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Tailoring conservation agriculture technologies to West Africa semi-arid zones: Building on traditional local practices for soil restoration

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ABSTRACT

Low inherent fertility of tropical soils and degradation, nutrient deficiency and water stress are the key factors that hamper rainfed agriculture in semi-arid West Africa. Conservation Agriculture (CA) is currently promoted in the region as a technology to reduce soil degradation, mitigate the effect of droughts and increase crop productivity while reducing production costs. CA relies on the simultaneous use of three practices: (1) minimum or zero-tillage; (2) maintenance of a permanent soil cover and; (3) diversified profitable crop rotation. The most prominent aspect of CA for degraded lands in the semi-arid tropics would be the organic soil cover that impacts on the soil water balance, biological activity, soil organic matter build-up and fertility replenishment. Yet, the organic resources are the most limiting factor in Sahelian agroecosystems due to low biomass productivity and the multiple uses of crop residues, chiefly to feed the livestock. Hence, CA as such may hardly succeed in the current Sahelian context unless alternative sources of biomass are identified. Alternatively, we propose: (1) to gradually rehabilitate the biomass production function of the soil through increased nutrient input and traditional water harvesting measures that have been promoted as "soil and water conservation" technologies in the Sahel, e.g. zaï, in order to restore soil hydrological properties as prerequisite to boosting biomass production; (2) to encourage during this restorative phase the regeneration of native evergreen multipurpose woody shrubs (NEWS) traditionally and deliberately associated to crops and managed the year around and; (3) to shift to classical, less labour intensive CA practices once appropriate levels of soil fertility and water capture are enough to allow increased agroecosystem primary productivity (i.e., an active 'aggradation' phase followed by one of conservation). The CA systems we propose for the Sahelian context are based on intercropping cereal crops and NEWS building on traditional technologies practiced by local farmers. Traditionally, NEWS are allowed to grow in croplands during the dry season; they reduce wind erosion, trap organic residues and capture the Harmattan dust, influence the soil hydraulics and favour soil biological activity under their canopies. They are coppiced at the end of the dry season, leaves and twigs remain as mulch while branches are collected for domestic fuel and other uses. Shoots re-sprouting during the rainy season are suppressed as weeds. Such CA systems have limited competition with livestock due to the poor palatability of the shrub green biomass, which may increase their acceptance by smallholders. Such aggradation–conservation strategy is not free of challenges, as it may imply initial soil disturbance that entail important labour investments, substantially change the structure and management of the cropping system (annual crop-perennial plant), and lead to emerging tradeoffs in the use of resources at different scales. This paper offers a state of the art around NEWS and their integration in relay intercropping CA systems, discusses the above mentioned challenges and the main research needs to address them.

1. Introduction

In sub-Saharan Africa food security remains a major concern (de Graaff et al., 2011; Kidane et al., 2006). The growth in agricultural production observed during the last decade was far from meeting the steady increasing population demand, 239 out of 863 million people were malnourished in 2010 (FAO, 2011). The yields remain among the lowest in the world; the increase in cereal

Abbreviations: CA, Conservation agriculture; SOM, Soil organic matter; SWA, Semi-arid West Africa; NEWS, Native evergreen woody shrubs; NEMRS, Native evergreen woody shrubs mulch based relay intercropping system.

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production observed during the last half century was explained for 60% by area expansion and 40% by yield increase (Challinor et al., 2007). This prompted African governments to undersign the Abuja declaration of 2006, placing the green revolution of agriculture in their political agendas and setting the goal of widespread fertilizer use in sub-Saharan Africa (www.nepad.org). In semi-arid West Africa (SWA) agriculture is mainly rainfed, i.e. vulnerable to climate variability and drought and based on small-scale farming with very low external inputs; current average annual fertilizers inputs is below 10 kg ha^{-1} (Vanlauwe et al., 2011). Soil degradation is widespread in the region, the total extent of severely degraded soil due to agricultural activities has been estimated at 1.1 million km^2 (Vågen et al., 2005). Lal (2008) portrayed the spiral of soil degradation and consequent social, economic, environmental and political impact, pointing to the continuous decline of soil organic matter (SOM) as a major driver of soil degradation processes and hence of poverty, hunger and malnutrition.

Soils in SWA are among the oldest and most intensively weathered of the world, exhibiting poor inherent fertility (Bationo et al., 1998; Eswaran et al., 1997). This includes: (i) reduced depth for root growth due to physical obstacles e.g. laterite hardpans (cuirasses) or to chemical limitations e.g. severe acidity or Al^{3+} toxicity layers; (ii) limited water holding capacity induced by impermeable layers, coarse texture and crusting and; (iii) limited nutrient availability in the topsoil. The latter is due to the inherently low SOM induced by poor biomass productivity, low soil clay content and rapid decomposition rates due to high soil temperatures or faunal activity; P immobilization by Fe or Al; deep leaching and limited nutrient holding capacity due to the dominance of low activity clay minerals and oxides. Bationo et al. (2007) reported high correlations between SOM and the cation exchange capacity for these soils, highlighting the importance of SOM for the retention, storage and release of plant nutrients. Although SOM maintenance in semi-arid tropical agroecosystems is crucial for the agricultural production, this is a hard task to accomplish. Early synthesis by Pieri (1989) of the results of 30 years research and development activities in SWA suggested the high sensitivity of SOM to landuse change and soil management, SOM declines rapidly in newly cleared and cropped lands. Feller and Beare (1997) showed the high susceptibility to cultivation of the particulate organic matter, which is an important fraction of SOM in coarse-textured soils; more than half of the SOM associated to the clay fraction can be lost over a period of 10–20 years of continuous cultivation. A recent study by Kintché et al. (2010) on a sandy soil (3.5–5% clay) in semi-arid Togo suggested that the largest proportion of initial SOM declined within a 5–10 years period after woodland clearance. On a loamy sand soil (6% clay, 52% sand) in Burkina Faso, Ouédraogo et al. (2006) evidenced a strong correlation between crop nitrogen uptake and the nitrogen associated to particulate organic matter in both tilled and no-tilled plots.

