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Biological Restoration of a Degraded Alfisol in the Humid Tropics Using Planted Woody Fallow: Synthesis of 8-Year-Results

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ABSTRACT

A case study was initiated in 1989 in Ibadan, Southwest Nigeria to evaluate the feasibility of using planted woody fallow (species: *Senna siamea*, *Leucaena leucocephala*, and *Acacia leptocarpa*) to restore productivity of a degraded Alfisol. The results, which have been reported in several peer-reviewed journals, are synthesized here to determine some indicators for evaluating the potential of planted woody fallow in soil regeneration in the humid tropics and evaluate comparative advantages of selected species in serving our objectives. After six years, woody fallow produced 87 - 157 t dry matter ha^{-1} with about 10 t ha^{-1} of annual litterfall. *Senna* produced 16.7 times more biomass than natural fallow and 80% higher biomass than other woody species. The pronounced change in soil microbiological quality was microbial biomass and alkaline phosphatase. Planted fallow, especially *Senna*, appeared to be superior to natural fallow in restoring the above two microbiological parameters. Levels of earthworm number reached those observed in adjacent secondary forest and in the region's non-degraded Alfisol. Increased population of soil microarthropods with planted fallow correlated with lignin concentration in litterfall. From 1989 to 1996, soil organic C was increased at a rate from 259 (natural fallow) to 680 (*Leucaena*) kg ha^{-1} under fallow as compared to a loss of 371 kg ha^{-1} under the continuous cropping. Potentially mineralizable N was increased from 41 kg ha^{-1} in continuous cropping to 176 under *Acacia* fallow. The Olsen P was 8.6 kg ha^{-1} in the continuous cropping and ranged from 14.1 kg ha^{-1} (natural fallow) to 29.2 kg ha^{-1} (*Leucaena* fallow). The improvement in soil physical quality came after the biological and chemical ones and the capacities of fallows in improving soil physical quality are not different between planted and natural fallows. Our synthesis of our 8-year observations on the performance of selected wood species in soil regeneration indicated all three species are promising and the choice of each species will depend on the target of soil restoration.

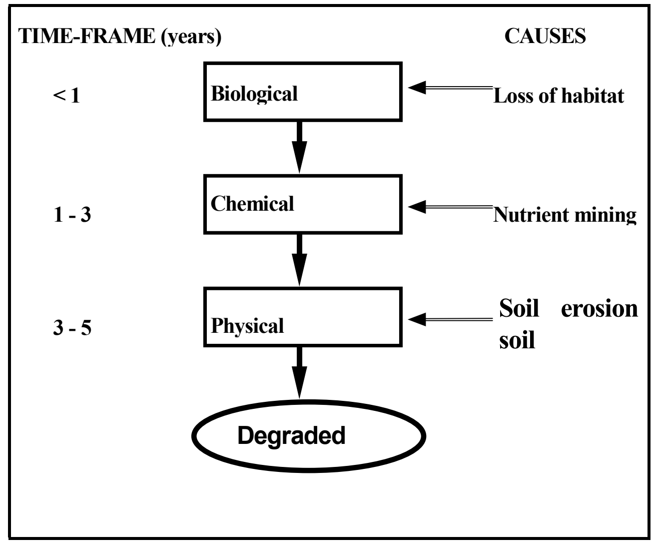

Figure 1. A conceptual model illustrating soil fertility decline/soil degradation with cultivation on a virgin land in the humid and subhumid tropics of Africa.

INTRODUCTION

Soil degradation is a process that lowers the current and/or potential productivity of soil, and can be divided into three integrative groups, i.e. biological, chemical and physical degradation (Fig. 1). Conversion of natural to agricultural systems may cause drastic changes in the environment for the soil biota. The buffer provided by dense vegetation against fluctuations in microclimate is lost with land clearing, resulting in large extremes in soil temperature and moisture conditions. A change from natural vegetation to annual crops often decreases organic matter input. In Nigeria, Critchley et al. (1979) observed that in the cultivated area at 10 cm depth the diurnal temperature ranged between 26-32 °C, compared to the bush fallow where the temperature at the same depth was almost constant at 25 °C over the four days of measurement. The bush fallow showed consistently higher soil moisture content than the cultivated area throughout the year. As a result, a lower activity of the majority of the surface soil fauna was observed in the cultivated compared to the bush area.

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Raindrops on exposed soils and human, animal and mechanical traffic cause soil compaction. Rainfall impact results in breakdown of surface soil aggregates leading to the formation of surface seals. Soil compaction and surface seals both reduce infiltration rate, which in turn increases water runoff and soil erosion during the high intensity rainstorms that characterize the region (Lal, 1987). The soil organic matter (SOM) in low activity clay (LAC) soils in the tropics declined rapidly under continuous cropping (Kang, 1993). Associated with loss of SOM is decrease in available N, P and exchangeable cations, Smaling et al. (1996) pointed out that most agricultural systems in sub-Saharan Africa can be labeled nonsustainable due to low nutrient resources and negative nutrient budgets.

