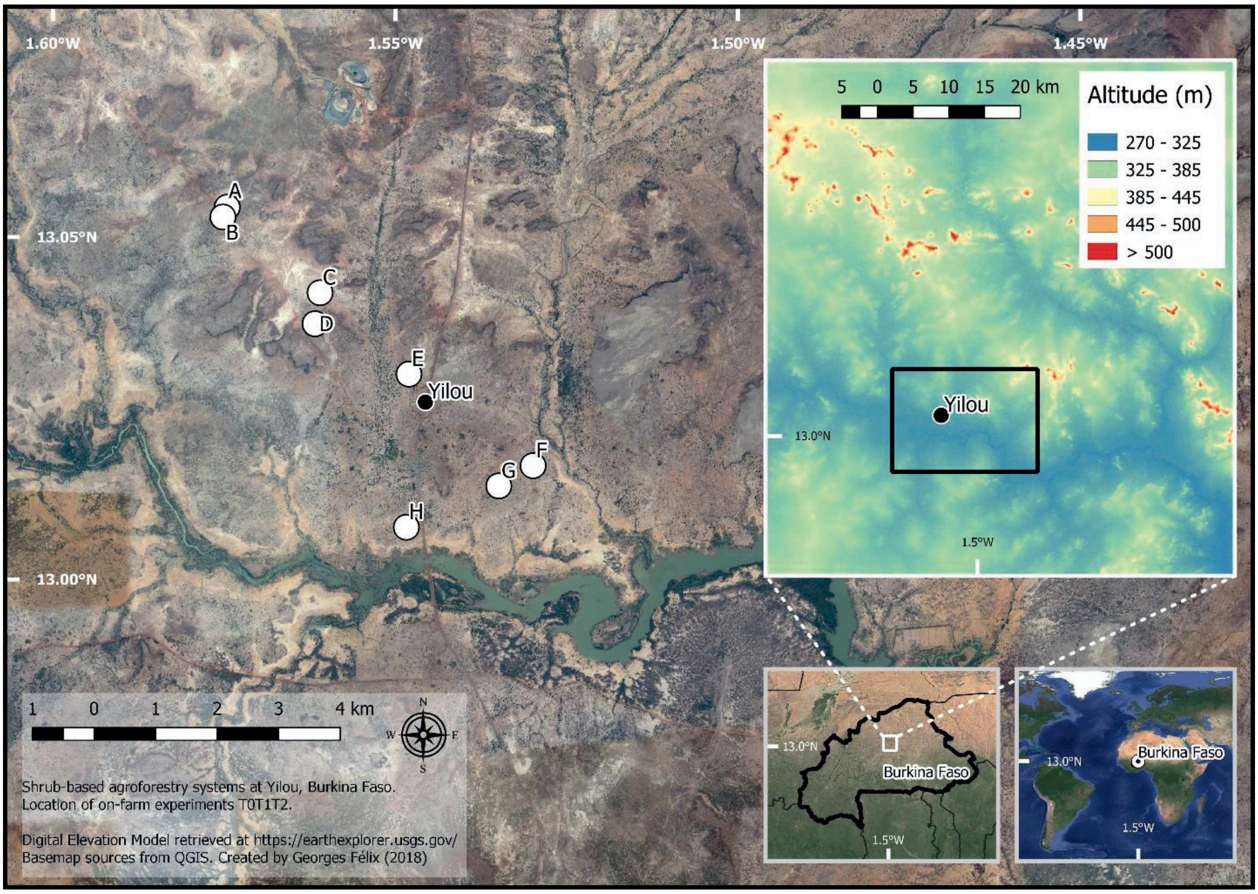


Figure 4.1. Study area and on-farm experiment locations in the village of Yilou, Burkina Faso.

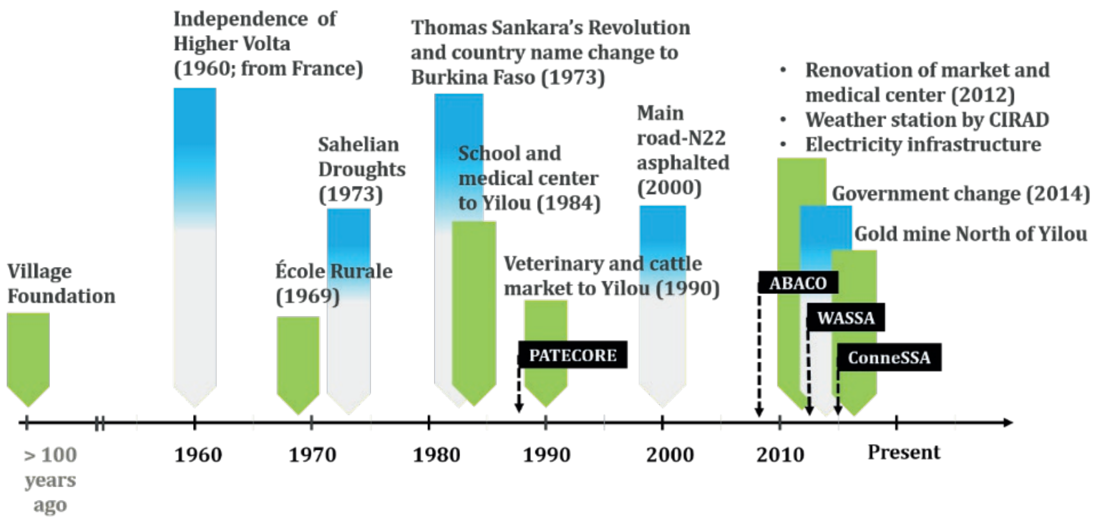


Figure 4.2. Village history of Yilou, Burkina Faso. Blue flags represent national events, green flags are local events, and black flags show external projects linked to agricultural research and/or development.

Local and global changes have shaped the structure and management of farming systems at Yilou, as well as the farmer's accessibility to production resources. A major change between 1960 and 2014 was the intensified use of external inputs such as chemical NPK and herbicides (fertilizer bag: 15,000-22,000 FCFA [US $25-37]; herbicide litre: 2,500 FCFA [US $4.25]). Livestock prices have been subject to a 15 to 25-fold increase. One bovine head would cost approximately 10,000 FCFA [US $17] in the 1960s while in 2014, a heifer could cost between 125,000 and 150,000 FCFA [US $212-255] per head and a plough ox not less than 250,000 FCFA [US $425]. The population size of Yilou has been subject to a five-fold increase between the 1960s and 2014. According to local villagers, diet preferences have shifted from traditional *tô* (*s*orghum-based paste) to more diversified diets that include cowpea, imported rice, and imported yam. The surrounding woody patches of natural vegetation seem to be rarer than in the past. The perennial grass *Andropogon guyanus* is present throughout the landscape and is preserved for its use as construction material. Sorghum remains the principal continuously cultivated crop. Fallows that would last from 2-3 years and up to 10-15 years have virtually ceased to be implemented in the village of Yilou (Diarisso *et al.*, 2015a).

2.2. Experimental layout

In 2014, trials were established on eight farmer fields to assess crop performance with and without *Piliostigma*-based RW applications, within an experimental set-up that intended to respect the 'normal' or 'usual' farmer cropping practices. Total rainfall in 2014, 2015, and 2016 was 653, 639, and 709 mm yr^{-1}, respectively (average of three years: 667 mm yr^{-1}). Rainfall pattern was unimodal, with a marked rainy season from May to August and a dry season from September to April (Fig. 4.3a). The rainy seasons were however, not homogeneous: in 2015 it started mid-May, while the first rains of 2016 arrived in March.

In the "slash-and-mulch" system (Fig. 4.3b), shrubs were pruned prior to the onset of the rainy season and fresh matter was applied on soils (as coarse RW-mulch) before crop plantation. The selection criteria for experimental locations were: (i) farmer willingness to participate in the on-farm experiment, (ii) homogeneity of soil conditions on their experimental field and (iii) homogeneous *in situ* density of native shrubs (specifically of *Piliostigma reticulatum* DC. Horscht.). Participating farmers (one female and seven male) established experimental fields that measured 600 m^2 and were divided in three plots of 200 m^2 each, all identical in length (20 m) and width (10 m). Three experimental treatments were applied (Fig. 4.3c): no-mulch, all shrub material coppiced and removed [T0], *in situ* shrub material remained as mulch [T1], and *in + ex situ* shrub material applied as mulch [T2]. These treatments were relative to each farmer field resources, according to *in situ* shrub and ramial wood availability. The experimental layout was materialized by using one-third of total shrub biomass on the T1 plot and concentrating the remaining two-thirds on the T2 plots.

Sorghum was sown at 0.8 by 0.4 m (densities of 31,250 planting holes ha^{-1}), and intercropped with cowpea (sown 15 days after) at same spacing. The cropping operations on the experimental plots were based on local farmer practices, such as manual ploughing and weeding, and fertilizer application 21 days after sowing at 100 kg ha^{-1} NPK (23-10-5). Planting and field preparation dates varied from mid-June to mid-July. Experiment was conducted on the same plots during three consecutive years (2014 through 2016).

2.3. Participatory methods

Focus group sessions were conducted periodically from 2013 through 2017 to capture farmer perception on crop performance. Local soil names were determined through a participatory classification matrix of soil characteristics on farmer fields, based on the local farmer knowledge of each soil's productive capacity. Using local classifications is one of the first steps to integrate local knowledge and synthesize it into a common "language" that both technicians and practitioners can understand (Geilfus, 1997). The farmers were asked to mention the names of the different types of soils that they encounter in the zone using samples as "header" of a matrix drawn on the ground and described characteristics, including colour tone, suitable crops, NPK/manure use, and preferred soil amendments (i.e. residues of crops or ramial wood), amongst others (Fig. 4.3d). The different descriptions along with the advantages and limitations of each soil "type" were noted as precisely as possible to stimulate discussion around soil fertility management amongst participating farmers. The methodologies were consistently supported by the presence of at least one French-Mooré translator.

2.4. Ecological data collection

Composite soil samples were collected on each farmer's field at the onset of planting seasons 2014 and 2015. These samples were analysed for soil physico-chemical characteristics at the Farming Systems Ecology lab, Wageningen University, The Netherlands. Soil organic C was determined after oxidation with dichromate sulphuric acid, following the Kurmies method. Total N and total P were measured spectrophotometrically with a segmented-flow system (Skalar San++ System), after samples were digested with a mixture of H_2SO_4–Se and salicylic acid at elevated temperature of 330°C. Extractable soil P (P-available) was determined following the Olsen method. Soil pH was measured with a pH / mV meter. Soil texture was obtained in 2016 via soil particle analysis at the IRD soil lab, Ouagadougou, Burkina Faso. Shrubs were counted at the onset of the rainy season to determine shrub density. All shrubs were coppiced and weighed to determine ramial wood (RW) *in situ* availability.

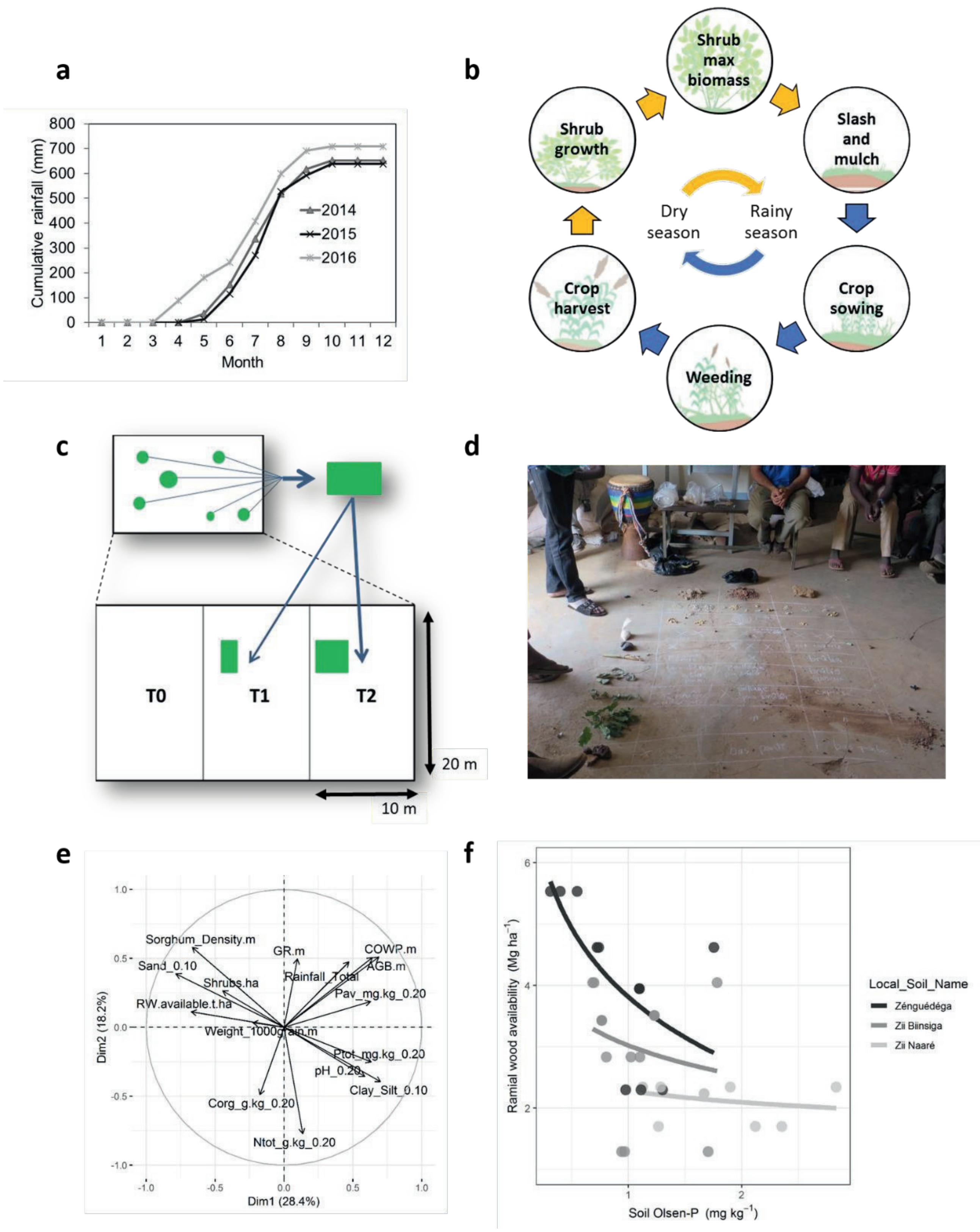
Sorghum and cowpea yields were collected and weighed at harvest (November) on three 8 m^2 sub-plots per treatment and farmer, where sorghum plant density was determined. Crop harvests and shrub residue sub-samples were oven-dried at 80°C during 48h to determine dry weight. The weight of 1000 grains of sorghum was determined as an indicator of grain filling. As a measure of crop response stability, the environmental mean (average of all observations per year) and the relative treatment-to-environmental mean ratio of each plot were calculated, following Ripoche *et al.* (2015):

$$Relative\ Yield\ Ratio = \frac{Entry\ Yield}{Environmental\ Mean}$$

2.5. Data exploration and statistical analyses

Crop yield data were recorded at the sub-plot level and averaged per plot. Data normality, homogeneity of variance and independence of observations were met and variables were transformed as needed in order to meet these assumptions. Comparisons between means of soil classes were assessed via one-way Analysis of Variance (ANOVA) and post hoc test Tukey HSD (Honest Significant Difference). The degree of correlation between quantitative variables was assessed through a Factorial Analysis of Mixed Data (FAMD). Sorghum grain, sorghum total biomass, and cowpea yields were response variables as a function of ecological resources available on each field. Quantitative explanatory variables included soil properties (texture and physico-chemical) and shrub resources. Analysis of experimental results took into account Local Soil Classification, RW input, and year, as well as the interactions between RW input and Local Soil Classifications. In a first step, soil physical, physico-chemical, and biological parameters were selected as explanatory variables to assess differences in crop performance. In a second step, experimental management variables and local soil classification were used as fixed factors to assess their impact on crop performance. In both cases, farmer was set as random factor since this variable was equivalent to experimental blocks. All analyses were conducted in the R environment (RCoreTeam, 2016). The ANOVA and post hoc test were conducted under the *agricolae* package (de Mendiburu, 2019). The Factor Analysis was implemented via the Factor Analysis of Mixed Data (FAMD) function of package *FactoMineR* (Lê *et al.*, 2008). Linear mixed models were conducted via the *lmer* function in the *lme4* package (Bates *et al.*, 2015). Best model fits were selected based on Akaike's Information Criterion (AIC).

Figure 4.3. (right) The "slash-and-mulch" technique is a farmer innovation that results from the adaptation of communities to environmental constraints in drylands of West Africa. Mean total rainfall during study period (2014 through 2016) was 667 mm yr^{-1}(a). Under continuous cereal cultivation, shrub-based agroforestry systems are part of the current management options (b, Diagram adapted from Lahmar *et al*. 2012). The on-farm experiment was designed to capture management diversity and assess crop performance with or without the use of shrub-based ramial wood amendments in parklands (c). The study was conducted on eight farmer fields following three treatments: no mulch (T0), *in situ* mulch (T1), and *in + ex situ* mulch (T2). During the dry season, participatory methodologies were conducted with local farmers to characterize local soil classifications and main management practices. Participatory methods allowed to document farmer knowledge and management options of local ecological resources (d, photo credit: P. Belliard). The photo illustrates the results of a participatory soil classification where farmers of Yilou, Burkina Faso, described three soil types, namely "shallow," "sandy," and "clayey" in order to analyse preferential use and management of ramial wood amendments. The Factorial Analysis of Mixed Data (FAMD; R package *FactoMineR*) using quantitative and qualitative variables explained 47% of the variability in the first two dimensions (e). Dimensions 3 and 4 explained an additional 23% of the variability. Data considered includes numeric data of years 2014 and 2015 of local ecological resources and farmer management practices. Ramial wood (RW) *in situ* availability (monitored during three consecutive years at the onset of each planting season) was negatively correlated to soil Olsen-P, suggesting more abundant shrub biomass on poorer fields (f).



a
Cumulative rainfall (mm)
800
700
600
500
400
300
200
100
0
1 2 3 4 5 6 7 8 9 10 11 12
Month
2014
2015
2016
b
Shrub max biomass
Slash and mulch
Crop sowing
Weeding
Crop harvest
Shrub growth
Dry season
Rainy season
c
T0
T1
T2
20 m
10 m
d
e
Dim2 (18.2%)
Dim1 (28.4%)
Sorghum_Density.m
Sand_0.10
Shrubs.ha
RW.available.t.ha
GR.m
COWP.m
AGB.m
Rainfall_Total
Pav_mg.kg_0.20
Weight_1000grain.m
Ptot_mg.kg_0.20
pH_0.20
Clay_Silt_0.10
Corg_g.kg_0.20
Ntot_g.kg_0.20
f
Ramial wood availability (Mg ha^{-1})
Soil Olsen-P (mg kg^{-1})
Local_Soil_Name
Zénguédéga
Zii Biinsiga
Zii Naaré

3. Results

3.1. Local soil classifications

Farmers participating in the focus groups described their soil resources in three categories: red shallow soils, yellow sandy soils, and ochre clayey soils (Fig. 4.3d). The local soil denominations and soil descriptions according to farmer views were captured in Table 4.1. "Shallow" soils were characterized as *zenguédéga* which refers to soils nearby a road and featuring gravels on the surface. On these soils, most crops can be cultivated, except for watermelon. On these soils, crop residues and RW amendments are preferably used as mulch, instead of burnt. *Zii biinssiga* class, which literally means "sandy soil" in local language Mooré, where the "sandy" type, according to farmer's perception. Chemical fertilization and manure were said to improve crop productivity on these soils, provided the rains are "good." These soils are favourable to crops like cowpea, millet, sesame and sorghum, during a "good" rainy season, while groundnut, maize and sorghum underperform during "bad" (dry) rainy seasons. On these soils, crop residues and RW amendments are often burnt or applied on certain areas of the field (e.g. crusted/hardened spots or around termite nests). "Clayey" soils or *zii naaré,* are often located nearby riverbanks and are considered to be highly valuable for agricultural production specially when rains are scarce. Most local crops do well on these soils, except maize. Chemical fertilization was more often applied than animal manure on these soils, while crop residues and RW amendments were either be burnt or exported, but seldom applied as mulch.

3.2. Resources variability

The baseline characteristics differed between the three local soil classifications and were heterogeneous within classes (Table 4.2). Sand content was most important on the *zii biinssiga* (50.5%) while silt and clay were most important on the *zii naaré* soils (49.2 and 9.3%, respectively). Total soil N was similar across the three classes (0.34-0.39 g kg^{-1}). Despite *zii naaré* soils had the lowest organic C contents, this class had the highest values for total P, Olsen-P, and pH. The C:N and the N:P ratios, as well as shrub density were highest for the *zii biinssiga* soil class.

Standing shrub vegetation ranged between 3000 to 8000 plants ha^{-1}, an equivalent *in situ* RW availability between 1 and 7 Mg ha^{-1} (Table 4.2). Fields classified as *zii naaré* had the lowest shrub densities (3000-5500 plants ha^{-1}). Fields classified as *zii biinsiga* had the highest shrub densities in our sample (4000-8000 plants ha^{-1}). The amounts of *in situ* RW availability on both classes was nevertheless similar (1-4 Mg ha^{-1}). Fields in the class *zénguédéga* had the largest amounts of RW availability, ranging from 2 and up to 7 Mg ha^{-1}.

The factor analysis (Fig. 4.3e) revealed that shrub density (Shrubs.ha) and ramial wood availability (RW.available.t.ha) were strongly correlated with soil sand contents and inversely correlated with soil pH, total P, Olsen-P and Clay+Silt contents. Sorghum total biomass (AGB.m) and cowpea yields (COWP.m) were correlated with rainfall and soil phosphorus, and sorghum grain yield (GR.m) was inversely correlated with soil organic C and soil total N. Trends depicted in Fig. 4.3f (one outlier not presented) indicate that shrub biomass was more important on the poorest soils (*zenguédéga*) and less available on the richest soils (*zii naaré*). No significant correlation was found between sorghum and cowpea yields with soil properties (Table 4.3).

3.3. Effect of ramial wood amendments on crop performance

The environmental mean crop yield consistently decreased after three years of continuous cultivation (Fig. 4.4a), from 0.6 to 0.5 Mg ha^{-1} for sorghum grain (20% decrease) and from 0.5 to 0.2 Mg ha^{-1} for cowpea yields (60% decrease). Yields were more important for sorghum than for cowpea but yield variability was more important for cowpea than for sorghum. Soil Olsen-P contents had an impact on sorghum total biomass productivity across treatments and years (Fig. 4.4b). The effect of RW soil amendments on crop performance was highly variable between farmer fields and between local soil classifications. Without any RW input, *zii naaré* soils outperformed the other two classes (Fig. 4.4c and 4.4d). The effect of RW input was positive for sorghum grain yield on *zenguédéga* and *zii biinssiga* soils. RW input had, however, a depressive effect on *zii naaré* soils (Figure 4c). For cowpea, RW input effects were mostly positive throughout the experimental period, and for all farmers/soil classes (Fig. 4.4d).

Relative yield ratios allowed to "rank" crop performance and assess yield stability across the study period as a function of RW input (Fig. 4.4e and 4.4f). To begin with, there was high variability on the no-mulch control (T0) situations for both sorghum grain and cowpea with a clear trend: *zii naaré* > *zii biinssiga* > *zenguédéga.* Secondly, because the initial shrub density was not the same in all soil classes (cf. Table 4.2), the absolute amounts of biomass applied on each soil class were different. *Zii naaré* soils received up to 5 Mg ha^{-1}, *zii biinssiga* soils up to 7 Mg ha^{-1}, and *zenguédéga* soils received up to 14 Mg ha^{-1} of fresh *Piliostigma* shrub biomass, as part of the experimental setup. Lastly, crop yield increases for both sorghum and cowpea on all three soil classes, were positive as RW inputs increased, except for the sorghum grain on *zii naaré* soils (Fig. 4.4e). Crop yield stability seems more related to soil type than to RW input application.

