Effects of major woody species of the Senegalese Great Green Wall on N mineralization and microbial biomass in soils

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Photo 1.
Acacia senegal (L.) Willd. adult.
Photo OHMi team.

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RÉSUMÉ

EFFETS DES PRINCIPALES ESSENCES DE LA GRANDE MURAILLE VERTE SÉNÉGALAISE SUR LES TAUX D'AZOTE MINÉRAL DU SOL ET LA BIOMASSE MICROBIENNE

L'article présente une expérience menée pendant neuf mois dans un agro-écosystème au nord du Sénégal, visant à déterminer les effets sur le cycle de l'azote (N) et la biomasse-C de cinq espèces végétales proposées pour la Grande Muraille verte au Sénégal : *Acacia senegal* (L.) Willd., *Acacia tortilis* var. *raddiana* (Savi) Brenan, *Balanites aegyptiaca* (L.) Del., *Boscia senegalensis* (Pers.) Lam. ex Poir. et *Sclerocarya birrea* (A. Rich.) Hochst. Les sols ont été échantillonnés à une profondeur de 0-10 cm, hors couvert (témoin) et sous couvert arboré. La biomasse microbienne, les teneurs en azote minéral et la minéralisation nette d'azote organique ont été déterminées pour les échantillons prélevés sous couvert arboré et comparées aux sols prélevés hors couvert. Les résultats montrent que les teneurs en azote minéral et en biomasse-C microbienne sont généralement plus élevées sous couvert arboré et diffèrent selon les essences. En mai 2014 (fin de saison sèche), la biomasse-C microbienne était plus importante sous *A. senegal* (31,8 mg C/kg sol) et plus faible sous *B. senegalensis* et dans l'échantillon témoin prélevé hors couvert (17 mg C/kg sol). La teneur en biomasse-C microbienne était plus élevée sous *A. senegal* (49 mg C/kg sol) et *B. aegyptiaca* (53,7 mg C/kg sol) en octobre 2014 (fin de saison des pluies) et en janvier 2015 (milieu de saison sèche). En mai 2014, la teneur en ammonium était sensiblement plus élevée sous *B. senegalensis* (11,17 µg/g sol), tandis que l'échantillon témoin (hors couvert) donne la valeur la plus faible (4,93 µg/g sol). Pour l'azote, aucune différence significative n'apparaît entre les essences du couvert (P ≤ 0,05). Ces résultats permettent de guider le choix des essences pour la Grande Muraille verte selon leur fonctionnement et leurs effets sur la qualité des sols.

Mots-clés : dynamique de l'azote, nitrification, Grande Muraille verte, agro-écosystème sahélien, Ferlo, Sénégal.

ABSTRACT

EFFECTS OF MAJOR WOODY SPECIES OF THE SENEGALESE GREAT GREEN WALL ON N MINERALIZATION AND MICROBIAL BIOMASS IN SOILS

An experiment was conducted over nine months in a field system in northern Senegal in order to determine the effects on soil nitrogen (N) cycling and the microbial biomass-C properties of five plant species proposed for the Senegalese Great Green Wall (GGW): *Acacia senegal* (L.) Willd., *Acacia tortilis* var. *raddiana* (Savi) Brenan, *Balanites aegyptiaca* (L.) Del., *Boscia senegalensis* (Pers.) Lam. ex Poir., and *Sclerocarya birrea* (A. Rich.) Hochst. Soil samples were collected to a depth of 0-10 cm, outside (control) and beneath tree canopies. Microbial biomass, inorganic N content and net mineralization of organic N were determined for the soil samples collected under trees, and compared to soils collected outside tree canopies. The results showed that concentrations of inorganic N and soil microbial biomass-C were generally higher under canopy cover and differed according to species. In May 2014 (end of the dry season), microbial biomass-C was higher under *A. senegal* (31.8 mg C/ kg soil) and lower under *B. senegalensis* and in the control sample from outside the canopy (17 mg C/kg soil). A higher microbial biomass-C content was found under *A. senegal* (49 mg C/kg soil) and *B. aegyptiaca* (53.7 mg C/kg soil) in October 2014 (end of the rainy season) and in January 2015 (middle of the dry season). In May 2014, the concentration of ammonium was significantly higher under *B. senegalensis* (11.17 µg/g soil), while the control sample (outside the canopy) had the lowest concentration (4.93 µg/g soil). For nitrates, there was no significant difference between canopy species (P ≤ 0.05). These results can provide guidance for selecting tree species for the GGW according to their functioning and their effects on soil quality.

Keywords: nitrogen dynamics, nitrification, Great Green Wall, Sahelian agro-ecosystem, Ferlo, Senegal.

RESUMEN

EFECTOS DE LAS PRINCIPALES ESPECIES DE LA GRAN MURALLA VERDE SENEGALESA EN LA MINERALIZACIÓN DEL NITRÓGENO Y LA BIOMASA MICROBIANA DEL SUELO