The impact of low inherent fertility and degradation of SWA soils is aggravated by rainfall scarcity and irregularity, population increase and the consequent reduced length of fallowing periods, plus the inability of smallholders to access fertilizers (Aina et al., 1991; Bationo et al., 1998; Breman et al., 2001; Buerkert et al., 2002; Drechsel et al., 2001; Lal, 2009; Pieri, 1989; de Ridder et al., 2004; Roose et al., 1993). The challenge of maintaining soil productivity through ensuring carbon and nutrient inputs to continuously cultivated soils calls for innovative approaches to cropping systems design. A number of approaches and experiences have been attempted including soil and water conservation techniques, agroforestry, integrated soil fertility management, etc., most of which require large initial investments and often drastic transformation of the agricultural landscape and practices. Conservation agriculture (CA) has been suggested decades ago (e.g. Lal, 1989) as an alternative that favours SOM build-up in situ, with relatively smaller investments in labour and resources. CA relies on the simultaneous use of three practices (www.fao.org): (1) minimum or zero-tillage; (2) maintenance of a permanent soil cover and; (3) diversified profitable crop rotation. The most prominent aspect of CA for degraded lands in the semi-arid tropics would be the organic soil cover that impacts on the soil water balance, biological activity, SOM build-up and fertility replenishment.

Our experience in the regions taught us, however, that CA is unlikely to be adopted by farmers in systems where crop residues may have higher value uses than mulching; e.g., crop residues in the Sahel may at times fetch higher prices than grain on local markets. On the other hand, soils that underwent severe degradation are likely unable to produce enough biomass during initial CA stages to foster soil biological activity and SOM build-up, with consequently poor results that deter farmers from implementing it. Poor initial biomass productivity may even lead to yield penalties for CA as compared with the conventional practice, and to inefficient use of applied inputs. Our approach to CA for SWA is one that makes use of traditional practices and farmers knowledge on soil fertility management using local resources to ensure 'aggradation' of degraded land followed by a phase of system stabilization and soil conservation through minimum tillage and mulching. This paper proposes an alternative CA system tailored to the conditions of smallholders in SWA in which annual crops and perennial native evergreen woody shrubs (NEWS) are intercropped, and suggests ways to implement such systems for gradual rehabilitation of degraded soils. It takes stock of the existing knowledge and results about current conservation and restoration practices suitable for SWA, suggests further research needs and discuses the opportunities, challenges and tradeoffs of the alternative proposed. We first review existing experiences on the potential of mulching and traditional water harvesting measures to enhance resource use efficiency in SWA. Then, we review existing scientific knowledge and challenges in the transition towards a perennial-annual system, and the consequences that this has for a new definition of CA that suits the context and conditions of SWA.

2. The potential of mulching to enhance soil productivity in SWA

CA properly implemented associates no-till/reduced till, soil cover by crop residue (mulch) or living plants (cover crops) and diversified crop rotations (www.fao.org). It is promoted as a technology to combat soil degradation while providing social and economic benefits to farmers. There is vast literature on CA for Africa that emphasizes the impacts of the technology on soil structure and water balance, biological activity, SOM build-up and fertility replenishment, which may results increased farm productivity and incomes (Lahmar, 2010). For many reasons, suitability of CA for SWA smallholders seems however to be a challenging matter (Giller et al., 2009). Considering only the biophysical aspects of CA suitability, the mulch seems to be an utmost factor that may determine the success of this technology in soil fertility improvement in SWA. Fortunately, mulching is a method traditionally used by smallholders in SWA, sometimes on very small patches of land, to improve crop production of degraded soils (Schlecht et al., 2006; Wezel and Rath, 2002). Research results have evidenced increased crop biomass and yields in mulched crops, particularly on degraded soils under dry conditions (Bationo and Buerkert, 2001; Buerkert et al., 2002).

On acid sandy soils of Niger (3% clay; 91–93% sand), increased millet production has been shown to result from both direct and indirect effects induced by millet residue mulch (Buerkert and Lamers, 1999). Direct effects include the physical protection of seedlings against the adverse effects of wind and water erosion provided by the mulch-induced surface roughness, improving crop stand density (Buerkert et al., 2002; Michels et al., 1995a). Indirect effects include the improvement of the soil chemical, physical and hydrological properties that enhanced the crop's water and mineral nutrition (Buerkert et al., 2002). Buerkert and Lamers (1999) reported greater soil water availability due to the lowering of the soil surface peak temperature by about 4 °C and to improved water infiltration partly associated with increased termite activity, which contributed to breaking the soil surface crust and decrease root penetration resistance. Mulching has been shown as contributing to higher pH, effective CEC, and base saturation in the topsoil (Kretzschmar et al., 1991; Michels et al., 1995b) as well as improved P availability, decreased exchangeable Al^{3+} and enhanced root growth (Buerkert and Lamers, 1999; Hafner et al., 1993; Kretzschmar et al., 1991). These improvements have been ascribed to mulch decomposition and to the dust captured by the mulch (Buerkert and Lamers, 1999; Buerkert et al., 2002). Results have been less conclusive regarding SOM. Michels et al. (1995a) observed an increased concentration of organic carbon in the 0–10 cm layer of the mulched soil while, for the same depth, the results of Buerkert and Lamers (1999) indicated no change in organic carbon content. It should be mentioned that most of the improvements reported here resulted from the application of 2 Mg ha^{-1} of millet straw; no significant change in soil properties occurred when smaller quantities were tested (e.g., 0.5 Mg ha^{-1}).

