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A Study of Methods for the Revegetation of Barren Crusted Sahelian Forest Soils

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Abstract

In a study on revegetation of barren crusted Sahelian forest soils, the following treatments: tillage (T), mulching with tree branches (M), and tillage followed by mulching (TM) were tested. Half the study area was exposed to grazing. No fertilizers or seeds were used. During the first rainy season (1983, rainfall 550 mm), winds and water-deposited sand left seed in the plots, particularly those with a mulch. After four months the TM-treatment area had an average dry matter stand equal to that found in naturally vegetated areas of the adjacent forest. Plots established in 1984 produced one-tenth the dry matter that the 1983 plots produced in their first year. The one-year-old TM plots produced five times more dry matter during the droughty 1984 season than did plots established in that season. The T treatment area lost and the M treatment area gained in relative dry matter production in the second year. By the third year, the T treatment lost most of its effectiveness. Plots exposed to grazing produced less biomass, partially due to the dispersal of branches by passing animals. Separate tests showed that natural areas of sand accumulation and termite activity decrease runoff rates. Mulch was shown to decrease and stabilize soil temperatures while permitting water to move deeper into crusted soil than even the tillage treatment. These effects help create a microenvironment that supports plant growth.

Résumé

Etude des méthodes de régénération des sols dégradés des forêts sahéliennes : *Quatre traitements, travail du sol (T), paillage (M) au moyen de branchettess, ou travail suivi de paillage (TM) ont été appliqués à des sol superficiels et encroûtés des forêts sahéliennes. La moitié des parcelles a été exposée aux animaux et aucun apport d'engrais ou de semences ne fut réalisé. Lors de la première saison des pluies (1983, 550 mm de pluie), le vent et le ruissellement apportèrent des semences dans les parcelles particulièrement celles paillées. Au terme des quatre mois on notait dans le traitement TM une biomasse moyenne égale à celle des zones naturelles de la zone adjacente boisée. La production de la biomasse des parcelles établies en 1984 fut dix fois moindre que celle de première année des parcelles établies en 1983. Cela est dû à la sécheresse de 1984, cependant les traitements TM et M conservèrent leur avantage. Si en première année, l'effet du travail du sol semblait proéminent quant à la conservation de l'eau du sol, en seconde année l'effet du paillis fut supérieur, et en troisème année l'effet du travail du sol était pratiquement nul à cet égard. Là où le broutage était permis, la production de la biomasse fut nettement moindre, principalement à cause de l'éparpillement des branchettes par les animaux. Des essais annexes ont montré que là où le sable s'est accumulé naturellement et où les*

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termites sont actives, le ruissellement était moindre. Le paillage diminue et stabilise les températures du sol tout en favorisant l'infiltration dans les sols encroûtés plus que dans le traitement T. Tous ces résultats positifs proviennent de la création d'un microenvironnement favorable à la croissance végétale.

Introduction

The population in the Sahel is growing rapidly. As farmers, herders, and city dwellers compete for forest products (Boudet 1970), the forests become overexploited (Grainger 1982, Weinstabel and Zech 1982). According to Delwaulle and Roederer (1973), city dwellers consume an average of 300 kg of firewood per person a^{-1} resulting in severe pressure on nearby forests. The deterioration of forestland owing to clearing, overgrazing, drought, and erosion is a major cause of desertification in the Sahel (Timberlake 1985, National Research Council 1983a and 1983b, Grainger 1982).

Aerial photographs indicate that 35–65% of the vegetation in the area selected for the present study has been lost during the last 34 years. Policymakers have recognized the need to maintain forest vegetation and reclaim degraded forestland. Since the drought of 1968–74, U.S. $160 million have been spent on forest-related projects in the Sahel (National Research Council 1984). However, application of reforestation techniques borrowed from temperate zones have either failed or have been economically impractical (Heermans 1984).

Practical and effective means must be evolved to reestablish a stable vegetative cover in degraded areas. Previous research has shown that soil tillage encourages the establishment of a herbaceous layer in sandy soils without seed or fertilizer application, but the treated areas routinely return to bare soil within a few years (Toutain 1977, Toutain and de Wespelaere 1977, Toutain and Piot 1980). Mulch, when placed on crusted soil surfaces in the tropics, often attracts termites whose channels provide stable macropores through which water can pass into the subsoil (Noirot and Alliot 1947, Bachelier 1978). Casual observations demonstrate that fallen branches and twigs tend to accumulate sediments, leaves, and seeds, creating a favorable microclimate for vegetative growth (Boudet 1972, Toutain and de Wespelaere 1977, Toutain and Piot 1980). The authors cited, however,conducted no experiments to study these effects. The value of mulching bare, deep sandy soils with tree limbs cut and transported to the site and of tillage with fertilizer application was studied in Mali (Penning de Vries and Djiteye 1982). Although both methods were successful in producing vegetation, neither was considered economically viable due to the value of wood as firewood, the labor involved in tillage and transport of wood, and the cost of the fertilizer applied. Based partly on this experience in sandy soils, it seemed evident that shallow, lateritic soil could not be brought back into worthwhile production using these methods.