El artículo presenta un experimento realizado durante 9 meses en un agroecosistema del norte de Senegal y cuyo fin era determinar los efectos en nitrógeno (N) y C-biomasa de cinco especies vegetales propuestas para la Gran Muralla Verde de Senegal: *Acacia senegal* (L.) Willd., *Acacia tortilis* var. *raddiana* (Savi) Brenan, *Balanites aegyptiaca* (L.) Del., *Boscia senegalensis* (Pers.) Lam. ex Poir., y *Sclerocarya birrea* (A. Rich.) Hochst. Se tomaron muestras de suelo a una profundidad de 0-10 cm, fuera del dosel (testigo) y bajo el dosel. Se determinaron la masa microbiana, el contenido de N mineral y la mineralización neta de N orgánico en las muestras tomadas bajo el dosel y se compararon con los suelos muestreados fuera de la cubierta de copas. Los resultados muestran que los contenidos de N mineral y de C-biomasa microbiana suelen ser más altos bajo el dosel y varían según las especies. En mayo de 2014 (final de la temporada seca), el C-biomasa microbiana era mayor bajo *A. senegal* (31,8 mg C/kg suelo) y menor bajo *B. senegalensis* y en la muestra testigo extraída fuera del dosel (17 mg C/kg suelo). El contenido de C-biomasa microbiana era mayor bajo *A. senegal* (49 mg C/kg suelo) y *B. aegyptiaca* (53,7 mg C/ kg suelo) en octubre de 2014 (final de la temporada de lluvias) y en enero de 2015 (mitad de la temporada seca). En mayo de 2014, el contenido de amonio era significativamente mayor bajo *B. senegalensis* (11,17 µg/g suelo), mientras que la muestra testigo (fuera del dosel) arrojó el valor más bajo (4,93 µg/g suelo). En cuanto a los nitratos, no aparece ninguna diferencia significativa entre las especies que componen el dosel (P ≤ 0,05). Estos resultados pueden ayudar a seleccionar las especies para la Gran Muralla Verde según su funcionamiento y sus efectos en la calidad del suelo.

Palabras clave: dinámica del nitrógeno, nitrificación, Gran Muralla Verde, agrocosistema saheliano, Ferlo, Senegal.

Introduction

The Sahelian zone of Africa has seen a significant reduction in ecological productivity and diversity (Ndiaye *et al.*, 2014; Ngaryo *et al.*, 2010). Between 1971 and 1990, drought led to a 120-km southward shift in precipitation isohyets. As precipitation deficits persist in the Sahelian zone, desertification continues (Janicot and Fontaine, 1993). In some cases, these climatic effects may have been exacerbated through overgrazing by pastoralists and tree pruning for fuel and harvesting (Garrity *et al.*, 2010). The recurrence and intensity of bushfires may also be contributing to the degradation of this ecosystem (Niang *et al.*, 2014).

To buffer against climate change and desertification, and remediate degraded soils, countries in the Sahel have implemented a large-scale tree planting project (Guisse *et al.*, 2013) known as the Great Green Wall (GGW). It was launched in July 2005, its goal being to create a 15-km-wide (north-south) corridor of trees south of the Saharan Desert (200 and 400 mm isohyet annual precipitation zone) across more than 11 African countries (Dia and Duponnois, 2012). The expectation was that in addition to the overarching goal of halting or reversing desertification, this tree corridor would also provide other services to ecosystems and local communities. This included shading and a resting environment, the protection of forage plants during the dry season for animals, and improved soil quality (Abdou *et al.*, 2013). Additionally, trees alter the micro-climate at the soil surface with shading and lowering of temperatures, which improves water conservation and cycling (Lopez-Pintor *et al.*, 2000; Chambers, 2001; Behnke and Mortimore, 2016).

Trees create direct effects on soil through the litter layer, which protects soils, with decomposition increasing soil organic matter. This, along with root turnover, promotes more diverse and active microbial communities (Hamilton *et al.*, 2001; Tian *et al.*, 2007). Trees mainly increase soil quality by improving soil structure, and thereby the water-holding capacity, the cation exchange capacity, and nutrient availability, particularly for nitrogen (N) (Diallo *et al.*, 2005, 2006, 2015). Leguminous trees can fix atmospheric N_2 for input to soils.

One of the selection criteria for plant species in the GGW was that they should be indigenous trees and create multi-canopy structures that promote ecological functions. However, little attention has been paid to or research undertaken on their impact on soils in general and on soil microbial communities (Duponnois *et al.*, 2005; Niang *et al.*, 2014). Furthermore, such effects on soils vary depending on tree species (Diallo *et al.*, 2006). This is particularly true for litter chemistry which affects decomposition, nutrient release, and microbial community diversity and functioning. Some of the important chemical properties of litter and root materials that affect these soil processes and biology are the C/N ratio and the concentrations of lignin, cellulose and polyphenolic compounds (Recous *et al.*, 1995; Diallo *et al.*, 2005, 2015). Additionally, it is important to understand the role of trees in N processes and cycling (Hart *et al.*, 1994). A key factor is the mineralization of organic N into inorganic forms for plant uptake.

