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

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Authors' contributions

This work was carried out in collaboration between all authors. Authors MD, RPD and MS designed the study. Author MD performed field and lab research, the statistical analysis and wrote the first draft of the manuscript. Authors RPD, MS and AKN assisted with data analyses and literature searches. All authors read and approved the final manuscript.

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ABSTRACT

This study investigated the effect of wind direction on spatial distribution of soil chemical and biochemical properties surrounding the indigenous shrub *Guiera senegalensis* in cropped fields of the semi-arid Sahel. Changes in some soil properties were measured at the center, beneath and outside the shrub canopy in relation to the prevailing wind direction. Results showed that the typical wind speed of 5 ms^{-1} coming from the north-northeast (NNE), had no significant effect on the directional spatial distribution of soil pH, organic carbon (SOC), total nitrogen (TN) and extractible phosphorus (EP); except for EP format the central south that was significantly higher than other

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directional locations (8.2 mg kg^{-1}). In contrast, soil biochemical properties such as arylsulfatase (AS), ß-glucosidase (ß-G), soil respiration (SR), and microbial biomass carbon (MBC) showed a more significant influence of wind direction, except SR. The highest concentrations of AS (11,8 µg g^{-1} soilh^{-1}), ß-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 contribute providing a basis for developing sustainable agriculture.

Keywords: Soil chemical and biochemical properties; G. senegalensis; spatial distribution; wind.

1. INTRODUCTION

In the arid and semiarid Sudano Sahelian zones, soils are inherent of low fertility [1], 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 [2,3]. Agricultural systems of semiarid sub-Saharan Africa are vulnerable because of ongoing anthropogenic soil degradation and declining soil productivity [4]. Organic matter input to the soil has been shown to be critical for improving soil quality and optimising nutrient and water efficiencies, and ultimately crop productivity in these degraded agro-ecosystems [5,6,7]. The improved soil quality beneath the shrub canopy may further stimulate mineralisation and plant availability of nutrients [8,9]. This system has received considerable attention concerning its biophysical interaction with soils and crops [10,11]. A native shrub (*Guiera senegalensis* J.F. Gmel.) is commonly found in farmers' fields in the Senegal Peanut basin, naturally distributed in the landscape [12]. 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 continues to grow, but in farmers' field they are cut at the soil surface and burned just prior to the rainy season [13]. Thus, under current management, this organic matter is not being utilised 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 farmers to increase agricultural acreage and meet food demands [14,15]. 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 utilisation (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 [16] within the so-called "islands of fertility" [17,18]. Additionally, it would be expected that litterfall, root exudates, and root turnover of woody perennial species would stimulate and shift microbial communities. Indeed, [19] reported elevated microbial biomass beneath shrubs influenced in a generating process of "islands of fertility" during decomposition in semi-arid regions. In these environments, the soil beneath the canopy of shrubs typically has higher C and N levels than soils outside the canopy [20]. In addition, the improved water conditions and microclimate beneath the shrub create a favourable environment for biological activity [6]. 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 "ratoon 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 [21]. 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} [6,14], 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 the 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 contributes 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 some soil chemical and biochemical properties beneath and outside the canopy of the *Guiera senegalensis*.

2. MATERIALS AND METHODS

2.1 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 NNE, 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 *Dior* fine sandy, mixed Haplic Ferric Lixisol [22] a leached ferruginous tropical soil. The dominant shrub species at the site is G. *senegalensis*, with stand density of 240 shrubs ha^{-1}.

2.2 Sample Collection

Soil samples were collected from a farmers' field on a 1000-m^2 surface area, in May, prior to the rainy season. From the average density of 240 shrubs ha^{-1}, 30% of the population was considered as the sampling size. Soil samples were then taken randomly from each of the shrubs, components of the sampling size, in three replicates. 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. For the sake of the design (represented by a single shrub), soil samples from the same position (radius from the center and soil depth) taken as composite, 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, ß-glucosidase), only samples taken at 0-10 and 10-20 cm depths were analyzed.

2.3 Soil Laboratory Analysis

Samples for soil C were air dried at room temperature 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) [5].

Soil microbial biomass was determined using the chloroform fumigation-incubation [23].

Arylsulfatase [24], ß-glucosidase [25] and soil respiration [26], soil total N [27], extractible P [28] and soil pH [29] were determined on soil samples.

2.4 Statistical Analysis

The experimental design was set up using comparisons among treatment means from three replicates. Each soil property determined was considered as a treatment. Effects of spatial distribution of the soil chemical and biochemical properties with shrub establishment were analyzed with a comparison between pairs of means. Data collected were first analyzed in mean values, using the least significant difference test (LSD) for equal replication [30]. All that was done to locate any pair of means whose difference exceeds the LSD. 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 CS_3) were used to plot the graphs.