In northern Burkina Faso, mulching of crusted sandy clay loam (21% clay, 49% sand) and sandy loam (20% clay, 37–53% sand) soils with organic resources of different qualities i.e. straw of *Pennisetum pedicellatum*, woody material of *Pterocarpus lucens* and a composite (1/3 straw and 2/3 wood), showed increased infiltration, soil water storage and deep drainage as a result of termite activity (Mando, 1997). These results has been supported by micromorphological investigation (Mando and Miedema, 1997) that showed an improved soil structure and porosity through macropores and termite pedofeatures in the initially degraded 0–7 cm layer. The authors suggested that mulch, through triggering termite activity, is an alternative to soil tillage in the rehabilitation of degraded soil structure in the Sahel. Analyzing data collected from bare plots, mulched plots with termite activity and mulched plots from where termite activity has been suppressed by an insecticide, Mando and Stroosnijder (1999) found significant associations between termite activity expressed by the density of voids (void m^{-2}) and water runoff, sediment accumulation, vegetation cover, and dry matter yield. They interpreted the regressions on this way: the density of termite voids was the only factor that reduced runoff on the plots; the accumulation of the sediments in the mulched plots was due to the physical effect of the mulch, the mulched plots with active termites accumulated greater quantity of sediments because they had higher natural vegetation coverage that participated in the dust capture. The accumulation of the sediments on termite-free mulched plots did not result in any increase of the natural vegetation despite their richness in nutrients and plant seeds because of the physical limitation of the crust and the water limitation. The authors concluded that termite activity, as a biological effect induced by mulching, is critical to the rehabilitation of Sahelian crusted soils. Once the rehabilitation process was started by termites, the sediment accumulation played a major role in its amplification. This conclusion would suggest that the rehabilitation process of the Sahelian crusted soils have to start first by creating a water reserve in the soil, following improved nutrient uptake increases water use efficiency. Both improved water and nutrient use efficiencies would lead to higher plant primary production.

Hence, even if there are still enough questions that need answers in the context of SWA, the mulch-induced effects reported here suggest the benefit that CA and, more generally, a mulch-based agriculture may provide to SWA's smallholders. This is however strongly challenged by the scarcity of organic resources due to poor crop biomass production and the competitive use of such biomass as fodder, fuel, building material, handicrafts etc. (Bationo and Mokwunye, 1991; Lal, 2007; Mulumba and Lal, 2008; Wezel and Rath, 2002). Growing cover crops, as a means to increase biomass inputs is not always a viable option for different reasons: cover crops production is attractive to smallholders only if it provides an immediate and direct benefit; it competes for land and exposes smallholders to the risk of grain shortage as it can be achieved only in rotation with cereals in semi-arid rainfed systems; it is practically impossible to maintain a dry cover crop on the soil during the long dry season due to animal browsing associated with customary grazing rules. It has also been argued that smallholders' reluctance to use the mulch may be caused by the cost incurred in its application (Mulumba and Lal, 2008) and by the amount of labour and means needed for the off-site collection and transportation of organic resources (Schlecht et al., 2006).

3. Aggradation of degraded lands in SWA agroecosystems

The term 'aggradation' as employed here was borrowed from clay mineralogy and stands for a reverse mechanism to degradation. The mechanism is gradual and the aggraded degraded clays may have the same lattice than the originals but not necessarily the same electrical charges and properties. This mirrors the step by step approach, rehabilitation phase and end-results observed in natural and agroecosystems that exhibit 'hysteresis' (Tittonell et al., 2008). Rehabilitating degraded soils, depending on the extent and type of degradation process, may require sustained efforts for long periods of time, and responses to interventions may be weak. Slow and weak responses to soil restoration are disincentive to smallholder farmers (Fig. 1). The hysteresis (h) of land rehabilitation is represented in Fig. 1 by the deviation between the trajectories of soil degradation and rehabilitation (purposely plotted towards the opposite direction). Measures to restore productivity may be hysteretic or not, and exhibit fast or slow responsiveness. Whether a response can be considered to be fast or slow, hysteretic or not depends also on the indicator chosen to characterize the response (productivity, efficiencies, and stocks), on the type of measure(s) implemented to restore productivity, on the biophysical properties of the agroecosystem under consideration, and on the behaviour of external drivers (e.g., rainfall).

In the context of SWA agroecosystems, the aggradation of degraded bare lands with surface crusted soils imposes to first start by the recovery of the soil surface and water properties, which highly conditions biomass productivity as evidenced by Mando and Stroosnijder (1999). The restoration of degraded soil water properties can be achieved through exploiting the mediation of faunal activity, particularly by termites. This can be facilitated by the use of mulch, as documented above, but this may be out of reach to smallholders due to insufficient organic resources. Alternatively, certain traditional water harvesting techniques such as the "zai" may also mediate termite and other biological activity by creating favourable micro habitats. The term zai in Burkina Faso, "tassa" in Niger and "towalen" in Mali, stands for the same native water harvesting technique consisting of digging planting pits, traditionally used by farmers to grow cereals in harsh dry conditions. These have been extensively promoted as a soil and water conservation technique in SWA (Droux, 2008). It has been well adopted by smallholders despite the strenuousness manual labour it requires: more than 300 man-h ha^{-1} i.e. about 60 working days during the dry season, by high temperatures (Barro et al., 2005; Clavel et al., 2008; Droux, 2008). Attempts to mechanize the digging of zai did not yet meet success (Barro et al., 2005).

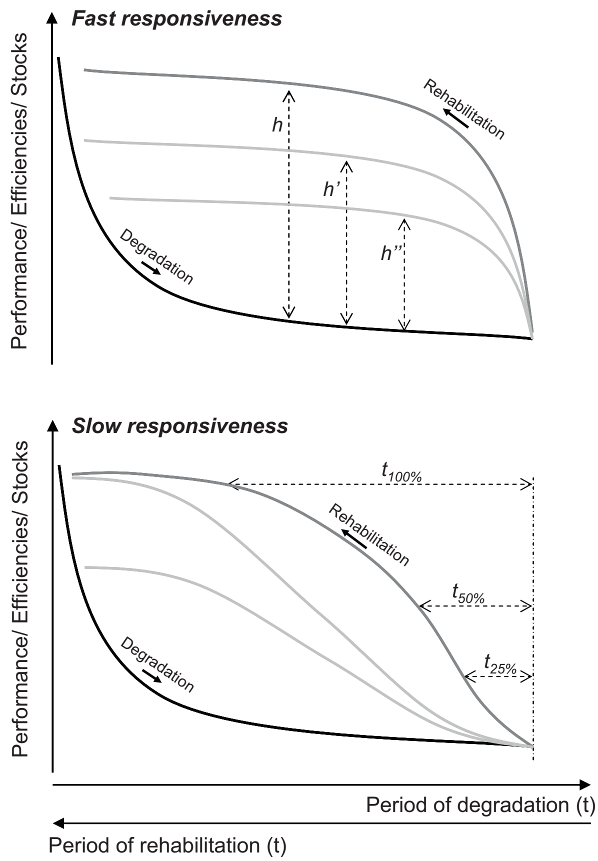

Fig. 1. Theoretical schemes representing the concept of hysteresis (*h*) of land rehabilitation. After having undergone a degradation phase, the response of the agroecosystem to rehabilitation measures may be fast or slow, and exhibit weak or strong hysteresis (i.e., *h*, *h*′ or *h*″). The periods *t*25%, *t*50% and *t*100% represent the delay necessary to achieve 25–100% of the original performance, efficiency or stock level.