Despite the well-established knowledge that trees significantly affect soils, little is known on this topic for the specific plant species being used for the GGW. Consequently, the overall objective was to detail the N cycling and microbial biomass-C of soils under some GGW tree species (*Acacia senegal* (L.) Willd., *Acacia tortilis* var. *raddiana* (Savi) Brenan, *Balanites aegyptiaca* (L.) Del., *Boscia senegalensis* (Pers.) Lam. ex Poir., and *Sclerocarya birrea* (A. Rich.) Hochst.). The specific objective of our study was to measure the dynamics of inorganic N content, net mineralization of organic N, and microbial biomass-C over time.
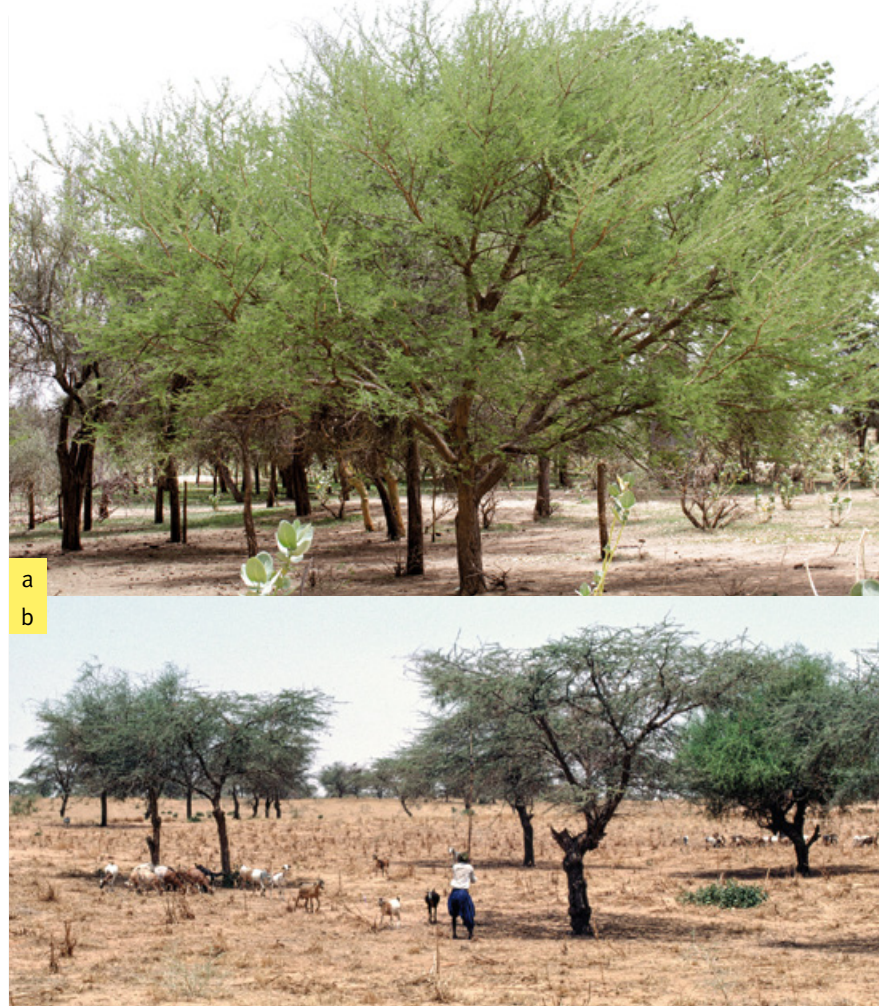
Photo 2.
Acacia tortilis var. *raddiana* (Savi) Brenan adult (a),
with goat breeder (b).
Photo OHMi team (a) and M. Arbonnier (b).

Materials and Methods

Site description

The Ferlo region is located in northern Senegal and occupies an area of roughly 70,000 km². The study was carried out at the Widou experimental field station (15°58'30 N, 15°17'90 W, 43 masl) in the region of Louga in Senegal (figure 1).

The area has a semi-arid climate. In 2014, the mean annual temperature was 29°C and the mean relative humidity was 43%. The annual precipitation was 138 mm with a peak in August 2014 (83 mm), and the mean annual evapotranspiration was 6 mm. The study areas had two seasons, i.e. a short rainy season from July to September and a long dry season from October to July. The natural vegetation was a shrub savanna dominated by *Balanites aegyptiaca*, with *Aristida mutabilis* which has a thick herbaceous litter layer. The soil was a ferruginous Lixisol (Maignien, 1965). It was mostly sandy (down to 10 cm), with a particle size distribution of 85% sand, 8% silt, and 7% clay. The soils averaged a pH of 7.4, 0.36 mg total C/g, and 0.04 mg total N/g.

Experimental Design and Soil Sampling

Trees were randomly chosen at the study site (5 ha study area) with a distance of at least 10 m between two individual trees. The species were average and representative of stands in terms of form and growth in the study area. The tree density was 78 individuals/ha in the study area, the mean canopy cover was 1,960 m²/ha and the species richness was 10 (Niang *et al.*, 2014). Each treatment (species) was replicated three times, giving a total of 15 trees. Microbial biomass, inorganic N content and net mineralization of organic N were determined on soils collected under trees compared to soils collected beyond tree canopies. The soil samples of the control treatment were collected outside the influence of tree cover. Soil samples were collected in May 2014, August 2014, October 2014 and January 2015. These periods corresponded to the middle of the dry season (January), the end of the dry season (May), the middle of the rainy season (August), and the end of the rainy season (October). Measurement of the dynamics of the inorganic N content, net mineralization of organic N and microbial biomass-C over time was important, because it showed the influence of climate variability on inorganic N and microbial biomass-C availability.

The soil samples were collected from a depth of 0-10 cm, beyond (control) and under tree canopies. Under each tree, four samples were collected from four points between 50 cm to 1 m from the tree trunk. They were mixed to form a composite soil sample.

Chemical analysis of leaf litter

The five GGW woody species studied were *Acacia senegal* Willd., *Acacia tortilis* var. *raddiana* Brenan, *Balanites aegyptiaca* Del., *Boscia senegalensis* Lam. ex Poir., and *Sclerocarya birrea* Hochst. Fifteen plants (3 individuals per species) were identified in the 5 ha area. They were randomly distributed in the area. Leaf litter was randomly collected from under the canopy of woody species from June to December 2014. The leaves were air-dried and ground and the initial chemical composition was determined. The physical characteristics of the species are shown in table I.