RW input had a marginally significant effect ($p<0.1$) on sorghum grain yield. RW input had no significant effect on sorghum total biomass nor on cowpea yields. Sorghum grain yields on local soil names *zii biinssiga* and *zii naaré* were significantly different from yields obtained on the *zenguédéga* class ($p<0.05$). In particular there was a significant negative effect of RW input on sorghum yield performance on "clayey" soils ($p<0.05$), and a marginally significant positive effect of RW application on cowpea grown on these “clayey” soils ($p<0.1$). This “clayey” soil type had an marginally significant ($p<0.1$) effect on sorghum total biomass and cowpea yields (Table 4.4). There were an important rainfall and year effects for sorghum total biomass and cowpea (Table 4.3 and 4.4). Sorghum total biomass productivity was significantly different ($p<0.05$) in 2015 and marginally different ($p<0.1$) in 2016 than in 2014. Cowpea yield significantly lower ($p<0.05$) in 2015 and 2016, as compared to 2014 production.

4. Discussion

The on-farm experiment was conducted with farmers in a drought-prone area of semi-arid West Africa. The results gathered during three years in Yilou, Burkina Faso , demonstrate that farmers have precise classifications to describe spatial heterogeneity of agricultural fields. The three local soil classifications were described by farmers as “shallow,” “sandy” and “clayey.” These were effectively correlated to soil texture but no significant differences were found in regards to chemical soil properties. Nonetheless, shrub densities and shrub aboveground biomass was inversely correlated to soil Olsen-P, with seemingly more native shrub vegetation growth on poorer fields. The effect of ramial wood amendments on crop performance was tested, based on *in situ* shrub biomass availability. Hereafter, we address the questions (i) on how farmers describe their soils, (ii) on the effectiveness of ramial wood amendments to improve yields under heterogeneous conditions, and (iii) on the importance of incorporating farmer knowledge to design improved crop management practices.

4.1. Targeting shrub-based practices through farmers´ soil classification

During the focus group sessions, several farmers pointed out the fact that woody perennials (shrubs and trees) are desirable and needed to maintain and restore soil fertility. Leaving the fields uncultivated for several years can indeed ensure enough organic matter accruement for nutrient reincorporation into soil layers (Warren Raffa *et al.*, 2015). Crop residues may be used to recycle organic resources into soil layers but these are generally used to feed livestock. On the other hand, the “slash-and-mulch” system was described in Yilou as a promising option to improve agricultural productivity via restoration of shrub-based organic residues as mulch (Lahmar & Yacouba, 2012). The shrub *P. reticulatum* has medicinal and culinary properties, and parts of it are used as construction material and fodder (Yélémou *et al.*, 2007). Its bark can be used to make ropes, leaves are useful for preparing local dishes, fruits constitute a rich fodder for livestock, and branches are commonly used as fuel wood for cooking. Indeed, shrub-based RW amendments are an available woody material that can be mobilized to prevent further soil degradation on agricultural fields (Félix *et al.*, 2018a).

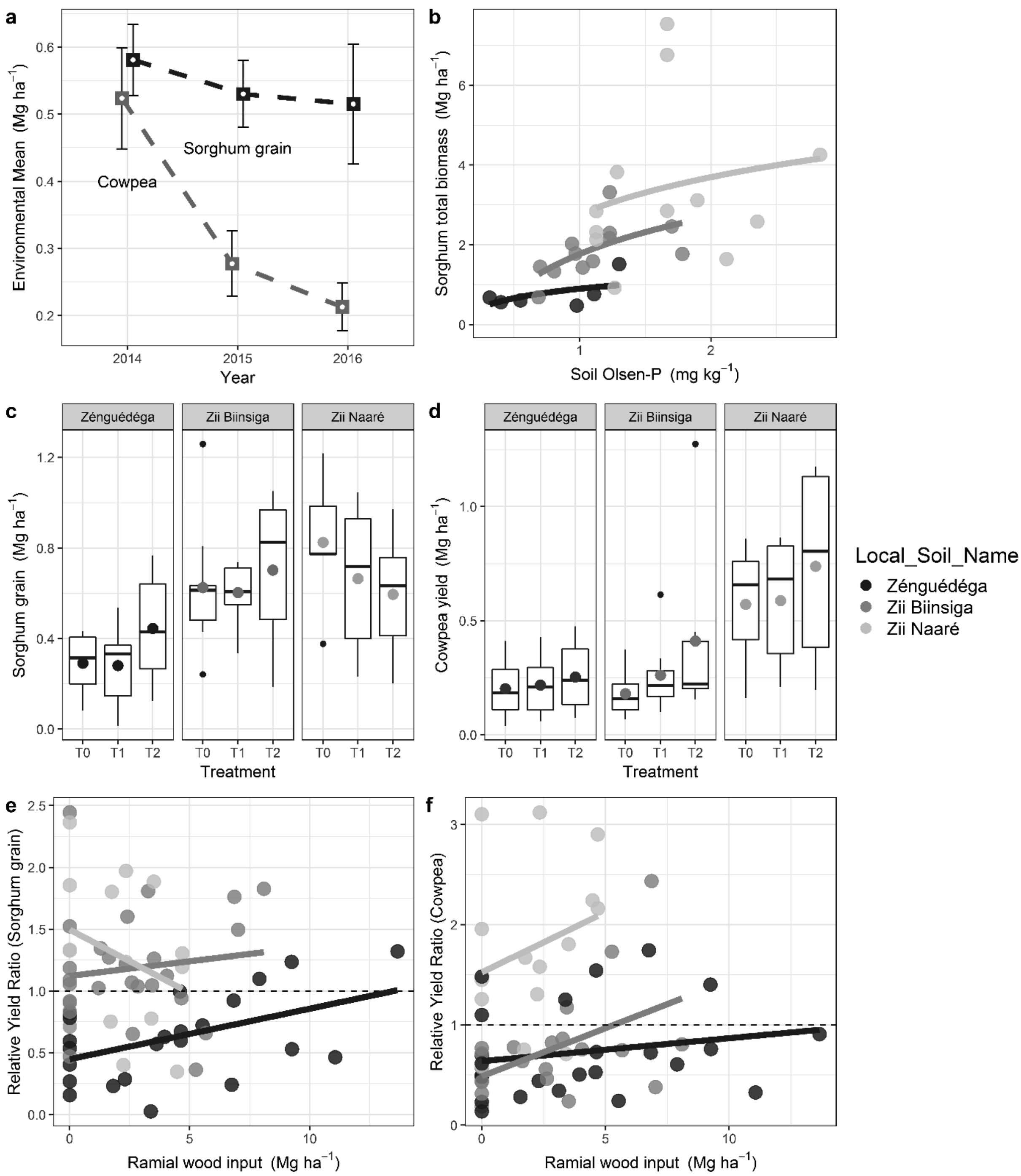


Figure 4.4. The environmental mean (±se) for sorghum and cowpea association was stable for the cereal but decreased for the legume (a) across the study period (2014 through 2016). The sorghum aboveground biomass productivity was affected by soil Olsen-P (b). The treatment-to-environmental mean ratio (Relative Yield Ratio) plotted against the RW input shows that local soil names override the RW treatment effect and that crop performance was highest for “clayey” soils and lowest for “shallow” soils (c, d), as compared to the environmental mean (dashed line). Experimental treatment effects for no RW-mulch [T0], simple [T1], and double RW application [T2], on sorghum (e) and cowpea yields (f) resulted in overall relative improvement on “shallow” and “sandy” soils, but resulted in highly variable and depressive effects on “clayey” soils.

Soil quality can be broadly understood as a combination of three aspects: physical, chemical and biological properties (El Mujtar *et al.*, 2019). Scientists use a variety of indicators to assess state and functions of soil resources (Bünemann *et al.*, 2018). Farmers have their own ways of describing their productive soil resources. Ethnopedology studies consider that members of social groups have an impact (positive or negative) on their surrounding environment based on their understanding and classification of different objects and resources (Talawar & Rhoades, 1998). Early studies on indigenous soil classifications have focused on either descriptive classifications of local categories, on comparisons between farmer's criteria and researcher's criteria, or on assessments of the scientific merit of indigenous soil classifications. More rarely has research targeted the re-design of agricultural management practices based on indigenous soil knowledge. Our study aimed at filling this still-existing gap by identifying local soil names and by examining their relation to the variability of crop performance in order to efficiently assess novel farmer-led management interventions.

In Yilou, Burkina Faso, local soil denominations referred to as *zenguédega* or *zipéllé* describe "shallow" or hardened soils that require mechanical breaking of the surface crust and are usually amended with organic matter (e.g. manure or ramial wood). Other farmers named the soils on their experimental fields as *zii binssiga* to describe "sandy" or loose textures, which are easy to work at the onset of the rainy season and where water infiltration is good. The local name *zii naaré* seemed to be the richest and most "clayey" type, which according to one of the farmers, are generated when "wastes" (organic matter resources) are accumulated for a long time, linked to micro-topography and sediment entrapment. According to local farmers, *zii naaré* soil types that are very valuable for sorghum production when rainfall is scarce, but perform poorly when rainfall is excessive. Farmers do not systematically use RW amendments on all soil types but rather on patches where "water does not infiltrate"[7], suggesting that RW amendments are commonly applied to restore soil functions principally on crusted areas of the field or around termite nests. When soil productive capacity becomes too "low" for sorghum, then millet is often planted for one or two seasons, after which sorghum is again planted for several seasons.

The classifications we documented in this study are similar to those reported by Diarisso *et al.* (2015a) in Yilou. Although we did not find significant differences between soil chemical properties between the local soil categories, crop responses between soil categories were variable. According to farmers' perception, *zii naaré* are the richest soil types because these render better yields than z*ii biinssiga* or *zenguédégua* soils, especially "when rains are scarce." Regarding the effect of RW amendments, a farmer expressed that RW application would make sorghum plants grow faster and taller yet the grain yields

[7] « *Moi je mets le pilio sur le sol là où l'eau ne passe pas trop* » (Farmer S.S.)

would be smaller as compared to no-mulch application[8]. This effect could be linked to the higher water demand (due to the higher vegetative growth) facing the low rainfall rates at the end of the crop cycle (when grain yield is setting in). There seemed to be a consensus around the fact that this effect is linked to increased soil water holding capacity when RW was applied on certain soil classes, which can affect sorghum biomass partitioning or harvest index. This indicates possible interactions of other environmental and/or crop factors with crop performance.

Several studies have demonstrated that farmer criteria can be validated by technical and scientific soil quality indicators such as soil organic matter, pH or nutrient availability (Barrera-Bassols *et al.*, 2006; Nezomba *et al.*, 2015). In our study, farmer soil classification was linked to differences in physical characteristics but the chemical properties were not significantly different between soil categories (cf. Table 4.2). Moreover, the local soil classifications were apparently linked to the agricultural potential of the field itself.

4.2. Unravelling the benefits of ramial wood amendments under heterogeneous conditions

Native shrubs were coppiced at the onset of the rainy season. After crop harvest these evergreen woody perennials re-gain biomass and restore root reserves that carry them through the dry season (Bogie *et al.*, 2018a). Since farming families use woody branches >2-cm diameter as firewood, the ligneous organic matter that is applied on the surface of the soil profile consists primarily of leaves and small-diameter branches (i.e. ramial wood, RW). Baseline soil conditions were heterogeneous between local soil classes, in terms of soil texture, woody vegetation densities and *in situ* availability of shrub-based agroforestry mulches. Thus, crop responses to RW experimental treatments were highly variable between fields.

In the drylands of semi-arid West Africa, farmers perceive decreasing cereal yields on continuously cultivated fields despite application of fertilisers. Across the study period, when RW was applied as soil amendment on treatments T1 and T2, data showed weak but mostly positive responses with 52, 66, and 84% of the cases above the no-mulch control (T0) for sorghum grain, sorghum aboveground biomass and cowpea yields, respectively. Contrast against the control showed that the better the site quality (yield without mulch), then the lower the effect of the RW practice. Observed yields in Yilou remain below 1 Mg ha-1 (ranges between 0.3 and 0.7), which is low. Making sense of this heterogeneity was only possible when local soil names were used in the analysis. Indeed, sorghum grain yields on “clayey” and “sandy” soils were superior than on “shallow” soils but crop response to RW input was more important on the latter. Our results also showed

[8] « *Chez moi, quand je mets du Piliostigma, ça pousse plus vite, ça fait de grandes tiges, mais les épis sont petits* » (Farmer D)

that local soil classification was associated with contrasted yield stability over the years, the lowest yield stability being associated with the *zenguédéga* soils ("shallow"), which are the less productive soils in our sample.

Increasing RW treatments improved yield outcomes on poorest soils but had depressive effects on cereal yields for richer soils. Thus, RW treatment effects were inversely proportional to site quality and the variability in crop responses between the soil categories is a consequence of shrub densities being more important on poorer fields. Finally, results indicate that differential productivity effects associated with the various local soil classes may be overriding the effects from the RW treatments on sorghum and cowpea yields.

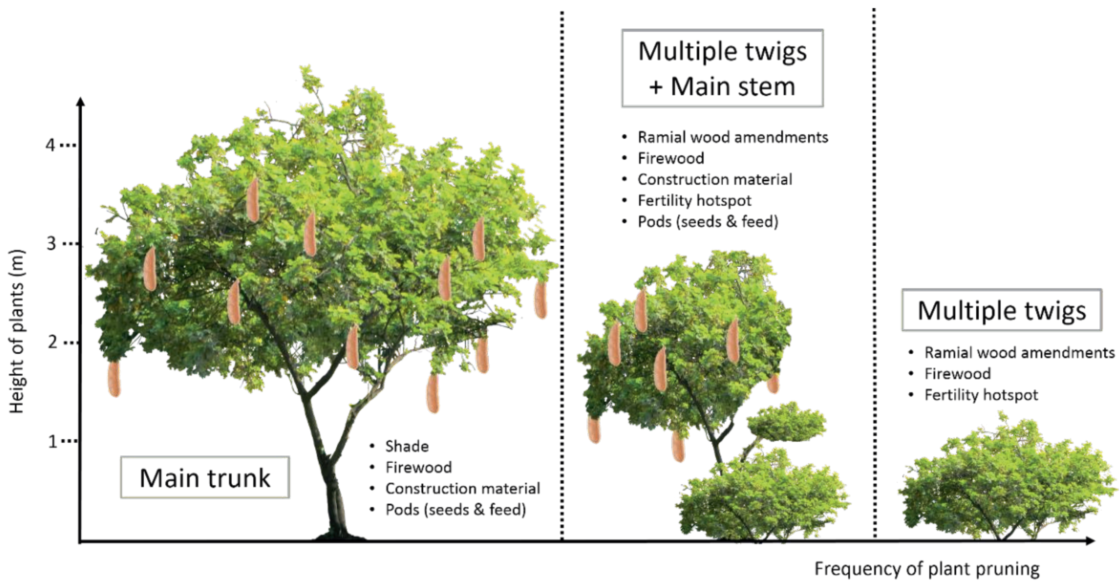


Figure 4.5. *Piliostigma reticulatum* DC. Horscht. is a versatile perennial woody shrub that can be pruned in different styles: in the form of small trees (main trunk), with a main trunk featuring multiple twigs at its base, or as a bush of multiple twigs. Each pruning style is a consequence of the frequency of coppicing. These pruning styles may result in different services to farmers and herders.

4.3. Incorporating farmer knowledge in management recommendations

High spatial variability of resources represents an opportunity to develop targeted options for reducing vulnerability of farming families by mobilising local biodiversity and knowledge (Tittonell *et al.*, 2015b). In dryland agroecosystems there is a strong potential for improvement of ecological processes via sound use and management of local biodiversity (Blanco *et al.*, 2017). This requires creative management and novel farming practices to sustain crop productivity (Timmermann & Félix, 2015). The methodologies employed in this study recognized that farmer knowledge has value in itself considering that the communities are (1) aware of the beneficial effects of shrubs on their fields and (2) that they are willing to invest in designing and managing optimal shrub-based agroforestry systems. Options to restore degraded soils (and increase yields) are not solely technical but are also constrained by social decision-making processes at household and community levels.

Changing rainfall patterns affects farmers across arid and semi-arid environments in West Africa through recurrent drought periods (West *et al.*, 2008). Average sorghum yields in 1960-65 for Burkina Faso were 0.49 Mg ha^{-1} and by 2012-16, these have increased to barely 1.03 Mg ha^{-1} nowadays (www.faostat.org). Such timid progress in productivity can be partly attributed to the advent of technological developments such as mechanized tillage, improved varieties and chemical fertilization, but also to generalised and expanding soil degradation in the region. Silver-bullet "solutions" have often failed when these technologies were brought on-farm because they are either inaccessible or do not satisfactorily perform when confronted to soil or crop management heterogeneity (Giller *et al.*, 2009). The potential to improve regional crop yields is limited, given the particular low and unimodal rainfall regimes and the inherently poor soil characteristics (Diarisso *et al.*, 2015a; Paresys *et al.*, 2018). Thus, establishing dialogues between knowledge bodies through participatory approaches is key to identify and analyse the elements that can improve several objectives (i.e. ecological, social and economic) simultaneously.

Shrubs not only produce organic matter useable as mulch, they also entrap wind-driven sediments that accumulate at their base, creating *fertility hotspots*. Several pruning styles for *Piliostigma reticulatum* shrubs were observed in the study area (Fig. 4.5). Shrubs managed under "slash and mulch" systems re-sprout with multiple twigs while shrubs managed with a single trunk often form crown similar to a small tree. Some farmers have developed a hybrid structure featuring shrubs with both multiple twigs *and* a main trunk. Further research should focus on describing *P. reticulatum* formations geographically and linking pruning styles with local soil classifications, terrain characteristics, and crop performance. Pruning of woody perennials requires tacit knowledge of the biological cycles. Therefore, additional studies would be required to optimize synergies and improve performance and designs of shrub-crop systems on drylands of Western Africa, based on indigenous soil classifications. Moreover, shrub-crop systems are promising as an option to work towards the 're-greening' of the Sahel (Dia & Duponnois, 2012). The functioning of these farmer-led shrub-based agroforestry systems can shed light into the design of climate-change-resilient cropping systems in any drought-prone region of the world.

4.4. Concluding remarks

The aim of this study was to assess, alongside farmers, the efficiency of a local innovation, and to explore options for optimization of the management practice. Particularly, we tested whether the intensified use of ramial wood amendments within shrub-based agroforestry parklands can improve soil productive capacity in farmer conditions of semi-arid Burkina Faso. The indicators that were monitored included soil physical and chemical properties, as well as soil productive capacity (sorghum-cowpea yields). The main conclusions of this study can be summarised as follows:

- High resources variability in space was materialized by heterogeneous soil conditions and patchiness in shrub densities between farmer fields.
- When RW amendments were applied on soils, we observed weak yet positive crop responses and high variability between fields.
- *In situ* availability of shrub material was more important on fields with lowest soil Olsen-P, suggesting that poorer fields have more shrub material than richer fields.
- Contrast of RW treatments (T1 and T2) against the control (T0) shows that the greater the yield-to-environmental mean ratio, the lower the effect of RW amendments. Otherwise said, responses were inversely proportional to site quality.
- Variability among local soil classes overrode experimental mulch treatment effects on crop productivity.
- Such variability was not evident from the results of laboratory soil analysis, calling for greater involvement of local farmer knowledge and perception to design and target management practices.

Intensification of ecological processes in agriculture can be catalysed by incorporating farmer and researcher knowledge in the design of novel management practices. Our results clearly demonstrate that incorporating farmers´ knowledge and perception of soil quality was the only meaningful way to make sense of spatial heterogeneity of agricultural fields.

Table 4.1. Participatory assessment of local soil classifications and their characteristics.

Description	*Zenguédéga*	*Zii Biinssiga*	*Zii Naaré*
Farmers	A, B, C	D, E, F	G, H
General characteristics	"Shallow"	"Sandy"	"Clayey"
Surface colour	Red	Yellow	Ochre
Adapted crops	Cowpea, Groundnut, Maize, Millet, Sesame, Sorghum	Cowpea, Millet, Sesame, Sorghum on "good rain" years	Cowpea, Groundnut, Millet, Rice, Sesame, Sorghum
Non-adapted crops	Watermelon	Groundnut, Maize, Sorghum on "bad rain" years	Maize
NPK use	+	++	+++
Manure use	+++	+	+
Crop residue use	As mulch	On certain spots	Burnt
Piliostigma RW use	As mulch; not burnt	On termitaria; sometimes burnt	Exported; thorny species burnt
Guiera RW use	As mulch; not burnt	On certain spots; sometimes burnt	Exported
Vitellaria RW use	As mulch; not burnt	On certain spots; sometimes burnt	Exported
Contour stone bunds	Yes	Yes	Yes
Farmer Remarks	(A) Soil nearby a road (B) Sandy soils with gravels "Binssiri Zenguédéga" (C) Soils with red gravel on the surface	(D, E) Sandy soils, with sparse *Vitellaria* trees and *Piliostigma* shrubs, "Zii Biinssiga" (F) Crusted surface "Zippellé"	(G) Soils rich in organic matter, highly valuable for agriculture when rains are scarce "Tampouziga/Zii Naaré" (H) Humid soils, often close to river banks – "Zippellé Banwogo/Zii Naaré"

Table 4.2. Overview of ecological resources per local soil name presented as mean (± SD) for soil physical, physico-chemical, and biological indicators at plot level (8 farmers x 3 plots x 3 years). Highest values are shown in bold when there are significant differences. Different letters on a line indicate significant differences with the Tukey HSD test at p<0.05 confidence interval. Variables were transformed when needed to meet assumptions of data normality, homogeneity of variance and independence.

Resources	Indicator	Local soil name (mean ± SD)*		
		Zenguédéga	*Zii Biinssiga*	*Zii Naaré*
Physical [(1)]	Sand (%)	42.2 ± 1.3 [b]	**50.5 ± 1.6 [a]**	37.7 ± 1.6 [b]
	Silt (%)	**47.5 ± 1.2 [a]**	37.6 ± 1.6 [b]	**49.2 ± 1.6 [a]**
	Clay (%)	8.7 ± 0.6 [a]	8.9 ± 0.6 [a]	**9.3 ± 0.8 [a]**
Physico-Chemical [(2)]	Soil organic C (g kg^{-1})	6.67 ± 1.82 [a]	6.68 ± 1.75 [a]	5.41 ± 0.78 [a]
	Soil total N (g kg^{-1})	0.39 ± 0.12 [a]	0.36 ± 0.09 [a]	0.34 ± 0.02 [a]
	Soil total P (mg kg^{-1})	142 ± 45 [ab]	123 ± 48 [b]	**161 ± 36 [a]**
	Soil Olsen-P (mg kg^{-1})	1.27 ± 0.79 [b]	1.05 ± 0.34 [b]	**1.68 ± 0.55 [a]**
	Soil pH	5.97 ± 0.27 [ab]	5.65 ± 0.62 [b]	**6.12 ± 0.29 [a]**
	C:N ratio	17.1 ± 2.1 [a]	**19.5 ± 6.5 [a]**	16.0 ± 2.3 [a]
	N:P ratio	**2.9 ± 0.7 [a]**	**3.1 ± 0.7 [a]**	2.2 ± 0.5 [b]
Biological [(3)]	Shrubs (plants ha^{-1})	4850 ± 1135 [b]	**6333 ± 1578 [a]**	4050 ± 1089 [c]
	RW availability (Mg ha^{-1})	**3.9 ± 1.7 [a]**	2.6 ± 1.0 [b]	2.1 ± 0.3 [b]
	Sorghum grain yield (Mg ha^{-1})	0.34 ± 0.19 [b]	**0.64 ± 0.25 [a]**	**0.69 ± 0.31 [a]**
	Sorghum total biomass (Mg ha^{-1})	0.69 ± 0.35 [c]	1.92 ± 0.88 [b]	**3.44 ± 1.76 [a]**
	Cowpea yield (Mg ha^{-1})	0.22 ± 0.14 [b]	0.28 ± 0.26 [b]	**0.63 ± 0.33 [a]**

[(1)]Characterized at 0-10 cm depth in 2016/Values do not add 100%, [(2)]Sampled at 0-20 cm depth in 2014 and 2015, [(3)]Aboveground vegetation measured from 2014 through 2016. *Different letters on a line indicate significant differences at p<0.05

Table4.3. Determinants of sorghum grain, sorghum total biomass, and cowpea yields using a linear mixed model (*lmer* function , R package *lme4*) when considering soil texture, soil organic C, total N, total P, Olsen-P, pH, shrub density, and rainfall as fixed factors. Farmer was set as random variable. Significant effects are shown in bold ($p < 0.05$). Marginally significant effects are underlined ($0.05 < p < 0.1$).