Adapted from: Tittonell et al. (2011).

During the dry season, the pits trap the dust and organic material moved by the wind; in the rainy season, they trap runoff water as well as the organic and mineral material carried along, resulting in reduced runoff and soil erosion (Bouzou Moussa and Dan Lamso, 2004; Roose et al., 1993). The organic resources trapped or applied in the pits by farmers (manure, compost) before sowing cereals trigger termite activity. The resulting porosity increases soil water infiltration and soil water storage in the rooting zone (Roose et al., 1993). Crops growing in the zai pits were shown to be less affected during dry spells (Fatondji, 2002). The concentration of water and the nutrients in the root zone induces a better development of the root system resulting in improved efficiency of the rainwater and nutrients use (Barry et al., 2008; Fatondji, 2002; Fatondji et al., 2006). Most of these studies also documented enhanced crop production in zai in the presence of organic resource amendments. Bouzou Moussa and Dan Lamso (2004) observed greatest yields when a mix of organic resources of low (millet straw) and high (manure) quality was applied in pits in Niger, likely because increasing both termite and microbial activity resulted in adequate nutrient release. Ouédraogo et al. (2004) showed that termites prefer low quality organic resources. Another non-less important aspect is that the zai favours the germination of seeds contained in trapped sediments and organic material or brought in through manure applications, the micro depression protects the seedlings from wind and animal damage, which lead to a rapid regeneration of a diversified herbaceous and ligneous flora (Roose et al., 1993).

Digging zai consumes time and effort, and farmers are unlikely to invest those if immediate yield increments are not substantial. Most constraining to the zai expansion would be thus the lack or insufficient availability of good quality organic resources (manure or compost) at farm level, which are necessary to concentrate nutrients in the zai. As any other technology, zai may have biophysical limitations that are generally overlooked. Particularly, zai seems to be not suitable when the soil water storage capacity is reduced, as in shallow soils, because it may expose the crop to the effects of both drought and waterlogging (Roose et al., 1993). Zai dug on soils down the slopes or in lower parts of the landscape are particularly susceptible to waterlogging. Out of these situations, zai seems to perform well when rainfall ranges between 300 and 800 mm (Roose et al., 1993) i.e. in the whole SWA. As for soil nutrient management, the long-term impact of the zai e.g. on SOM build-up and nutrients replenishment remains unclear and it has been seldom investigated. Short-term trials by Fatondji (2002), Kabore (1994) and Roose et al. (1993) did not reveal dramatic changes in soil chemical properties, suggesting that the resources captured in the zai the year around as well as those brought in soil amendments could be consumed during one cropping season; indeed when zai is manured intermittently, a decreasing effect of the manure on the crop production may be observed 2 to 3 years after the manure application (Dan Lamso, 2002). Soils with swelling clay minerals may limit termite activity; on sandy soils, zai may induce deep drainage and nutrient leaching (Fatondji et al., 2009). These authors suggest this to be due to poor synchronization between nutrient release and crop nutrient uptake, as nutrient release occurs soon after the application of the organic amendment when the root system is not well developed. Moreover, zai is not appropriate for sandy soils with instable structure as the pits collapse at the first rains (Ambouta et al., 2000; Evéquoz and Guéro, 2000). Looking at in situ practices, it is not clear if, when and why do farmers abandon the practice of zai, which are their motivations, and what system they put in place afterwards.

4. Alternative shrub-based CA systems for SWA

The use of alternative low cost organic resources, such as woody debris and leaves of shrubs co-existing with crops, has been documented to be locally practiced in SWA (Wezel and Rath, 2002). We propose a CA alternative that builds on what we observed in practice by smallholders in two localities in SWA: Guidan Bakoye in South-eastern Niger (N 13°41′; E 7°46′) and Yilou in Centre-East of Burkina Faso (N 13°1′; W 1°32′). Despite the great distance between the two localities, about 1000 km, farmers practice a similar management of two native evergreen woody shrubs (NEWS): *Piliostigma reticulatum* (D.C.) Hochst (Ceasalpinacea) and *Guiera senegalensis* J.F. Gmel (Combretacea), both are multipurpose shrubs. At Guidan Bakoye, *G. senegalensis* shrubs density is low and shrubs are scattered in the field, the land is completely open and farmers ox-plough to incorporate the pruned leaves and twigs which otherwise are moved by the wind. At Yilou, the *P. reticulatum* density is high, the shrubs are scattered in some parts of the field and concentrated in some other parts and the land is not completely open; land borders are marked by individual trees or incomplete hedgerows. Ploughing is not systematically practiced each year; fields with high shrub densities are only hoe-tilled. Determinants of the spatial distribution and density of the shrubs in both sites are not yet understood; beside the natural causes (e.g. soil, water and erosion), livestock browsing and farmers' management are certainly contributing factors (Yélémou et al., 2007).