The leaf litter was air-dried and ground to produce samples <0.2 mm. The total N content was measured by the Kjeldahl method (Bremner, 1996). Soluble C compounds were extracted by mixing 2 g of litter with 60 ml of water for 2 hours. The soluble C content in water extracts was then determined by the chemical oxygen demand (COD) using the HACH method (Jirka and Carter, 1975). Lignin and cellulose were analysed by sequential digestion of fibres (Van Soest, 1963). Samples were first extracted with neutral detergent. Lignocellulose ("acid detergent fibre" or ADF) was obtained after extraction with acid detergent. Lignin ("acid detergent lignin" or ADL) was obtained after hydrolysis with 72% H_2SO_4. Cellulose was obtained from the difference between Lignocellulose (ADF) and Lignin (ADL). Total soluble phenols were extracted with 70% methanol then measured colorimetrically using the Folin-Ciocalteu method (Marigo, 1973). Tannins were measured with a colorimeter after precipitation with bovine serum albumin (Hagerman and Butler, 1978).
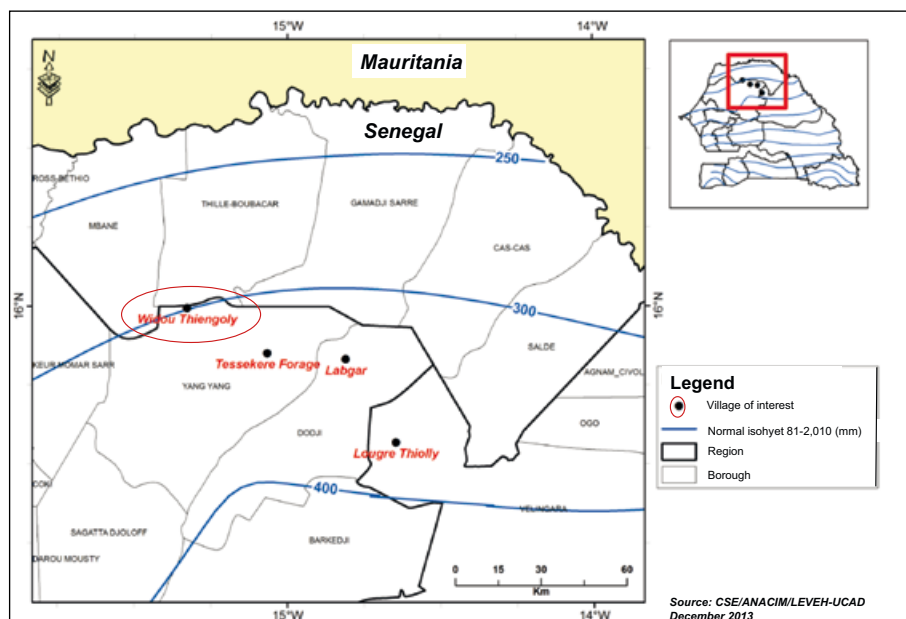
Figure 1.
Study site location at the Widou research station in the Louga region of Northern Senegal (source: adapted from Niang, 2009).

Table I.
Characteristics of the five plants species and trees studied.

Species	Family	Geographical location area	Height (m)	Age (years)	Circumference at 30 cm above soil level (cm)	Canopy (m²)
Acacia senegal	Fabaceae	5°58'20'' N and 15°17'15'' O	3	13	30-40	17
Acacia tortilis var. *raddiana*		15°58'30'' N and 15°17'8'' O	3	13	30-40	20
Balanites aegyptiaca	Zygophyllaceae	15°58'27'' N and 15°17'12'' O	5-7	20	60-70	40
Boscia senegalensis	Capparaceae	15°58'26'' N and 15°17'11'' O	1-2	13	30-40	20
Sclerocarya birrea	Anacardiaceae	15°58'30'' N and 15°17'9'' O	5-7	20	60-70	50

Inorganic N and microbial biomass-C analyses

The inorganic N (N-NH$_4^+$ plus N-NO$_3^-$) content was determined according to the Bremner method (1965). Soil samples (20 g air-dried) were suspended in 75 ml of KCl solution (1:3, dry soil=solution, w=v, 2 M KCl final concentration), shaken at 25°C for 1 h and then filtered with 0.45 mm Whatman filters, and stored in the freezer for analysis. Soil inorganic N (N-NH$_4^+$ and N-NO$_3^-$) was determined by flow injection analysis (Evolution II, Alliance Instrument, France). N-NO$_3^-$ was reduced by a Cu-hydrazine solution to N-NO$_2^-$ and subsequently reacted with sulphanilamide and N-(1-naphtyl)-ethylene-diamine. N-NH$_4^+$ was measured by a modification of the Berthelot reaction (Bremner, 1965).

Soil microbial biomass-C was determined by a fumigation-extraction method (Amato and Ladd, 1988), using ninhydrin-N reactive compound extracted from soils with 2M KCl after a 10-day fumigation period. Fumigated and unfumigated soil samples were suspended in a KCl solution (1:3 dry soil/solution, w/v; 2M final concentration), shaken at 25°C for 1 h and then centrifuged for about 5 min (2,000 x g). Extracts were filtered (0.45 μm) and stored frozen pending further analysis. Ninhydrin-reactive N was determined from 0.5 ml of extract from each of the fumigated and unfumigated soils. Aliquots were mixed with 1.5 ml of 2M KCl and 2.0 ml of freshly prepared ninhydrin reagent. Tubes were placed in a boiling waterbath for 15 min, cooled, and 5 ml of 50% ethanol was added to each. Absorbances at 570 nm were calibrated against standard solutions of l-leucine and ammonium sulphate. Microbial biomass-C was determined by the following equation:

Biomass-C = ninhydrin-N x 21 (mg C/kg of dry soil).

