Agroforestry and soil productivity in the West African Sahel

Mike McGahuey

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“Trees in Sahelian farmlands make a significant impact by adding soil organic matter and providing other services.”

Introduction

Sahelian farmers are among the world’s poorest. In Niger, for example, smallholders produced an average of only 318 kg of cereals per hectare (ha) from a mean farm size of 2.17 ha, while supporting households of 12 people (Binam et al. 2015). Much of this low productivity is explained by poor soils, small farm sizes, loss of traditional soil restoration systems, and erratic rainfall (Bationo et al. 1998). On the positive side, researchers, practitioners and farmers have made progress in developing approaches to restoring soils, reducing vulnerability to climate shocks and building a foundation for greater productivity.

Key challenges

Increasing soil productivity and reducing vulnerability requires overcoming a complex web of challenges.

Weathered soils: Africa has some of the world’s oldest, most weathered soils; only 10% still have nutrient-rich sediments (Breman et al. 2007). In Sahelian West Africa, 95% of soils are sandy and nutrient poor. Crucially, they are also low in soil organic matter (SOM), which is important for the soils’ structural integrity and in the capacity to retain moisture and nutrients in the crops’ root zone (Bationo et al. 2005).

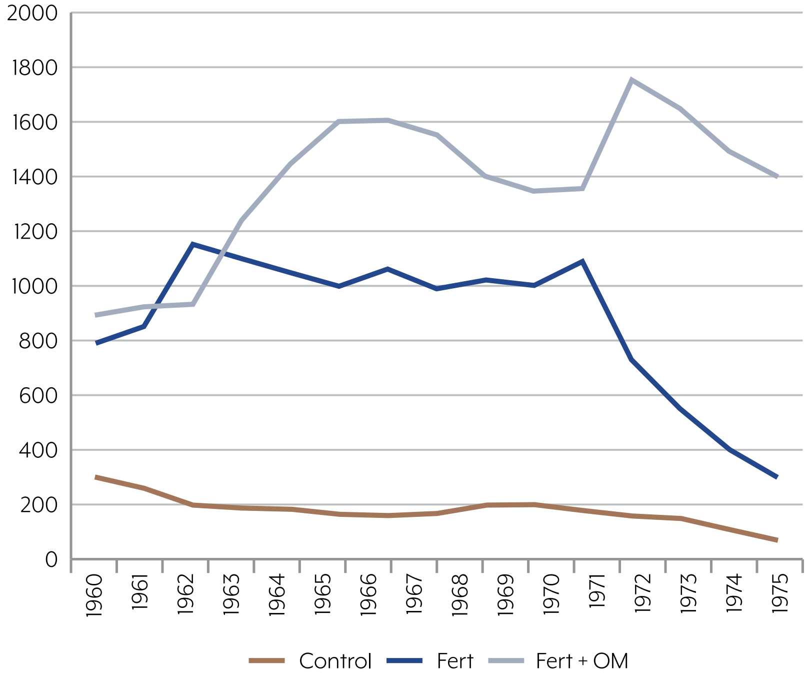
An erratic and dynamic climate: Intensive rainfall events pulverize weakly-structured soils, forming crusts with high runoff rates. Dry periods of one week or more weaken or kill newly germinated crops, which then require re-sowing. This shortens the growing season, especially in sandy soils that lack the capacity to retain moisture in the root zone. Consequently, rainfall-use efficiency is very low, with only 15–20% of rainfall used for productive crop growth (Kablan et al. 2008).

High population pressure and loss of fallow: Up until the 1960s, many farmers restored soil productivity by fallowing 2 to 3 hectares for every hectare they cultivated (Jones and Wild 1975). These long fallows, which lasted 5 to 15 years, allowed trees to cycle nutrients from deep soil horizons to the topsoil, reduced erosion, and produced large amounts of biomass that became soil organic matter (SOM). The regenerated trees and shrubs produced wood fuel, fruit and condiments, pharmaceuticals, high-quality animal browse, and construction materials. In years of crop failure these products provided revenue to purchase food. However, since the 1970s, population pressure has forced most farmers to reduce or abandon fallows (Wopereis et al. 2005), weakening their ability to restore soil productivity.

Periodic catastrophic droughts: In the 1970s and early 1980s, recurring droughts coincided with the loss of fallows that had previously served as safety nets during crop failures. Smallholders were forced to sell productive assets and seek paid work to buy food. Food aid became a ubiquitous part of rural life.