	Sorghum grain yield			Sorghum total biomass			Cowpea yield		
	Est.	S.E.	*p*-value	Est.	S.E.	*p*-value	Est.	S.E.	*p*-value
(Intercept)	-3.25	4.46	0.47	-92.04	24.69	**0.00**	-12.69	4.20	**0.00**
Sand	0.02	0.02	0.29	0.01	0.08	0.90	-0.02	0.02	0.33
Clay + Silt	0.02	0.02	0.34	-0.02	0.07	0.80	-0.02	0.01	0.15
Soil $C_{organic}$	-0.01	0.04	0.80	-0.03	0.16	0.86	-0.03	0.03	0.34
Soil N_{total}	0.13	0.86	0.88	-1.91	3.64	0.61	0.49	0.94	0.60
Soil P_{total}	0.00	0.00	0.96	0.02	0.01	<u>0.05</u>	0.00	0.00	0.19
Soil Olsen-P	0.07	0.07	0.32	1.15	0.41	**0.01**	-0.10	0.07	0.16
Soil pH	-0.01	0.12	0.93	-0.60	0.53	0.27	-0.02	0.13	0.87
Shrub density	0.00	0.00	0.70	0.00	0.00	0.84	-0.00	0.00	0.76
Total Rainfall	0.00	0.01	0.63	0.15	0.03	**0.00**	0.02	0.01	**0.00**

Table 4.4. Determinants of sorghum grain, sorghum total biomass, and cowpea yields using a linear mixed model (*lmer* function , R package *lme4*) when considering ramial wood amendment input, local soil name and year as fixed factors. Farmer was set as random variable. Local soil name *Zénguédéga* and year 2014 were reference variables. Significant effects are shown in bold ($p < 0.05$). Marginally significant effects are underlined ($0.05 < p < 0.1$).

	Sorghum grain yield			Sorghum total biomass			Cowpea yield		
	Est.	S.E.	*p*-value	Est.	S.E.	*p*-value	Est.	S.E.	*p*-value
(Intercept)	0.29	0.09	**0.01**	1.12	0.62	0.10	0.38	0.09	**0.00**
Ramial wood input	0.02	0.01	<u>0.08</u>	0.02	0.07	0.73	0.00	0.01	0.67
Soil Name (*Zii Biinssiga*)	0.35	0.11	**0.01**	1.08	0.79	0.22	-0.06	0.12	0.64
Soil Name (*Zii Naaré*)	0.56	0.14	**0.00**	2.05	0.89	<u>0.05</u>	0.25	0.13	<u>0.08</u>
Year 2015	-0.05	0.07	0.43	-0.78	0.29	**0.01**	-0.22	0.06	**0.00**
Year 2016	-0.08	0.07	0.26	-0.64	0.33	<u>0.06</u>	-0.25	0.07	**0.00**
RW input : *Zii Biinssiga*	-0.00	0.02	0.94	0.06	0.10	0.55	0.03	0.02	0.10
RW input : *Zii Naaré*	-0.08	0.04	**0.04**	0.22	0.14	0.13	0.06	0.03	<u>0.06</u>

Chapter 5: Use and management of biodiversity by smallholder farmers in semi-arid West Africa

Abstract:
Strategies that strengthen and use biodiversity are crucial for sustained food production and livelihoods in semi-arid West Africa. The objective of this paper was to examine the role of biodiversity in sustaining diverse forms of multifunctional farming practices while at the same time providing ecological services to subsistence-oriented farming families in the region of study through mechanisms as (a) crop species diversification, (b) management of spatial heterogeneity, and (c) diversification of nutrition-sensitive landscapes. Our analysis shows that crop associations between cereals and legumes or between perennials and annuals, have overall positive effects on soil characteristics and often improve crop yields. Soil heterogeneity is produced by woody perennials and termites. Local management provides opportunities to collect a diversity of nutrition-rich species year-round and sustain household nutrition.

Keywords:
Agroforestry, Ecological Engineering, Intercropping, Nutritional Functional Diversity, Termites

Published as: Félix GF, Diedhiou I, Le Garff M, Timmermann C, Clermont-Dauphin C, Cournac L, Groot JCJ, & Tittonell P. 2018. Global Food Security 18: 76-85. DOI: 10.1016/j.gfs.2018.08.005.

1. Introduction

Management of biodiversity is the cornerstone of agriculture. Historically, the perspective of 'ecology in agriculture' was introduced by Hanson (1939), underlining the need for ecologists to broaden the spectrum of study from wild native plants to domesticated, exotic, and cultivated crops. Agroecological 'theory' suggests that the strategic use of locally-available biological diversity (cultivated or wild) is key in supporting ecological functions and maintaining food cultures (Gliessman, 2011). A growing body of knowledge recognizes the importance of anchoring these designs in local food cultures and household objectives (Duru, 2013; Luckett *et al.*, 2015; Bellon *et al.*, 2016; Nicholls *et al.*, 2016), and of integrating scientific and local farmer knowledge in the co-design of more sustainable farming systems (Dogliotti *et al.*, 2014; Speelman *et al.*, 2014; Geertsema *et al.*, 2016; Garibaldi *et al.*, 2017).

Rain-fed agriculture in semi-arid West Africa (SWA) is characterized by soils that are naturally poor in nutrients and organic matter content. Production indices for countries of semi-arid West Africa show increases in total staple food production yet average yields for local consumption remain alarmingly low, below 1 t ha^{-1} (www.faostat.org). While food security assessments and recommendations often focus on increasing production of staple food crops (i.e. cowpea, millet, sorghum, rice), it is unlikely that smallholder farmers in SWA sustain on grains exclusively. The strategic use of locally-available biological diversity (cultivated or autochthonous) is key in the design of agricultural management systems able to (1) produce sufficient food and ecosystem services, (2) diversify diets to meet food security and nutrition, and (3) support and sustain local food systems. In particular, woody perennial vegetation in Sahelian ecosystems provide an array of services to farming families, from the regulation of on-farm and landscape ecological processes to supporting local livelihoods (Sinare & Gordon, 2015a). Despite a wide diversity of initiatives to cope with erratic environmental and market conditions (West *et al.*, 2008; Sissoko *et al.*, 2010), financial constraints and low institutional support rarely help in recognizing smallholders as innovators with valuable expertise to share with peers.

Farming practices that include biodiversity make use of spatial and temporal resource heterogeneity, while simultaneously generating sources of heterogeneity at various scales having consequences for soil functions, food production, and habitat provision for wildlife (Tittonell *et al.*, 2015b). At regional scales, several environmental characteristics may shape landscapes. These include biophysical aspects, such as heterogeneous soil types and topography (i.e. lowlands and salinization), soil fertility hotspots (i.e. termite nests or presence of woody perennials), and anthropogenic drivers such as accumulation of organic matter around household compounds (i.e. biomass transfers of woody or organic amendments and plant associations) (see Fig. 5.1).

Moreover, it is common in SWA to encounter different types of actors in farming territories, including pastoralists (nomadic or sedentary), market-oriented farmers (cotton, horticulture), and subsistence-oriented farmers (cereals, legumes, wild edible plants) (Diarisso *et al.*, 2015a). These actors use and manage biodiversity following food and livelihood objectives in different ways, but mainly through the combination of plant and animal species, the spatial and temporal management of fields and natural habitats, or through the direct collection of wild foods, medicinal plants and other resources from their landscape.

The objective of this paper is to examine the role of biodiversity in sustaining diverse forms of multifunctional farm and food systems and in providing ecological services. This is done through the analysis of farmer-driven (i) plant species diversification, (ii) management of spatial heterogeneity at field level and (iii) strategic use of nutritional functional diversity at landscape level. Illustrations and quantitative examples are built with own research data from semi-arid Burkina Faso.

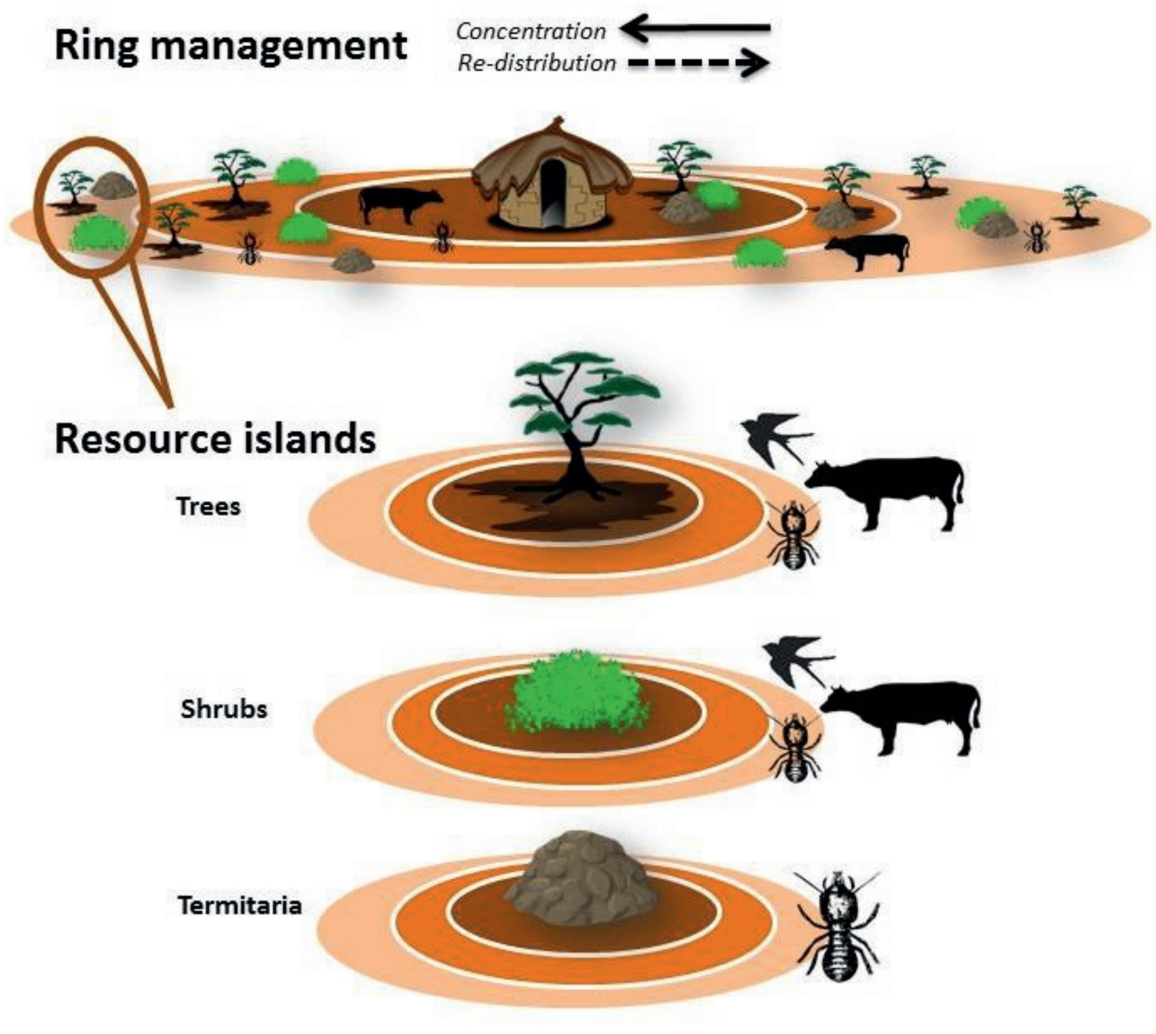


Figure 5.1. Ring management results in continuous soil fertility gradients, catalysed by biodiversity management at the landscape level. Nested rings are formed by trees, shrubs, and termite nests constitute 'resource islands' that provide conditions for other organisms to thrive.

2. Management of plant species diversification

2.1.Annual plant associations

Annual plant association or intercropping is an ancient and widespread agricultural practice in semi-arid West Africa (Mbaye *et al.*, 2014). It consists of establishing two or more crops with overlapping development cycles simultaneously on the same plot during the same season (Zongo, 2013), with the objectives of diversifying and/or securing agricultural production and integrated fodder systems, but also for the management of soil fertility, weed control, labour reduction, and intensive management of the available land (Essecofy, 2011; Karim *et al.*, 2016). In traditional farming systems, the geometric arrangement of cultural associations may vary widely, from crops grown in different rows, or alternated within the same row, to distributed randomly without a specific geometric arrangement (Table 5.1). Associated crops can be sown in the same planting hole, as well (Zongo, 2013), or planted at different growth periods according to expected outputs or functions. The most represented combinations were cereals (sorghum, millet, or maize) associated to legumes (cowpea, groundnuts, or Bambara nut-*voandzou)*. Some associations may also include cereals and forage legumes (cowpea, *Mucuna pruriens, Stylosanthes hamata, Pueraria phaseoloides*). Cowpea (*Vigna ungiculata*), for example, may be combined to millet to obtain grains in the outer fields (food security objective) or to obtain fodder biomass in the fields closest to the households (animal feed objective). Associations between grasses and agroforestry plants and occasionally, associations between grasses (*Panicum* sp.*, Brachiaria* sp.) or tuberous plants (yam or cassava) with forage legumes have also been documented. Scientific literature reports more than 21 species tested for their forage potential or fertilizer properties in semiarid zones of Benin (Kouelo *et al.*, 2014), Burkina Faso (Coulibaly *et al.*, 2012) and Nigeria (Abayomi *et al.*, 2001).

The comparative performance of crop mixtures is often assessed by calculating the land equivalent ratio (LER), or the sum of all crop yields in the mixture, weighed by their area share and divided by their respective yields when grown as monocultures (Vandermeer, 1981; Gliessman, 2002). An LER value equal to 1 means that the crop mixture performs as well as the monoculture, and values greater than 1 denote enhanced productivity of the mixture. Trail *et al.* (2016) showed in Senegal that millet associated with cowpea yielded 20 to 55 % more grain than millet grown as sole crop (1500 kg ha^{-1}). They found LER values in Senegal ranging from 1.34 to 1.95 for combinations of millet and cowpea, an overall favorable outcome. Partial LER values (i.e., the ratio of each crop in the mixture to its monoculture) calculated with data from on-farm experiments during four consecutive years in Yilou, Burkina Faso (Félix *et al.*, 2016), showed that sorghum-cowpea mixtures allow for improved LER index as compared to sole crop cultivation (Fig. 5.2). Average monoculture yields were 470 kg ha^{-1} for cowpea and 1000 kg ha^{-1} for sorghum. LER values greater than 1 were observed in 50% of the cases throughout the experiment (2013-2016), indicating that the performance of plant associations varies greatly, and could be influenced by date and density of sowing, soil preparation or nutrient additions. High LER values could indicate higher workload requirements yet Kermah *et al.* (2017) showed that grain-legume intercrops not only improve productivity per area but also make a better use of labour inputs than sole crop cultivation, especially on marginal fields.

Numerous studies in West Africa have shown that it is possible to significantly improve the yield of cereals associated with legumes by choosing methods of tillage or fertilization adapted to this type of associations (Cissé, 2013; Sarri *et al.*, 2013; Zongo, 2013; Kouelo *et al.*, 2014; Mbaye *et al.*, 2014; Karim *et al.*, 2016).

Legume-crop rotations are another means to take advantage of agricultural diversity in time. A recent review by Mason *et al.* (2014) compiles data from several studies in semiarid West Africa where millet- or sorghum-cowpea rotations were tested, following conservation agriculture principles (i.e. zero or minimum tillage, crop rotations or associations, and permanent soil cover). This review showed that millet grain yields increased by 10-50% in rotations with cowpea, while sorghum yields increased up to 100%, especially when environmental conditions were not favourable (i.e. control yields < 1 t ha^{-1}), and up to 20% when conditions were more favourable (i.e. control yields > 1 t ha^{-1}).

2.2. Woody perennials in cropping systems

Integration of trees within croplands is a widespread and well documented practice in West Africa (Bayala *et al.*, 2014; Sinare & Gordon, 2015a). Based on data retrieved in Bayala *et al.* (2014), the relative crop yield difference (in %), in presence of 9 woody species of SWA, was plotted against the relative crop yield without the influence of trees or shrubs (Fig. 5.3). Beneficial effects (positive values) of woody perennials on crop growth appear above the dotted line while depressive effects (negative values) are below this line.

Faidherbia albida is a well-known native species that has an inverted phenology (Vandenbeldt, 1992). Leaves grow during the dry season, providing shade and additional fodder for livestock when rainfall and grasses are scarce. Inversely, the trees remain leafless during the rainy season, allowing sufficient sunlight for crops to grow successfully nearby its trunk (Fig. 5.3C). Other trees such as *Parkia biglobosa* (Fig. 5.3E) and *Vitellaria paradoxa* (Fig. 5.3I), may have depressive effects on crop growth, but are kept in agroforestry parklands for their economic importance to farming families (i.e. commercial and highly-nutritious seeds/fruits). Trees and shrubs function as 'resource islands' in dry savannah ecosystems (Hernandez *et al.*, 2015). The processes involved include above- and below-ground biomass production, which improve carbon and nutrient cycling in the vicinity of trees through organic matter transfers and *in-situ* decomposition of leaf litter and root material (Buerkert & Schlecht, 2013). Deep root systems pump water and nutrients from the deeper soil layers, making these available for crop plant uptake in the upper soil layers. The process known as 'hydraulic lift' increases soil moisture and promotes soil microbial communities *in situ* (Bayala *et al.*, 2008; Kizito *et al.*, 2012; Diedhiou-Sall *et al.*, 2013; Diakhaté *et al.*, 2016). Moreover, higher infiltration rates around perennials are likely to contribute in maximizing groundwater recharge (Bargués Tobella *et al.*, 2014; Ilstedt *et al.*, 2016).

Shrubs in cropping systems in SWA accumulate organic residues and nutrients around their base (i.e. organic C, total N, and total P). A series of 16 *Piliostigma* shrubs monitored in Yilou, Burkina Faso during the dry season of 2015 (Cheriere, 2015) confirmed that shrubs form a 'fertility hotspot' at their base (Fig. 5.4). Shrubs however did not significantly modify soil pH.

Studies conducted in Niger support the promotion of farmer-managed natural regeneration with trees as a cost-effective way of enhancing rural livelihoods, more attractive than classical reforestation efforts that tend to rely on investments in planting and seeding of native and/or exotic trees (Haglund *et al.*, 2011). Although agroforestry systems can contribute to sustainable land use only when they are maintained over time (van Noordwijk *et al.*, 2014), farmers in West Africa will rarely invest in planting trees but rather take advantage of the existing vegetation in novel or ancestral ways.

Much has been written on the benefits of trees for cropping systems (Bayala *et al.*, 2014; Bayala *et al.*, 2015; Sinare & Gordon, 2015a), but studies on the contribution of shrubs to agroecosystem productivity and sustainability have been less common. Native shrubs such as *Guiera senegalensis* (Fig. 5.3D) and *Piliostigma reticulatum* (Fig. 5.3F) are an important component of biodiversity and of spatial heterogeneity in West African agroecosystems. In an experiment of 11 years in Senegal, Bright *et al.* (2017) found that groundnut and millet rotations performed better in presence of *P. reticulatum* shrubs than in absence of these perennial shrubs. Relative yield differences were greater when environmental conditions were more limiting and yields without shrubs lower. Overall differences between shrub and no-shrub systems were smaller with increasing fertilizer doses.

Areas of land left uncultivated during a certain number of years, or fallows, allow for native vegetation re-growth following a succession of herbaceous, shrub and tree strata (Bonetti & Jouve, 1999). In this sense, setting land as fallow is also a plant species diversification practice that operates at landscape level. Fallows are common in shifting agriculture around the world and are key in restoring soil fertility on extensive systems (Wezel & Haigis, 2002). In West Africa, the traditional fallow system is a biodiversity-based soil management practice that is becoming rarer and shorter due to the shortage of land caused by population growth, soil deterioration and desertification (Bonetti & Jouve, 1999; Diarisso *et al.*, 2015a). In Loukoura, Burkina Faso, fallows account for 53% of the village territory while cultivated lands only occupy 16% (Cabral, 2011). In other places like Yilou, Burkina Faso (Sudano-Sahelian region), fallows will last no more than two to three years (Lahmar & Yacouba, 2012). Such short periods of rest may seem far from ideal to restore soil productivity (Kintché *et al.*, 2015) or to maintain soil functions or habitats for biodiversity. Nevertheless, remnant trees and shrubs are ever-present on continuously cultivated cropping systems in the region (Hiernaux *et al.*, 2016), contributing also to create spatial heterogeneity.

3. Managing spatial heterogeneity

3.1. Nutrient and water concentration

Contour stone-bunds are barriers placed along the contour lines of farmer fields to reduce erosion, increase soil water retention and the accumulation of sediments, organic matter and nutrients (Critchley et al., 1994). As a complement, or a substitute to stone rows, farmers sometimes sow seeds and/or allow the regeneration of *Andropogon gayanus* grass as erosion control barriers (Zougmoré *et al.*, 2009). These grass strips have similar benefits for soil and water conservation as stone-bunds (Spaan, 2003). *Andropogon* also provides construction material, since the stalks may be used to build some types of silo where harvests are kept year-long. With time, small trees and shrubs tend to settle in these contours, consequently increasing ecosystem services supporting food and cropping systems.

A traditional way of sustaining soil productivity is the addition of organic inputs (i.e. animal manure, crop residues, woody amendments). Animal manure is a soil amendment commonly used in SWA (Zorom *et al.*, 2013), but its supply is too limited to sustain soil fertility at landscape scale, and is directly linked to livestock production (Dongmo *et al.*, 2012a). Resource concentration occurs in SWA through either (a) *active* by grazing animals (macro) or termites (micro) or (b) *passive* through accumulation around heterogeneities in the landscape (trees, shrubs, termite nests) after movement through wind or water.

Livestock typically roams around the landscape freely during the dry season (Dongmo *et al.*, 2012a; Diarisso *et al.*, 2015a). During the rainy season, organic matter and manure depositions are concentrated around homesteads, leading to fertility gradients, described by Prudencio (1993) as ´ring management´ (see Fig. 5.1). This practice has largely shaped the landscape and biodiversity distribution structure of the Mossi Plateau of Burkina Faso. But spatial heterogeneity is also important at field and plant-scales. Nested rings of 'fertility' such as in the vicinity of semi-perennial landscape structures like tall grasses, trees, shrubs and termite nests often act as ´resource islands´ that concentrate water and nutrients (see Fig. 5.1). Farmers recognize and manage this diversity intensively in West Africa by integrating crop-livestock systems in time (Ramisch, 2005) and by maintaining complex tree-shrub-crop systems such as parklands in space (Lahmar *et al.*, 2012).

Manure collection and re-distribution may eventually lead to increased diversity of plants present during the dry season, both through enhanced fertility locally by nutrient addition, but also by a seeds contained in manure after livestock has digested pods of locally-available and palatable perennial species and their distribution through animal movement at landscape level. *Zaï* pits or micro-basins dug by farmers to establish their crops in semiarid West Africa typically provide excellent conditions for seeds contained in manure to germinate and produce additional biomass that can be recycled into the system, including perennial grasses, shrubs or trees (Sawadogo, 2011). Zaï and half-moons are well known techniques for soil restoration and nutrient concentration in cropping systems of W-Africa, and they are dug during the dry season particularly on crusted soils (Hien *et al.*, 2010; Tsozué *et al.*, 2014). Perspectives for optimizing this technique have been explored, especially in combination with other management practices like crop residue or woody mulch to further increase soil organic matter decomposition locally (Lahmar & Yacouba, 2012).