The objective of our study was to determine whether tilling and/or mulching shallow, lateritic soils would reestablish a stable layer of vegetation on the degraded forest soils near Niamey, Niger.

Materials and Methods

Soil and Vegetation

The primary research site was located at the Guesselbodi forest, 15 km southeast of Niamey, Niger. The area can be divided into three components (Chase and Boudouresque 1987). The first, approximately 18% of the total area, is a wooded layer, dominated by the family Combretaceae: *Combretum nigricans, C. glutinosum, C. micranthum,* and *Guiera senegalensis.* The second is a herbaceous zone that can be further subdivided into a denser stand of forage plants covering 33% of the study area, and a sparse stand of *Tripogon minimus* and *Microchloa indica,* covering 20% of the area, and located in micro-depressions that hold water for a short time after each rainfall. The wooded and productive herbaceous components are usually located on a sandy layer of surface soil, often raised above the level of the crusted soils. The psammophilous *Scytonema* sp (Cyanophyceae), associated with degraded grasslands (Dulieu et al. 1977), is also common in the micro-depression and covers some sandy areas effectively blocking other vegetative growth.

The third component, covering 29% of the study area comprises of shallow (10–40 cm), barren, crusted loamy sand, sandy loam, and sandy clay loam soils, tentatively classified as a sandy skeletal, isohyperthermic Typic Paleustult, (L. West, Texas A&M University Soil Laboratory, personal communication). The subsoil is a thick layer with 40–65% fractured laterite. These crusted soils are characterized by high runoff rates and high daytime surface soil temperature that result in a dry soil profile.

Studies on the effects of crusting and termite activity were carried out on a similar forest ecosystem located at the ICRISAT Sahelian Center (ISC), 40 km south of Niamey. The 10–30 cm deep crusted soil, a loamy, siliceous isohyperthermic shallow Petroferric Haplustult, is underlaid by an indurated or a fractured layer of laterite (West et al. 1984) Microdunes, 5–30 cm thick were observed on the crusted surface at irregular intervals. Intensive termite activity was seen in soils at both locations where leaves and branches had fallen.

The Revegetation Experiment

In May 1983, twenty 10 × 10 m experimental plots were established in Geusselbodi forest on barren, crusted soils between vegetated areas. Ten plots were located within a fence erected 2 years earlier to protect the enclosed area from grazing. The other 10 plots were located outside and well away from the fence and exposed to grazing.

The experiment began in early June following the first rains of the 4-month rainy season. Each 10 × 10 m site was divided into four plots and the following treatments randomly applied:

C = Control plots left untouched.

T = Tillage with a traditional hoe to a depth of about 10 cm. An attempt was made to leave large clods to keep the surface as rough as possible.

M = A mulch of branches placed on the crusted soil, creating a 15–20% shade on the soil surface as determined by a solarimeter. These branches are a byproduct of nearby firewood-cutting operations. Wooden stakes anchored the branches to keep strong prestorm winds from carrying them away.

TM = Tillage followed by mulching with branches.

Soil samples (0–30 cm) were taken in all plots twice during the first year (7 Jul and 4 Oct) and every 2-3 weeks during the second year. Gravimetric soil-moisture content was determined and volumetric water content was then calculated using soil bulk density.

In September 1983, 1984, and 1985, at the end of the rainy season, a detailed inventory of the natural and induced vegetation was made (Chase and Boudouresque 1987), permitting a comparison between the two. Except for soil and plant sampling, the initial 20 plots were left undisturbed throughout the later years of the experiment.

During the second year of the experiment (1984), six additional parcels (three exposed to, and three protected from grazing) were established using the same experimental format as in the previous year.

Supplemental Experiments

During the 1985 rainy season, three experiments were conducted to better understand the effects of applied mulch on natural accumulations of materials on crusted soils. The first experiment was conducted on the Gagani series soil at the ICRISAT Sahelian Center (ISC) to determine the effect of natural deposits of sand and ligneous matter on the otherwise crusted, barren soil. Plots were located in barren, debris-strewn, and micro-dune-covered areas of the forest. Five undisturbed 1 × 1 m micro-plots in each area were isolated by excavating around each of them to the laterite subsoil, and a cement casing was poured on all sides. A 4-cm high ridge was built above the plots on all but the downhill side, isolating the plots from outside surface runoff and permitting runoff from the plots to fall into a collecting trough. This water was pumped into a measuring container which permitted continuous monitoring of runoff. A rainfall simulator of the type described by Morin et al. (1970) was obtained from the Wageningen Tillage Laboratory project at the ISC and used to provide 100 mm h^{-1} simulated rainfall on each plot for periods of 30–90 min. The time to initial runoff and 5-min readings of the accumulated volume of runoff were taken for each plot.

