Spatial Distribution of **Soil Chemical and Biological Properties** beneath Native Shrubs (*Guiera senegalensis*) in the Southern Semiarid Zone of Senegal

**ABSTRACT**

This study relates the physical environment of *Guiera senegalensis* to spatial distribution of soil chemical and biochemical properties in semi-arid areas. Changes in soil properties were measured at the center, beneath and outside the shrub canopy in relation to wind effect. Results show that with a wind of 5 m s⁻¹ speed, blowing direction NNE, soil pH, soil organic carbon (SOC), soil total nitrogen (TN) and extractible phosphorus (EP) were not affected in their distribution excepted EP which showed greater contents (8.2 mg kg⁻¹) from the center to the south. Soil biochemical properties such as Arylsulfatase (AS), β-glucosidase (β-G), Soil respiration (SR), and Microbial Biomass Carbon (MBC) showed greater influence of the wind dominate direction, except SR. The highest concentrations of AS (11.8 µg g⁻¹ soilh⁻¹), β-G (75.4 µg g⁻¹ soilh⁻¹), and MBC (116.1 mg kg⁻¹) soil were found at the center, at 1R, mainly in the north-southern direction. Results provide a basis for developing sustainable agriculture.

**Keywords:** Soil chemical and biochemical properties, *G. senegalensis*, Spatial distribution, Wind.

**INTRODUCTION**

In the arid and semiarid Sudano Sahelian zones, soils are inherently of low fertility (Bationo and Buerkert, 2001), and intensive cropping combined with shorter fallow periods and greater livestock pressure is causing significant loss of organic matter and depletion of nutrient reserves in soils (Sanchez, 2002; Dossa et al., 2008). Agricultural systems of semiarid sub-Saharan Africa are vulnerable because of ongoing anthropogenic soil degradation and declining soil productivity (Lal, 2002). Organic matter input to the soil has been shown to be critical for improving soil quality and...
optimizing nutrient and water efficiencies, and ultimately crop productivity in these degraded agro-
ecosystems (Sinaj et al., 2001; Tschakert et al., 2004; Kizito, 2006 et al., and 2009). The improved soil
quality beneath the shrub canopy may further stimulate mineralization and plant availability of
nutrients (Iyamuremye et al., 2000; Diack et al, 2016). This system has received considerable attention
with regard to its biophysical interaction with soils and crops (Samba, 2001; Kizito et al, 2007). A
native shrub (Guiera senegalensis J.F. Gmel.) is commonly found in farmers’ fields in the Senegal
Peanut basin, naturally distributed in the landscape (Dick et al, 2010). Traditionally, it is in association
with annual food crops (millet: Pennisetum glaucum (L.) R. Br. and groundnut: Arachis hypogaea (L.).
If left uncut, this shrub continue to grow, but in farmers’ field they are cut at the soil surface and
burned just prior to the rainy season (Diack et al, 2000). Thus, under current management, this organic
matter is not being utilized effectively. Burning the residue reduces the amount of C and N returned to
soils, does not build organic matter, and would be largely unavailable for biological activity. However,
it can be vulnerable to destruction by famers in order to increase agricultural acreage and meet food
demands (Lufafa et al., 2008; Dossa et al, 2009). In Senegal, soils are intensively cultivated with
peanuts (60% of production is exported) and millet as the principal crops. Additionally, there is an
exceptionally high degree of land utilization (3% of the land is annually fallow). Agricultural
management involves coppicing and burning aboveground residue in the spring, prior to the planting
of row crops to clear fields. Shrubs in arid and semi-arid environments create heterogeneity of soils
chemical properties (Van Miegroet et al, 2000) within the so-called “islands of fertility” (Wezel et al,
2000; Witford, 2002). Additionally, it would be expected that litter fall, root exudates, and root
turnover of woody perennial species would stimulate and shift microbial communities. Indeed,
Diedhiou et al (2012) reported elevated microbial biomass beneath shrubs influenced in a generating
process of “islands of fertility” during decomposition in semi-arid regions. In these environments, soil
beneath the canopy of shrubs typically has higher C and N levels than soils outside the canopy (Kieft
et al., 1998). In addition, the improved water conditions and microclimate beneath the shrub create a
favorable environment for biological activity (Kizito et al, 2006). As a first step towards understanding
the ecology and effective management of *Guiera senegalensis* that co-exists with other crops in
farmer’s fields, information is needed on the potential of residues (leaves and stems) to release
nutrients, how they are spatially distributed and how soil beneath the shrub canopy may influence this
process. *Guiera senegalensis* could be considered as a “ratooon cover crop” after the rainy cropping
season. If left uncut during the dry season, it will typically regrow to a height of 1.0 m and have a 1.5
m canopy diameter (Lufafa et al. 2005). Subsequently, it may become an organic resource to improve
soil quality. In this region, *G. senegalensis* nearly covers the landscape with an average density of 240
ha⁻¹ (Kizito et al, 2006; Lufafa et al, 2008b), but in others there is a less dense distribution. These
differences in density may be due to differences in soil types. Basic information is needed on the
distribution of associated nutrients that are contained in the litter that could be incorporated into the
soil.