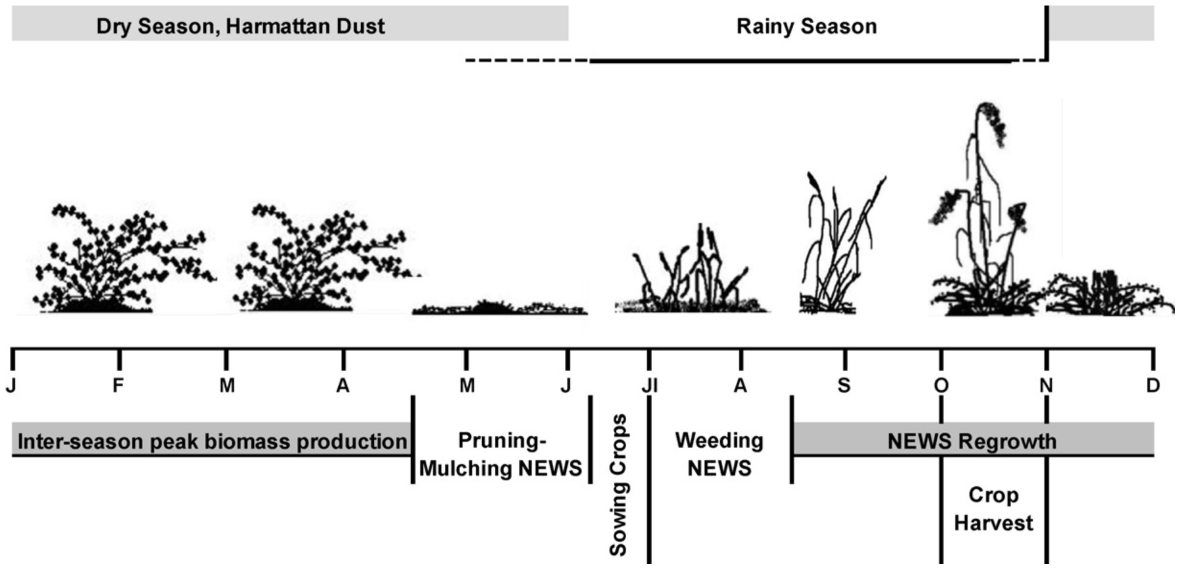

Fig. 2. Management of native evergereen woody shrub (NEWS) in semi-arid West Africa cropping systems. Example of the management of *Piliostigma reticulatum* by some farmers at Yilou village in Burkina Faso: during the dry season, *P. reticulatum* grows, reduces erosion and intercepts dust; it is cut at the starting of the rainy season to install the main crop; during the rainy season it is weeded then subsequent sprouts are allowed to continue growing and reform the shrubs.

4.1. Ecology and traditional uses of P. reticulatum and G. senegalensis in SWA

P. reticulatum and *G. senegalensis* are very common across the Sahel, from Senegal/Mauritania to Sudan/Eritrea. They are found in both fallow and cropped land where they are voluntary kept by the farmers. *P. reticulatum* seems to be sensitive to soil depth and moisture, as it does not occur on compacted soils (Arbonnier, 2009; Poilcot et al., 2009; Yélémou et al., 2007; Wezel and Boecker, 1998). *G. senegalensis* seems to adapt to poor, depleted and sandy soils, hardpans and to drier situations (Hejcmanovā-Nežerková and Hejcman, 2006; Thiombiano et al., 2006; Wezel and Boecker, 1998). They grow during the dry season and their leaves are persistent, so they are often the only source of green plant material during the long dry season. In some areas they coexist in the same sites, in others they form monospecific gregarious populations with high densities (Arbonnier, 2009; Poilcot et al., 2009; Yélémou et al., 2007; Wezel and Boecker, 1998).

P. reticulatum and *G. senegalensis* are known by local populations and used for many purposes. They are extensively used in traditional human medicine (Akinsinde and Olukoya, 1995; Arbonnier, 2009; Salawu et al., 2009) and as energy source (Arbonnier, 2009; Louppe, 1991; Nouvellet et al., 2003). They are also used as timber, for roofing materials and granaries, fencing around the households, dye preparation and handicrafts e.g. skills' handles, baskets, chairs and stools, utensils, masks and many other items that, when marketed, contribute to household income (Diack, 1998; Gustad et al., 2004; Yélémou et al., 2007). Their leaves and fruits are browsed by ruminants, camels and equines. *P. reticulatum* pods seem to be appreciated also by pigs (Yélémou et al., 2007). However, as mentioned by Wezel and Böcker (1999) regarding *G. senegalensis* and, may be except for *P. reticulatum* pods, livestock do not browse the leaves of the two shrubs until the end of the dry season when almost no other fodder is available. Indeed, *G. senegalensis* and *P. reticulatum* leaves present poor fodder quality (Wezel and Böcker, 1999), they contain tannins that reduce proteins availability and enzyme activity, affecting animal productivity (Makkar and Becker, 1998; Zimmer and Cordesse, 1996). This allows for considerable aboveground biomass to grow and accumulate over the dry season (Lufafa et al., 2008a) that can be used as mulch.

4.2. Observed management of P. reticulatum and G. senegalensis in cropping systems

At Guidan Bakoye, soil is sandy and *G. senegalensis* is the dominant multi-stem shrub in cropped lands. Before the rainy season starts, i.e. from late April to June, farmers prune *G. senegalensis* stems at the soil surface, except for one or two robust stems that may be left in some shrubs. Part of the cut stems are left on the ground around the shrub place. The other part is taken to serve as fodder for the small ruminants kept around the homestead. After leaves have been removed by animals or senescence, branches are collected from the fields and used as firewood. At the beginning of the rainy season, in June/July, millet is sown more densely in and around the shrub base or crown, a place often termed "island of fertility" that is easily identifiable due its elevated micro-topography. New shoots produced by the stumps during the rainy season are removed as weeds twice during the cropping season. After the last weeding, the shoots are allowed to grow to continue during the dry season, and the multi-stem shrub structure is restituted.

At Yilou, *P. reticulatum* is the dominant multi-stem shrub. It is coppiced in April–June; all the stems of all the shrubs on the plot are cut at the soil surface and left on the ground. When the stems are dry and free from the leaves, they are collected by women and children for firewood. So, only leaf biomass remains on the soil surface. After the first rains (May–June), sorghum is sown more densely in and around the shrub crown. Shrub shoots growing during the cropping season are weeded once or twice. Subsequent sprouts are allowed to continue growing until the end of the next dry season. We also observed that a number of smallholders, mainly women, in Northern Burkina Faso collect *P. reticulatum* foliage to fill in their zaï pits and half-moons early before sowing (Fig. 2).