Taking into account the multiple services provided by woody perennials in the semi-arid regions of West Africa (Bayala *et al.*, 2014; Sinare & Gordon, 2015a), at low input levels cropping systems supported by interactions with integrated shrubs can both have higher productivity and provide more products and functions than monocultures. Wezel (2000) observed two-fold millet productivity improvements in Niger when crops were grown in the vicinity of shrubs of *Guiera senegalensis* (i.e. 0.6-0.9 t ha^{-1}) as compared to millet plants growing more than 2 m away from the shrub (i.e. 0.3-0.4 t ha^{-1}). The authors attributed these differences to improved soil fertility due to sediment siltation and entrapment.

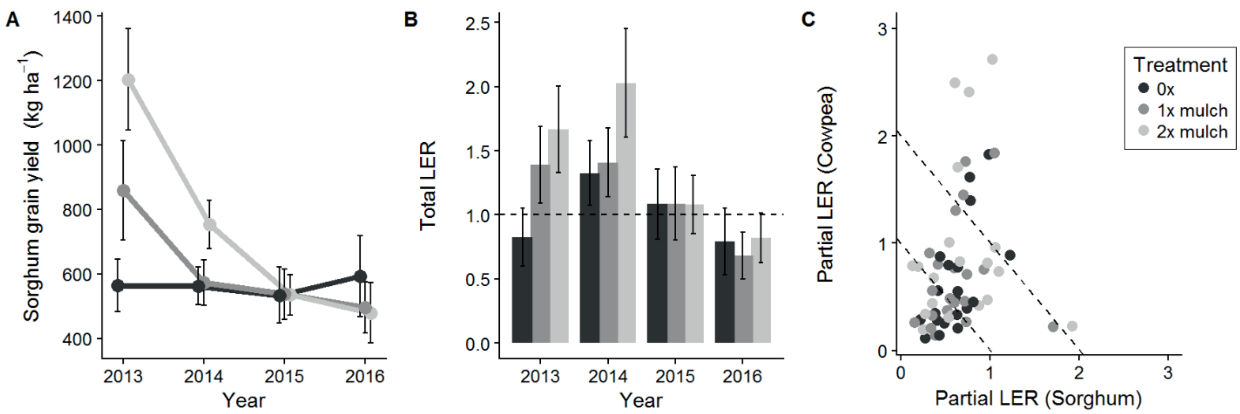


Figure 5.2. On-farm experiment with varying amounts of ramial wood (RW) amendments on sorghum-cowpea intercrops (panel A). Total land equivalent ratio (LER, panel B) and partial LER for sorghum and cowpea intercropping systems (panel C). Yilou, Burkina Faso. Data adapted from Félix *et al.* (2016).

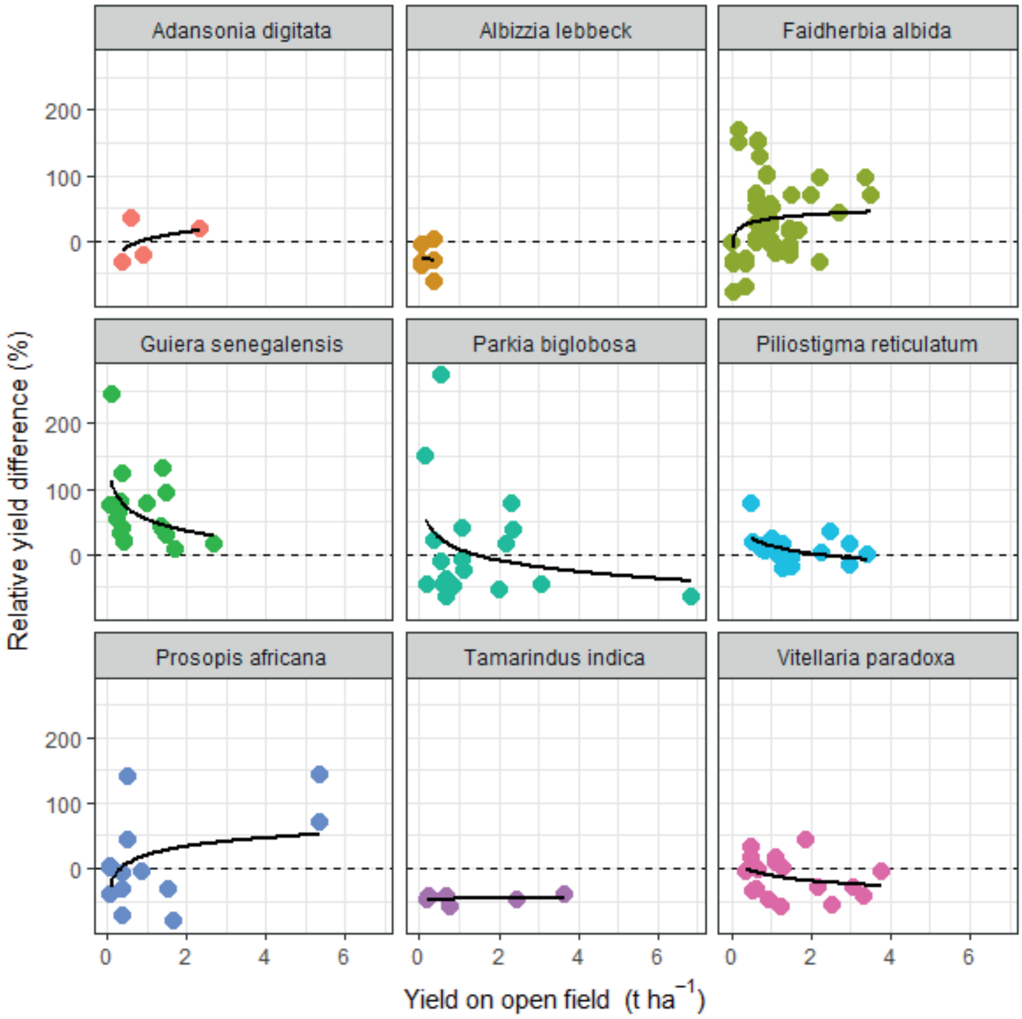


Figure 5.3. Relative yield difference in the vicinity of trees or shrubs as a function of yields outside the area of influence of 9 woody species of semi-arid West Africa. Data points were fitted to exponential model to show trends for each species. Data adapted from supplementary material found in Bayala *et al.* (2014).

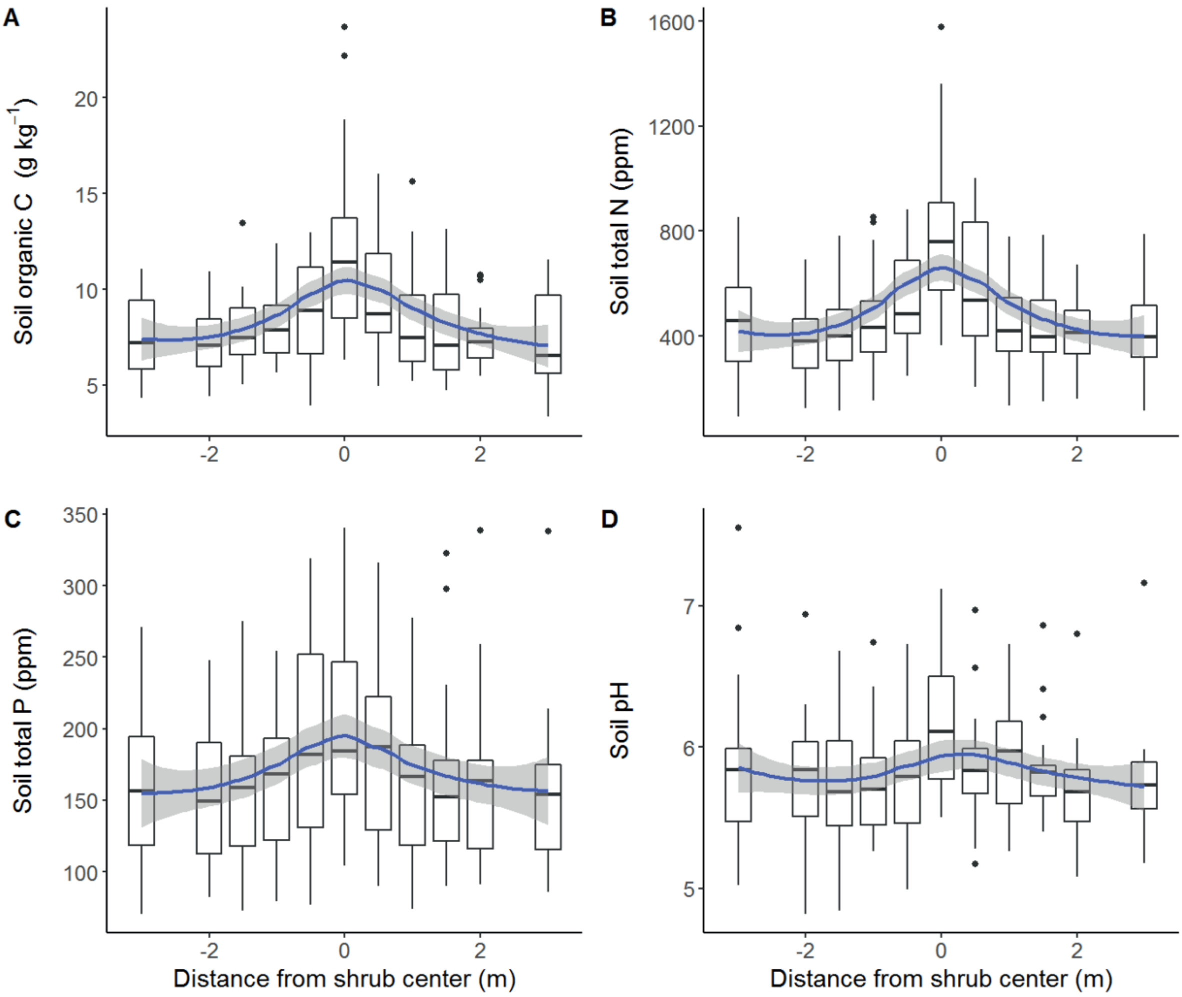


Figure 5.4. Soil fertility in the vicinity of *Piliostigma reticulatum* shrubs (n=21), Yilou, Burkina Faso. Analysis of soil organic C (panel A), soil total N (panel B), soil available P (panel C), and soil pH (panel D) across 6-m transects, from direction North-East (-3 m to shrub center) towards direction South-West (shrub center to +3 m). This coincides with Harmattan winds orientation occurring during the dry season. Data adapted from Cheriere (2015).

3.2. Biomass transfers

Re-locating carbon-rich plant material to rehabilitate patches of crusted soils is a technique practiced by smallholder farmers in West Africa (CSFD, 2015). This allows the restoration of degraded lands (Mando & Stroosnijder, 2006), often resulting in an increase of crop yields (Félix *et al.*, 2015). Prior to the cropping season, farmers prune the shrubs on the fields and use the biomass of both leaves and branches as soil amendment, usually in the surroundings of the shrub (Lahmar *et al.*, 2012; Bright *et al.*, 2017). These biomass amendments can improve soil water content and organic matter cycling via reduced erosion, increased sediment trapping, increased rainfall infiltration, and enhanced nutrient retention (Buerkert *et al.*, 2000; Mason *et al.*, 2014). Other mechanisms involved in soil aggradation (as opposed to *degradation*) processes *via* crop residue and ramial wood application include the reduction of soil organic matter losses due to the reduction of soil temperature and enhancement of soil biological activity, including the development of termite-mediated processes (Ouédraogo *et al.*, 2006). Research conducted for seven years at Gampéla Research Station in Burkina Faso (Barthès *et al.*, 2015; Félix *et al.*, 2018a) showed that although sorghum yields are lower than 1 t ha^{-1}, increasing doses of ramial wood (RW) improved crop yields significantly as compared to no RW application (Fig. 5.5A and 5.5C). Enhanced sorghum grain yields were attained with increasing soil organic C content (Fig. 5.5B). This effect was independent from treatments. Greater termite activity (Fig. 5.5D) was observed where high doses of RW were applied.

3.3. Termite nests

Termites play an important role in nutrient cycling and soil dynamics in SWA (Mando, 1998; Sileshi *et al.*, 2010), through their metabolic activity and the creation of termite nests. On the one hand, termites contribute to nutrient transfers through foraging carbon-rich materials from their surroundings (Ouédraogo *et al.*, 2004). Concentrating organic resources on degraded or crusted surfaces has proven that termites improved soil structure (Mando, 1998; Laguemvare, 2003; Ouédraogo *et al.*, 2004).

The termite nests or *termitarium* building activities contribute to the modification of the soil micro-topography, porosity, and water infiltration capacity (Sileshi *et al.*, 2010). A series of 12 termitaria on farmer fields (i.e. deserted termite nests) were monitored from May through November 2015 at Kindi, Burkina Faso . Soil organic C, available P, and pH, were significantly higher towards the middle (¼ and ¾ radius from center) of the termite nest as compared to the conditions of the open field (Fig. 5.6A through 6C).

Sorghum grain yields were in average twice as large on the termite mound area as compared to the open field (Fig. 5.6D, i.e. 2 vs. 1 t ha^{-1}). This boosting effect on termite mounds was quite noticeable on low-yielding fields (Fig. 5.6E) and corresponds to differences in soil pH (Fig. 5.6E). In cases where open fields yield low (~ 0.1 t ha^{-1}), sorghum grown on neighbouring termite mounds (properly mulched with straw or woody debris) could yield up to 1 t/ha. Farmers recognize the most fertile areas on the field as ‘dead’ termite mounds. Occasionally, grain harvested on these ‘fertile spots’ are kept as seed for next season.

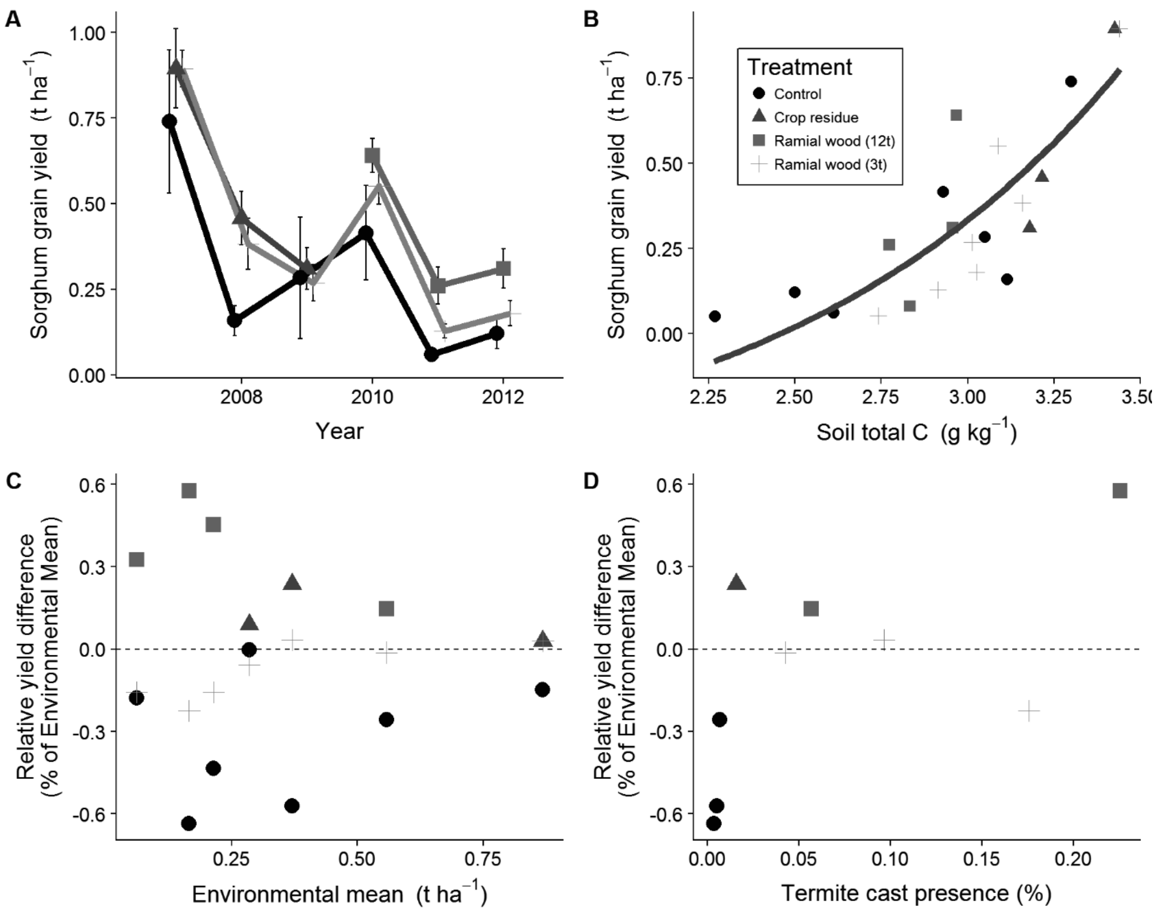
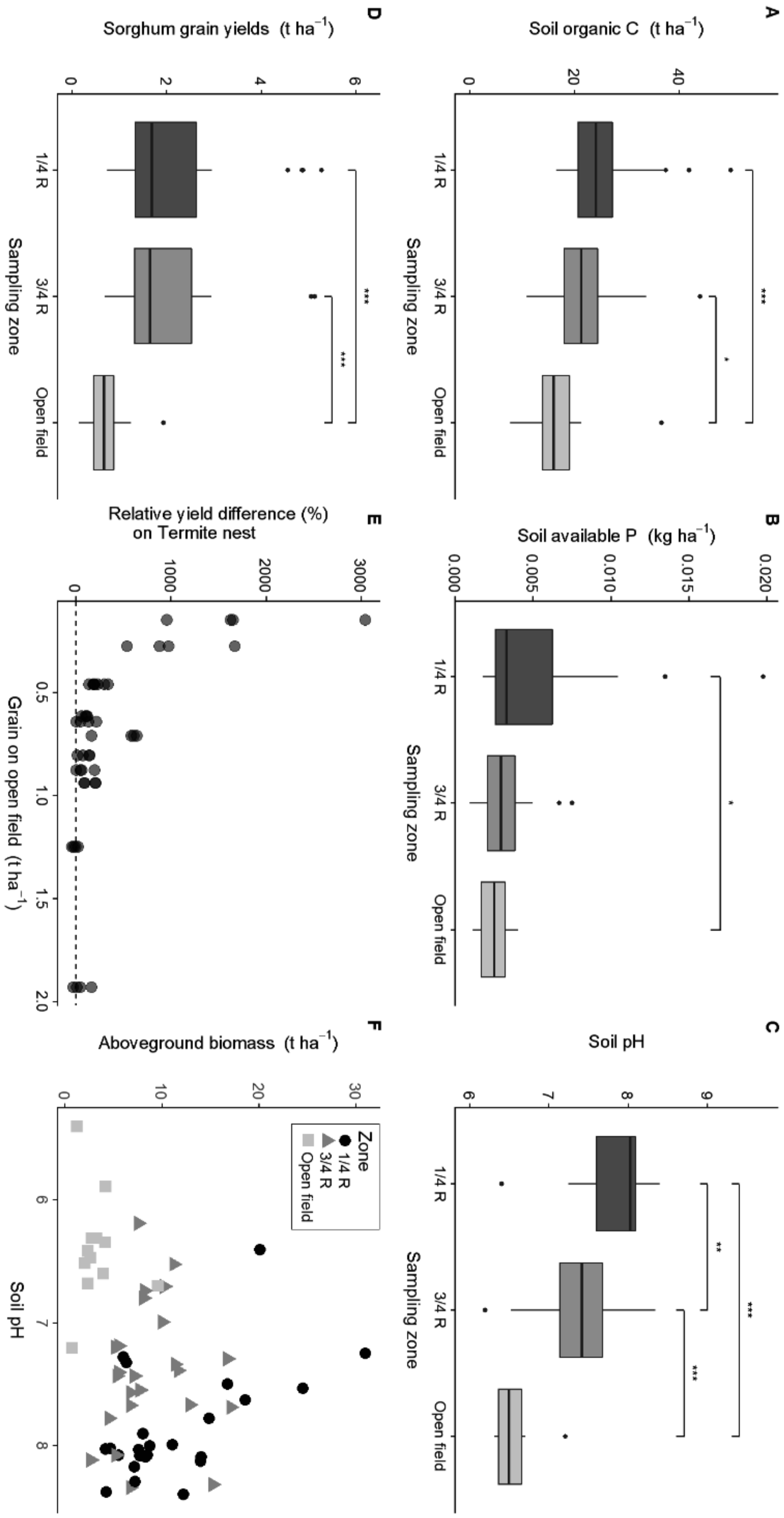


Figure 5.5. Sorghum yields on continuously cultivated plots decreased over a six-year period (2007-2012) at Gampéla, Burkina Faso (panel A), with or without soil amendments. Soil total C increased sorghum yields (panel B). Use of ramial wood (RW) or crop residue amendments improved yields as compared to environmental mean (panel C). When environmental conditions were favourable (e.g. high environmental mean), the differences between treatments were less noticeable than when environmental conditions were low. Termite activity (measured in 2009, 2010, and 2011) was enhanced in presence of high rates of RW application (panel D). Data adapted from Barthès *et al.* (2015) and Félix *et al.* (2018a).

Figure 5.6. (right) Soil properties and crop performance of sorghum crop on termite nests present on 16 farmer fields in Kindi, Burkina Faso. 1/4 R is the sampling zone that corresponds to 25% of the radius (from centre of each termitaria), 3/4 R corresponds to 75% of that radius, and open field were samples taken outside the zone of influence of the termitaria. Soil organic C (panel A), soil total P (panel B), and soil pH (panel C), at 0-20 cm depth, show fertility gradients, with higher nutrient stocks and increased yields towards the centre of the nest (panel D). Relative yield differences between on termite nests were more important when yields on the open field were low (panel E). Soil pH was close to 6 on open field and close to 8 in the termite nest centre, also showing highest yields in aboveground biomass (panel F). Significant differences: * <0.05, ** <0.01, *** <0.001. Original data, with contributions from Patrick Winterhoff.


A
Soil organic C (t ha^{-1})
B
Soil available P (kg ha^{-1})
C
Soil pH
D
Sorghum grain yields (t ha^{-1})
E
Relative yield difference (%) on Termite nest
F
Aboveground biomass (t ha^{-1})
1/4 R
3/4 R
Open field
Sampling zone
Grain on open field (t ha^{-1})
Soil pH
Zone
1/4 R
3/4 R
Open field
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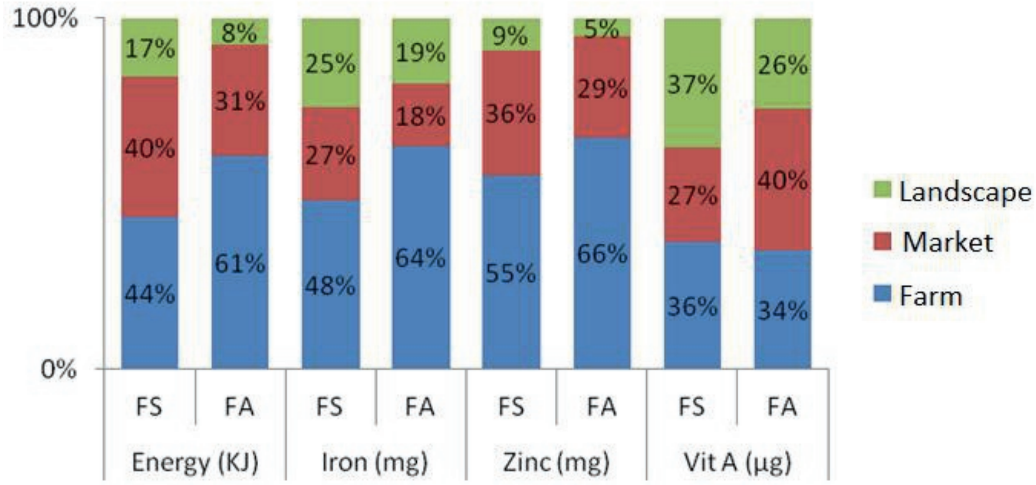

Figure 5.7. Landscape, market and farm contribution to household nutrition, Yilou, Burkina Faso (FS=food shortage, FA=food abundance). Data adapted from Le Garff (2016).