The second study, which was conducted at the Guesselbodi forest during the 1985 rainy season, monitored the effect of mulching and tillage of barren soils on infiltration rates. The advance of the wetting front was followed using the neutron

attenuation technique in barren soils which were undisturbed (except to install the neutron probe access tube) and in 5 × 5 m areas of crusted soils that were (a) hand tilled to an approximate depth of 10 cm and (b) mulched with tree branches, producing 25% shade as determined by a solarimeter. Three replications of each treatment were monitored.

In the last experiment, the effect of mulch on soil temperature was studied. In 1985, thermocouples were buried at 2, 5, 10, 25, 50, 100, 150, and 250-cm depths at two sites in a barren area and one site in an adjacent wooded area in the Guesselbodi forest. The shallow thermocouples (50 cm or less) were buried in a trench with 50 cm of lead wire at the depth of the junction to avoid heat transfer to the sensor. All others were placed in a vertical hole drilled by a well-drilling rig. Maximum and minimum soil temperatures of the entire profile were monitored daily and 15-min readings taken over a 24-h period once each month. All data were collected with a CR7 Campbell Scientific data logger and transferred to computer by cassette tape. After 1 mo of data collection, one of the two barren areas was mulched with tree branches, to a density producing 35% shade as determined by a solarimeter. Subsequent changes in soil temperature were compared with those in the wooded area (with 35% natural shade) and those in a nonmulched control area.

Results and Discussion

The Revegetation Experiment

A drought in 1984 (241 mm rainfall) after the wetter 1983 rainy season (550 mm) provided an ideal contrast for vegetation studies under different rainfall regimes. More normal rainfall in 1985 (approximately 543 mm) permitted comparisons of vegetative development between similar years (1983 and 1985).

Soil moisture. Soil moisture was measured twice in all plots during the 1983 rainy season (Chase and Boudouresque 1987) and was compared with standing biomass in September that year. Both the soil moisture during the 1983 rainy season and the loss of soil moisture between sampling dates were highly correlated with standing biomass (Fig. 1).

During the second rainy season (1984), soil moisture was determined regularly in all plots (Figs. 2a and 2b). The crusted soils of the control plots contained little soil moisture during the rainy

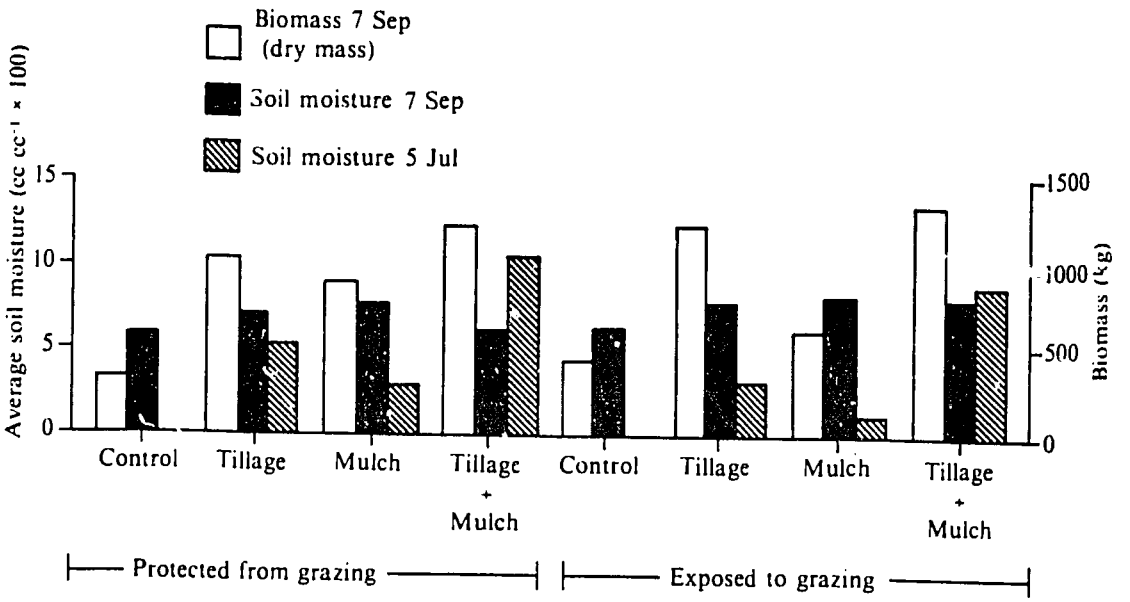

Figure 1. The increase/decrease of soil moisture (0–30 cm depth) between the middle and the end of the rainy season (1983) and the associated biomass yield. Note: Control plots were essentially devoid of vegetation.