Thus, in both localities, farmers associate an annual crop with a ligneous perennial and developed an ingenious management system where the NEWS is likely used as a 'facilitator' to the annual crop – as opposed to the generalized practice of uprooting and burning the shrubs. From an agronomic point of view, the system is comparable with relay intercropping. Ecologically, the system is meaningful; it maintains the soil covered almost the year around, even in patches during the dry season, which certainly limits soil erosion. Farmers' knowledge of these shrubs, their active incorporation into the cropping systems and the way they manage the organic resources deriving from these shrubs, particularly the pruning–mulching of *P. reticulatum* as practiced in Yilou, are elements of paramount importance for the designing of an adapted NEWS mulch-based relay intercropping system (NEMRS) that may contribute to an ecological intensification of agriculture in SWA.

4.3. Available knowledge and research needs on shrub-based cropping systems

The benefit of intercropping of *P. reticulatum* and *G. senegalensis* and the use of their biomass as mulch or soil amendment have been investigated since the early 1990s in South-western Niger and in the Senegal's Peanut Basin. However, the potential role of the NEWS as a central component in no-till mulch-based cropping system as we propose here has been seldom investigated. Many aspects of the ecology and hydrology of both NEWS and their impact on soil fertility and crop production have been studied mainly on sandy soils. Investigations included the effect on millet yields (Wezel, 2000; Wezel and Böcker, 1999) and soil properties and fertility (e.g., Dossa, 2007; Dossa et al., 2010; Wezel et al., 2000); mulching with small branches of *G. senegalensis* has been shown to increase millet yield on infertile soils with only 1 Mg ha^{-1} of mulch biomass (Wezel and Böcker, 1999); NEWS biomass production and soil carbon stocks (Lufafa et al., 2008a, 2008b, 2009); organic matter quality, decomposition patterns, micro-organisms involved in the processes, and nutrients release (Diack, 1998; Diack et al., 2000; Diedhiou et al., 2009; Dossa et al., 2009); rooting patterns and effect on soil water and use and balance (Gaze et al., 1998; Kizito et al., 2006, 2007). Soil beneath the shrub canopies has been shown to support greater millet yields as compared to soil out of the canopy influence. Soil water storage was improved in the presence of *P. reticulatum* and *G. senegalensis* which also provided water facilitation to the associated annual crops through the hydraulic redistribution (Kizito et al., 2006, 2007). Competition for water and nutrients between the NEWS and the associated crops may also occur at the starting of the rainy season, when rainfall is still low and sporadic and the soil surface is dry (Gaze et al., 1998). Consequently, Wezel (2000) recommended to adapt pruning practices and shrub densities in crop fields, keeping up to 225 shrubs partly coppiced, with 3–5 branches, and homogeneously scattered in space to benefit from their anti-erosive and dust capture effects. Such management seems to have been adopted by the smallholders in Guidan Bakoye.

These findings suggest great potential of shrub-based technologies to improve systems productivity and stability under Sahelian conditions. However, research is still incipient and most results have been obtained on the sandy soils and particular agroecological conditions of the Senegal Peanut Basin, where burning and/or ox-ploughing for biomass incorporation into the soil is common practice. The impact of the NEWS and derived mulch on water and nutrient dynamics needs to be studied and confronted across soils of different textures, and under the no-till situation of the proposed NEMRS. Available data (e.g. Diack, 1998; Diack et al., 2000; Dossa, 2007; Louppe, 1991) show that the amount of shrub above-ground biomass produced in farmer fields during the inter-season vary widely, from 0.3 to 2.4 Mg ha^{-1}, probably do to shrub density and age, soil nature, annual rainfall and the management of the associated crop. Research is needed to quantify the tradeoffs between adequate provision of organic resources for mulching, shrub densities and their competition for space, light, water and nutrients with the crop, the dynamics of the system at different temporal and spatial scales. The fine-tuning of the NEMRS requires also a better understanding of NEWS-derived mulch decomposition and nutrient release; the above- and belowground relationships and ecological mechanisms associated with the interaction between the shrubs and the annual crops. This includes resource allocation, mediation/facilitation, plant–plant competition, biotic and abiotic constraints, etc. Furthermore, the impact of the proposed system on the farming system as a whole, on the flow of resources at farm and village scales, their interaction with livestock management in agro-pastoral systems, as well as socio-economic aspects such as labour needs and productivity should be understood in order to adapt the system and to increase its benefits and attractiveness to smallholders. The potential impact of the proposed system on annual water balances, landscape hydrology and underground water reserves recharge should be also approached at the appropriate, aggregated scales.

4.4. The transition towards NEMRS

Although this technology is built on farmers' knowledge and on a certain body of research findings that attests the benefit of shrub-crop associations under smallholder low input farming, the transition towards a shrub-based CA system should be well targeted:

(1) In situations where these shrub species already exist in the field, the transition towards a NEMRS may require to optimize the current system, i.e.: to target optimal density and spatial arrangements of the shrubs and associated crops, to optimize the timing of the pruning–mulching operations in order to benefit from the dust capture and to reduce the wind and water erosion of the early rains, to ensure efficient capture and use by the crop of nutrients released through mulch decomposition; i.e., a better synchronization of the release and uptake of nutrients, reducing the potential risk of nitrogen immobilization due to the low quality of the shrub-derived organic matter.

(2) In critical situations where soil is degraded and the land is bare, which is widely spread in SWA, the system should be aggraded i.e. drawn to adequate primary productivity prior to shift to CA (Fig. 3). The aggradation can be achieved through: (i) a gradual rehabilitation of the biomass production function of the soil through the restoration of the soil hydrological properties as a prerequisite to boosting biomass production then; (ii) to encourage during this restorative phase the regeneration and the densification of the shrubs through traditional management measures.