4. Biodiversity contribution to household nutrition

Diets are mainly determined by local food availability and diversity (i.e. cultivated crops and animals, wild edible plants collected from the surrounding landscape, or products exchanged and bought at the market). Food diversity is a relevant indicator for nutrient adequacy and health, positively correlated to micronutrient intake (Foote *et al.*, 2004; Allen *et al.*, 2014), and is an indicator for ecologically and socially sustainable diets (Remans *et al.*, 2014). In particular, the nutritional functional diversity (NFD) indicator is useful to link the effect of biodiversity in natural and managed systems with human nutrition, and considers nutrient trait diversity in the intake of families within a given social-ecological system (Luckett *et al.*, 2015). The diversity of food items consumed over the year was monitored in a study in 12 households at Yilou, Burkina Faso (Le Garff, 2016).

Total diversity inventoried among these 12 families ranged between 64 and 88 food items per household during the year considered. Markets accounted for 50% of food item diversity, farm-produced items constituted 30%, and food items collected from the landscape accounted for 20% (Fig. 5.7). On-farm sources of food diversity were slightly more important during food abundance (FA) and food shortage (FS). A list of woody perennials contributing to household nutrition may be found in Table 5.2. The proportion of NFD collected from the landscape was more important during FS than during FA (39% of total food items compared to 33%). Contribution of market and farm produce was similar between FS and FA (81% compared to 84%, and 38% compared to 39%, respectively). In the case of vitamin A, households derived about one third of their intake from wild foods collected from the surrounding landscape, both during food shortage or abundance periods. Wild food contribution to energy intake was less significant at both periods.

While food availability may be in short-supply at times, local ecological knowledge of wild edible plants (trees, shrubs) allows for accessibility to nutritious food items. Moreover, in times of FS, nutrient-rich food items for household use may be collected from landscape elements such as leaves of *Adansonia digitata* (baobab). According to Lamien *et al.* (2009), the contribution of local fruit snacks plays a fundamental role in sustaining nutritional intake of rural populations drylands of Burkina Faso. Yet the selection of available local fruits varies throughout the seasons. From October through December, *Diospyros mespiliformis, Ziziphus mauritiana,* and *Balanites aegyptiaca* were most consumed per person. From January to March, *Z. mauritiana* and *D. mespiliformis* are collected along with *Gardenia erubescens* and *Detarium microcarpum.* During the wet season (April through June), the selection of fruits available includes species featured in parkland systems such as *Lannea microcarpa*, *Saba senegalensis*, *Ximenia americana*, *V. paradoxa*, and *P. biglobosa.*

Biodiversity sustains an array of ecological functions for farming families on their territories (Culman *et al.*, 2010; Altieri *et al.*, 2011; Blanco *et al.*, 2013; Sinare & Gordon, 2015a; Garibaldi *et al.*, 2017; Wilson *et al.*, 2017). The examples illustrated show that the development of appropriate strategies to reduce vulnerability of resource-poor farmers and move biodiversity-based approaches forward, is a process that emerges from a variety of contextualized 'options,' and not, from silver-bullet 'solutions' (Mortimore & Adams, 2001; Isgren, 2016).

5. Conclusion

The underlying functional hypothesis "the more complex the structure, then the more services are obtained from the system" was challenged in this paper, with examples from SWA. We analyzed three levels at which farmers manage biological diversity: crop mixtures, resource islands, and household nutritional diversity. Particularly, we focused on effective resource extraction (i.e. crop yields) in heterogeneous environments by showing (a) how multiple species explore different niches, and (b) how temporal fluctuations of resource availability are managed.

Most common associated annual crops in SWA feature cereals and legumes, and the available evidence suggests that their intercropping can improve field-level productivity by concentrating nutrients, biomass, and water at the plant roots. Crop associations not only represent a risk-aversion strategy in case of crop failure, but their implementation requires tacit knowledge on synergetic (or antagonistic) relations between plants (i.e. system components). In presence of woody perennials soils are improved and crops may perform better. Tree-crop or shrub-crop combinations are based on perceived benefits and trade-offs by farmers. Managing spatial heterogeneity includes termite nests that have been abandoned and weathered. Indeed, termite activity leads to a concentration of soil nutrients (C, N, P) and a clear difference between the center of the termite nests and the open field. Our analysis shows that yields are systematically improved in presence of termite nests.

Wild plants (i.e. grasses, shrubs, vines, and trees) collected from surrounding landscape play an important role in sustaining micronutrient accessibility at the household level. On-farm diversity contributes mainly to household nutrition, and this diversity comes from the capacity of farming families to combine crops in smart ways. Local ecological knowledge is very valuable to extension and rural development services since in revisiting past practices, then new skills or methods can be developed in their own areas. This would thus make clear that farmer creativity is a valid form of knowledge acquisition and application to co-innovate on the use of biodiversity and its role in multifunctional farming systems.

Table 5.1. Examples of spatio-temporal arrangements in intercropping practices of West Africa.

Location	**Association**	**Spacing (cm)**
Sub-humid Senegal	Millet (2 rows)	100 x 90
(Diangar *et al.*, 2004; Mbaye *et al.*, 2014)	Cowpea (1 row; 10-15 days after)	100 x 60
Burkina Faso	Millet (1 row)	80 x 60
(Sanou *et al.*, 2016)	Cowpea (1 row)	80 x 40
Sahelian zone	Millet (1 row)	150 x 50
(Sarr *et al.*, 2009)	Cowpea (2 rows)	150 x 50
	Millet (1 row)	100 x 80
	Groundnut (1 row)	100 x 30
(Garba, 2007)	Sorghum (1 row)	100 x 80
	Cowpea (1 row; 10 days after)	100 x 50
	Maize (2 rows)	80 x 50
	Cowpea (1 row; 10 days after)	80 x 50
	Maize (2 rows)	120 x 80
	Groundnut (2 rows; 10 days after)	40 x 15

Table 5.2. Calendar of collected fruit and vegetables from landscape species and accessibility in time. Green indicates produce harvested from the landscape, blue denotes dried spices from wild trees that are available throughout the year, and red denotes seasonal availability at local market. Data is adapted from a case study in Yilou, Burkina Faso (Le Garff, 2016).

Food item	Species	June 2015	July 2015	Aug. 2015	Sept. 2015	Oct. 2015	Nov. 2015	Dec. 2015	Jan. 2016	Feb. 2016	Mar. 2016	Apr. 2016	May 2016
Leaves	*Adansonia digitata*	X	X	X	X	X	X	X	X	X	X	X	X
	Bombax costatum	X	X	X	X	X	X	X	X	X	X	X	X
	Ipomoea aquatica	X	X	X	X	X	X	X	X	X	X	X	X
	Cassia obtusifolia	X	X	X	X	X	X	X	X	X	X	X	X
	Tamarindus indica	X	X	X	X	X	X	X	X	X	X	X	X
	Leptadenia hastata						X	X	X	X	X	X	
	Cratevia religiosa										X	X	X
	Balanites aegyptiaca										X	X	
	Acacia macrostacchya	X	X	X	X	X	X	X	X	X	X	X	X
Fruits	*Tamarindus indica*	X	X	X	X	X	X	X	X	X	X	X	X
	Mangifera indica	X									X	X	X
	Sclerocarya birrea	X	X	X								X	X
	Acacia sp. ('gumvine')	X	X	X	X								X
	Vitex doniana	X	X	X									X
	Ximenia americana	X	X	X	X	X	X						
	Vitellaria paradoxa	X	X	X	X								
	Lannea microcarpa	X	X	X									
	Adansonia digitata				X	X	X	X	X	X	X		
	Diospyros mespiliformis						X	X	X	X	X	X	
	Ziziphus mauritiana						X	X	X	X	X	X	
	Annona senegalensis						X	X					

Chapter 6: General Discussion

1. Introduction

In the drylands of West Africa the opportunities for regeneration of natural vegetation have gradually declined due to growing needs of local populations for fuelwood and freely-roaming livestock for feed (Ickowicz *et al.*, 2012; Usman & Nichol, 2019). At the same time, the frequency of drought periods featuring short and intense rainfall episodes is increasing. In the Sahel, barren lands with crusted soil surface represent the degraded state while regenerated ecosystems comprise diverse native shrub, tree, and herbaceous species (Brandt *et al.*, 2018). Agricultural techniques and management practices that have the potential to restore degraded land and optimise resource-use result from the dynamic interaction between human societies and their environment (Tambo & Wünscher, 2017). This thesis explored the role that shrubs and shrub-based woody amendments could play in order to reverse degradation patterns in the Sahel, based on scientific literature, field and lab experimentation, participatory action-research, and on-farm data collection. In particular, I aimed:

- To document and describe the diversity of management practices using woody perennials and their impact on crop performance and soil properties in semi-arid West Africa **(Chapter 2)**
- To evaluate the potential of ramial wood amendments to cope with agricultural soil degradation on topsoil organic carbon content, nutrient stocks and sorghum yields in a continuously cultivated system **(Chapter 3)**
- To explore the applicability and performance of ramial wood amendments on heterogeneous farmer fields by incorporating local ecological knowledge and perception **(Chapter 4)**, and
- To examine farmers' use of biodiversity-mediated ecosystem services with emphasis on food production **(Chapter 5)**

In the following sections, I demonstrate how agroforestry systems based on agroecological principles can contribute to land restoration through plant diversification in time and space, through the concentration of carbon and nutrients, and through their potential for bio-irrigation. I then analyse the effects of shrub-based ramial wood amendments on soil quality and crop performance, in light of experimental results. Finally, I examine the role of farmer perception, culture and management practices at fostering ecological, social and economic sustainability through shrub-based agroforestry.

2. Agroecology in the Sahel

While doing fieldwork in Burkina Faso, I understood that smallholder African farmers are not “by default” agroecological yet the principles of agroecology are often present in traditional practices and local innovations. The use of chemical fertilizers, pesticides and herbicides is nowadays prevalent (Son *et al.*, 2017; Theriault *et al.*, 2017), monocultures and improved varieties are extensively established (Sanou *et al.*, 2016), and even genetically-modified cotton can be commercially found in the country (Gray & Dowd-Uribe, 2013; Vitale *et al.*, 2016).

As long as population pressure was low, traditional systems could take advantage of the natural processes of regenerating fertility and maintaining the level of agricultural production. They were agroecological through the maintenance of biodiversity, through the use of crop varieties and associations well adapted to climate variability, and through their knowledge of the environment. The integration between crop production activities and animal production would provide crop residues to feed livestock which in turn, would provide manure to regenerate nutrient-poor cultivated soils. Farming systems integrated not only yield objectives, but also sustainable management of the most limiting resources by taking into account climatic and economic risks. The knowledge on which this systemic management is based has various origins: agronomic knowledge disseminated by development organizations, local ecological knowledge, and farmer adaptability.

The increase in demographic pressure means that it is necessary to produce more on reduced surfaces. The process of intensification of Sahelian agriculture was largely inspired by the model of high input agriculture in the Global North where each factor, each state of the environment is controlled by a specific input or a particular technique, as if these environmental features were independent from each other, or as if each technique, or each input had effects only on a single state of the environment. Interacting effects of practices are important in both conventional and agroecological approaches. Nevertheless, agroecology builds on contextual conditions and variability, and is focused on the long term sustainability of the systems, while conventional agriculture tries to undo variability and differences in contexts and conditions in time and space. From an agroecological perspective much effort needs to be made in order to design sustainable and resilient farming systems that take more effective account of the interactions between techniques.

For example, the choice of the sowing date or the choice of varieties or sowing densities may be reasoned not only to reduce water-related risks, but also to reduce the risk of leaching of the nutrients brought, the risks of attack of a pest and therefore, the use of pesticides. The practices of zero-tillage and mulching can improve soil porosity and consequently improve soil aeration and biological functioning, causing changes not only on the soil water dynamics but also that of nutrients. Soil management under minimum or zero-tillage techniques also impacts the location of residues from the previous crop and weed seeds, with consequences for weed and parasite inoculum dynamics. The choice of agroforestry practices responds to needs of pest regulation, to improve the efficiency of water and nutrients in agroecosystems, and to diversify harvested products. The innovative agroecological systems should thus, allow to: (a) optimise the efficiency of external input use, (b) detoxify and minimise the use of unsafe agricultural inputs, and (c) intensify ecological processes on-farm. Understanding current production strategies and exploring possible low-cost and low-external input alternatives would allow for increased food self-sufficiency, by making use of landscape heterogeneity, and ultimately, fostering resilience in drought-prone regions

2.1. Ecosystem boundaries

The “slash-and-mulch” system consists of pruning perennials to transfer biomass from woody “sources” towards soil “sinks,” which are agricultural fields where organic matter is needed (Mando & Stroosnijder, 2006; Lahmar *et al.*, 2012). This farmer technique can be practiced *ex situ* as exposed in **Chapter 3** or *in situ* as reported in **Chapter 4**. Its applicability is highly dependent on the available sources of woody biomass since carbon allocation strategies in Africa show high variations across farm communities (Tittonell *et al.*, 2015b). In semi-arid Burkina Faso, aboveground carbon stocks in parklands and natural ecosystems vary between 5-7 Mg ha^{-1} (Fischer *et al.*, 2011) and 10-20 Mg ha^{-1} (Dayamba *et al.*, 2016), respectively. In Yilou, Burkina Faso, we estimated similar biomass stocks based on species-specific allometric equations, with an average of 6-10 Mg ha^{-1} aboveground biomass (Fig. 6.1A; range between 0-20 Mg ha^{-1}). These values are contrasting with reports from Senegal’s Peanut Basin, where regional aboveground biomass stocks in agricultural fields averaged 0.01-0.45 Mg ha^{-1} (Lufafa *et al.*, 2008a), a difference between the two countries that could be attributed to historically prevailing “slash-and-burn” practices in Senegal as compared to Burkina Faso (Loum *et al.*, 2014). In Yilou, Burkina Faso, 50% of the contribution to overall biomass availability was provided by small-volume species (Fig. 6.1B). The fraction corresponding to woody shrub biomass that can potentially be used as ramial wood amendments (i.e. *Piliostigma reticulatum, Guiera senegalensis, Combretum micranthum*), averages 0.75 Mg ha^{-1}. The shrub biomass reported in Senegal by Lufafa *et al.* (2008b) was 1.3-2.0 Mg ha^{-1} for *P. reticulatum,* and 0.9-1.4 Mg ha^{-1} for *G. senegalensis.* The practice of “slash-and-mulch” of shrub biomass for soil restoration needs to take into account the regeneration potential of the natural vegetation as well as the perceived short- and long-term benefits (and investments), from a farmers’ perspective.

A

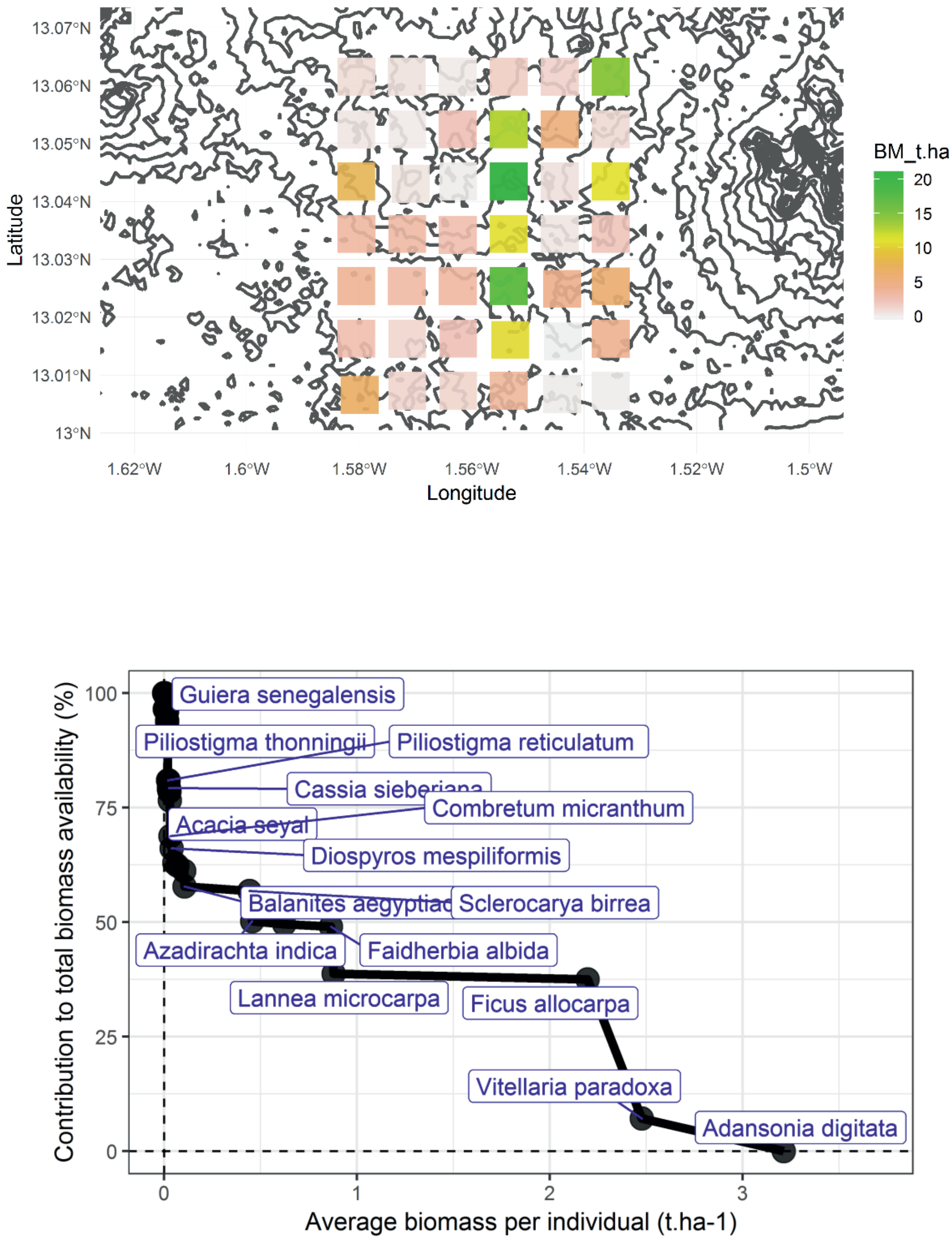

Figure 6.1. (A) Natural vegetation biomass and (B) cumulative aboveground biomass of individual woody species found in the Sahelian village of Yilou, Burkina Faso. Data adapted from Feur (2014).

2.2. The limited effect of ramial wood amendments on crop performance

Sudano-Sahelian conditions require crops that can resist short periods of drought and respond well on poor soils with erratic rainfall patterns. Local diets are diversified and often include imported rice, locally-grown leafy greens, small amounts of animal protein, and parts of wild edible plants (**Chapter 5**). The most common staple crops grown by smallholder family farmers in Burkina Faso, Mali and Senegal are sorghum, millet, cowpea, and groundnut. According to FAOstat data, the average sorghum productivity in Burkina Faso has nearly doubled since 1960 (0.5 to 1 Mg ha^{-1} in 55 years). The trends depicted from these data are meaningful and informative: *Sorghum yields in the Sahel can only be improved by so much!* Locally, increased nutrient input, improved crop varieties, and conventional tilling may have contributed to obtaining higher yields since 1960s, but unresponsive soils are yet extensive across Africa (Tittonell & Giller, 2013). The use of shrub-based ramial wood amendments in the Sahel was documented as a promising practice by Dr. Alexander Wezel in Niger with *G. senegalensis* on-farm (Wezel & Böcker, 1999) and by Dr. Richard Dick in Senegal with *G. senegalensis* and *P. reticulatum* on-station (Bright *et al.*, 2017).

In this thesis, I used combined methods to study crop responses to RW through on-station and on-farm trials using *P. reticulatum* in drought-prone areas of Burkina Faso. The study of the "slash-and-mulch" cropping system in Burkina Faso originated from a local farmer innovation (Lahmar *et al.*, 2012), then became part of a short-term experimental trial on-station (Barthès *et al.*, 2015), and later progressed into a long-term RW test (**Chapter 3**). Dr. Yélémou Barthélémy had already studied (ethno)botanical aspects of *P. reticulatum* and *P. thonngii* on farmer fields of Burkina Faso, thus clearing the path in the characterization of the shrub-crop interactions (Yélémou *et al.*, 2007; Yélémou *et al.*, 2012; Yélémou *et al.*, 2013b; Yélémou *et al.*, 2014). Could RW be a pathway to sustainable crop production in the Sahel? Yes... and no. I expected that increasing doses of agroforestry mulches would proportionally increase cereal yields in the field experiments (**Chapters 3, 4 and 5**). I also expected that the use of shrub-based mulches would induce more favourable conditions for crop growth through increased soil-water retention capacity, structure, and nutrients.

Part of my contribution to the advancement of science lies in the analysis of RW applications from the farmers' perspective (**Chapters 4 and 5**). Throughout the project, I based my research on the approach "*from local innovation to experimental agronomy... and forward!"* I gathered a comprehensive database and reported in **Chapter 2** that RWA can have weak but overall positive effects on crop yields region-wide compared to no-mulch application. This result was confirmed in the on-station experimental results at Gampéla, Burkina Faso (**Chapter 3**). Mulch applications of *P. reticulatum* material at doses of 3 and 12 Mg ha^{-1} improved yields by over 100% as compared to no-mulch (control), especially during the first cropping year. At low yield values for the control (<0.2 Mg ha^{-1}), the use of RW resulted in variable yet remarkable positive effects on sorghum grain and total biomass yields. The long-term effects revealed a linear yield decline during seven years of continuous cereal cultivation and marginally significant yield effects at the highest RWA input level as compared to control. Consequently, the RWA practice was not detrimental to crop productivity and its application can be targeted for restoring soil productive capacity of degraded fields.

The on-farm experimental results at Yilou showed that crop responses to RW applications in farmer conditions can be heterogeneous in space and time (**Chapter 4**). The characterization of local soil classes by farmers was an accurate indicator to predict crop productivity and RW effect on crop performance. “Clayey” soils yielded better than “shallow” and “sandy” soils. The effect of RW on crop performance was inversely proportional to site quality. Highest yield improvements were observed on the “shallow” and “sandy” soil classes, which responded better to RW treatments and increasing RW doses than “clayey” soils. These results highlight the limited capacity of RWA alone to reverse soil degradation patterns in the Sahel. From a farmer’s perspective the success of RW through *in situ* or *ex situ* applications is encompassed in a form of “precision agriculture” that is not guided by remote sensing or computer modelling but rather, by a fine sense of landscape heterogeneity and a recognition of ecological interactions between parkland system components.

Additionally, in these systems termites play a major role as soil engineers. Termite dietary regimes (i.e. woody debris) interact with the RW practice: the more the RW input, the more the evidence on the surface of termite foraging activity with simultaneous improved yields (**Chapter 3**). The influence of termites on soil quality is widely recognized yet the influence of termites on improved crop performance is a direct contribution from my thesis to the advancements of science. Understanding the relation between termite activity, diet patterns, and nest-building dynamics on crop productivity in the Sahel is a pertinent area for future research (**Chapter 5**).

2.3. Agroforestry mulches to improve soil quality

To counter land degradation, experience from semi-arid Burkina Faso, Niger and Senegal shows that farmers have developed temporal and spatial arrangements using native evergreen woody shrubs (i.e. *Piliostigma reticulatum* and *Guiera senegalensis*). These shrubs provide *in situ* organic mulch material, thereby supporting soil protection while not conflicting with traditional feed use for crop residues (Yélémou *et al.*, 2007; Dossa *et al.*, 2009; Lahmar & Yacouba, 2012). The targeted management of organic woody sources in dryland agroecosystems can efficiently restore soil carbon of degraded agricultural soils (Ouédraogo *et al.*, 2007).