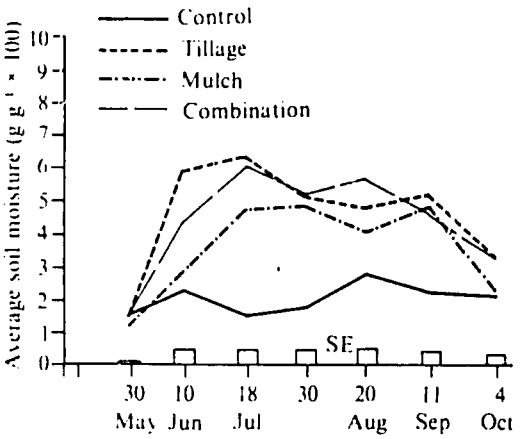

Figure 2a. Average soil gravimetric water content (0–30 cm depth) during the 1984 rainy season in newly established, protected plots.

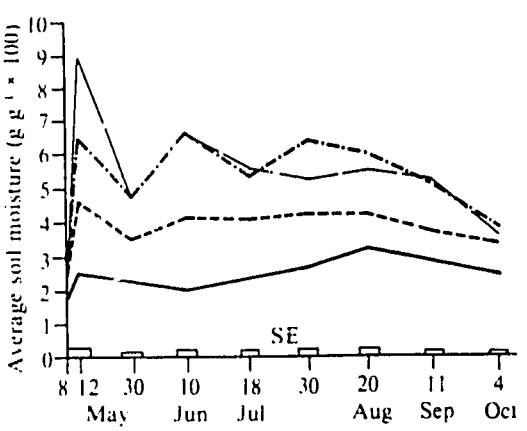

Figure 2b. Average soil gravimetric water content (0–30 cm depth) during the 1984 rainy season in 1-year old protected plots.

season. The new plots in Figure 2a were established after the first rainfall which moistened the soils in the 1983 plots (Fig 2b). Tillage, mulching, and a combination of the two were effective in raising soil moisture in the upper 30 cm for at least two rainy seasons after the treatments were established. In the newly established plots, tillage appears to be the dominant factor in increasing soil moisture above that found in the control. In 1-year-old plots, however, mulching appears to be the dominant factor. This change was undoubtedly related to the crust that gradually re-formed on the tilled-only treatment. Mulched treatments had considerable termite activity and continuously accumulated sand and leaves that eventually affected the infiltration of water and soil-moisture retention.

Vegetation. A detailed description of the first year's results (herbaceous plant species found in each treatment, forage value, tree species, etc.) are reported elsewhere (Chase and Boudouresque 1987). To summarize, at the end of the first rainy season, the TM plots protected from grazing had an average vegetative cover of 96%, T plots had 48%, and M plots had 32%. Ninety-seven newly germinated Combretaceae seedlings were counted in 60% of the treated plots (50 seedlings in the protected, 47 in the nonprotected parcels). The greatest number of seedlings was found in the TM treatment, while the T treatment supported the fewest.

The flora was composed of 48 taxons, most of which were annuals and 34 of which were forage species. The nutritious leguminous annual *Zornia glochidiata* was the dominant species and, in the protected parcels, produced a cover averaging 61% on the TM plots. This induced pasture was found to be similar in composition to the natural grass cover growing on neighboring nondegraded soils.

Probably due to the drought in 1984, plots established in that year produced much less vegetative cover during their first rainy season than did those established in the previous year. Vegetative cover between plots established in 1984 was highly variable with an average cover of 11–13% for the three treatments. The high variability between replications and small differences between treatments indicate that factors other than the treatments were controlling the establishment of vegetation. These factors undoubtedly included the drought and the low frequency of windstorms in 1984 which blew sand, leaves, and seeds into the plots. The 1984 plots produced an average of less than one-third of the number of tree seedlings found in the 1983 plots at the end of the 1983 growing season.

Vegetative cover in the plots established in 1983 decreased considerably in 1984 and increased again in 1985 in response to the fluctuation in rainfall in those years (Table 1). A consistently high proportion of the *Zornia glochidiata* remained in all protected plots throughout the experiment.

During the dry 1984 season, the TM plots established in 1983 produced nearly five times as much dry matter as those newly established in 1984

Table 1. Effects of tillage and mulching on the relative proportion of *Zornia glochiolata* and the total vegetative coverage of experimental plots established in 1983.

		Protected from grazing						Exposed to grazing					
	Rainfall	*Zornia glochiolata*			Total			*Zornia glochiolata*			Total		
Year	(mm)	T[1]	M	TM	T	M	TM	T	M	TM	T	M	TM
1983	550	25.5	16.8	61.3	49.4	31.5	96.0	24.3	12.1	44.0	42.1	25.2	70.0
1984	241	4.4	16.3	44.6	5.7	24.0	54.9	3.8	14.7	23.0	4.0	17.5	26.9
1985	543	4.0	39.7	53.2	7.0	95.5	96.2	4.6	13.1	29.5	8.2	34.2	59.5

T = tillage; M = mulch; TM = tillage followed by mulch.