Nitrogen mineralization determination

The net mineralization of soil organic N was determined using the method of Lemée (1967). About 500 g of soil was placed in plastic tubes (225 ml and 7 cm height). Pots were covered with nylon tulle and sealed by plastic ties. They were buried at a depth of 0-10 cm in an area from which the tested sample was collected. The sealed part (nylon cover) of the tube was positioned downwards. The sides of the pots were perforated from top to bottom to allow good aeration and possible wetting by capillarity. After 30 days, the soil in the pots was collected and the inorganic N and microbial biomass contents were determined. The difference between the inorganic N content measured before and after incubation corresponded to the net mineralization of organic N. This operation was carried out in May 2014, August 2014, October 2014 and January 2015. We refer to immobilization when N mineralization was negative and to net mineralization when it was positive.

Data analyses

To test treatment differences between inorganic N species (N-NH$_4^+$ and N-NO$_3^-$), microbial biomass-C, or net N mineralization, a two-way analysis of variance (ANOVA) was applied using SAS Software version 9.4.0 (SAS Institute Inc., Cary, NC, USA). The usual assumptions of homogeneity of variances and normality were checked using Bartlett's Test and the Shapiro-Wilk statistic (Snedecor and Cochran, 1989). A one-way ANOVA was used to analyse the effect of the different tree species litters on the different parameters measured, followed by a LSD multiple mean range test.

Simple linear regression models, Y = ax + b, were performed between each chemical characteristic of the leaf materials (SOM, Cellulose, Lignin, Hemicellulose, N and Total Phenols) and soil (N-NH$_4^+$, N-NO$_3^-$, microbial biomass-C, net N-NH$_4^+$, net N-NO$_3^-$, and net microbial biomass-C, respectively). Each chemical characteristic was considered as a *y* variable and each of the other variables as *x* variables. For each of the regressions, the coefficient of correlation (R) was determined and an F test (Tomassone *et al.*, 1992) at 5% was performed in order to see which of the different regressions were significant. For these different treatments, SAS Software version 9.4.0 (SAS Institute Inc., Cary, NC, USA) was used.

Results

Litter chemistry

The analysis of litter chemical composition (table II) showed that a higher total phenol content was measured for *Sclerocarya birrea* (12.5% DM) and *Acacia tortilis* var *raddiana* (5.4% DM) leaves compared to those of the other tree species. The lowest N and hemicellulose contents were measured for *Sclerocarya birrea* litter (4.6% DM and 4.2% DM respectively).

Soil microbial biomass-C

Soil microbial biomass-C varied across woody species (P < 0.05) in May 2014, August 2014, October 2014 and January 2015. The lowest microbial biomass was found under *B. senegalensis* (figure 2A). In May 2014, the highest microbial biomass-C was under *A. senegal* (31.8 mg C/kg soil) and the lowest under *B. senegalensis* and the beyond-canopy control (17 mg C/kg soil). In August 2014, no significant difference (P ≤ 0.05) was found between treatments. However, the highest microbial biomass-C was obtained under *A. senegal* (49 mg C/kg soil) in October 2014 and under *B. aegyptiaca* (53.7 mg C/kg soil) in January 2015.

Over a one-month *in situ* incubation period, there were similar patterns of microbial biomass-C over time for the various tree species (figure 2B). In June 2014, following one month of incubation in pots, microbial biomass-C decreased by 11 mg C/kg for *A. senegal* and by 1 mg C/kg for *B. aegyptiaca*. In contrast, *B. senegalensis* had an increase of 23.7 mg C/kg after 30 days of incubation. During the August 2014 period, microbial biomass-C increased from 16 to 20 mg C/kg but there were no significant differences due to tree species. For the November period, there was no change in microbial biomass-C over time, whereas it decreased during the February 2015 period, except for the beyond-canopy control and *B. senegalensis* for which no change occurred.
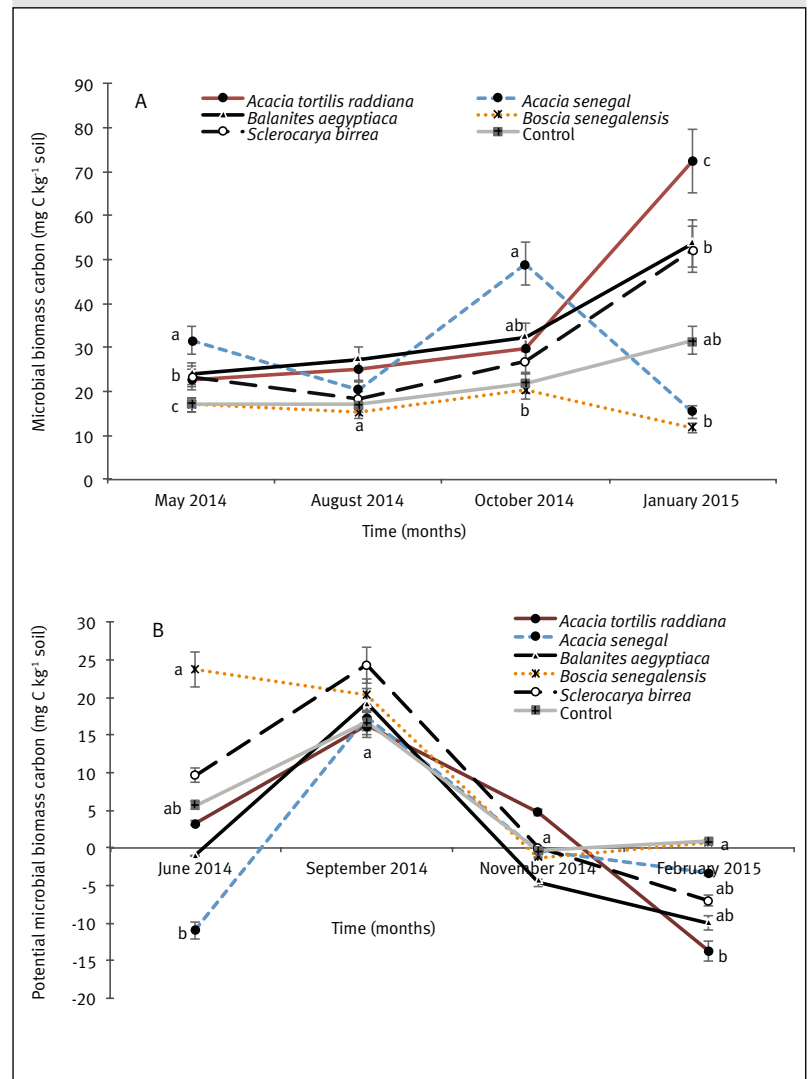
Figure 2.
Microbial biomass (A) and potential microbial biomass (B) at different periods under tree canopies. Bars represent standard errors and values with the same letter are not significantly different according to the Fishers LSD test (P ≤ 0.05; n = 3).