We hypothesize that *G. senegalensis* is important in soil dynamics and that through better
management, this species could be of relevant use in long-term sustainability of the cropping systems
in the peanut region for the following reason:

This species provides leaf/stem litter, root mass and root activity, which provide in a spatially
distributed way organic matter, conserves nutrients, and stimulates biological activity in soils.
Therefore, the objectives of the study were to determine spatial (vertical and horizontal) distribution of
soil chemical and biochemical properties beneath and outside the canopy of the *Guiera senegalensis*.

**MATERIALS AND METHODS**

**Study sites description**

The study site is located at Nioro, in the southern region (N 13°45 W 15°47), slope range of 0-2% of
the Peanut Basin, with a mean annual precipitation of 750 mm and temperatures ranging from 20°C in
December–January to 36°C in April–June. Due to inland and continental features, the prevailing winds
are characterized by their origin: the dry winds, called the dry monsoon (harmattan), originate from the
continental interior and the moist maritime winds that bring the rains. The dry winds, sometimes,
consist of the northeast trade winds. Over the years (Table 1), winds have been blowing at relatively
high speed (5.0 m s\(^{-1}\)) with the dominant direction north-north east (N-NE), during the dry season
(December-April). During the rainy season (June-November), winds blow at lower speed (3.5 m s\(^{-1}\)),
in the direction N-NW. The soil is a \textit{Dior} fine sandy, mixed Haplic Ferric Lixisol (FAO, 2006), a
leached ferruginous tropical soil. The dominant shrub species at the site is \textit{G. senegalensis}, with stand
density of 240 shrubs ha\(^{-1}\).

\textit{Sample collection}

Soil samples were collected in May in three replicates, prior to the rainy season. The sampling points
were directional (north, east, south, and west) at two intervals from the center of the plant [1/2 canopy
radius (1xR/2) to 2xR/2 (canopy edge), beneath the shrub, and 6xR/2 (outside the canopy)]. All
sampling intervals were covered for the 0-10 cm, 10-20 cm, 20-40 and 40-80 cm depths. \textit{Sampled}
were characterized for: pH, total soil C and soil N, and extractible P. For the biochemical properties:
microbial biomass C, soil respiration and enzyme activities (Arylsulfatase, \(\beta\)-glucosidase), only
samples taken at 0-10 and 10-20 cm depths were analyzed.

\textit{Soil laboratory analysis}

\textit{Samples for soil C were air dried} and analyzed for total C by combustion on a LECO C-144 C
analyzer (LECO Inc. St Joseph, Michigan). No attempts were made to correct for carbonate as near-
surface soil horizons and the study area is predominantly acidic (pH < 7.0) (Tschakert et al., 2004).
Soil microbial biomass was determined using the chloroform fumigation-incubation (Horwath and
and soil respiration (Anderson, 1982), soil total N (Keeney and Nelson, 1982), extractible P (Murphy
and Riley, 1962) and soil pH (Mclean, 1982) were determined on soil samples.

\textit{Statistical analysis}
Effects of spatial distribution of the soil chemical and biochemical properties with shrub establishment were analyzed as repeated measures ANOVA (SAS Institute Inc., 1996). Data collected were first analyzed in mean values, using the LSD for equal replication (Gomez and Gomez, 2009). Those values were then used to build an illustrative diagram representing a *G. senegalensis* plant around which soil property contents were placed into the geographic orientation (north, south, east and west), the different soil depths of sampling, beneath and outside the canopy, based on the radius. For the illustration process, Infographics softwares (Adobe Illustrator, Version CS3) were used to plot the graphs.