(Table 2). This could be due to a combination of the following factors:

1. The new plots were established after the first rainfall (51 mm) so that runoff effectively nullified the effects of this relatively large storm.
2. The older plots had an accumulation of sand and leaf mulch at the beginning of the year, which increased infiltration rates from the onset of the season. New litter-free plots slowly accumulated litter during the rainy season due to the lack of windstorms.
3. The old plots had seeds already in place from the previous year's plant growth.

Table 2. Means of estimated standing biomass (kg ha^{-1}) from 20 plots established in 1983 and 6 plots established in 1984.

	Newly established plots		1983 plots in later years	
	1983	1984	1984	1985
Treatment	550 mm	241 mm	241 mm	543 mm
Protected from grazing				
Control	0 a[1]	0 a	0 a	0 a
Mulch	290 b	89 a	230 c	1300 c
Tillage	530 b	190 a	37 ab	80 a
Mulch + Tillage	1030 c	95 a	470 d	1550 c
Native vegetation	(890)	(230)	(230)	(935)
Exposed to grazing				
Control	0 a	0 a	0 a	0 a
Mulch	140 b	0 a	78 ab	320 ab
Tillage	350 b	16 a	28 ab	61 a
Mulch + Tillage	890 c	60 a	150 bc	630 d
Native vegetation	(680)	(140)	(140)	(580)

1. Values followed by the same letter are not significantly different at $P \leq 0.05$ level.

The fact that the 1983 M plots sustained significant quantities of dry matter even in a droughty year shows that the mulch treatment resulted in lasting changes in the soil's ability to absorb moisture and support plant growth.

In comparing the relative proportions of vegetation produced over years and treatments, the tillage treatment ranked second in 1983, but its productivity dropped substantially in 1984, when it ranked third. More important, however, the mulch-only treatment that ranked third in 1983, producing about 24% as much biomass as the TM treatment in that year, produced biomass nearly equivalent to the TM treatment by the third year (Table 2).

Vegetative growth potential in the Sahel is greatly influenced by rainfall (Le Houerou 1980). To study plant response to treatments between years of very different rainfall, the biomasses in the experimental plots in the natural forest areas were compared.

When using these ratios, one sees a continuing decrease in the relative productivity of the tillage treatment, and a continuous increase in that of the mulched plots over native vegetation in all years, particularly in the protected plots (Fig. 3). This further establishes that even in dry years, mulch applied to crusted soils continues to improve the soil environment for increased vegetative growth.

Exposure to grazing retards the reestablisment of vegetation (Fig. 3). Standing vegetation in areas exposed to grazing was approximately half of that found in the mulched treatments protected from animals. This could be due to the consumption of plant material, dispersal of the mulch by trampling, or due to other factors.

The high productivity of the mulched plots protected from grazing as compared with the native