Table II.
Leaf litter characteristics of the plant species.

Species	Soluble organic matter (% MS)	Cellulose (% MS)	Lignin (% MS)	Hemicellulose (% MS)	Total N (% MS)	Total phenols (% MS)
Acacia senegal	73.6	7.2	6.8	12.3	16.5	1.7
Acacia tortilis var. *raddiana*	66.0	10.2	13.6	10.2	14.2	5.4
Balanites aegyptiaca	70.4	7.7	10.4	11.5	10.4	1.1
Boscia senegalensis	63.7	13.8	6.6	15.9	11.7	1.7
Sclerocarya birrea	63.8	17.2	14.8	4.2	4.6	12.5

Nitrogen release dynamics

The amount of inorganic N (N-NH$_4^+$ and N-NO$_3^-$) was measured under and beyond plant canopies on four different dates (table III). The amount varied depending on the tree species and was significantly higher under the canopy than beyond the canopy (control soil) regardless of the species (F = 5.28 and P = 0.0125). Also, for certain periods, the N-NO$_3^-$ concentration was higher than that of N-NH$_4^+$. During the first soil collection in May 2014, the ammonium concentration was significantly higher under *B. senegalensis* (11.2 µg/g soil) while the control (beyond the canopy) showed the lowest concentration (4.9 µg/g soil). For nitrate, there was no significant difference between species (F = 3.87 and P = 0.0267). In August 2014, the ammonium concentrations were higher under *B. senegalensis* (22.8 µg/g soil) and *B. aegyptiaca* (31.5 µg/g soil). In January 2015, small amounts of inorganic N were recovered from all treatments and they were not significantly different compared to the control except for *B. aegyptiaca* for N-NH$_4^+$ and *B. senegalensis,* and *S. birrea* for N-NO$_3^-$. Overall, *B. aegyptiaca* and *B. senegalensis* exhibited only small variations in the concentrations of soil inorganic N over time, unlike the other three tree species studied.

Net mineralization of soil organic nitrogen

Net N flux in incubated soil from beneath or beyond the tree canopies is presented in table IV. The results showed that net mineralization (= sum of the N-NH$_4^+$ and N-NO$_3^-$ amounts) occurred in September 2014 with a tendency for higher net mineralization under *B. senegalensis* (16.3 µg N/g soil) and *S. birrea* (16.1 µg N/g soil) compared to the other three tree species. We also observed periods of net mineralization in June and November 2014 for some species, although it remained quite low. However, in February 2015, strong immobilization of inorganic N was observed, particularly for *B. aegyptiaca* (-19.4 µg N/g soil) and *B. senegalensis* (-12.1 µg N/g soil). The same tendencies were observed for *B. senegalensis* in June 2014 (-8.1 µg N/g soil) and *S. birrea* in November 2014 (-3.6 µg N/g soil).

Correlation analyses

Correlation analyses were carried out for all the chemical properties of the litter and soil parameters (table V). The results showed a negative correlation between lignin and hemicellulose and the net N-NO$_3^-$ or the net total inorganic N (P ≤ 0.05). The correlations were not significant (*NS) at the P = 0.05 level for the other litter characteristics, inorganic N and microbial biomass.

Photo 3.
Balanites aegyptiaca (L.) Del. adult.
Photo OHMi team.

Discussion

Microbial biomass-C

Microbial biomass-C is a valuable property as an indicator of the size of the microbial community (Gil-Sotres *et al.*, 2005). Microbial biomass-C was significantly higher in soil from beneath the tree canopy than beyond the canopy. This probably resulted from regular inputs of litter and root turnover by the trees, which have a positive effect on the activity of soil microorganisms. Indeed, according to Smith and Paul (1990), microbial biomass is proportional to the bioavailability of organic matter in the soil. Thus, when organic matter is incorporated into soil, microorganisms such as bacteria (*Agrobacterium*, *Arthrobactrium*, *Bacillus*, *Actinomyces*, *Nocardia*, *Streptomyces*) and fungi (*Penicillium*, *Aspergilus*) (Paul and Clark, 1996), begin a series of transformations in

Table III.
Soil inorganic N (N-NH$_4^+$ and N-NO$_3^-$) under plant canopies and beyond thecanopy (control) at different periods.