**RESULTS AND DISCUSSION**

*Soil pH*

With *G. senegalensis*, pH values were slightly acidic (5.8-6.2) with depth from the center to 1R. They did not vary (5.9-5.8) in between the four geographical directions. At a gradient outside the canopy (3R), mean values of pH showed no significant difference (5.7–6.2) with soil depths across the directions (5.9-5.8) and the center (Figures 1, 2, 3 and 4). From the above observations, it could be concluded that, soil acidity has not varied spatially at the soil surface, around the shrub, beneath and outside, at all directions. It also did not change in depth. For a leached ferruginous tropical soil with 95% sand, mainly originates from eolian deposits and has no distinct horizonation in the top layer, with a pH 5.5 (Badiane *et al*, 2000), the presence of *G. senegalensis* which is a source of organic matter (McClintock and Diop, 2005), may have contributed to maintain the acidity to this level.

*Soil organic carbon*

At the center of the shrub, the soil organic carbon (SOC) content was not different from the ones determined at the four geographical directions, as well as at the 0-10 cm shallow layer (Figure 1). At deeper levels (20 cm, 40 cm, and even 80 cm), SOC values were 45.2%, 48.5%, and 4.1% greater than that from the center respectively (Figures 2, 3, and 4). With regards to the directions, at one radius (1R) distance level beneath the shrub, differences not significant however were noted between the
center of *G. senegalensis* and the south (6.7%), the east (4.6%), the north (1.7%), and the west (0%)
(Figure 1). A slight decrease in SOC contents was noted from a 1R distance to 3R (Figure 1), around
the center of the shrub, as follows: north (3.2%), east (1.2%), south (4.2%), and west (8.2%). Values
of SOC obtained from the study were similar to those found by Badiane et al, (2000) at the top soil (0-
10 cm). Furthermore, the first and uncommon findings could be due to the texture of the soil (95%)
total sand and relatively low SOC and the hydraulic lift effect on the soil. Data showed seemingly that
the SOC from the litter, residues, and the rooting system was degraded at the top level and its
substance was accumulating at the sub-soil level, due probably to the hydraulic lift effect (Kizito et al,
2006). Shrubs could supplement soil moisture demands for annual crops in these fragile Sahelian
sandy soils, with erratic rainfall differences. Differences in SOC contents, related to the geographical
directions could be due to the wind dominant directions (Table 1). Winds blowing in the NNE
directions might have favored an increase in SOC contents on the south and west zones around the
shrub, even though the differences were not significant. Lufafa (2008) found through a comparison
across different grids of shrubs and trees that variability around the shrubs was higher at the *G.
senegalensis* site and that mean total organic C was consistently lower under the shrubs.

**Soil total nitrogen**

With soil total nitrogen (TN) contents, no differences were noted with soil depth (290.2–232.2 g kg\(^{-1}\))
but significant differences (P < 0.05) were noted in between the geographical directions and the center
(319.4–199.4 g kg\(^{-1}\)) under the canopy (1R). Outside the canopy (3R), TN concentration values
showed no significant difference with depth (253.8–232.2 g kg\(^{-1}\)). It however presented significant
difference (319.4–172.0 g kg\(^{-1}\)) with the four directions around the center (Figures 1, 2, 3 and 4).

However, the center did not follow the trend as greater TN values were noticed in the 10-20 cm depth
(383.6 g kg\(^{-1}\)) and 20–40 cm depth (436.8 g kg\(^{-1}\)). With regards to the directions, an increase in TN was
noted on the northern (9.4%) and the southern (12.1%) areas, at 1R distance from the center of the
shrub. On the other hand and still at the same distance, a decrease in TN was observed on the west
(4.6%) and the east (10.1%). At 3R from the center of the shrub, TN concentrations were reduced to 
22.2%, 14.3%, 2.9%, and 5.3% on the northern, eastern, southern and western zones respectively. In 
this case, the NNE wind dominant directions did not seem to have a positive impact on TN 
concentrations.