Clearing trees: To replace extended fallows as a means to restore soil productivity, Senegal initiated a fertilizer programme, removing field trees to allow easier passage by ploughs. However, these trees had been a part of traditional agroforestry systems that were documented to increase soil productivity by increasing soil organic matter and cycling nutrients (Charreau and Vidal 1965). Fertilizer applications initially increased yields, but the yield response and fertilizer use eventually declined, even with subsidies (Dancette and Sarr 1985). Lack of attention to soil organic matter reduced the efficiency and cost-effectiveness of fertilizers.

Figure 1: Annual sorghum yield responses (in kg) to fertilizer alone (Fert) and fertilizer with annual application of 5 tonnes of organic matter (Fert + OM) at the Saria Research Station, Burkina Faso, 1960–75 Source: Pieri (1989).



Soil organic matter and fertilizer-use efficiency

Long-term research initiated in 1960 at the Saria research station in Burkina Faso tracked yield responses on sandy soils. Figure 1 shows sorghum yields over 15 years, with annual applications of fertilizer plus 5 tonnes of biomass compared to fertilizer application alone, with crop residues annually removed (Pieri 1989). Both approaches produced positive responses in the first three years, but after year four, the yield response to fertilizer alone began to decline while the yield response to fertilizer and biomass continued to increase until reaching 1.4–1.8 t/ha. The FERT yield leveled off over the next eight years and then declined sharply, resembling the response in the Senegal fertilizer initiative discussed above; by the 16th year it was not much higher than the control.

Research was carried out on the impact of soil organic matter (SOM) on fertilizer-use efficiency in northern Togo. It found that over three years, an average of 41% of applied nitrogen was taken up by the crop on SOM-rich soils, while only 33% was taken up on SOM-poor fields, the difference being greatest in a low rainfall year (Wopereis et al. 2006). In a three-year trial in Niger, researchers found that without fertilizer, millet grain yields on SOM-poor fields were only 150–180 kg/ha, compared to 490–570 kg/ha on SOM-rich fields. Following fertilizer applications, the yields increased to 1,220 and 1,940 kg/ha, respectively, with every kg of nitrogen producing an extra 35 kg of millet grain per ha on the SOM-poor fields, and an extra 47 kg on the SOM-rich fields (Breman et al. 2007).

These experiments demonstrated that soil organic matter had a positive effect on fertilizer-use efficiency and yields, particularly on sandy soils, and by extension, that declining responses to fertilizer in Senegal were related to declining SOM. As Wopereis et al. (2005) observed, the best yields are usually obtained where treatments combine inorganic and organic inputs, with inorganic sources providing necessary nutrients and organic sources helping to increase water retention, strengthen soil structure and increase cation-exchange capacity. Cation-exchange capacity (CEC) is a measure of a soil's capacity to retain critical nutrients; this capacity is highest in organic soils, lowest in sandy soils and intermediate in clays.

Early millet under the crown of *Faidherbia albida* in Senegal.
Photo: Gray Tappan

The critical role of humus

Most of SOM's benefits come from humus, the relatively stable organic matter that is left behind after the decomposition by microbiota of SOM's more easily converted substances (Ahn 1970). The properties of humus are particularly important for sandy soils, and directly address key challenges faced by smallholders. Humus is "sticky," coating soil particles and binding them together to form crumbs. This is particularly important in stabilizing soil structure and resisting crusting, which affects infiltration and moisture retention in the root zone. Humus holds many times its own weight in water, making it very effective in retaining soil moisture, particularly in sandy soils during extended dry periods. Humus also has a high capacity to retain nutrients and accounts for much, if not most, of a sandy soil's cation-exchange capacity. This explains the high correlation between the SOM content of sandy soils and their fertilizer-use efficiency. Although humus is relatively stable, it is ultimately broken down by soil microbiota, thereby acting as a slow-release source of nutrients.

Increased levels of humus in the soil explain the FERT+OM curve in Figure 1. With the annual addition of biomass, the SOM level was built up over the first several years. This increased CEC and nutrient-retention capacity, increased moisture retention in the root zone and strengthened soil structure. The latter two benefits increased rainfall-use efficiency. In order to receive continued benefits from humus, adequate SOM levels must be maintained through regular applications of biomass. If not, reductions in the amount of humus may lead to spectacular decline in soil productivity (Ahn 1970), as was seen in the fertilizer-only treatment in Figure 1.