Vegetative fallow is a biological approach to regenerating the productivity of degraded soils in the tropics. During the fallow period, plant nutrients are taken up from various soil depths and stored in the fallow vegetation (Nye and Greenland, 1960). The nutrients depleted are replenished with those from fallow vegetation. The litter-fall from the fallow vegetation increases the soil organic matter content. The residues or canopy from fallow vegetation enhances soil biological activity. Increases in soil organic matter and the biological activity would ameliorate the soil compaction and improve soil structure. Traditionally, farmers in the humid tropics use fallow with natural vegetation (natural fallow) mainly shrub species - *Chromolaena odorata* for soil regeneration. Over the years, researchers have emphasized the use of planted vegetation (woody and herbaceous) to replace natural vegetation (Kang et al., 1997), aiming at shortening the fallow period. Woody fallow with a deeper rooting system could effectively pump nutrients from the sub-soil depths. Planted woody fallow often has high biomass production, resulting in high nutrient yield from vegetation. Additional benefits from planted woody fallow are timber and fuel-wood, which can generate income for farmers. On the other hand, a large proportion of biomass from planted woody fallow (72 to 95%, Salako and Tian, 2001) is partitioned into wood. This might cause nutrient depletion and be contrary to the objective of soil regeneration. To better understand the potential of planted woody fallow in soil regeneration, the effect of the planted fallow on soil quality needs to be established.

This paper synthesizes results from a case study at the International Institute of Tropical Agriculture (IITA) main campus, Ibadan (7º 3º 'N, 3º 54 'E), Nigeria, on the rehabilitation of the degraded Alfisol under the planted woody fallow, for illustrating the potential of planted woody fallow in restoring soil quality in the humid tropics.

RESEARCH APPROACHES

The soil (Oxic Paleustalf) was severely degraded due to depletion of SOM and nutrients, loss of soil biota, soil erosion, and compaction during land clearing and 10 years cultivation (Table 1). The woody species planted in 1989 on a slope of 8-10% for soil regeneration experiment included *Acacia leptocarpa*, *Senna siamea* and *Leucaena leucocephala*. Natural regrowth vegetation dominated by *Chromolaena odorata* and continuous cropping with maize (*Zea mays*) /cassava (*Manihot esculenta*) were also included in the study. The mean annual rainfall of the experimental site is 1250 mm with a bimodal distribution. The site is located in the forest-savanna transition zone. The surface soil texture is sandy loam and subsoil texture is sandy clay or clay (Moormann et al., 1975). The rainy season is from March to November with a short break in August. For more detail in experiment set-up and maintenance, refer to Salako and Tian (2001). Biomass production of planted woody fallow (87 - 157 t dry matter ha^{-1}) was far higher than the natural fallow (9.4 t ha^{-1}) as shown in Table 2. *Senna* produced 80% higher biomass than other three woody species (Table 2). The litter-fall was on average 10.4 t ha^{-1} for planted fallow with little variation among species and 13.6 t ha^{-1} for natural fallow (Salako and Tian, 2001).

Microbial biomass and enzyme determinations were done in 1993 by Wick et al. (1998). Acid and alkaline phosphatase and β-glucosidase activity were measured according to Tabatabai and Bremner (1969) and Eivazi and

Table 1: The land use history of experimental plots (Sources: Lal and Couper, 1990).

Year	Watershed A	Watershed B
1963-1978	Bush fallow	Bush fallow
1978	Treepusher/rootrake clearing	Manual clearing
1978-1982	Conventional tillage, maize/cassava intercrop (1979), maize followed by cowpea (1980-82)	No-tillage, maize/cassava intercrop (1979), maize followed by cowpea (1980-82)
1983	Maize followed by *Mucuna*	Maize followed by *Mucuna*
1984-85	Maize followed by cowpea	Maize followed by cowpea
1986	Maize followed by cowpea	*Mucuna*
1987-1988	*Mucuna*	Maize followed by cowpea

Table 2 Biomass production (t ha^{-1}) of 6-year-old planted woody fallow on a degraded Alfisol in southwestern Nigeria (Salako and Tian, 2001).

	Leaves/twigs	Branches/stems	Undergrowth	Total
Natural fallow†				9.4
S. Siamea	11	145	1.4	157
L. leucaephala	4	80	5.0	89
A. leptocarpa	12	71	3.7	87

†No partitioning was done for the natural fallow.