Woody mulches can improve soil structure, enhance soil water-holding capacity, and stimulate nutrient cycling and biological activity (Bünemann *et al.*, 2018; Hueso-González *et al.*, 2018). In laboratory conditions, *P. reticulatum* amendments performed the same as crop residues in terms of biological soil respiration (Fig. 6.2), validating the proposed RW-based management option as a replacement for crop residue mulches. In **Chapter 2**, I gathered data from academic literature on the use of agroforestry prunings and showed that nine out of ten different woody species consistently boosted productivity indicators (e.g. relative yield increases). Productivity indexes were linked to the overall positive effects of mulched RW amendments on soil C, N and P. Buried RW applications did not significantly contribute to total soil C, and in certain circumstances, appeared to immobilize total soil N and P-available.

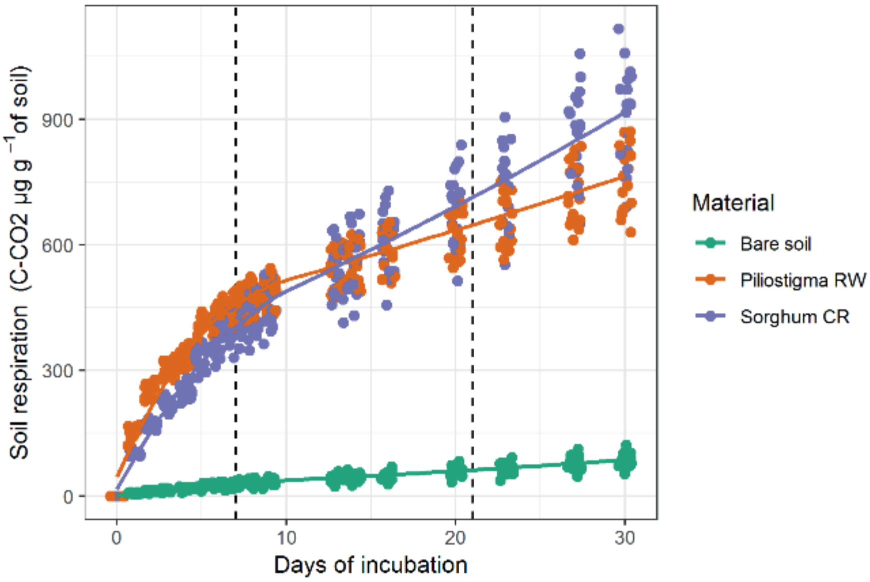

Figure 6.2. Soil biological respiration (C-CO_2) of incubated crop residue or shrub-based mulches in laboratory conditions in Dakar, Senegal. Methodology: Ten grams of humidified soil (70 ± 10% of its capacity in the field) were placed in a cup inside a sealed 125mL-flask and oven-dried at 28 ± 0.5 ° C. The air contained in the flasks was pumped into a gas chromatograph to measure CO_2 in helium (He) as carrier gas. The result was obtained in% of CO_2 contained in the volume of the bottle, then converted into mol of C-CO_2 per g of dry soil. Data adapted from Gabaud (2015).

The short- and long-term effects of different RW application doses were examined in controlled conditions at Gampéla, Burkina Faso (**Chapter 3**). Barthès *et al.* (2015) reported no significant differences on soil properties during the first three years of study between the use of crop residue-mulch and 3 Mg ha^{-1} RW-mulch. The experiment was continued during four additional years to compare different rates of RW application on soil properties and crop performance without mulch (as control), and with 3 Mg ha^{-1} or 12 Mg ha^{-1} fresh matter of *Piliostigma*-based RW (the latter in replacement of the crop residue treatment). After seven years of continuous application of coarsely chopped RW amendments, cereal yields and topsoil C, N and P linearly decreased for all treatments. The exception to this trend was that topsoil C loss was mitigated under RW applications of 12 Mg ha^{-1}. For all treatments, the net contribution of RW applications to topsoil C was 15%. The limited effect size was attributed to underground termite activity. Indeed, lignin-rich RW inputs should mineralize slower than manure or even crop residues but termites, which are the principal soil engineers in semi-arid conditions of Burkina Faso, have the capacity to export organic particles away from the "sink" via foraging on woody materials (Jouquet *et al.*, 2011; Mettrop *et al.*, 2013). This implies that mitigation of topsoil degradation on continuously cultivated soils would require much larger amounts of woody leaf and branch material than what is currently available in drylands of Burkina Faso.

In **Chapter 3**, I reported that "*ramial wood amendments mitigate soil degradation but do not replenish nutrient exports*" because the amounts of RW input needed to maintain soil C contents unchanged are far larger than the RW *in situ* availability on farmer fields. Moreover, the additional effort needed to gather RW material for soil restoration above the *in situ* availability comes with no guarantee of improved yields, at least in the short- and medium-terms (**Chapters 3 and 4**). Consequently, farmer perception has an influence on the processes of development and of adoption of an innovative practice.

3. Dynamics of local socio-ecological system

During my fieldwork in semi-arid Burkina Faso, I observed variations in farmers' perception towards native shrubs in cropping systems (**Chapter 4**). I found out that farmers had already a keen sense of where and how their practice works, also known as *local ecological knowledge*. As a foreigner to the territory of study, my contribution to local farming livelihoods was restricted to the in-depth documentation and exploration of a farmer practice in *controlled* and in *real* situations. I gathered quantitative data and contributed to the identification of relevant mechanisms implied in the success of this farmer innovation. Farmers in the Sahel have adapted to changing conditions (i.e. demographic, markets, political, climate...) and have also adopted foreign technologies that have impacted the food production systems. The contextualized study of farmer perception, adoption, and adaptation of innovative cropping systems needs to be examined in the light of contextualized historical trajectories of change in the region.

3.1. Environmental, social and economic considerations

The recognition of social and cultural aspects revolving around the long-term planning of natural resources use and management should not be underestimated in view of sustained provision of ecosystem services. Agroecological research requires improved understanding of underlying processes governing the natural ecosystems in order to design ecologically-sustainable farming practices, based on site-specific productivity potential and guided by local social values (Nicholls *et al.*, 2016).

In the case of farmers in the Sahel, there is an urgent need to stimulate environmentally-sound, socially-adapted, and economically-profitable farming practices. Shrub agroforestry is a low-cost and locally-accessible option that may have the potential to improve the delivery of ecosystem services, and increase the efficiency of farming systems in arid to semi-arid regions of Africa (Yélémou *et al.*, 2012; Hernandez *et al.*, 2015). Nonetheless, the native shrub resource quality and quantity could decline in the case where all farmers would indiscriminately exploit it, unless its use and management is accompanied by long-term institutional support and strong community action planning.

The evidence gathered in **Chapter 2** shows that agroforestry systems across Sahelian countries can impact positively the environmental and economic status via diversification strategies. Nonetheless, the implications of local land tenure rules are two-fold. First, the continued exploitation of the natural resource base without renewal can be at high risk of degradation (e.g. soil nutrient loss and erosion, loss of biodiversity, loss of culturally-appropriate wild plants). Second, the restoration efforts need to be undertaken collectively, and not by individuals or small groups. One could argue that a collective in-depth understanding of agroecosystem processes and functions would stimulate an adjustment of local *cosmovision* (e.g. taboos such as cutting or planting trees) to integrate scientific evidence, at the least to support agroforestry, sound agronomy, and ecology. Political and social organisation could catalyse such efforts in order to regenerate the ecosystem status and ensure the continued provision of ecological services for generations to come.

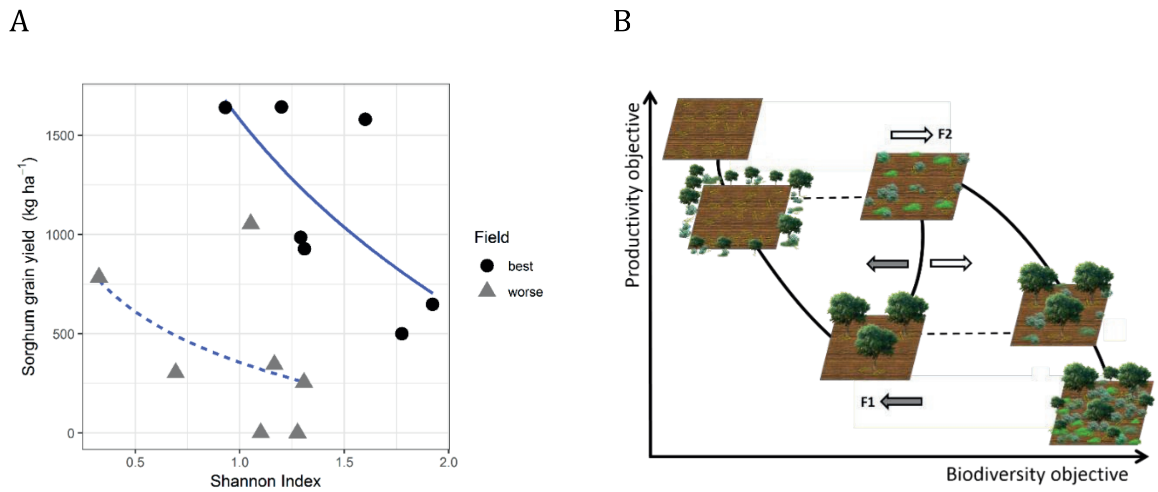

Figure 6.3. (A) Farmer perception of crop productivity as a function of species diversity (Shannon Index), where seven farmers were asked to identify and characterize their “best” and “worst” fields (n=14) in Yilou, Burkina Faso during the dry season. Biodiversity data adapted from Cheriere (2015). (B) A conceptual interpretation of transitional states, as proposed by Scheffer et al. (2000), and applied to resource states and stresses induced to cropping fields in semi-arid Burkina Faso. Grey arrows represent anthropogenic pressure, white arrows represent recolonization of natural vegetation, and F2/F1 are the two switch points before/after system collapse.

Regarding the bottlenecks to enhance the natural resource base in the Mossi Plateau, I explored whether the soil fertility perception of farmers (i.e. “best” vs. “worst” fields) has a link with *in situ* biodiversity of trees and shrubs on their fields. In Fig. 6.3A, I show that the relation between crop productivity and standing woody is inverse and non-linear. Beyond a given tree density, greater tree diversity on agricultural land means greater competition with crops for space and hence smaller grain yields. But the coordinates that define such a tradeoffs curve vary according to the soil fertility status of the land, implying that it is possible to increase in both crop productivity and biodiversity through restoring degraded soils. In Yilou, the dynamics between the ecosystem state (i.e. biodiversity objective) and the anthropogenic stress on the resource (i.e. productivity objective) seem to respond to what Scheffer *et al.* (2000) call the "catastrophic fold" (Fig. 6.3B). When the ecosystem state is on the right-hand branch, or wooded, multi-strata regime, it will not transition smoothly to the left-hand branch, or mono- and bi-strata regime. Thus, F1 is considered the "switch point" at which the system recovers (to the right) and F2 is considered as the threshold after which a "catastrophic" collapse can occur (to the left) due to increased anthropogenic pressure. Reversibility of a degraded to a regenerated ecosystem state can imply high costs.

Farmer Managed Natural Regeneration (FMNR) has been pointed out as a promising and low-cost pathway to restore woody vegetation biomass by excluding animal grazing on small patches of land for several years (Weston *et al.*, 2015). Even though the benefits perceived by smallholders practicing FMNR can be numerous, the FMNR approach remains inaccessible to many who are constrained by local tenure regulations or cannot acquire the required fencing material. The relation between field productivity and agroecosystem design, particularly in drylands, would need further investigation in view of increasing farmer resilience to extreme events. Local populations manage agro-biodiversity to increase food security in a variety of ways (**Chapter 5**). The recognition of complex nutrient-rich landscapes should become a central element of research agendas and local policies for food security and nutrition.

3.2. The way forward: Triggering agroecological transformations in the Sahel

Previous meta-analysis and literature synthesis on woody perennials in agricultural fields have focused on the effect of tree species in cereal cropping systems (Bayala *et al.*, 2015; Sinare & Gordon, 2015a). Further studies should focus on exploring long-term performance of shrub-crop intercropping systems in combination with other soil restoration techniques such as *zaï*, stone-bunds and manure. Studies in controlled conditions would allow to set local performance potential while studies conducted on-farm would allow to explore the applicability of combined practices based on farmer objectives. From a farmer's perspective, the innovations must be low-cost enough for farming households and rural communities to quickly learn and adopt, and should generate tangible economic benefits rapidly. Cooperative relations and capacity-building are likely to reinforce the resilience of farmers to a greater extent than competitive relations do. Social networks around farming systems are central for resource and information exchanges which can be optimized when farmers transition from simply trading “*goods*” to sharing “*knowledge, organization and information*” (González de Molina, 2015).

Farmer adaptations and innovations should be encouraged and recognised as valid forms of knowledge production process. RW practice was improved by incorporating farmer perception and knowledge of local resources to better target the application of RW inputs within the heterogeneity of soil conditions in Yilou village (**Chapter 4**). Reforestation efforts with shrubs should take into account the limitations due to governance issues around trees that impede plantation of perennial species on communal plots. Are shrubs *really* excluded from the local land tenure rules? How can their management style influence adoption of shrub-crop systems? Farmer-to-farmer exchanges should be promoted as means to collectively analyse trade-offs and explore options for re-design. Experiences of *co-innovation* with family farmers and researchers in Uruguay (Dogliotti *et al.*, 2014), show a relevant methodological approach that could be adapted to improve resilience and reduce vulnerability of Sahelian family farmers. Moreover, the combination of remote sensing data with ground-truthing fieldwork to analyse degradation phases of change (Easdale *et al.*, 2018) would further solve the “Sahel degradation vs. re-greening” debate (Niemeijer & Mazzucato, 2002; Giannini *et al.*, 2008; West *et al.*, 2017) and would allow to verify the real impacts of the Great Green Wall Initiative in the region (Dia & Duponnois, 2012). Opportunities to scale the use of shrub-based intercropping systems would need to be further anchored in the shrubs’ contribution to ecosystem services (e.g. decreased soil erosion, decrease water run-off, improve soil water infiltration, increase soil organic matter, provide fuelwood, provide habitat for migratory birds and native flora, contribute to complexity of landscape matrix). While there is still work ahead, the findings from this thesis suggest that the use and management of shrubs can be considered an adapted practice to implement agroecology principles in the Sahel.

Sustainable agroecosystems are based on efficient resource conversion by combining enhanced concentration and increased capture processes of various resources at the same time such as water, carbon, nitrogen, phosphorus and other nutrients and natural regulation of pests and diseases of the crops. Understanding the underlying dynamics of such systems can greatly enhance productivity and ecosystem functioning. Agroecology-based intensification aims to explore possible options and re-design farming systems based on sound resource management practices and science-based operational framework for more sustainable production in a “more with less” scheme. Many of the practices today considered as agroecological, have been in fact developed and used by farmers for a long time in the Sahelian context. Long fallow periods have disappeared due to increased demographic pressure, while organic animal manure application tends to diminish in contexts where livestock decrease. Cereal yields have been relatively stable in the last couple of decades while the level of external inputs has remained low. Indeed, availability and quality of natural vegetation resources are diminishing, but farming families keep producing food in light of environmental and demographic constraints. Sahelian soils may not be impoverishing as fast as expected. Rather, farmers have developed smart and resilient systems through an intensified use of biodiversity, the choice of improved crop varieties and the encouragement of synergies between system components that make the agroecosystems resilient to external shocks.

4. Conclusions

In this thesis I explored the role that shrub-based agroforestry systems and shrub-based ramial wood amendments have for smallholder farmers in the Sahel. The main conclusions of this thesis are the following:

- The benefits perceived by farmers from scattered woody perennials in parklands include improvement of soil productive capacity, contribution to household nutrition, and provision of opportunities for biodiversity to thrive on agricultural fields.
- Compared to trees, native woody shrubs show less trade-offs for crop growth, and the use of shrub-based ramial wood amendments improves soil conditions and is not detrimental to short-term crop yields.
- The amounts of shrub material needed as mulch to detect a mitigation effect on soil degradation, particularly the maintenance of soil carbon, are far larger than available natural vegetation.
- Farmer knowledge should thus, be an integral part of research processes and a pre-requisite for ecological intensification of agricultural systems in the Sahel.
- Shrub-based agroforestry systems are desirable for smallholder farmers in the Sahel but should be re-designed with farmers in order to improve delivery of ecosystem services on agricultural fields.

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Summary

This thesis aims to explore the role of native shrub-based agroforestry systems and the use of shrub-based woody amendments for smallholder farmers in the Sahel. Low-cost and effective options need to be explored and tested in order to restore soil productive capacity, addressed as the combination between improved soil quality and enhanced crop performance. Through literature reviews and experimental results, both on-station and on-farm, the thesis examines the viability of shrub-sourced soil amendments for rain-fed subsistence farmers in Burkina Faso. Bottlenecks and limitations of the practice are discussed and critically analysed from an agroecological perspective.

In **Chapter 1,** the General Introduction, the issues related to soil degradation are described for countries of semi-arid West Africa. The scientific approach used to analyse and explore re-design options for Sahelian farming systems is based on ecological principles (i.e. diversity, synergies, interactions, recycling and efficiency) applied to agricultural production. Agroforestry systems are considered a promising option for building up drought resistance on drylands. Whereas much has been documented about the impact of trees on agricultural fields, not so much has been published on the use of native shrub species in combination with annual crops.

Soil degradation in semi-arid West Africa can be reversed through an intensified application of organic matter, especially on coarse soils. Woody perennials have been promoted in the region to secure organic matter sources and improve soil productive capacity, yet the mechanisms by which perennials provide benefits to soils and crops remain poorly understood, and no effective, generalizable agronomic recommendations exist. The effects of trees and shrubs on soil properties and on crop yields in semi-arid West Africa (<1000 mm year^{-1}) were reviewed and compiled in the form of a meta-analysis in **Chapter 2.** Specific objectives of this meta-analysis were to (i) describe and (ii) quantify the effects of the presence of woody perennials and of ramial wood amendments on crop productivity and soil characteristics, and (iii) identify general recommendations on the integration of perennials with crops. An iterative keyword search was conducted to gather relevant literature. The search string consisted of four parts: source, practice, responses, and countries of interest. In total, 26 references on agroforestry parklands and 21 on woody amendments were included in the meta-database (314 entries, 155 for Parklands and 159 for ramial wood). It was shown that: (1) the presence of shrubs and trees on agricultural fields had an overall positive but variable effect on soil total C (i.e. +20 to 75%); (2) millet and sorghum yields were often higher in the presence of shrubs (-25 to +120%); (3) more yield variability was observed in presence of trees (-100 to +200%); and (4) the use of shrub- and tree-based ramial wood

resulted in equal or higher cereal yields as compared to the control (-30 to +100%). Upscaling the use of biodiversity-driven processes in farming systems of West Africa may provide benefits to overall ecosystems but species' choice and trade-offs perceived at the farm level, including labour management and low ramial wood availability should be addressed through future research.

The objective of the study presented in **Chapter 3** was to evaluate on-station a local farmer's technique that uses ramial wood (RW) as soil amendment (*Piliostigma reticulatum* shrub species). Three treatments were applied in an experimental plot in Burkina Faso: control (no amendment), low-RW (3 Mg FM ha^{-1} yr^{-1}), and high-RW (12 Mg FM ha^{-1} yr^{-1}), RW was chipped to <5 cm pieces and either buried or mulched. Topsoil carbon (C), nitrogen (N) and phosphorus (P) in control and low-RW treatments declined after seven years of continuous sorghum cultivation. Use of high-RW amendment stabilized soil C content while N and P declined, thus not replenishing nutrient exports. Net contribution to soil C in the 0-15 cm layer was 15% of the applied C in the high-RW amendments. Although biomass and grain yields were higher in high-RW treatments, crop productivity declined throughout the experiment for all treatments. Termite casts on RW treatments evidenced the potential role of wood-foraging termites in diluting the impact of RW on soil fertility build-up and soil water content. Thus, mitigating soil degradation under semi-arid conditions in Burkina Faso would require large amounts of woody amendments, particularly if the level of termite activity is high. Additional nutrient sources could be needed to compensate for removal in exported products so that biomass and grain production can be stabilized or increased.

In **Chapter 4,** the impact of ramial wood (RW) amendments on crop yields within *Piliostigma reticulatum* shrub-based agroforestry parklands of semi-arid Burkina Faso was tested using varying amounts of shrub material. The test compared results between eight farmer-led experimental plots. Soil properties and crop productivity were monitored during three consecutive years. Participatory methods allowed characterizing three "local soil classes" that describe spatial heterogeneity. Local soil knowledge allowed to make sense of observed heterogeneous effects of mulch on crop performance. Shrub-based mulches improved crop productivity on "shallow" and "sandy" soils, but their use was not recommended on "clayey" soils since the extra labour investments are not compensated by short to medium-term crop yield benefits. Rarely has research targeted the re-design of agricultural management practices based on indigenous soil knowledge.

Strategies that strengthen and use biodiversity are crucial for sustained food production and livelihoods in semi-arid West Africa. The objective of **Chapter 5** was to examine the role of biodiversity in sustaining diverse forms of multifunctional farming practices while at the same time providing ecological services to subsistence-oriented farming families in the region of study through mechanisms such as (a) crop species diversification, (b) management of spatial heterogeneity, and (c) diversification of nutrition-sensitive landscapes. The analysis shows that crop associations between cereals and legumes or between perennials and annuals, have overall positive effects on soil characteristics and often improve crop yields. Soil heterogeneity is produced by woody perennials and termites. Local management provides opportunities to collect a diversity of nutrition-rich species year-round and sustain household nutrition.

In **Chapter 6,** the General Discussion, the findings from the previous chapters are critically examined. Sudano-Sahelian ecosystems produce a limited amount of aboveground biomass which can be used for soil aggradation. In conclusion, the benefits perceived by farmers from scattered woody perennials in parklands feature several aspects, including improvement of soil productive capacity, contribution to household nutrition, and provision of opportunities for biodiversity to thrive on agricultural fields. Compared to trees, native woody shrubs show less trade-offs for crop growth. Also, the use of shrub-based ramial wood amendments improves soil conditions and is not detrimental to short-term crop yields. The amounts of shrub material needed as mulch to detect a mitigation effect on soil degradation, particularly the maintenance of soil carbon, are far larger than available in the natural vegetation. Also, the effect of ramial wood amendments on crop yields does not necessarily compensate the effort put into gathering great amounts of ramial wood. Farmer knowledge should thus, be an integral part of research processes and a pre-requisite for ecological intensification of agricultural systems in the Sahel. Shrub-based agroforestry systems are a desirable option for smallholder farmers in the Sahel but their integration in the agroecosystem should be re-designed with farmers in order to improve delivery of ecosystem services on agricultural fields.

Samenvatting

Dit proefschrift heeft als doel de rol te onderzoeken van inheemse struikgebaseerde agroforestry-systemen en het gebruik van houtachtige aanpassingen op struikbasis voor kleine boeren in de Sahel. Goedkope en effectieve opties moeten worden onderzocht en getest om de bodemproductieve capaciteit te herstellen, aangepakt als de combinatie tussen verbeterde bodemkwaliteit en verbeterde gewasprestaties. Door middel van literatuuroverzichten en experimentele resultaten, zowel op het station als op het bedrijf, onderzoekt het proefschrift de levensvatbaarheid van bodemaanpassingen van struikgewassen voor door regen gevoede zelfvoorzienende boeren in Burkina Faso. Knelpunten en beperkingen van de praktijk worden besproken en kritisch geanalyseerd vanuit een agro-ecologisch perspectief.

In hoofdstuk 1, de algemene inleiding, worden de problemen met betrekking tot bodemdegradatie beschreven voor landen in semi-aride West-Afrika. De wetenschappelijke benadering die wordt gebruikt voor het analyseren en verkennen van herontwerpopties voor Saheliaanse landbouwsystemen is gebaseerd op ecologische principes (d.w.z. diversiteit, synergieën, interacties, recycling en efficiëntie) toegepast op landbouwproductie. Agroforestry-systemen worden beschouwd als een veelbelovende optie voor het opbouwen van droogteweerstand op droge gebieden. Hoewel er veel is gedocumenteerd over de impact van bomen op landbouwvelden, is er niet zo veel gepubliceerd over het gebruik van inheemse struiksoorten in combinatie met eenjarige gewassen.