Providing soils with sufficient biomass to maintain effective SOM levels is a challenge. The loss of fallows removed a major source of biomass, and crop residue has many competing uses for fodder, construction and cooking (Bationo et al. 2005). However, agroforestry systems have a proven record in providing large quantities of biomass as well as other services.

Agroforestry systems for biomass and diversification

Research on agroforestry systems shows that they provide services similar to those of extended fallows, including annual supply of the biomass

Fuelwood for sale in Niger. Photo: Chris Reij

necessary for building and maintaining SOM levels. They also provide marketable tree products that reduce smallholder vulnerability to droughts and other shocks. Two agroforestry systems are important in the Sahel: the traditional *Faidherbia albida* system, and farmer managed natural regeneration, which was introduced in Niger in the mid-1980s.

The *Faidherbia albida* system

Faidherbia albida is a nitrogen-fixing legume. It is the foundation of agroforestry systems across the Sahel and is known to farmers as a multipurpose "fertilizer" tree. It also has the unusual feature of dropping its leaves just prior to the rainy season, providing an ample supply of biomass at precisely the right time; it remains without foliage during the growing season. Felker (1976) summarized three studies in Senegal on the tree's effects on soil characteristics and yields. Compared to soils outside the tree's crown, soils under the canopy had 100% more soil organic matter and higher levels of key nutrients (nitrogen, phosphorus, potassium and sulphur), soil moisture and microbiota (which are important for breaking down complex compounds so that plants can assimilate them). In addition, the partial shade provided by the trees reduced soil temperatures at critical times during crop growth. These factors resulted in grain yields under the tree's crown averaging 900 kg/ha versus 500 kg/ha away from trees. The early advantages to grain crops are particularly important in years of poor rainfall.

Humus content under trees was 1.21% versus 0.85% away from trees, and CEC was significantly greater at 42.7 me/kg versus 33.4 me/kg (Charreau and Vidal 1965). This could be attributed to the annual production of dry organic matter of 5,350 kg/ha and 11,580 kg/ha, with densities of 20 and 44 mature trees per ha, respectively (Charreau 1974). Note that these quantities exceeded the amount of biomass applied in the FERT+OM treatment in Burkina Faso.

Beyond improving soil productivity, *F. albida* leaves and pods are also a nutritious and economically important browse. During the long dry season, browse makes up to 85%, 50% and 23% of food for goats, sheep and cattle respectively (Fall et al. 2002). *F. albida* pods are particularly sought after due to their high protein content. At a density of 44 mature trees per hectare, *F. albida* produce 175 kg of pods per hectare per year. In years of crop

Faidherbia albida pods, a sought-after livestock feed marketed or used domestically. Photo: Gray Tappan.

failure, the sale of these pods helps households purchase food and other necessities.