Species	May 2014		August 2014		October 2014		January 2015	
	N-NH$_4^+$ (µg N/g soil)	N-NO$_3^-$ (µg N/g soil)	N-NH$_4^+$ (µg N/g soil)	N-NO$_3^-$ (µg N/g soil)	N-NH$_4^+$ (µg N/g soil)	N-NO$_3^-$ (µg N/g soil)	N-NH$_4^+$ (µg N/g soil)	N-NO$_3^-$ (µg N/g soil)
Acacia tortilis var. *raddiana*	6.70±0.85 bc	11.06±5.17 a	8.84±1.05 bc	9.93±1.31 bc	7.77±2.49 b	7.14±3.43 b	9.97±2.87 b	8.97±6.47 ab
Acacia senegal	8.98±1.21 abc	12.46±3.79 a	6.77±0.78 c	13.55±0.45 bc	8.20±1.68 b	6.21±3.06 b	7.47±3.15 b	2.73±2.05 b
Balanites aegyptiaca	10.40±1.26 ab	17.14±3.99 a	13.82±2.50 b	31.50±11.17 ab	6.39±0.49 b	6.35±4.00 a	23.4±4.50 a	11.73±2.05 ab
Boscia senegalensis	11.17±5.35 a	15.09±6.22 a	22.84±6.69 a	16.37±0.68 b	22.68±9.25 a	31.22±8.56 b	11.23±1.69 ab	24.80±3.35 a
Sclerocarya birrea	7.77±0.46 abc	9.41±2.03 a	11.21±6.67 bc	17.72±4.74 b	7.18±1.50 b	16.40±7.08 ab	7.17±2.00 b	14.37±10.36 a
Control	4.93±0.65 c	1.34±0.69 b	6.29±0.50 c	4.83±2.64 c	5.55±0.55 b	2.39±1.58 b	8.9±4.86 b	2.60±1.71 b

* Ammonium (N-NH$_4^+$), nitrate (N-NO$_3^-$).
Values with the same letter within each column are not significantly different according to the Fishers LSD test (P ≤ 0.05; n = 3).

Table IV.
Net soluble inorganic N (N-NH$_4^+$ and NNO$_3^-$) during the 30 days of field incubation.

Species	June 2014		September 2014		November 2014		February 2015	
	N-NH$_4^+$ (µg N/g soil)	N-NO$_3^-$ (µg N/g soil)	N-NH$_4^+$ (µg N/g soil)	N-NO$_3^-$ (µg N/g soil)	N-NH$_4^+$ (µg N/g soil)	N-NO$_3^-$ (µg N/g soil)	N-NH$_4^+$ (µg N/g soil)	N-NO$_3^-$ (µg N/g soil)
Acacia tortilis var. *raddiana*	1.11±0.66 a	-0.47±1.50 abc	0.26±2.95 a	4.02±9.50 a	0.76±0.64 a	0.95±3.39 a	-0.8±1.31 a	-4.17±6.02 ab
Acacia senegal	1.91± 2.97 a	2.09±0.96 ab	0.66±3.15 a	7.18±0.59 a	0.71±0.67 a	0.70±0.54 a	-0.8±1.35 a	1.83±1.10 a
Balanites aegyptiaca	0.37±3.79 a	-6.35±8.11 bc	0.86±12.13 a	10.02±2.91 a	0.98±0.32 a	2.70±2.09 a	-8±5.54 b	-4.13±2.5 a
Boscia senegalensis	-0.92±2.51 a	-7.23±7.35 c	4.84±13.60 a	11.42±11.61 a	0.13±1.78 a	0.21±5.47 a	-1.63±1.36 a	-17.80±29.99 b
Sclerocarya birrea	1.66±0.44 a	4.6±1.95 a	-2.54±7.18 a	18.67±24.76 a	0.74±0.57 a	-4.39±6.29 a	0.77±3.59 a	-2.40±9.64 a
Control	1.2±1.14 a	-0.06±0.67 abc	-1.10±0.17 a	6.25±1.75 a	0.49±0.23 a	-0.06±0.57 a	-1.9±1.57 a	-0.20±0.30 a

* Ammonium (N-NH$_4^+$), nitrate (N-NO$_3^-$).
Values with the same letter within each column are not significantly different according to the Fishers LSD test (P ≤ 0.05; n = 3).

Table V.
Correlation coefficients (R values) between chemical characteristics of the leaf litter materials and soil N-NH$_4^+$, N-NO$_3^-$, microbial biomass, net N-NH$_4^+$, net N-NO$_3^-$ and net microbial biomass.

Litters characteristics	N-NH$_4^+$ (µg N/g soil)	N-NO$_3^-$ (µg N/g soil)	Total inorganic N (µg N/g soil)	Microbial biomass (mg C/kg soil)	Net N-NH$_4^+$ (µg N/g soil)	Net N-NO$_3^-$ (µg N/g soil)	Net Total inorganic N (µg N/g soil)	Net Microbial biomass (mg C/kg soil)
Soluble organic matter	-0.262ns	-0.378ns	-0.179ns	+0.446ns	-2.021ns	-0.143ns	-0.306ns	+0.405ns
Cellulose	+0.072ns	+0.319ns	+0.123ns	-0.447ns	+1.917ns	+0.315ns	+0.460ns	+0.707ns
Lignin	-0.531ns	-0.236ns	-0.181ns	+0.130ns	-0.256ns	+1.194*	+1.11ns	-0.262ns
Hemicellulose	+0.722ns	+0.295ns	+0.238ns	-0.129ns	+0.360ns	-1.366*	-1.263*	+0.192ns
N	-0.070ns	-0.350ns	-0.133ns	+0.153ns	+1.345ns	-0.641ns	-0.494ns	-0.384ns
Total Phenols	-0.634ns	-0.159ns	-0.175ns	-0.140ns	+1.389ns	+1.286ns	+1.335ns	+0.187ns

* Significant at P ≤ 0.05; ns: not significant.