Both *P. reticulatum* and *G. senegalensis* are often reported in the floristic inventories carried out in fields in which zai were dug. Recent studies in Burkina Faso (Yélémou et al., 2007) and Niger (Larwanou and Saadou, 2011) showed that *P. reticulatum* and *G. senegalensis* were among the most dominant woody species in the sites where water harvesting measures had been implemented and when farmers used local techniques and knowledge to maintain the seedlings – which are often documented as 'farmer managed natural regeneration practices' (Vohland and Barry, 2009). Roose et al. (1993) reported that some farmers of the Yatenga province (Burkina Faso) are used to preserve seedlings every five pits. Enlightening examples of aggradation of degraded lands can be seen nowadays in this province where, starting by the zai and managing the natural regeneration, some farmers turned bare lands into woodlots and, where the aggradation steps can be still tracked at farm level. According to Botoni and Reij (2009) both water harvesting techniques and farmer natural regeneration practices resulted in a promising greening of millions of hectares in the Sahel.

5. Discussion

The major constraint discouraging the implementation of classical CA in the SWA small-scale farming is the limited production of and competing uses for crop residues. Mulching is a crucial component of CA that has been shown to be efficient in the aggradation of

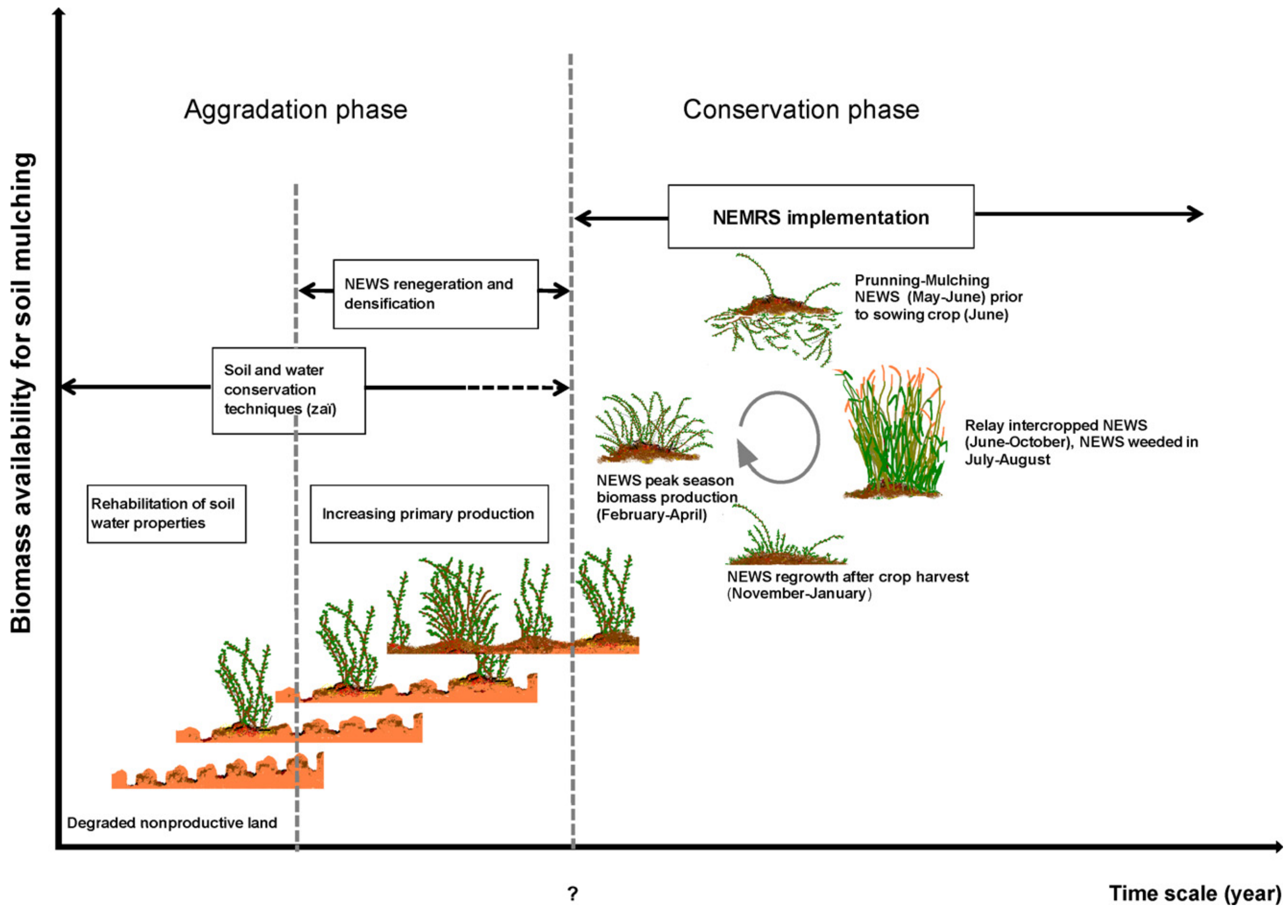

Fig. 3. Aggradation–conservation agriculture for semi-arid West Africa agroecosystems. Starting from bare degraded soil, zai implementation allows the recovery of soil water properties that favour biomass production. Further increases in biomass availability due to the implementation of natural regeneration measures and densification of native evergreen woody shrubs (NEWS) allow shifting towards a native evergreen woody shrubs mulch-based relay intercropping system (NEMRS).

degraded lands in SWA agroecosystems (Mando and Stroosnijder, 1999). Alternative organic resources supplied by native shrubs are locally used to mulch the soil and, in some places, these shrubs are completely integrated in ingenious relay intercropping systems. In such systems, the perennial native evergreen shrub provides facilitation to the annual crop. During the eight months-long dry season (October–May), the shrub cover reduces wind erosion and intercepts the dust which is an important source of fertility (Valentin et al., 2004). Nutrients concentrated under their canopies in the so-called "islands of fertility" are harvested by a crop that is sown more densely within the island. Both shrub species considered here, *P. reticulatum and G. senegalensis,* are able to re-sprout from a stump. While early shoots during the cereal cycle are weeded, late season shoots are allowed to grow during the dry season. Such simple yet knowledge intensive system has proven potential to contribute to soil restoration and resource conservation in SWA, as we showed here. We have also seen that aggradation can be achieved through implementing traditional soil and water conservation measures that proved effective in the Sahel.