Bodemdegradatie in semi-droog West-Afrika kan worden teruggedraaid door een intensievere toepassing van organisch materiaal, vooral op grove gronden. Houtachtige vaste planten zijn in de regio gepromoot om bronnen van organische stoffen veilig te stellen en de productiecapaciteit van de bodem te verbeteren, maar de mechanismen waardoor vaste planten voordelen bieden voor bodems en gewassen blijven slecht begrepen en er bestaan geen effectieve, generaliseerbare agronomische aanbevelingen. De effecten van bomen en struiken op bodemeigenschappen en gewasopbrengsten in semi-aride West-Afrika (<1000 mm jaar^{-1}) werden beoordeeld en verzameld in de vorm van een meta-analyse in hoofdstuk 2. Specifieke doelstellingen van deze meta-analyse moesten (i) beschrijven en (ii) kwantificeren van de effecten van de aanwezigheid van houtachtige vaste planten en van ramiale houtamendementen op gewasproductiviteit en bodemkenmerken, en (iii) algemene aanbevelingen identificeren voor de integratie van vaste planten met gewassen. Er werd een iteratief zoeken op trefwoord uitgevoerd om relevante literatuur te verzamelen. De zoekreeks bestond uit vier delen: bron, praktijk, antwoorden en interessante landen. In totaal werden 26 referenties over agroforestry-parkland en 21 over houtachtige wijzigingen opgenomen in de meta-database (314 ingangen, 155 voor Parklands en 159 voor ramial wood). Er werd aangetoond dat: (1) de aanwezigheid van struiken en bomen op landbouwvelden een algemeen positief maar variabel effect had op de totale C-bodem (d.w.z. +20 tot 75%); (2) gierst- en

sorghumopbrengsten waren vaak hoger in aanwezigheid van struiken (-25 tot + 120%); (3) meer opbrengstvariabiliteit werd waargenomen in aanwezigheid van bomen (-100 tot + 200%); en (4) het gebruik van struik- en boomgebaseerd ramiaal hout resulteerde in gelijke of hogere graanopbrengsten in vergelijking met de controle (-30 tot + 100%). Opschaling van het gebruik van door biodiversiteit aangedreven processen in landbouwsystemen in West-Afrika kan voordelen opleveren voor de algehele ecosystemen, maar de keuze van soorten en afwegingen waargenomen op bedrijfsniveau, inclusief arbeidsbeheer en lage ramiale beschikbaarheid van hout, moeten worden aangepakt door toekomstig onderzoek.

Het doel van de in hoofdstuk 3 gepresenteerde studie was om op locatie een techniek van een lokale boer te evalueren die ramial wood (RW) gebruikt als bodemaanpassing (Piliostigma reticulatum heestersoort). Drie behandelingen werden toegepast in een experimenteel plot in Burkina Faso: controle (geen wijziging), low-RW (3 Mg FM ha^{-1} jr^{-1}) en high-RW (12 Mg FM ha^{-1} jr^{-1}), RW werd afgebroken tot <5 cm stukken en begraven of gemulleerd. Bovengrondse koolstof (C), stikstof (N) en fosfor (P) in controle- en laag-RW-behandelingen namen af na zeven jaar van continue sorghumteelt. Het gebruik van een high-RW-amendement stabiliseerde het bodem-C-gehalte terwijl N en P daalden, waardoor de export van nutriënten niet werd aangevuld. De netto bijdrage aan bodem C in de laag van 0-15 cm was 15% van de toegepaste C in de hoge RW-wijzigingen. Hoewel biomassa en graanopbrengsten hoger waren bij behandelingen met hoge RW, daalde de gewasproductiviteit gedurende het experiment voor alle behandelingen. Termietafgietsels op RW-behandelingen hebben de potentiële rol aangetoond van termieten voor het foerageren van hout bij het verdunnen van de impact van RW op de opbouw van de bodemvruchtbaarheid en het bodemwatergehalte. Aldus zou het verzachten van bodemdegradatie onder semi-aride omstandigheden in Burkina Faso grote hoeveelheden houtachtige wijzigingen vereisen, met name als het niveau van de termietactiviteit hoog is. Aanvullende voedingsbronnen kunnen nodig zijn om de verwijdering in geëxporteerde producten te compenseren, zodat de productie van biomassa en graan kan worden gestabiliseerd of verhoogd.

In hoofdstuk 4 werd de impact van wijzigingen in ramial wood (RW) op gewasopbrengsten in *Piliostigma reticulatum* struikgebaseerde agroforestry parklanden van semi-aride Burkina Faso getest met verschillende hoeveelheden struikmateriaal. De test vergeleek resulteer ligt tussen acht door boeren geleide experimentele percelen. Bodemeigenschappen en gewasproductiviteit werden gedurende drie opeenvolgende jaren gemonitord. Met participatieve methoden konden drie "lokale bodemklassen" worden gekarakteriseerd die ruimtelijke heterogeniteit beschrijven. Lokale bodemkennis maakte het mogelijk om de waargenomen heterogene effecten van mulch op de gewasprestaties te begrijpen. Op mulches gebaseerde struiken verbeterden de gewasproductiviteit op "ondiepe" en "zandige" gronden, maar het gebruik ervan werd niet aanbevolen op "kleiachtige" gronden, omdat de extra arbeidsinvesteringen niet worden gecompenseerd door voordelen voor de opbrengst van de korte tot middellange termijn. Zelden is onderzoek gericht op het opnieuw ontwerpen van landbouwbeheerspraktijken op basis van inheemse bodemkennis.

Strategieën die de biodiversiteit versterken en gebruiken, zijn cruciaal voor duurzame voedselproductie en middelen van bestaan in semi-aride West-Afrika. Het doel van hoofdstuk 5 was om de rol van biodiversiteit te onderzoeken bij het in stand houden van verschillende vormen van multifunctionele landbouwmethoden en tegelijkertijd ecologische diensten te bieden aan op levensonderhoud gerichte boerenfamilies in het onderzoeksgebied via mechanismen zoals (a) diversificatie van gewassoorten, (b) beheer van ruimtelijke heterogeniteit, en (c) diversificatie van voedingsgevoelige landschappen. De analyse toont aan dat gewasassociaties tussen granen en peulvruchten of tussen vaste planten en eenjarigen over het algemeen positieve effecten hebben op de bodemkenmerken en vaak de gewasopbrengsten verbeteren. Bodemheterogeniteit wordt geproduceerd door houtachtige vaste planten en termieten. Lokaal management biedt kansen om het hele jaar door een verscheidenheid aan voedingsrijke soorten te verzamelen en huishoudelijke voeding te ondersteunen.

In hoofdstuk 6, de algemene discussie, worden de bevindingen uit de vorige hoofdstukken kritisch onderzocht. Sudano-Saheliaanse ecosystemen produceren een beperkte hoeveelheid bovengrondse biomassa die kan worden gebruikt voor bodemverergering. Kortom, de voordelen die boeren ervaren van verspreide houtachtige vaste planten in parkgebieden, hebben verschillende aspecten, waaronder verbetering van de bodemproductieve capaciteit, bijdrage aan huishoudelijke voeding en het bieden van kansen voor biodiversiteit om te gedijen op landbouwvelden. In vergelijking met bomen vertonen inheemse houtachtige struiken minder afwegingen voor gewasgroei. Het gebruik van struikgewassen op ramiaal hout verbetert ook de bodemgesteldheid en is niet schadelijk voor de opbrengst van de korte termijn. De hoeveelheden struikmateriaal die nodig zijn als mulch om een verzachtend effect op bodemafbraak te detecteren, met name het onderhoud van bodemkoolstof, zijn veel groter dan beschikbaar in de natuurlijke vegetatie. Ook compenseert het effect van ramiale houtaanpassingen op gewasopbrengsten niet noodzakelijk de inspanning die wordt geleverd om grote hoeveelheden ramiaal hout te verzamelen. Kennis van boeren zou dus een integraal onderdeel moeten zijn van onderzoeksprocessen en een voorwaarde voor ecologische intensivering van landbouwsystemen in de Sahel. Op struik gebaseerde agroforestry-systemen zijn een wenselijke optie voor kleine boeren in de Sahel, maar hun integratie in het agro-ecosysteem moet opnieuw worden ontworpen met boeren om de levering van ecosysteemdiensten op landbouwgebieden te verbeteren.

Resumen

Esta tesis tiene como objetivo explorar el papel que juegan los sistemas agroforestales con arbustos nativos y el uso de enmiendas leñosas a base de arbustos para pequeños agricultores en el Sahel. Se exploraron opciones efectivas y de bajo costo para restaurar la capacidad productiva del suelo, abordadas como la combinación entre una mejor calidad del suelo y un mejor rendimiento del cultivo. A través de revisión de literatura y con resultados experimentales, tanto en la estación como en la granja, la tesis examina la viabilidad de las enmiendas del suelo de origen arbustivo para los agricultores de subsistencia de secano en Burkina Faso. Los cuellos de botella y las limitaciones de la práctica se discuten y analizan críticamente desde una perspectiva agroecológica.

En el Capítulo 1, Introducción general, se describen los problemas relacionados con la degradación del suelo para los países de África occidental semiárida. El enfoque científico utilizado para analizar y explorar las opciones de rediseño para los sistemas agrícolas del Sahel se basa en principios ecológicos (es decir, diversidad, sinergias, interacciones, reciclaje y eficiencia) aplicados a la producción agrícola. Los sistemas agroforestales se consideran una opción prometedora para desarrollar resistencia a la sequía en las tierras secas. Si bien se ha documentado mucho sobre el impacto de los árboles en los campos agrícolas, no se ha publicado mucho sobre el uso de especies de arbustos nativos en combinación con cultivos anuales.

La degradación del suelo en África occidental semiárida puede revertirse mediante una aplicación intensificada de materia orgánica, especialmente en suelos pesados. Las plantas perennes leñosas han sido utilizadas en la región para asegurar fuentes renovables de materia orgánica y mejorar la capacidad productiva del suelo, sin embargo, los mecanismos por los cuales las plantas perennes proporcionan beneficios a los suelos y cultivos siguen siendo poco conocidos, y no existen recomendaciones agronómicas generalizables y eficientes. Los efectos de los árboles y arbustos en las propiedades del suelo y en los rendimientos de los cultivos en África occidental semiárida (<1000 mm año^{-1}) se revisaron y los datos se compilaron en un meta-análisis en el Capítulo 2. Los objetivos específicos de este meta-análisis fueron (i) describir y (ii) cuantificar los efectos de la presencia de plantas perennes leñosas y de enmiendas de madera y hojas en la productividad del cultivo y las características del suelo, e (iii) identificar recomendaciones generales sobre la integración de plantas perennes con cultivos. Se realizó una búsqueda sistemática en base de datos con palabras clave para recopilar literatura relevante. La cadena de búsqueda constaba de cuatro partes: fuente, práctica, respuestas y países de interés. En total, 26 referencias sobre parques agroforestales y 21 sobre enmiendas leñosas se incluyeron en la meta-base de datos (314 entradas, 155 para parques y 159 para madera y hojas). Se demostró que: (1) la presencia de arbustos y árboles en los campos agrícolas tuvo un efecto generalmente positivo pero variable sobre el C total del suelo (es decir, +20 a 75%); (2) los rendimientos de mijo y sorgo a menudo fueron mayores en presencia de arbustos (-25 a + 120%); (3) se observó una mayor variabilidad

del rendimiento en presencia de árboles (-100 a + 200%); y (4) el uso de madera y hojas a base de arbustos y árboles dio como resultado rendimientos de cereales iguales o mayores en comparación con el control (-30 a + 100%). Mejorar el uso de los procesos impulsados por la biodiversidad en los sistemas agrícolas de África occidental puede proporcionar beneficios para los ecosistemas en general, pero la elección de las especies y las compensaciones percibidas a nivel de granja, incluida la gestión laboral y la baja disponibilidad de madera y hojas como enmiendas, deberían abordarse a través de investigaciones futuras.

El objetivo del estudio presentado en el Capítulo 3 fue evaluar en la estación experimental la técnica de un agricultor local que utiliza madera y hojas (RW, por sus siglas en inglés) como enmienda del suelo (especies de arbustos *Piliostigma reticulatum*). Se aplicaron tres tratamientos en una parcela experimental en Burkina Faso: control (sin enmiendas), poco-RW (3 Mg FM ha^{-1} $año^{-1}$) y mucho-RW (12 Mg FM ha^{-1} $año^{-1}$). El RW se troceó en piezas de <5 cm y se enterró o cubrió con mantillo, según el tratamiento. El carbono de la capa superficial del suelo (C), el nitrógeno (N) y el fósforo (P) en los tratamientos de control y bajo RW disminuyeron después de siete años de cultivo continuo de sorgo. El uso de la enmienda de alto RW estabilizó el contenido de C del suelo mientras que el N y el P disminuyeron, por lo que no reponían las exportaciones de nutrientes. La contribución neta al suelo C en la capa de 0-15 cm fue del 15% del C aplicado en las enmiendas de alto RW. Si bien los rendimientos de biomasa y granos fueron más altos en los tratamientos de alto RW, la productividad del cultivo disminuyó durante todo el experimento para todos los tratamientos. Los moldes de termitas en los tratamientos de RW evidenciaron el papel potencial de las termitas recolectoras de madera para diluir el impacto de RW en la acumulación de fertilidad del suelo y el contenido de agua del suelo. Por lo tanto, mitigar la degradación del suelo en condiciones semiáridas en Burkina Faso requeriría grandes cantidades de enmiendas leñosas, particularmente si el nivel de actividad de termitas es alto. Se podrían necesitar fuentes de nutrientes adicionales para compensar la eliminación en los productos exportados de forma que la producción de biomasa y granos se pueda estabilizar o aumentar.

En el Capítulo 4, se probó el impacto de las enmiendas de madera y hojas (RW) en los rendimientos de los cultivos en los parques agroforestales basados en arbustos de *Piliostigma reticulatum* en el semiárido de Burkina Faso, utilizando cantidades variables de material de arbusto. La prueba comparó resultados entre ocho parcelas experimentales dirigidas por agricultores. Las propiedades del suelo y la productividad del cultivo fueron monitoreadas durante tres años consecutivos. Los métodos participativos permitieron caracterizar tres "clases locales de suelo" que describen la heterogeneidad espacial. El conocimiento local del suelo permitió dar sentido a los efectos heterogéneos observados del acolchado en el rendimiento del cultivo. Los acolchados a base de arbustos mejoraron la productividad de los cultivos en suelos "poco profundos" y "arenosos", pero su uso no se recomendó en suelos "arcillosos" ya que las inversiones en mano de obra adicional no se ven compensadas por los beneficios de rendimiento de los cultivos a corto y mediano plazo. Rara vez la investigación se ha dirigido al rediseño de prácticas de manejo agrícola basadas en el conocimiento del suelo indígena.

Las estrategias que fortalecen y utilizan la biodiversidad son cruciales para la producción alimentaria sostenida y los medios de vida en el África occidental semiárida. El objetivo del Capítulo 5 era examinar el papel de la biodiversidad en el mantenimiento de diversas formas de prácticas agrícolas multifuncionales y al mismo tiempo proporcionar servicios ecológicos a las familias de agricultores orientados a la subsistencia en la región de estudio a través de mecanismos tales como (a) la diversificación de especies de cultivos, (b) la gestión de la heterogeneidad espacial, y (c) la diversificación de paisajes sensibles a la nutrición. El análisis muestra que las asociaciones de cultivos entre cereales y leguminosas o entre plantas perennes y anuales tienen efectos positivos generales sobre las características del suelo y a menudo mejoran los rendimientos de los cultivos. La heterogeneidad del suelo es producida por plantas perennes leñosas y termitas. La gestión local brinda oportunidades para recolectar una diversidad de especies ricas en nutrición durante todo el año y mantener la nutrición del hogar.

En el Capítulo 6, Discusión General, se examinan críticamente los hallazgos de los capítulos anteriores. Los ecosistemas sudano-sahelianos producen una cantidad limitada de biomasa aérea que se puede utilizar para la degradación del suelo. En conclusión, los beneficios percibidos por los agricultores de las perennes leñosas dispersas en los parques agroforestales presentan varios aspectos, que incluyen la mejora de la capacidad productiva del suelo, la contribución a la nutrición de los hogares y la provisión de oportunidades para que la biodiversidad prospere en los campos agrícolas. En comparación con los árboles, los arbustos leñosos nativos muestran menos desventajas para el crecimiento de los cultivos. Además, el uso de enmiendas de madera y hojas a base de arbustos mejora las condiciones del suelo y no es perjudicial para los rendimientos de los cultivos a corto plazo. Las cantidades de material arbustivo necesarias como mantillo para detectar un efecto de mitigación en la degradación del suelo, particularmente el mantenimiento del carbono del suelo, son mucho mayores que las disponibles en la vegetación natural. Además, el efecto de las enmiendas de madera y hojas en los rendimientos de los cultivos no compensa necesariamente el esfuerzo realizado en la recolección de grandes cantidades de material leñoso. Por lo tanto, el conocimiento de los agricultores debería ser una parte integral de los procesos de investigación y un requisito previo para la intensificación ecológica de los sistemas agrícolas en el Sahel. Los sistemas agroforestales basados en arbustos son una opción deseable para los pequeños agricultores en el Sahel, pero su integración en el agroecosistema debe rediseñarse con los agricultores para mejorar la prestación de servicios ecosistémicos en los campos agrícolas

Résumé

Cette thèse vise à explorer le rôle des systèmes agroforestiers à base d'arbustes indigènes et l'utilisation d’amendements ligneux à base d'arbustes pour les petits producteurs agricoles du Sahel. Des options efficaces et peu coûteuses doivent être explorées et testées afin de restaurer la capacité de production du sol, considérée comme la combinaison entre l'amélioration de la qualité du sol et l'amélioration des performances des cultures. À travers des revues de la littérature et des résultats expérimentaux, en station et à la ferme, cette thèse examine la viabilité d’utilisation d'amendements du sol provenant d'arbustes pour les agriculteurs de subsistance pluviaux au Burkina Faso. Les goulots d'étranglement et les limites de la pratique sont discutés et analysés de manière critique dans une perspective agroécologique.

Au chapitre 1, Introduction générale, les problèmes liés à la dégradation des sols sont décrits pour les pays d'Afrique de l'Ouest semi-aride. L’approche scientifique utilisée pour analyser et explorer les options de reconfiguration des systèmes agricoles sahéliens s’appuie sur des principes écologiques (diversité, synergies, interactions, recyclage et efficacité) appliqués à la production agricole. Les systèmes agroforestiers sont considérés comme une option prometteuse pour renforcer la résistance à la sécheresse dans les zones arides. Alors que beaucoup d’informations ont été documentées sur l’impact des arbres sur les terres agricoles, il n’en a pas été autant pour l’utilisation des espèces d’arbustes indigènes en combinaison avec les cultures annuelles.

La dégradation des sols dans l’Afrique de l’Ouest semi-aride peut être inversée par une application intensive de la matière organique, en particulier sur les sols lourds. Les plantes pérennes ligneuses ont été encouragées dans la région pour sécuriser les sources de matière organique et améliorer la capacité de production des sols. Cependant, les mécanismes par lesquels les plantes pérennes apportent des avantages aux sols et aux cultures restent mal compris et il n'existe aucune recommandation agronomique efficace et généralisable. Les effets des arbres et des arbustes sur les propriétés du sol et le rendement des cultures en Afrique de l'Ouest semi-aride (<1000 mm par an) ont donc été examinés et compilés sous la forme d'une méta-analyse au chapitre 2. Les objectifs spécifiques de cette méta-analyse étaient de (i) décrire et (ii) quantifier les effets de la présence de plantes vivaces ligneuses et d'amendements en bois raméaux sur la productivité des cultures et les caractéristiques du sol, et de (iii) dégager des recommandations générales sur l'intégration des plantes pérennes sur les cultures. Une recherche systématique par mot clé a été réalisée pour rassembler la littérature pertinente. La chaîne de recherche était composée de quatre parties: source, pratique, réponses et pays d'intérêt. Au total, 26 références sur les parcs agroforestiers et 21 sur les amendements ligneux ont été prises en compte dans la méta-base de données (314 entrées, 155 pour les parcs et 159 pour le bois raméal). Il a été démontré que: (1) la présence d’arbustes et d’arbres sur les terres agricoles avait un effet globalement positif

mais variable sur la teneur totale en carbone du sol (+20 à 75%); (2) les rendements de mil et de sorgho étaient souvent plus élevés en présence d'arbustes (-25 à + 120%); (3) une plus grande variabilité de rendement a été observée en présence d'arbres (-100 à + 200%); et (4) l'utilisation de bois raméal à base d'arbustes et d'arbres a permis d'obtenir des rendements céréaliers égaux ou supérieurs à ceux du témoin (-30 à + 100%). Augmenter l'utilisation des processus liés à la biodiversité dans les systèmes de production d'Afrique de l'Ouest pourrait être bénéfique pour l'ensemble des écosystèmes, mais les recherches futures devraient porter sur le choix des espèces et les compromis perçus au niveau de la ferme, y compris sur la gestion de la main-d'œuvre et la faible disponibilité en bois.

L'étude présentée au chapitre 3 avait pour objectif d'évaluer sur place la technique d'un agriculteur local qui utilise le bois raméal (RW, sigle en anglais) comme amendement de sol (espèce arbustive *Piliostigma reticulatum*). Trois traitements ont été appliqués dans une parcelle expérimentale au Burkina Faso: contrôle (sans amendement), faible dose-RW (3 Mg FM ha^{-1} an^{-1}) et forte dose-RW (12 Mg FM ha^{-1} an^{-1}), RW était fragmenté en morceaux de moins de 5 cm et enterré ou paillé. Le carbone de la couche supérieure (C), l'azote (N) et le phosphore (P) dans les traitements témoin et à faible-RW ont diminué après sept ans de culture continue de sorgho en monoculture. L'utilisation de la teneur élevée en C du sol a été stabilisée par l'amendement, tandis que les teneurs en N et en P ont diminué, ne reconstituant ainsi pas les exportations d'éléments nutritifs. La contribution nette au C du sol dans la couche de 0-15 cm était de 15% du C appliqué dans les amendements à haute RW. Bien que les rendements en biomasse et en grains aient été plus élevés avec les traitements à forte RW, la productivité des cultures a diminué tout au long de l'expérience pour tous les traitements. Les traitements anti-RW mis en évidence par les termites ont démontré le rôle potentiel des termites en quête de bois dans l'atténuation de l'impact des RW sur l'accumulation de fertilité et la teneur en eau du sol. Ainsi, pour atténuer la dégradation des sols dans des conditions semi-arides au Burkina Faso, il faudrait beaucoup d'amendements ligneux, en particulier si le niveau d'activité des termites est élevé. Des sources de nutriments supplémentaires pourraient être nécessaires pour compenser l'élimination des produits exportés, de sorte que la production de biomasse et de céréales puisse être stabilisée ou accrue.

Au chapitre 4, l'impact des amendements du bois ramial sur les rendements des cultures dans les parcs agroforestiers à arbustes de *Piliostigma reticulatum* du Burkina Faso semi-aride a été testé avec différentes quantités d'arbustes. Le test a comparé les résultats entre huit parcelles expérimentales dirigées par des agriculteurs eux-mêmes. Les propriétés du sol et la productivité des cultures ont été surveillées pendant trois années consécutives. Les méthodes participatives ont permis de caractériser trois «classes de sol locales» décrivant l'hétérogénéité spatiale. Les connaissances locales sur les sols ont permis de comprendre les effets hétérogènes observés du paillis sur les performances des cultures. Les paillis à base d'arbustes ont amélioré la productivité des cultures sur les sols «peu profonds» et «sableux», mais leur utilisation n'a pas été recommandée sur les sols «argileux», car les investissements supplémentaires en main-d'œuvre ne sont pas compensés par des avantages de rendement à court et à moyen terme. Les recherches ont rarement été axées sur la co-conception des pratiques de gestion agricole fondées sur les connaissances des sols des autochtones.