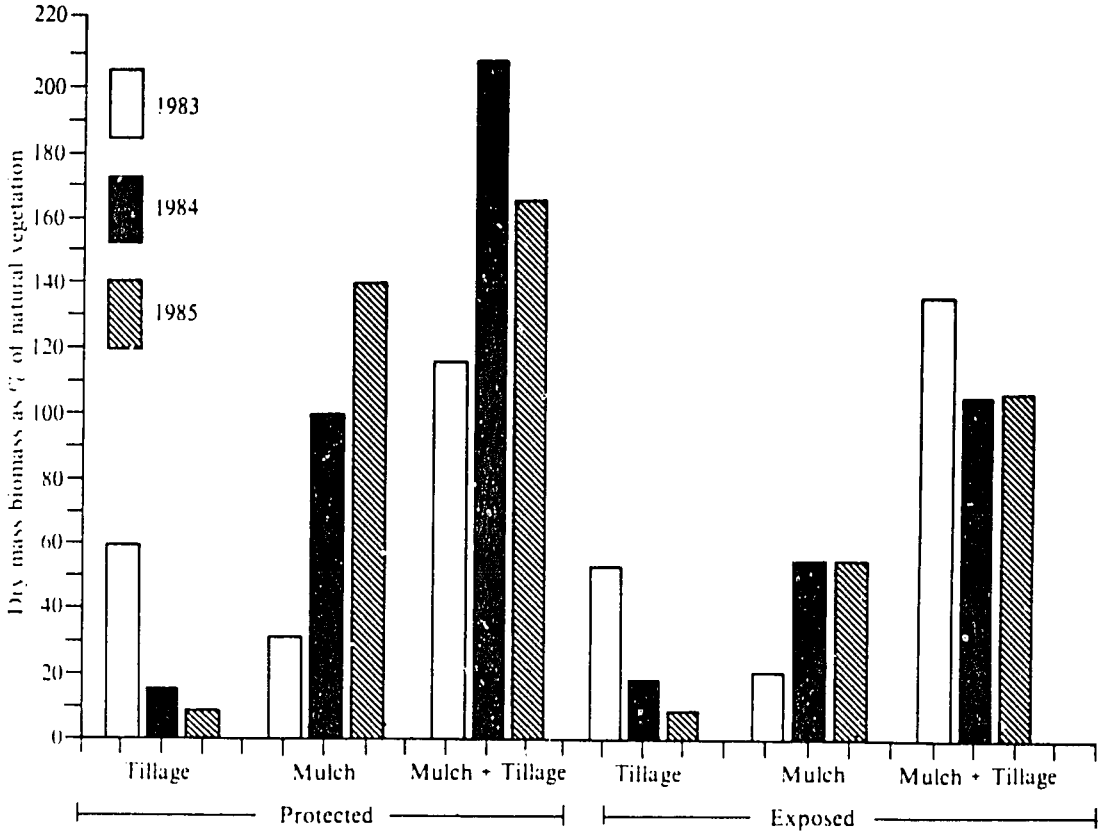

Figure 3. The ratio (%) of standing biomass in 1983 plots to the standing biomass found in naturally vegetated areas of the surrounding forest as a function of grazing and year.

vegetation may be due to the absence of trees nearby that compete with the herbaceous layer for moisture.

Supplemental Experiments

Two effects observed of placing mulch on crusted surfaces are: (1) the accumulation of sand and leaves, and (2) termites attracted by branches and leaves trapped by the branches. The results of experiments on the effects of naturally occurring sand and termite activity and on the effects of applied mulch and tillage treatments show how these factors improve the soil environment, supporting vegetative regrowth.

Simulated rainfall runoff in naturally occurring forest soils. Runoff was strongly affected by sand and litter accumulation on crusted forest soils. On crusted soils, standing water was seen almost immediately upon the initiation of artificial rainfall. Where water was not trapped by soil surface irregularities, runoff began almost immediately after rainfall initiation. Where termite activity had formed stable macropores in crusted soils with accumulated debris, runoff from test plots began later and total runoff after one hour was half the amount measured from the crusted soils (Fig. 4). There was a slow, irregular increase in runoff rate from this soil which appeared to be due, partly, to the gradual plugging of the termite channels with floating debris (Fig. 4).

Termite channels were shown to have an important effect on infiltration in another experiment where water was poured down a single 0.8 × 1.0 cm diameter termite channel. Flow rates of 500–700 mL min^{-1} were sustained during the 30-min test. A

single channel located on one of the test plots would have had sufficient capacity to drain one-third of the 1 × 1 m runoff plot of the 100 mm h^{-1} simulated rainfall applied.

Sand cover in the form of microdunes, 3-15 cm deep, resting on the crusted soil surface had a highly variable effect on runoff rates (Fig. 4). Runoff patterns were similar to those in soils with termite activity in two of the five sites tested. Runoff rates increased more slowly at the remaining three sites. The differences in infiltration appeared to be associated with the thickness of the microdune.

The effect of tillage and mulch on infiltration in a crusted forest soil. Although the results were variable, particularly early in the rainy season, mulching apparently permits water to move deeper into the soil than does tillage (Fig. 5). This may be due to the fact that the tilled plots, like the crusted plots, were exposed to the heating effect of direct sunlight and the drying effect of the air. Mulch can reduce these effects by shading the surface, thereby reducing soil temperature. Mulch also decreases convective vapor loss to the air. These effects can reduce evaporation rates, permitting water to infiltrate further into the soil.

The effects of mulch on soil temperature. Soil temperature profiles were recorded before and after a mulch was applied to the crusted surface and then were compared with profiles from crusted "control" plots and naturally vegetated soils. The soil to be mulched was initially slightly cooler than the crusted control due to partial shading by nearby trees. When mulched, however, both the