Farmer managed natural regeneration

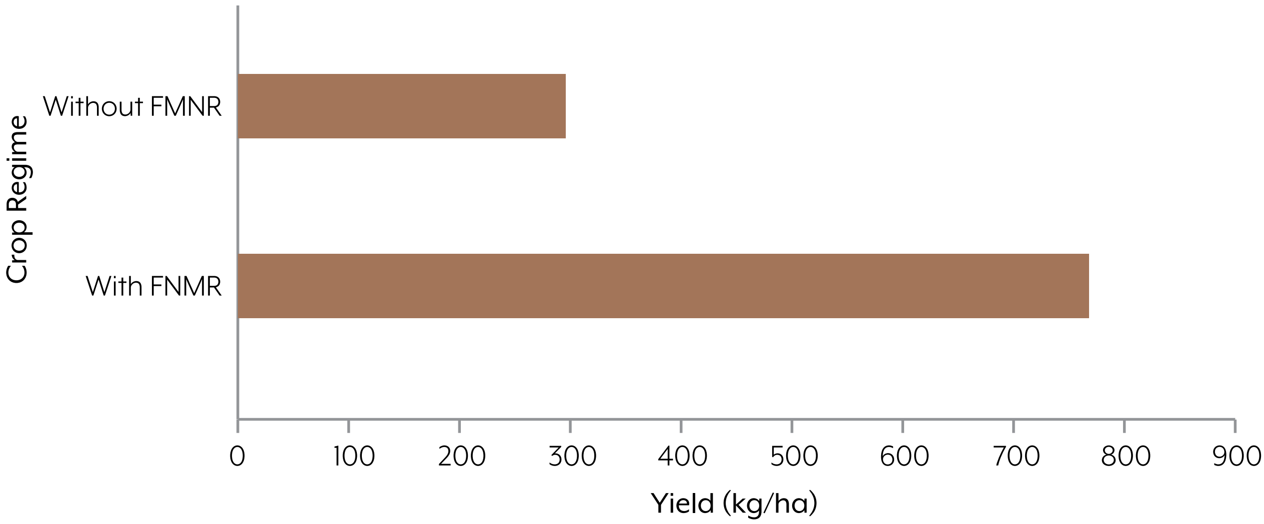
Farmer managed natural regeneration (FMNR) is an agroforestry system whereby farmers manage trees that they allow to regenerate naturally in their fields. This has positive impacts on soil productivity and vulnerability to shocks. As with *F. albida* systems, FMNR trees mine deeper soil horizons for nutrients and cycle them back to the topsoil. They provide biomass that eventually becomes SOM, and provide products such as fuelwood, browse and foods that are consumed or generate revenue. Trees are pruned back to a few healthy stems just prior to the rainy season. The larger stems and pruned branches are used for wood fuel. Leaf-bearing branches are stripped of their leaves and left on the soil, with branches subsequently used for kindling or fencing. Given that FMNR was initiated and extended in a region with little fallow, it has essentially replaced traditional extended fallows as a means to restore soil productivity.

Improved crop yields are the best proxy for FMNR's impact on soil productivity, such as an almost threefold increase in Senegal from about 300 kg/ha to nearly 800 kg/ha (Figure 2). In addition to increasing yields, FMNR produces fuel, high-quality browse, construction material, marketable fruits, and other products that are less vulnerable to climate and other shocks than annual crops. During a drought in 2004, FMNR farmers generated revenue to purchase food from firewood sales and were less dependent on food aid than non-FMNR farmers were (Abdoulaye and Ibro 2006).

Conclusions

Over the past 60 years, many Sahelian smallholders lost their fallow-based soil restoration systems, which also served as a critical safety net during crop failures and other shocks. Population pressure led to smaller farm sizes and expansion into more marginal land. Recurring droughts forced many people to sell productive assets and seek off-farm work to feed their families. In response, millions of farmers adopted forms of agroforestry to restore soil productivity and reduce vulnerability. These efforts have doubled and even tripled agricultural yields on poor sandy soils. However, meeting the ongoing and worsening challenges of population growth, erratic climate and

Figure 2. Grain yields on fields with and without FMNR. Source: Beysatol project activity report, October/December 2010, with research conducted by the Senegalese Agricultural Research Institute (ISRA) and World Vision International.



weathered soils requires that smallholders double or triple those yields once again.

Producing the yields necessary to meet the above challenges is likely to be beyond the ability of agroforestry systems by themselves. Inorganic inputs will also be required, but in the Sahel's weathered and sandy soils, fertilizer-use efficiency will have to increase significantly for those inputs to be economically effective. Agroforestry systems can deliver substantial quantities of biomass to soils at the right time and in the right place, thereby increasing SOM and CEC, improving soil structure and improving both nutrient and rainfall-use efficiencies. In addition, livestock feed, fuel, poles and fruit generate income that smallholders can use to improve livelihoods and reduce farmers' vulnerabilities to climatic and other shocks.

The evidence shows that improving soil productivity and yields is possible by incorporating fertilizer into more intensive agroforestry systems. But, most work in agroforestry and inorganic fertilizers has moved on two separate tracks. Given the high potential for each to complement the other in increasing soil productivity in the Sahel, it is time for researchers, practitioners and farmers to work together to exploit that potential for the benefit of the Sahel's rural poor.

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Cover photo: Women transporting woodfuel to the market. In addition to increasing soil productivity, agroforestry systems produce marketable products that increase and diversify household incomes.
Photo: Gray Tappan

ETFRN
c/o Tropenbos International
P .O. Box 232,
6700 AE Wageningen,
the Netherlands
etfrn@etfrn.org
www.etfrn.org