Les stratégies qui renforcent et utilisent la biodiversité sont cruciales pour une production alimentaire durable et des moyens de subsistance en Afrique de l'Ouest semi-aride. L'objectif du chapitre 5 était d'examiner le rôle de la biodiversité dans la préservation de diverses formes de pratiques agricoles multifonctionnelles tout en fournissant des services écologiques aux familles d'agriculteurs de subsistance de la région à travers des mécanismes tels que: a) la diversification des espèces cultivées, b) la gestion de l'hétérogénéité spatiale et c) la diversification des paysages sensibles à la nutrition. L'analyse montre que les associations de cultures entre céréales et légumineuses ou entre plantes pérennes et annuelles ont des effets globalement positifs sur les caractéristiques du sol et améliorent souvent les rendements des cultures. L'hétérogénéité des sols est produite par les plantes pérennes ligneuses et les termites. La gestion locale des ressources naturelles offre la possibilité de collecter toute l'année une diversité d'espèces riches en nutrition et de soutenir la nutrition des ménages.

Au chapitre 6, Discussion Générale, les conclusions des chapitres précédents sont examinées de manière critique. Les écosystèmes Soudano-Sahéliens produisent une quantité limitée de biomasse aérienne qui peut être utilisée pour l'aggradation des sols. En conclusion, les avantages perçus par les agriculteurs de plantes pérennes ligneuses dispersées dans les parcs présentent plusieurs aspects, notamment l'amélioration de la capacité de production des sols, la contribution à la nutrition des ménages et la possibilité pour la biodiversité de s'épanouir dans les champs agricoles. Comparés aux arbres, les arbustes ligneux indigènes présentent moins de compromis pour la croissance des cultures. De plus, l'utilisation d'amendements de bois raméaux à base d'arbustes améliore les conditions du sol et ne nuit pas aux rendements des cultures à court terme. Les quantités d'arbustes nécessaires comme paillis pour détecter un effet d'atténuation sur la dégradation du sol, en particulier le maintien de son carbone, sont beaucoup plus importantes que celles disponibles dans la végétation naturelle. En outre, l'effet des amendements raméaux sur le rendements des cultures ne compense pas nécessairement les efforts consacrés à la collecte de grandes quantités de bois raméal. Les connaissances des agriculteurs devraient donc faire partie intégrale des processus de recherche et constituer une condition préalable à l'intensification écologique des systèmes agricoles au Sahel. Les systèmes agroforestiers à base d'arbustes sont une option souhaitable pour les petits exploitants agricoles du Sahel, mais leur intégration dans l'agroécosystème devrait être repensée avec les agriculteurs afin d'améliorer la fourniture de services écosystémiques sur les terres agricoles.

Acknowledgements

I&I livicate this work to my beloved grandmothers and grandfathers for inspiring me into natural farming and showing me the first steps into indigenous medicine. In Crâs, France: Claire Esposito and Georges Lancelloti. In Río Piedras, Puerto Rico: Isabel Arroyo and Francisco "Paco" Félix.

Special thanks to my parents for their continued guidance, love and support during this PhD-process: Line Lancelloti, Luis Armando Félix, Cindy Rodríguez, and Frankie Pola Jr. Love you!

To my friends in Puerto Rico, I think "we live where you vacation!" kind of sums it up as a powerful message to share with the rest of the world if we want to invite them to our lovely Caribbean paradise. Let's keep it rocking: Erick Senior, Catherine Vargas, Karisa Cruz, Christine Bahr, Samuel Morales, Nellisa Andrades, Julio Ortiz, Natalia Pujols, Ivette Núñez, Gabriel Mulero, Amílcar Vélez, Aixa Tolentino, Gustavo González, Benjamín Curet, Magha, Elena, all members of *Organización Boricuá de Agricultura Ecológica*, and many many many others!

To my friends in the Netherlands, thanks for the good food and the good times, the great bicycle paths and the perfect hospitality. The Farm, Droevendaal 93, 31 and 39, Jan Biermann, Verónica Barrajón, María Arredondo, the Laura's, Romanos, Carmencita, Julia, Clem, Serena, Tobia, Isti, Hestia, Lucca, Hanno, Milan, Marjolein, Bart, Jean-Yves, Annemiek, Adriá, Ángel, María Borrás, Javi & Juan, Isabel, Paula, and to many many more at the Farm, the Creative Garden, WUR, Wageningen centrum and Amsterdam! Thank you Europe!

Very grateful and blessed for the *Boricuas en Holanda*, a group of great Puerto Ricans living across the Netherlands. Every encounter was regenerating and helped me keep it together during the winter times, *¡Viva Borikén Libre y Soberana!* Antonio Carmona Báez, Giselle Schrills, Rebeca Pabón, Melisa Soto Lafontaine, Nicole Medina, Vilmaris González, Almi, Xavier, Jaime, Are, Manuel, Leslie, and all the others! I would enjoy very much having you all at the PhD-party at Wageningen.

To my friends in Burkina Faso and Senegal, *mes ami(e)s... que puis-je dire ? Merci de m'avoir accueilli chez vous comme un frère, dans vos maisons, dans vos parcelles, dans vos paysages, dans vos villages. Merci de m'avoir enseigné ce que veulent dire les philosophes par « simplicité », « sobriété heureuse », et « souveraineté alimentaire ». L'Afrique a certainement bousculé chez moi les piliers de la vie en société (Dieu, le travail, la famille)* *avec pour conséquence une sorte de « rappel à l'ordre » dans, au moins, ces trois rangées. Je souhaite pouvoir venir vous voir bientôt pour vous donner un coup de main dans vos cultures et partager quelques histoires autour d'une calebasse de dôlo. Wêend naa kô Pãanga !* Zérôme Ouedraogo, Jean Sawadogo, Rakiéta, Fatimata, Harouna, Hamidou, Salam, Millionaire, Paténéma, Alassane, Boureïma, Ousmane, Pamoussa, Edmond, Alice Rouault, Sidy Diakhaté, Laure Tall : blessings and protection to you, your families and friends.

Cheers to the students and field technicians involved in the experimental data collection and analysis: Hennie Halm, Marcel Ouédraogo, Salif Konané, Philippe Belliard, Oumaru Dem, Patrick Winterhoff, Gaëlle Feur, Marie Le Garff, Justine Santamaria, Renée van Dis, Louis Gabaud, Timothée Cheriere, Théo Saunier-Zoltobroda. Thanks to the IRD-Ouagadougou for hosting me at your campus for several months per year. Great times!

Very special thanks to my colleagues, mentors, and supervisors. Without your advice, it would have not been the same story! Laurent Cournac, Cathy Clermont-Dauphin, Jeroen Groot, Johannes Scholberg, Rabah Lahmar, Edmond Hien, Denis Gautier, Raphaël Manlay, Bernard Barthès, Dominique Masse, Richard Dick, Lydie Lardy, Hennie Halm, Wampie van Schouwenberg, Santiago Dogliotti, Miguel Altieri, Clara Nicholls, Nils McCune, Fernando Funes-Monzote, Eric Holt-Giménez, Leonor Hurtado, Ivette Perfecto, John Vandermeer, Rogier Schulte, Vivian Valencia, Blair van der Pelt, Walter Rossing, Felix Bianchi, Kees van Veluwe, Gemma, Stephanie Álvarez, Erika Speelman, Floor Ambrosius, and to the Farming Systems Ecology group.

I am thankful to the co-founders of *Cultivate!* Collective, for the opportunity to co-design a horizontal and democratic platform from where to support farmer movements across the Globe: Janneke Bruil, Margriet Goris, Diana Quiroz, Jessica Milgroom, and Leonardo ven der Berg.

Standing ovation for Prof. Pablo Tittonell and to *The Planeteers*, Yodit Kebede, Victoría Alomía, and Pablo Modernel. Especially thankful to Lenora, Carl, Francine, Daniel, Heitor, Roos, Lienneke, Mirja, Uma, Lennart van Wolfswinkel, Cristian Reyna, and all the PhD Candidates at FSE, CSA and PPS. Best support anyone can get anytime and anywhere! Also, best hang out ideas to re-design the world together. Hopefully this is just the beginning of a great *outernational* collaboration. All the best to you all!

Last but not least, a token of appreciation to Cristian Timmerman who is a grumpy person but helps me become a better person in how to apply the *carpe diem* philosophy into my personal and professional lives. My first scientific publication is indeed thanks to you, my friend! Many more to come!

Finally, I hope this thesis contributes to the scientific advancement by pursuing societal needs. I trust the text will become an interesting piece (in this form on another) for scholars and farmers of the future to recall the voices of the past and as a consequence better re-design their present.

About the author

"Love the life you live. Live the life you love."
Vaughn Benjamin, singer & poet, Midnite Akae Beka (St. Croix)
Rest In Power – 2019

Georges F. Félix Lancelloti is native from Puerto Rico, with French roots as well. His specialty is analysis and co-design of tropical agroforestry systems. The agroecological approach (science, movement and practice) is ever-present in his work. He was born and raised in the Caribbean, and often visited family in Europe. Georges went to High School at Colegio San Ignacio de Loyola in Río Piedras. He started university by studying environmental sciences in 2003 at the University of Puerto Rico – Río Piedras Campus. He then moved to France to continue at Université Paris VII – Denis Diderot and completed a bachelor degree in biology. In 2007, he joined ENITA de Bordeaux where he specialized in agronomy, tropical forestry and sustainable agro-ecosystem management. After conducting his master thesis research in ecological coffee production at Puerto Rico (Envirosurvey) and Costa Rica (CATIE), he moved back to Puerto Rico for three years to contribute to the re-design of sustainable food systems in the region.

He gained experience in community agroecology and stabilisation agriculture while in Haiti after the 2010 earthquake, in Cuba through farmer-to-farmer exchanges, and in Puerto Rico through agricultural education in urban and rural neighborhoods. He also worked in the Long-Term Ecological Research plots (LTER) as field research technician at El Verde, Río Grande, and for a few months, as a business manager with AgroExpress to provide fresh and locally-produced veggie boxes to urban consumers in Puerto Rico. Georges was lucky to meet Prof. Pablo Tittonell in 2012 who supported him into pursuing doctoral studies at Wageningen University. The PhD opened new windows of possibilities for international research, anchored at Wageningen while conducting extensive fieldwork in semi-arid Burkina Faso. Definitely an enriching experience at both professional and personal levels. After hurricane María hit Puerto Rico (September 2017), Georges was actively involved in the food system reconstruction process through agroecology, organizing solidarity caravans and hands-on practical work to rebuild local farms.

Currently Georges is a lecturer and researcher in agroecology and agroforestry at the University of Puerto Rico – Utuado Campus. Georges regularly teaches students (via Skype) in courses at Wageningen University and ISARA (Lyon). He also facilitates learning processes on agroecology with farmers in Puerto Rico, West Africa, and Mauritius. Additionally, he collaborates with Organización Boricuá-CLOC-La Via Campesina, SOCLA, CELIA, and FoodFirst. He is a member of the Puerto Rican Chapter of SOCLA, the Latin American Scientific Society for Agroecology, and co-founder of the international feminist food and farming collective *Cultivate!*

List of publications

Peer-reviewed journal articles

Félix GF, Clermont-Dauphin C, Douzet J-M, Hien E, Saunier-Zoltobroda T, Groot JCJ, Cournac L, Tittonell P. 2019. On-farm participatory assessment of shrub-based agroforestry systems in dryland Burkina Faso. *Agroecology and Sustainable Food Systems.* (Under review)

Laguarta JA, Algoed L, **Félix GF**, Carmona Báez A. 2019. Thinking through storm: Theorizing Puerto Rico in times of 'crisis'. *CENTRO Journal of the Centre for Puerto Rican Studies* (Under review)

Félix GF, Scholberg J, Clermont-Dauphin C, Cournac L, & Tittonell P. 2018. Enhancing agroecosystem productivity with woody perennials in semi-arid West Africa. A meta-analysis. *Agronomy for Sustainable Development*. DOI: 10.1007/s13593-018-0533-3

Félix GF, Diedhiou I, Le Garff M, Timmermann C, Clermont-Dauphin C, Cournac L, Groot J, Tittonell P. 2018. Use and management of biodiversity by smallholder farmers in semi-arid West Africa. *Global Food Security*. DOI: 10.1016/j.gfs.2018.08.005

Félix GF, Clermont-Dauphin C, Hien E, Groot JCJ, Penche A, Barthès BG, Manlay R, Tittonell P, & Cournac L. 2018. Ramial wood amendments (*Piliostigma reticulatum*) mitigate degradation of tropical soils but do not replenish nutrient exports. *Land Degradation & Development*. DOI: 10.1002/ldr.3033

Wezel A, Goris M, Bruil J, **Félix GF**, Peeters A, Bàrberi P, Bellon S, & Migliorini P. 2018. Challenges and Action Points to Amplify Agroecology in Europe. *Sustainability* 10(5). DOI: 10.3390/su10051598

Timmermann C, **Félix GF**, & Tittonell P. 2017. Food sovereignty and consumer sovereignty: Two antagonistic goals? *Agroecology and Sustainable Food Systems*: 1-25. DOI: 10.1080/21683565.2017.1359807

Timmermann C, & **Félix GF**. 2015. Agroecology as a vehicle for contributive justice. *Agriculture and Human Values* 32(3): 523-538. DOI: 10.1007/s10460-014-9581-8

Book chapters

Álvarez Febles N. & **Félix GF**. 2019. Hurricane María, agroecology and resiliency. In Tokar B (Ed.), *Climate Justice and Community Renewal.* London: Routledge (In press)

Timmermann C, & **Félix GF**. 2019. Ethical issues involving long-term land leases: a soil sciences perspective. Book Chapter, In: *Sustainable governance and management of food systems: ethical perspectives*, edited by Eija Vinnari and Markus Vinnari, 287-292. Wageningen: Wageningen Academic Publishers. DOI: 10.3920/978-90-8686-892-6

Tittonell P, Klerkx L, Baudron F, **Félix GF**, Ruggia A, van Apeldoorn D, Dogliotti S, Mapfumo P, & Rossing WAH. 2016. Ecological Intensification: Local Innovation to Address Global Challenges. In E Lichtfouse (Ed.), *Sustainable Agriculture Review - Volume 19* (Vol. 19, pp. 1-34). Switzerland: Springer International Publishing.

Timmermann C, & **Félix GF**. 2016. Food Sovereignty and the Global South. In *Encyclopedia of Food and Agricultural Ethics*, eds. P. B. Thompson & D. M. Kaplan, 1-6. Dordrecht: Springer Science+Business Media.

Conference proceedings

Félix, GF, Clermont-Dauphin C, Hien E, Douzet J-M, Groot JCJ, Tittonell P, Cournac L. 2019 (October). *Crop performance in shrub-based agroforestry systems of Burkina Faso: An on-farm experiment* (Oral presentation). 2éme Conférence Intensification Durable 2019, Dakar, Senegal

Fortuño-Bernier F, Algoed L, Carmona-Báez A, **Félix GF**. 2018 (October). *Thinking through the storm: Theorizing Puerto Rico in times of 'crisis'* (Panel Proposal). 13th Biennial Conference of the Puerto Rican Studies Association, Rutgers University, New Jersey, USA

Félix GF. 2017. *Native woody shrubs for soil restoration in West African dryland farming systems.* Conférence Intensification Durable 2017: Biodiversité et Ingénierie Écologique, Dakar, Senegal

Félix GF, Hien E, Lahmar R, Douzet J-M, Saunier-Zoltobroda T, Founoune-Mboup H, Ndour Y, Niang D, Séguis L, Gautier D, Zongo E, Manlay R, Barthès BG, Clermont-Dauphin C, Attané A, Masse D, Belem M, Groot J, Scholberg J, Tittonell P, & Cournac L. 2016. *Shrubs and trees to enhance agroecosystem productivity and counter land degradation in semi-arid West Africa*. Paper presented at the EcoSummit 2016 - Ecological Sustainability: Engineering Change, Montpellier, France. www.wassa-eu.org

Félix GF, Douzet J-M, Ouédraogo M, Belliard P, Lahmar R, Clermont-Dauphin C, Scholberg J, Tittonell P, & Cournac L. 2015. *Ecosystem services for West African farming families: the role of woody shrub mulch*. Paper presented at the 5th International Symposium for Farming Systems Design, Montpellier, France.

Diemont E, Draugelyte E, **Félix GF**, Atuga G, Bos R. 2014. *Democratising knowledge: co-creating the future*. Conference paper, Copenhaguen, Danemark. http://www.st-otherwise.org/wp-content/uploads/democratising-knowledge.pdf

Other

Félix GF. 2018. Increasing Farmer Resilience to Climate Change with Agroecology in Mauritius. Consultancy report for UNDP Mauritius.

Félix GF, González E, Sanfiorenzo-Barnhard C. 2018. *Rapid Assessment: Impact of Hurricanes Irma and María on Forest Cover, Farmers and Stakeholders in Puerto Rico.* Consultancy report for World Central Kitchen, J/P HRO and Centro para la Conservación del Paisaje. https://www.worldcentralkitchen.org/wckagreport

Félix GF. 2018. *Rural-urban linkages in Ouagadougou*. Nyéléni Newsletter 35 (Via Campesina). https://nyeleni.org/DOWNLOADS/newsletters/Nyeleni_Newsletter_Num_35_EN.pdf

Félix GF, Rodríguez H, & Vázquez J. 2018. *Puerto Rican EcoFarms after María: Bouncing Back with a Little Help From Our Friends.* Food First Blog. https://foodfirst.org/puerto-rican-ecofarms-after-maria-bouncing-back-with-a-little-help-from-our-friends/

Félix GF, & Holt-Giménez. 2017. *Hurricane María: An Agroecological Turning Point for Puerto Rico?* Food First Backgrounder 23(4) https://foodfirst.org/publication/hurricane-maria-an-agroecological-turning-point-for-puerto-rico/

Félix GF. 2017. *Puerto Rico: A Showcase for Vulnerability in the Caribbean.* Food First Blog. https://foodfirst.org/puerto-rico-a-showcase-for-vulnerability-in-the-caribbean/

Timmermann C, & **Félix GF**. 2015. *Adapting Food Production to Climate Change: An Inclusive Approach*. In Climate Change and Human Rights: The 2015 Paris Conference and the Task of Protecting People on a Warming Planet, eds. M. Di Paola & D. Kamal. Durnham: Global Policy. https://www.globalpolicyjournal.com/blog/23/11/2015/climate-change-and-human-rights-adapting-food-production-climate-change-inclusive-ap

Félix GF. 2015. *From slash and burn to 'slash and mulch'*. Farming Matters, 31.1, 14-17. http://orgprints.org/29411/

Mendonça MA, & **Félix GF**. 2014. *Agroecology Symposium at the FAO: a small step for farming families, a big step for policymakers*. ILEIA. http://www.academia.edu/8922145/Agroecology_Symposium_at_the_FAO_a_small_step_for_farming_families_a_big_step_for_policy_makers_2014_

Félix GF, & Timmermann C. 2013. *Agro-ecology: beyond food.* Farming Matters, December 2013. http://orgprints.org/24949/1/2013_felix_timmermann_agroecology.pdf

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)

- Enhancing agroecosystem productivity with woody perennials in semi-arid West Africa; a meta-analysis

Writing of project proposal (4.5 ECTS)

- Innovative uses of indigenous woody amendments to enhance soil aggradation and crop productivity of Sudano-Sahelian agroecosystems

Post-graduate courses (5.7 ECTS)

- Bugs at your service; PE&RC (2014)
- Companion modelling; PE&RC, WIAS, WASS (2014)
- 6th ESSA Summer school; PE&RC, WASS, ESSA (2015)
- Generalized linear models; PE&RC (2017)
- Mixed linear models; PE&RC (2017)

Laboratory training and working visits (4.5 ECTS)

- Soil restoration via shrub woody biomass in Sudano-Sahelian West Africa; Eco&Sols, IRD, CIRAD, Université Ouaga I Joseph Ki-Zerbo (2013-2017)
- Resilience and vulnerability assessment in farming systems after natural disasters; SOCLA, CELIA, Food First (2017-2018)

Invited review of (unpublished) journal manuscript (3 ECTS)

- Agriculture, Ecosystems and Environment: Soil carbon and nitrogen sequestration as affected by distance from smallholder homestead and fertilisation management on Arensols and Luvisols in Zimbabwe (2013)
- Journal of Rural Studies: Trends in farmland tree stocks in the agroforestry landscape of northern Nigeria (2018)
- Agronomy for Sustainable Development: Agroforestry is a win-win solution for smallholder farmers in Sub Saharan Africa (2019)

Deficiency, refresh, brush-up courses (3 ECTS)

- Analysis and design of organic farming systems; FSE (2013)
- Systems simulation; CSA (2013)

Competence strengthening / skills courses (1.5 ECTS)

- Scientific writing; WGS (2014)

PE&RC Annual meetings, seminars and the PE&RC weekend (0.9 ECTS)

- PE&RC PhD Symposium (2016)
- PE&RC Last year weekend (2018)

Discussion groups / local seminars / other scientific meetings (5.5 ECTS)

- SIAS, Sustainable Intensification of Agricultural Systems (2013-2016)
- R Meetings (2015-2018)

International symposia, workshops and conferences (16.6 ECTS)

- IV Congreso Latinoamericano de agroecología SOCLA; Lima, Perú (2013)
- 1st FAO International symposium on agroecology for food security and nutrition; Rome, Italy (2014)
- 5th International symposium on farming systems design; Montpellier, France (2015)
- EcoSummit; Montpellier, France (2016)
- 1st Sustainable intensification conference; Dakar, Senegal (2017)
- 13th Biennial conference of the Puerto Rican studies association; NJ, USA (2018)
- 10th Annual agroecology symposium SOCLA; Utuado, Puerto Rico (2018)
- European economic and social committee; Brussels, Belgium (2019)
- International forum on landscapes, agriculture and women; El Priorat, Catalunya (2019)
- 2nd Sustainable intensification conference; Dakar, Senegal (2019)

Lecturing / supervision of practicals / tutorials (4.5 ECTS)

- Organic agriculture and society; Wageningen, the Netherlands (2014, 2016)
- Agroecology; Puerto Rico, France (2016, 2018)
- Ethnobotany; Wageningen, the Netherlands (2017)
- Farm experience internship; Wageningen, the Netherlands (2017, 2018)

Supervision of MSc students (18 ECTS)

- Marie Le Garff: Nutritional Functional Diversity (2016)
- Justine Santamaria: Gender roles in agricultural systems (2016)
- Timothée Cheriere: Fertility islands around native shrubs (2015)
- Louis Gabaud: Microbiology of shrub resource islands (2015)
- Patrick Winterhoff: Use of termite nests for subsistence agriculture (2015)
- Salif Konané: Soil water infiltration and ramial wood amendments (2015)
- Philippe Belliard: Sorghum allometric equations on farmer fields (2014)
- Gaëlle Feur: Woody perennial inventory at landscape level (2014)
- Marcel Ouédraogo: On-farm experiment with native woody shrubs (2013)

This thesis work was part of the projects WASSA (Woody Amendments for Sudano-Saharan Africa) and ConneSSA (CONNEcting knowledge, scales and actors: An integrated framework for adaptive organic resource management, targeting soil aggradation and agroecosystems' resilience in SSA). The collaboration between Wageningen University (The Netherlands), IRD (France), CIRAD (France), Université de Ouaga I Joseph Ki-Zerbo (Burkina Faso), and local partners (in Yilou, Gampéla, Kindi and Ouagadougou) was made possible via the financial support from the European Union (ERA-ARD II and ERAfrica) and the CGIAR Research Program on Grain Legumes and Dryland Cereals (GLDC). Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author/PhD candidate and do not necessarily reflect the view of the partner or funding institutions. Financial support from Wageningen University for printing this thesis is gratefully acknowledged.

Printed by Digiforce, Amersfoort, The Netherlands on FSC-certified paper