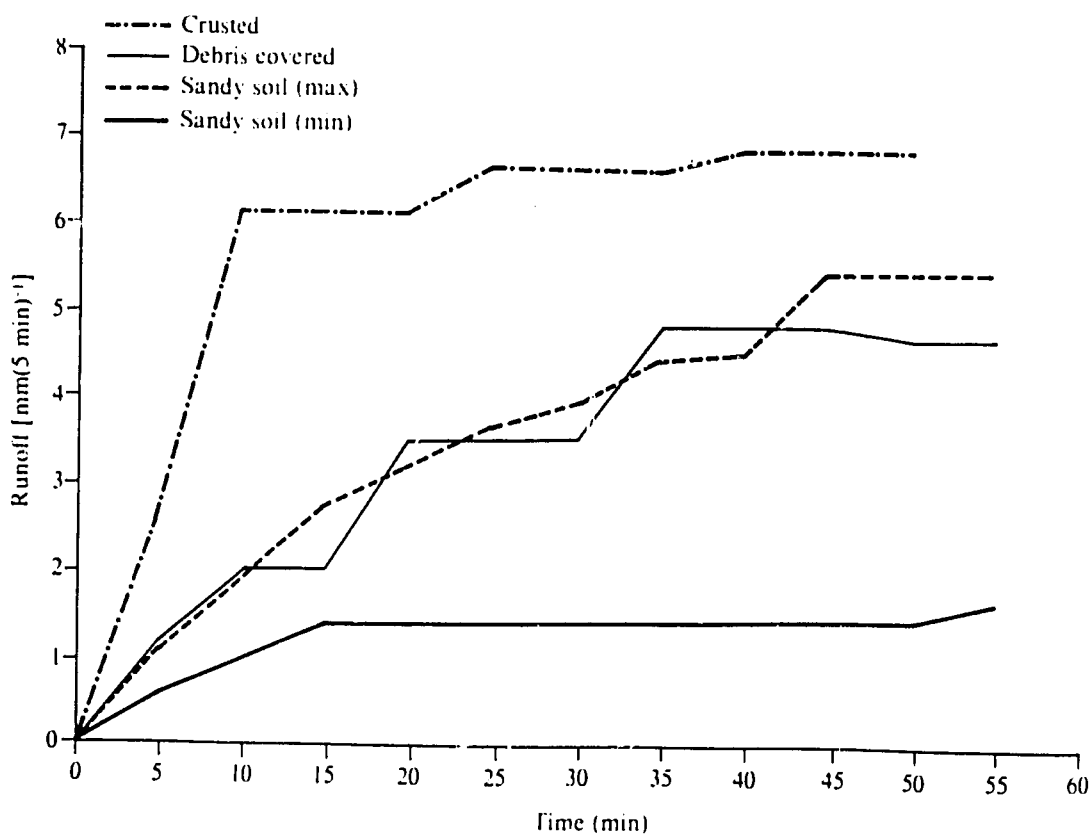

Figure 4. Five-minute rainfall runoff from representative trials on forest soil using a rainfall simulator, producing a rainfall of 100 mm ha^{-1}.

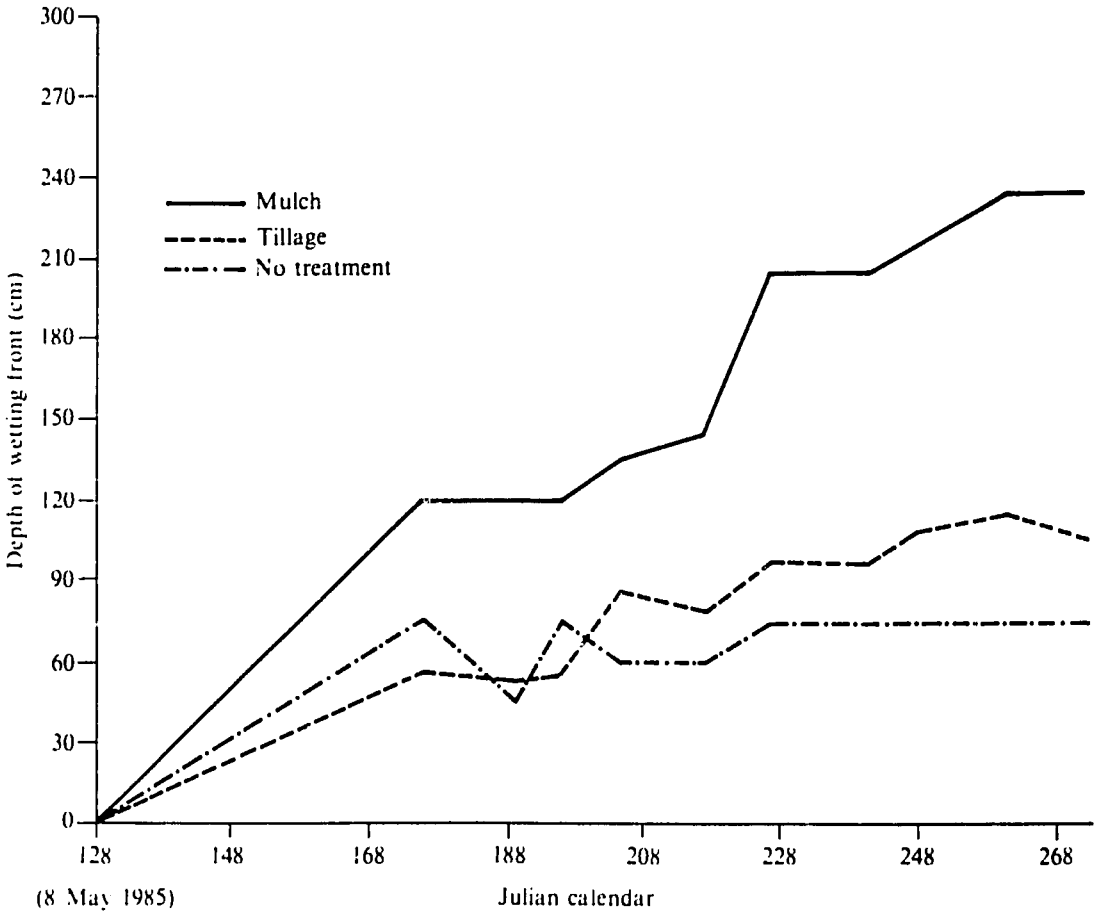

Figure 5. The effect of treatment on soil moisture.

daily fluctuation of the surface soil temperature and the temperature of the soil profile (Fig. 6) were reduced. Decreased temperature fluctuation may be a direct result of shading and the increase in soil moisture which, by increasing soil heat capacity, stabilizes soil temperatures.