Tabatabai (1988). Protease (casein-hydrolyzing) activity of the soil was determined according to Ladd and Butler (1972). Microbial biomass carbon was determined by the chloroform-fumigation-extraction method for biomass ninhydrin-N after pre-extraction of roots. Earthworms were sampled during 1994-1995 by Tian et al. (2000) using a hand sorting method (Anderson and Ingram, 1993). Soil microarthropods was sampled during 1996-1997 by Adejuyigbe et al. (1999) using a core sampler and extracted using Tullgren-type extractor (Crossley and Blair, 1991). Bulk density and penetrometer resistance was measured in 1996 by Salako et al (2000). using core samplers and pocket penetrometers (Bradford, 1986). Soil organic carbon, potentially mineralizable N and available P in surface was determined by Tian et al (2001) using samples collected in 1996. Soil organic C (SOC) was determined by the wet combustion method (Nelson and Sommers, 1975). Potentially mineralizable N (PMN) was measured using anaerobic incubation, based on Waring and Bremner (1964). The soil available P was measured using the Olsen method (Olsen and Sommers, 1982).

Impact of Planted Fallows on Soil Quality

Biological quality

The microbial biomass is part of the active soil organic matter pool, and had been proposed as an indicator of the state and change of total soil organic matter. Acid and alkaline phosphatases catalyze the hydrolysis of P-ester bonds from organic matter with subsequent release inorganic P. β-glucosidase belongs to a group of enzymes that catalyze the hydrolytic conversion of cellulose to glucose. Soil proteases reflect protein degradation capacity. The fallow, especially planted fallow *Senna* improved microbial biomass (Table 3). All enzymes tested had higher values under the fallow than the continuous cropping control, however, fallow effect on the enzyme activity was only significant in case of alkaline phosphatase. *Leucaena* and *Senna* improved the activity of alkaline phosphatase even more than the natural fallow (Table 3).

Earthworms contribute to soil restoration by casting, burrowing and perturbation and participating in the organic matter decomposition (Tian et al., 2000). In the study, both natural and planted fallows caused a significant increase in earthworm population (Table 3). The earthworm population levels in the planted woody and natural fallow reached those observed in nearby secondary forest (Tian, 1998). This indicated that both planted and natural fallow could restore the population of earthworms in a relatively short period. The restorative effect of planted woody fallow on earthworm population was mainly due to higher litter input, lower temperature, and higher soil moisture under the fallows, as compared to maize/cassava cropping (Tian et al., 2000). The question, which still needs to be answered is how long the improved earthworm population can be maintained when the plot is again cultivated.

Soil microarthropods, comprised of soil mites (*Acari*) and springtails (*Collembola*) with body-width between 0.08 mm and 0.5 mm, have a "buffering effect" on leaf decomposition and N release in the humid tropics (Tian et al., 1998). Population density and composition of the soil fauna in soil is an indicator of soil condition (Haq, 1994). Adejuyigbe et al. (1999) monitored soil microarthropods under natural and planted fallow, and maize/cassava. During the 1996 rainy season (May to October), populations were greater under natural fallow than under maize/cassava (Table 3). Soil microarthropod populations were positively correlated with lignin contents of leaf litter and soil moisture content (Adejuyigbe et al., 1999).

Chemical quality

The role of SOM in maintaining the productivity of agricultural systems includes supplying soil nutrients, increasing cation exchange capacity, improving soil structure and maintaining soil biological activity. The contribution of SOM to soil productivity is particularly important in LAC Alfisols of tropical Africa, as SOM accounts for a major portion of the ECEC in the surface horizon of LAC Alfisols (Juo and Adams, 1986), thus contributing to the soil fertility. Fallow might be the only practical approach to replenishing SOM, as it cannot be replenished under cultivation due to the fast oxidation rate (Giller et al., 1997).

Soil organic carbon levels were improved with both natural and planted fallow (Table 4). Increase in soil organic matter due to fallow was higher from *Leucaena* than the natural fallow, though not statistically significant. Kang et al. (1994) observed higher total soil C content under 10 years of plantation trees compared to fallow grass in Nigeria. The differences were more pronounced in Alfisol than Ultisol. The potentially mineralizable N (PMN), an indicator of labile SOM pool and soil available N, was higher under planted woody fallows than natural fallow (Table 4).

Table 3. Effect of natural and planted fallows on microbiological parameters at 0-5 cm in 1993 (Wick et al., 1998), earthworm population at 0 -30 cm depth in 1994 (Tian et al., 2000), and soil microarthropod population at 0 - 6 cm depth in 1996 (Adejuyigbe et al., 1999) of a degraded Alfisol during the wet months in southwestern Nigeria.