Soil extractible P

Soil extractible P (EP) contents showed significant differences (P < 0.05) with depth (5.7–3.0 mg 
kg\(^{-1}\)) and highly significant differences (P < 0.1) in between the four directions and the center of the 
shrub, at 1R (8.2-2.2 mg kg\(^{-1}\)). Outside the canopy (3R), there were significant differences at P < 
0.1 with soil depths (6.7-3.0 mg kg\(^{-1}\)) and across the directions and the center (8.2-3.14 mg kg\(^{-1}\))
(Figures 1, 2, 3 and 4). With geographical directions, at 1R distance from the center, there was a 
decrease in EP contents of 3.0 % in the north, 4.4% in the east, and 2.1% in the west. In the south, 
no change was noticed. At a greater distance 3R from 1R, there was an increase of 33.3% in the 
north, and 17.5% in the east. There was however a decrease of 15.5% in the south, and 23.6% in the 
west. It could be concluded from the observed data that the dominate direction NNE of the wind 
might have contributed to improve the EP concentrations at a 1R distance but had not help 
increasing the EP value contents outside the shrub canopy (3R).

Arylsulfatase activity

Under the canopy (1R), significant differences were noticed (4.2-6.2 µg g\(^{-1}\) soilh\(^{-1}\)) with depth across 
the geographical directions (3.5-6.9 µg g\(^{-1}\) soilh\(^{-1}\)). Concentrations of Arylsulfatase (AS) increased by 
30.2%, 64.3% and 68.3% from the north, the east, and the west respectively to the center of the shrub. 
AS values had also increased by 71%, this time, from the center of the shrub to the south. With the 
southern direction, showed a highly significant difference (Figures 5 and 6), not only from the soil 
surface down to 20 cm (11.8-4.6 µg g\(^{-1}\) soilh\(^{-1}\)), but also with the east, west and north directions. 
Outside the canopy (3R), highly significant differences were noticed (3.6–6.9 µg g\(^{-1}\) soilh\(^{-1}\)) with depth 
across the directions and the center (6.3–1.2 µg g\(^{-1}\) soilh\(^{-1}\)). It was also noted that 35.9%, 16.7%, 
46.3%, and 68.3% from the north, the east, and the west respectively to the center of the shrub.
168.1%, and 9.8% of AS activities were reduced from the distance 1R to 3R with the north, east, south, and east directions, at 10 cm depth (Figure 5). At 20 cm depth, the same trend was noted, with an AS activity equal in the south, which led to the statement that as a biochemical property, AS were sensitive to environmental and management practices, therefore they could be good soil quality indicators (Dick, 1994, Baligar and Wright, 1991).

**β-Glucosidase activity**

Highly significant differences were showed in β-Glucosidase (β-G) activity with depths (75.4-24.2 µg g⁻¹ soilh⁻¹) and significant difference across directions (40.9-26.3-µg g⁻¹ soilh⁻¹) (Figures 5 and 6). At 3R, significant differences were noted (41.0–26.3 µg g⁻¹ soilh⁻¹) with soil depths across geographical directions (75.4–9.8 µg g⁻¹ soilh⁻¹). Soil enzyme activities are directly proportional to the content of soil organic carbon (Baligar et al, 1991). They are higher in surface than in subsurface horizons and follow the distribution of organic C in the soil profile (Frankenberger and Tabatabai, 1991a). Distinguishing the fraction of soil enzyme activity most closely associated with the living biomass from residual immobilized activities should significantly improve our ability to link microbial function (expressed enzyme activities) with microbial physiology (nutrient stress) and resource availability.

**Soil respiration**

Under the canopy (1R) Soil respiration (SR) contents did not show any significant difference with depth (0.3-0.4 mg CO₂kg⁻¹) across the directions (0.30 mg CO₂kg⁻¹) in (Figures 5 and 6). The same trend was also noted outside the canopy (3R) with soil depths (0.3-0.4 mg CO₂kg⁻¹) across the directions (0.30–0.4 mg CO₂kg⁻¹). There has been any variability due to environmental conditions. Knowing that microbial respiration (soil respiration), as a soil biological activity, consists of numerous individual activities, soil respiration should result from the degradation of organic matter (e.g. mineralization of harvest residues). It should be about oxygen uptake or carbon dioxide evolution by...
bacteria, fungi, algae and protozoans, and include the gas exchange of aerobic and anaerobic metabolism (Anderson 1982).