Conclusion

Tree branches are a waste product of firewood gathering in the Guesselbodi forest and are normally available immediately adjacent to crusted areas. Mulching these barren, crusted soils with branches provides an effective means to establish substantial vegetative growth over a period of years, particularly if the area is protected from animals. The combination of tillage with mulching, while labor-intensive, has the effect of establishing a good vegetative cover during a single season of normal rainfall, which is not the case for tillage without mulch. More cost-effective, however, is the simple placement of mulch on degraded soils. Although it takes longer to establish a vegetative cover, it requires very little investment of time and energy. Exposure to grazing and trampling substantially decreases the advantages of mulching, but the treatment still has a positive effect under grazing pressure. Unless soils in this area are protected from the wind, solar radiation, and rainfall impact, rainfall runoff and evaporation limit infiltration. Impact of rainfall on tilled soils results

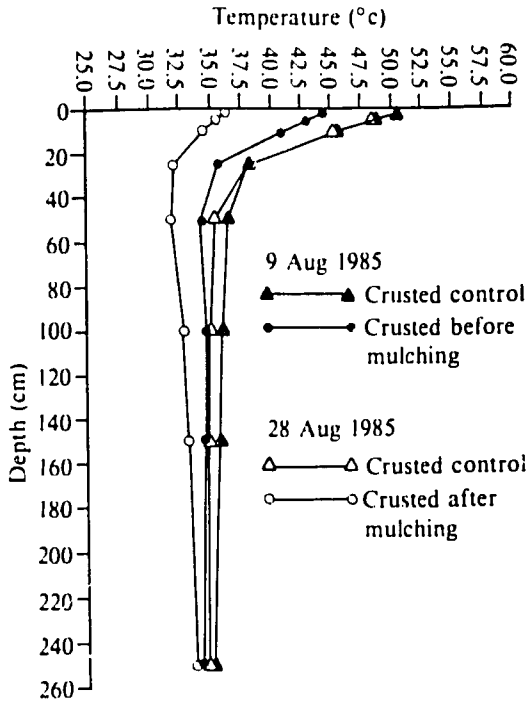

Figure 6. Soil temperature profiles (°C) 10 days before and 9 days after mulching a barren forest soil at Guesselbodi.

in the destruction of surface soil structure, the reformation of the crust, and a return to the original barren surface.

There appear to be several reasons for the positive effects of a branch mulch. Visibly, it collects sand, leaves, and seeds, particularly during the high winds associated with large storms in the area, and continues to do so as long as the mulch remains in place. The captured sand and leaves further mulch the soil, providing shade and a means for rainfall to pass more readily into the previously crusted soil. Termite activity, associated with both branches and leaves, also increases infiltration of rainwater. The moist soil beneath the mulch creates a more stable temperature regime due to an increase in the heat capacity of the soil. The shade provided by the branch, leaf, and sand mulch reduces heat influx, and results in a cooler soil. The cool, moist soil is conducive to the germination of seeds captured by the mulch and supports their growth.

The authors of this study suggest that the limited branches available for mulching the highly degraded forest soils are most effective:

1. when placed immediately adjacent to where the trees have been harvested, thus minimizing transport difficulties;
2. when placed along the edge of vegetated areas, taking advantage of any effect the vegetation may have on the nearby microclimate, i.e., shade, elevated humidity, decreased temperature, or mulch barren soils separating adjacent vegetated areas; and
3. when placed in narrow strips around or between vegetated areas. Since debris is captured at the leading edge of a mulched area, broad mulched areas may not be as efficient in collecting material as narrow strips.

The Forest and Land Use and Planning Project (FLUP) has shown that, in the forests studied, trees cut for firewood and protected from grazing regenerate in 5-8 years. FLUP has developed an incentive package where, over several years, villages can harvest large areas of previously protected firewood if the village agrees to use a percentage of its profits to guard cut areas from animals. Once resprouting trees grow large enough that they cannot be grazed, animals can return to the regenerated area. The research reported here lends itself well to this type of activity, providing a simple means to produce richer pastures for renewed grazing.

To optimize the use of these techniques, however, three questions must be answered:

1. What is the optimal (economic) density of branch mulch?
2. What is the optimal placement pattern with respect to vegetated and barren areas?
3. What are the optimal dimensions of a mulched area?

With these data, aerial photographs, and tree-stand estimates, a complete reclamation program and a cost/benifit ratio can be readily determined for large areas of degraded Sahelian forests.

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