Photo 4.
Boscia senegalensis (Pers.) Lam. ex Poir. adult (a) with fruits (b).
Photo OHMi team.

the various organic compounds. The incorporation of litter stimulates the activity and development of soil microorganisms through a direct effect on the supply of carbon substrate (Vance and Chapin, 2001). The availability of soluble compounds (Floret, 1999) and the amount of C input into soils are important in regulating microbial communities because C is typically the most limiting growth factor (Gunapala and Scow, 1998).

Leaf litter stimulates soil microbial communities by available C and N sources in soil. Thus, our results showed that microbial biomass-C under the canopy was significantly increased. Similar results were found by Kanchikerimath and Singh (2001) and Marschner *et al.* (2003). Microbial biomass-C was positively correlated with N mineralization, which, according to Gil-Sotres *et al.* (2005), indicates a positive effect on soil quality.

The amount of litter biomass produced between seasons had a greater effect on the soil microbial biomass-C. This seasonal effect can be attributed to significant differences in rainfall between the rainy and dry seasons (Kabir *et al.*, 1994).

Soil inorganic N

The climate zone of this study has a short rainy season from July to September and a long dry season from October to July. Inorganic N was significantly higher under the tree canopies than beyond the canopies (control). These results tallied with the results reported by Guedira *et al.* (2008) and Abdou *et al.* (2013) for shrubby legumes in a Mediterranean climate, by Daldoum and Nimer (2002) and El Tahir *et al.* (2004) for *A. Senegal,* and by Belsky *et al.* (1993) and Kumar *et al.* (1998) for another perennial tree species. The high inorganic N levels beneath trees was probably due to the regular input of leaf, stem, and fruit litter on the soil surface, and root turnover. The annual accumulation of these materials under trees restores nutrient levels in the soil.

The release of inorganic N from litter is driven by soil microbial activity (Belsky *et al.*, 1993; Prinsley and Swift, 1994). Indeed, the higher concentration of microbial biomass-C living under canopies at a depth of 0-10 cm for certain species may explain these results. Moreover, many leguminous tree species, which are symbiotically associated with rhizobium (soil bacteria), have the ability to fix atmospheric N_2, which provides an external input of N to soils. This is the case of all *Acacia* species (Dommergues *et al.*, 1999), such as *A. senegal* and *A. tortilis* in our study.

Another source of higher soil inorganic N content at the base of the plant is probably related to litter from the spontaneous herbaceous species and root turnover (Buresh and Tian, 1999). Diallo *et al.* (2015) showed that herbaceous biomass was greater under the canopy than beyond the canopy.

Nitrate concentrations were similar to those of ammonium. This shows that nitrification was in equilibrium with N mineralization. This is in contrast to other studies, where nitrate concentrations in soil were higher than ammonium (Chen and Stark, 2000; Diallo *et al.*, 2005) in the nitrification process, or where there were higher ammonium concentrations (Laverman *et al.*, 2000; Uri *et al.*, 2003). This corresponds to acidic forest soils where ammonium is the only N form available for plant nutrition (Uri *et al.*, 2003).

Net mineralization of soil organic N

Initial net N mineralization in June 2014 and February 2015 was low for both *B. aegyptiaca* and *B. senegalensis*, due to the slow degradability of their litters (Wedin and Tilman, 1990). The values measured for these two dates

showed N immobilization of the inorganic N in the pots. This could be explained by low soil moisture during the dry season. The low mineralization rate obtained during incubation was a result of the limited residual effect of litters due to low bacterial activity in the pots because of low soil moisture (Diallo *et al.*, 2006).

Net N mineralization is the result of two opposing processes: gross N mineralization and gross immobilization. When plant residues are added to soil, the quantity of N released during their decomposition is affected by the C/N ratio of the added residue. The decomposition of residues with a low C/N ratio leads to net N mineralization while a high C/N results in N immobilization. This is because N is limiting and all available N is taken up by microorganisms (Trinsoutrot *et al.*, 2000).

Lignin and hemicellulose were correlated with the nitrate concentrations and the net total inorganic N. It is well established that the rate of plant residue decomposition in soil is a function of litter chemistry (soluble C, hemicellulose, cellulose and lignin) (Abiven and Recous, 2007). Previous studies on the mineralization of ^{14}C labelled lignin showed that after two years of decomposition, the C released from lignin was not incorporated into microbial biomass (Kassim *et al.*, 1981). These authors concluded that lignin mainly contributes to the stable fraction of soil organic matter, but this interpretation has been challenged by recent work showing that stable organic matter is not necessarily highly recalcitrant (Lehmann and Kleber, 2015).

Conclusion

This study highlighted the positive influence that trees can have on soil microbial biomass-C properties and inorganic N. For instance, the results showed that soils under the tree canopies had more inorganic N than the soil beyond the tree canopies. On the other hand, net mineralization of soil organic N showed the importance of the seasonal climate, particularly rainfall and temperature, on microbial biomass-C and inorganic N. Low soil moisture limited bacterial activity in the pots and the mineralization rate. Besides seasonal shifts, the incubation study showed that soil inorganic N levels were in part controlled by the tree species and their associated organic inputs to soil. The availability of inorganic N during the *in situ* incubation experiment was not closely related to the biochemistry of the litters incorporated into the soil (soluble C, lignin, polyphenols, cellulose, and hemicellulose). In the ferruginous leached soils of this study, microbial biomass-C in soil beneath canopies varied with tree species and was higher than in soil beyond the influence of tree canopies. Thus, out of the tree species, *B. senegalensis* and *B. aegyptiaca* had the most positive effects on soil inorganic N and microbial biomass-C contents and would therefore be good candidates for the Great Green Wall project. The results provided information on the plant species that have the potential to repair damaged soils.

Photo 5.
Sclerocarya birrea (A. Rich.) Hochst. adult.
Photo OHMi team.

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