**Microbial biomass carbon**

Microbial biomass carbon (MBC) presented, under the canopy (Figures 5 and 6), highly significant differences with depth (105.4-53.0 mg kg\(^{-1}\) soil) across the directions and the center (103.7-40.7 mg kg\(^{-1}\) soil). At a gradient of 3R, highly significant differences in MBC were noted (116.1–60.1 mg kg\(^{-1}\) soil) with depths across directions and the center of the shrub (103.7-25.8 mg kg\(^{-1}\) soil). At 1R distance, MBC contents decreased by 73.7%, 15.1%, and 46.5% with east, south and west directions from the center of the shrub, whereas in a northern direction, a low increase by 1.67% was noted. From that point to a 3R distance, MBC contents were reduced by 7.0%, 6.9%, and 23.3% in the east, south and west directions; in the north, an increase of 10.2% was noted rather.

It was noted that for all these biochemical properties, with the exception of soil respiration, the center of *Guiera senegalensis* held or hosted the highest concentrations/contents of the activities. This was probably due to an accumulation of most litter and residues under environmental and management practices, making aeration available due the wind blowing mostly from the north–north east direction and moisture due the hydraulic lift process. With 98.4% of the land area in the basin under cultivation (Ba et al., 2000), crop residues represent a potential source of C. The biggest percentage of the cultivated land however, is cropped to pearl millet (51.1%) and peanut (38.2%) (Ba et al., 2000) which produce 1.0–2.0 and 0.7–1.0 Mg crop residue ha\(^{-1}\), respectively (Badiane et al., 2000).

**CONCLUSION**

Existing soil chemical and biochemical properties (likely good indicators of soil quality), spatially distributed through native shrubs (a source of soil organic carbon), within a physical environment, mainly characterized by wind blowing dominant directions across a landscape, were likely to play an important role in preventing soil degradation. Indeed, one of the native shrubs (*Guiera senegalensis*) present in an appropriate density, on a fragile landscape susceptible to degradation, due to the nature of
the soil, contributed to soil chemical and biochemical build up beneath and outside the influence of the
shrub canopies and rooting zone, and therefore enhancing soil productivity. The higher pH, soil
organic carbon, soil total nitrogen, extractible phosphorus, microbial biomass, soil respiration, enzyme
activities, and moisture in soil beneath and outside the shrub canopy have important implications for
restoring and reinforcing lands degraded for sustainable agricultural development.

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Source: National Agency for Civil Aviation and Meteorology (ANACIM, 2015)

DD: Dominate direction
WS: Wind speed
Figure 1: Spatial distribution of the soil chemical properties beneath and outside the *Guiera senegalensis* at 10-cm depth. Values for pH, soil organic carbon (SOC), soil total nitrogen (TN), or extractible phosphorus (EP), followed by an asterix (*), are significantly different (P < 0.05).
Figure 2: Spatial distribution of the soil chemical properties beneath and outside the *Guiera senegalensis* canopy at 20-cm depth. Values for pH, soil organic carbon (SOC), soil total nitrogen (TN), or extractible phosphorus (EP), followed by an asterix (*), are significantly different (P < 0.05).
Figure 3: Spatial distribution of the soil chemical properties beneath and outside the *Guiera senegalensis* canopy at 40-cm depth. Values for pH, soil organic carbon (SOC), soil total nitrogen (TN), or extractible phosphorus (EP), followed by an asterix (*), are significantly different (P < 0.05).
Figure 4: Spatial distribution of the soil chemical properties beneath and outside the *Guiera senegalensis* canopy at 80-cm depth. Values for pH, soil organic carbon (SOC), soil total nitrogen (TN), or extractible phosphorus (EP), followed by an asterix (*), are significantly different ($P < 0.05$).
Figure 5: Spatial distribution of the soil biochemical properties beneath and outside the *Guiera senegalensis* canopy at 10-cm depth. Values for arylsulfatase (AS), β-glucosidase (β-G), soil respiration (R) and microbial biomass carbon (MBC), followed by an asterix (*) are significant (P < 0.05); those with two asterix (**) are highly significant (P < 0.1).
Figure 6: Spatial distribution of the soil biochemical properties beneath and outside the *Guiera senegalensis* canopy at 20-cm depth. Values for arylsulfatase (AS), $\beta$-glucosidase ($\beta$-G), soil respiration (R) and microbial biomass carbon (MBC), followed by an asterix (*) are significant ($P < 0.05$); those with two asterix (**) are highly significant ($P < 0.1$).