Treatment	Microbial C (μg g^{-1})	Alkaline phosphatase (μg g^{-1} h^{-1})	Acid phosphatase (μg g^{-1} h^{-1})	β-glucosidase (μg g^{-1} h^{-1})	Protease (μg g^{-1} h^{-1})	Earthworms (no. m^{-2})	Micro-arthropods (x1000 m^{-2})
Maize/cassava	58a	102a	273a	31a	131a	58a	22a
Natural fallow	103ab	152ab	351a	41a	151a	194b	31bc
L. leucocephala	122b	254b	324a	68a	194a	118b	32ab
A. leptocarpa	ND	ND	ND	ND	ND	100b	42c
S. siamea	144b	268b	282a	65a	171a	142b	43c

Values in a column followed by the same letter are not significantly different at $P = 0.05$.
ND: not determined

Many studies have found little or no benefit of trees on extractable inorganic soil P, with some reported the decreases, presumably because of P sequestration in tree biomass (Haggar et al., 1991). Drechsel et al. (1991) observed a decrease in topsoil P for 5-yr fallows of *S. siamea*, *Albizia lebbek*, *Acacia auriculiformis* and *A. indica* in central Togo, as compared to non-afforested soils. On the other hand, tree roots may change soil pH of the rhizosphere by releasing exudates, resulting in a changed P supply (Barber, 1995). Many tree species in the tropics form associations with ectomycorrhizal or vesicular-arbuscular mycorrhizal fungi (Mason and Wilson 1994), enhancing P uptake by the tree through the extensive proliferation of mycorrhizal hyphae. Mycorrhizal fungi may also increase the availability of soil P through production of phosphatase enzymes and the release of organic acids (Bolan, 1991; Handreck, 1997). Four years after planting woody species, there was no change in extractable P at the 0-15 cm soil depth in plots of woody fallows (Kang et al., 1997). However, extractable P in the surface soil was higher under 6-year-old planted fallows as compared to maize/cassava continuous cropping and the natural fallow (Table 4). The pronounced effect was observed with two *Leucaena*.

Table 4 Amounts of soil organic matter, potentially mineralizable N (PMN) and available P within 0-15 cm depth of a degraded Alfisol in 1995 under planted and natural fallow and maize cassava in southwestern Nigeria (Data derived from Tian et al., 2001).

	SOC	PMN	Available P
	---------- (kg ha^{-1}) ----------		
Maize/cassava	19087 a	41 a	8.6 a
Natural fallow	23496 ab	100 ab	14.1 a
S. Siamea	24520 b	111 bc	24.2 bc
L. leucocephala	26444 b	159 bc	29.2 c
A. leptocarpa	23521 ab	175 c	20.9 b

Physical quality

Unlike after 4 years of woody fallows (Kang et al., 1997), there was greater improvement in the soil physical properties after 6 years of planted woody fallow. Surface soil bulk density under 6-year old fallows was 13 - 18% lower than that under maize/cassava (Table 5). The soil bulk density was close to the value in the non-degredated soil. (Tian, 1998). The decrease in soil penetrometer resistance by the natural and planted fallow was 71% and 51%, respectively (Table 5). Natural and planted fallow both have the same capacity to reduce soil bulk density and penetrometer resistance. Two-year fallow with *S. sesban* could decrease soil bulk density and penetration resistance of an Alfisol in eastern Zambia (Torquebiau and Kwesiga, 1996). Lal (1989ab) compared contour hedgerows of *L. leucocephala* and *Gliricidia sepium* with plow-till and no till on an Alfisol in Western Nigeria. He found that soil bulk density and penetrometer resistance was lower for the agroforestry base. Apart from the root activity, high earthworm populations under trees partially accounted for the reductions.

Table 5 Bulk density and penetrometer residence within 0-10 cm depth of a degraded Alfisol under natural and planted fallow and maize cassava in 1996 in southwestern Nigeria (Salako et al., 2001).

	Bulk density ($t\ m^{-3}$)	Penetrometer resistance (kPa)
Maize/cassava	1.42 b	295 b
Natural fallow	1.18 a	85 a
S. Siamea	1.23 a	ND†
L. leucocephala	1.21 a	145 a
A. leptocarpa	1.17 a	ND

ND: not determined.

CONCLUDING REMARKS

After 6 years, a planted fallow could be as efficient as the natural fallow in restoring soil biological, chemical and physical properties of a degraded Alfisol, even while accumulating more biomass and nutrients in the wood. Planted fallows were even superior to the natural fallow in improving some biological and chemical quality indicators. *Senna,* greatest biomass producer, seems to be good for improving soil biological quality, *Leucaena* good for SOM build-up, and *Acacia* good for short term N accumulation. The improvement in soil physical quality was slower than the biological and physical quality. Longer term monitoring on the resilience of the degraded Alfisol under fallow will be necessary to determine the optimum time frame of soil regeneration with planted fallows.

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