The zai, particularly, allows the recovery of the degraded soil hydrophysical properties through triggering termite activity and facilitates the natural regeneration of native shrubs. The observed farmer practice of selecting and protecting seedlings grown naturally in their fields, often by zai-adopters, can be oriented towards a proactive densification of native shrubs. This may include sowing seeds in the zai pits or planting seedlings grown in nurseries which is valid for *P. reticulatum* or through amplifying the vegetative propagation which is valid for *G. senegalensis* (Bationo et al., 2005). This may accelerate the transition towards a higher system primary productivity, which is a pre-requisite for CA measures to succeed. Zai systems are particularly well adapted to smallholders conditions, as this allows (i) increasing production in the short term while restoring lands in the long term; (ii) to be implemented in small patches of land that can be gradually expanded; (iii) accommodating smallholders' strategies of concentration of scare resources such as animal manure. These reasons likely explain why zai has been adopted despite the labour and drudgery its implementation requires. Despite its claimed greening effect, zaï remains a complex system whose functioning and long-term impacts are not well understood. Tacking stock of the existing knowledge on the zai in SWA, Droux (2008) and Vohland and Barry (2009) concluded that the system has been insufficiently explored scientifically.

The shrub-based CA systems we aim to develop and fine tune for location specific targeting represent a clear example of ecological intensive agriculture, as they capitalize on ecological processes and local lay knowledge to support efficient resource use (Doré et al., 2011). The design and optimization of such systems is at the core of the EU-funded ABACO (Agroecology-Based Aggradation–COnservation agriculture – cf. www.act.org) project, which aims at targeting innovations to combat soil degradation in dry areas of West, East and Southern Africa. Rehabilitating degraded soils may require sustained efforts for long periods of time, and responses to interventions may be weak (cf. Fig. 1), deterring smallholders who generally prefer to invest labour and scarce resources in the fields that exhibit high and rapid responses (e.g., Tittonell et al., 2008). Approaches to aggradation–conservation agriculture should ensure short-term benefits to be attractive to smallholders. The shrub-based CA systems implemented on degraded – often abandoned – land allows producing crops from the onset, i.e. during the aggradative phase, while its performances may be increased and sustained during the conservation phase. In agro-pastoral systems, improved crop biomass production may also contribute larger amounts of crop residues to be traded off between soil mulching and livestock feeding, while pods of *P. reticulatum* represent high quality feed complements.

In West Africa, annual rainfall useful for crop is concentrated in a four month period (June–September), and the rainy period is not free from dry spells that continually challenge the decision on when to install a crop to minimise impact on crop production (Sultan and Janicot, 2004; Sultan et al., 2005). In such climatic context, the aggradation–conservation approach would limit the negative effect of rain shortage on crops and increase rainwater use efficiency. The NEMRS are very much in line with the evergreen agriculture approach that integrates trees into annual food crop systems (Garrity et al., 2010). A significant advantage of the shrub-based CA system is the production of organic resources needed for mulching in situ without competing with other crops, i.e. not immobilizing land for the sole purpose of biomass production, and without recurring to off-site organic resources, i.e. biomass and fertility transfers from the surroundings that may compromise ecological sustainability.

However, reluctance to adoption of shrub-based CA systems may also be met with due to the heavy load of labour during the aggradative phase, and possible slow and weak land responses to the investment according to the extent and type of soil degradation being faced. The conservation phase is normally less labour consuming. However, it is not free of challenges and tradeoffs as it imposes to adapt management to a new system. For example, the pruning–mulching operation may cause peaks of labour demand in years with early rains. Although the resources and the knowledge the approach mobilizes are local and can be easily shared, it is well known that knowledge-intensive systems such as CA need continuous refreshment, adjustment and adaptation, especially during the first years. Yet, the success of these systems requires a substantial scientific input into a better understanding and an appropriate use of the biodiversity processes and mediations, in order to increase resource use efficiency in the SWA's low external input farming. Conceptually, CA eliminated soil tillage as a source of accelerated soil degradation and adopted the mulch that, among other effects, meditates the faunal activity to ensure soil porosity for air and water, nutrient fluxes, root system expansion etc. Since CA cannot perform well in SWA degraded lands due to insufficient mulching material, paradoxically, a particular soil tillage practice such the zai may provide the same service as the mulch by trapping organic resources that trigger faunal activity. The aggradative phase of the system based on the zai (cf. Fig. 3) should be seen as an integral part of a CA strategy for the Sahel. Widening the CA concept and enlarging its body of knowledge may help improving SWA agriculture production while conserving soils, water and biodiversity.

6. Conclusion

CA is being promoted in semi-arid Africa as a technology to combat soil degradation, mitigate the effect of droughts and increase crop productivity of rainfed agriculture while reducing production costs. The utmost aspect of CA for degraded lands in SWA would be the mulch which proved to be efficient to aggradate degraded bare lands with crusted soil through rehabilitating soil hydrophysical properties and improving soil fertility. The subsequent increase of rainwater use efficiency results in improved land primary production. Application of classical CA is however challenged in SWA by the scarcity of organic resources at farm level due to poor crop biomass production and the competition for the use of crop residues, mainly as fodder. Alternative CA systems integrating native evergreen woody shrubs (NEWS) (*P. reticulatum and G. senegalensis*) in a relay intercropping system (NEMRS) seems promising. The shrub accumulates soil fertility, provides material for mulching and facilitates water supply to the associated crop. Implementing such management system may be time and labour consuming, and should be seen as a phase of an aggradation–conservation agriculture approach. Starting by the rehabilitation of soil degraded properties using native water harvesting methods such as the zai, and then increasing primary productivity through facilitating the propagation of the NEWS using traditional natural regeneration measures. NERMS rely on the local Sahelian resources and knowledge, and they are likely to meet smallholders' acceptance in SWA as they respond to their mid-term expectations. However, as any innovative system, they are not free from challenges and tradeoffs and call for a substantial research input for their development, fine-tuning and, further improvements.

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