3. RESULTS AND DISCUSSION

3.1 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

Table 1. Monthly means of wind direction and speed (ms^{-1}) over time

Parameters	Years	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
DD	2000	NNE	NNE	N	N	N	NNW	NW	NW	NW	N	N	NNE
WS		5.0	4.6	4.3	4.9	4.9	3.9	3.4	2.8	2.8	3.4	3.8	4.2
DD	2001	NNE	NNE	NNE	N	WNW	WNW	NW	NW	NW	NNW	N	NE
WS		4.1	4.2	4.6	4.8	3.9	3.5	3.7	3.5	3.4	3.3	4.3	4.1
DD	2002	NNE	N	NNE	N	N	NW	NW	NNW	SW	N	N	NNE
WS		4.4	4.5	4.7	5.0	4.5	3.6	3.8	3.2	3.7	3.6	4.9	4.5
DD	2003	N	N	N	N	NNW	NW	WNW	WNW	NNW	N	N	NNE
WS		5.2	5.5	5.1	5.6	4.6	4.1	3.4	3.7	3.1	3.4	4.9	4.5
DD	2004	NNE	NNE	N	N	N	NW	WNW	NNW	WNW	N	N	NNE
WS		5.0	4.9	5.1	5.6	5.1	3.8	3.6	3.6	3.0	3.6	4.9	4.2
DD	2005	NNE	N	NNE	N	NW	NNW	W	WNW	WNW	NNW	NNE	NNE
WS		4.9	6.1	5.5	5.8	4.0	4.2	3.6	3.2	3.5	3.4	5.3	4.8
DD	2006	NNE	N	N	N	N	NW	NW	NW	N	N	N	NNE
WS		5.7	5.3	5.2	5.2	5.0	4.0	3.8	3.5	3.4	3.8	4.1	5.1
DD	2007	N	N	N	N	N	NNW	NW	N	N	N	N	N
WS		5.1	5.4	6.0	5.6	5.1	3.9	3.7	3.7	3.1	3.9	5.2	5.5
DD	2008	NNE	N	N	N	N	N	NW	NNW	NW	N	N	N
WS		5.0	5.4	5.1	5.3	5.4	4.0	4.0	3.6	2.7	3.5	4.5	5.4
DD	2009	N	N	N	N	N	NNW	NW	NW	N	N	N	N
WS		6.0	6.5	6.1	5.9	4.5	4.1	3.7	3.1	3.3	3.6	4.1	4.9
DD	2010	N	N	N	N	N	NNW	NW	WNW	S	NW	N	N
WS		4.5	4.9	5.3	5.4	5.1	4.4	3.7	3.5	3	3.2	4.1	5.4
DD	2011	N	N	N	N	N	NNW	NW	NW	NW	N	N	N
WS		5.1	5.4	6.1	5.5	5.2	4.0	3.8	3.5	3.0	3.6	5.2	5.3
DD	2012	N	N	N	N	N	WNW	NW	W	WNW	N	N	N
WS		5.3	5.9	5.2	6	4.6	3.8	3.6	3.6	3	3.4	5.1	5.5
DD	2013	N	N	N	N	N	NW	NW	NNW	NW	N	N	N
WS		4.9	5.1	5.5	5.3	3.6	3.1	3.9	3.8	3.1	3.1	4.5	4.7
DD	2014	N	N	N	N	N	NNW	NW	WNW	WNW	NNW	N	N
WS		5.3	5.9	5.6	5.2	5.0	3.6	3.9	3.4	3	3.5	5.4	5.2

Source: National Agency for Civil Aviation and Meteorology (ANACIM, 2015)
DD: Dominate direction, WS: Wind speed

(Figs. 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 [31], the presence of *G. senegalensis* which is a source of organic matter [32] may have contributed to maintain the acidity to this level.

3.2 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 (Fig. 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 (Figs. 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%) (Fig. 1). A slight decrease in SOC contents was noted from a 1R distance to 3R (Fig. 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 [31] 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 were degraded at the top level and its substance was accumulating at the sub-soil level, due probably to the hydraulic lift effect [6]. 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. [14] 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.

3.3 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), concentration values for TN 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 (Figs. 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.

3.4 Soil Extractible P

Soil extractible P (EP) contents showed significant difference ($P < 0.05$) with depth (5.7–3.0 mg kg^{-1}) and highly significant difference ($P < 0.1$) 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}) (Figs. 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 dominant 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).

3.5 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. The southern direction was highly significantly different (Figs. 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. Samples were highly significantly different (3.6–6.9 µg g^{-1} $soilh^{-1}$) outside the canopy (3R) 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%, 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 (Fig. 5). At 20 cm depth, the same trend was observed 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 [33,34].

3.6 ß-Glucosidase Activity

The *ß-Glucosidase* **(**ß-G) activities were highly significantly different with depths (75.4- 24.2 µg g^{-1} $soilh^{-1}$) and significantly different across directions (40.9-26.3-µg g^{-1} $soilh^{-1}$) (Figs 5 and 6). At 3R, significant differences were observed (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 [35]. They are higher in surface than in subsurface horizons and follow the distribution of organic C in the soil profile [36]. 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.

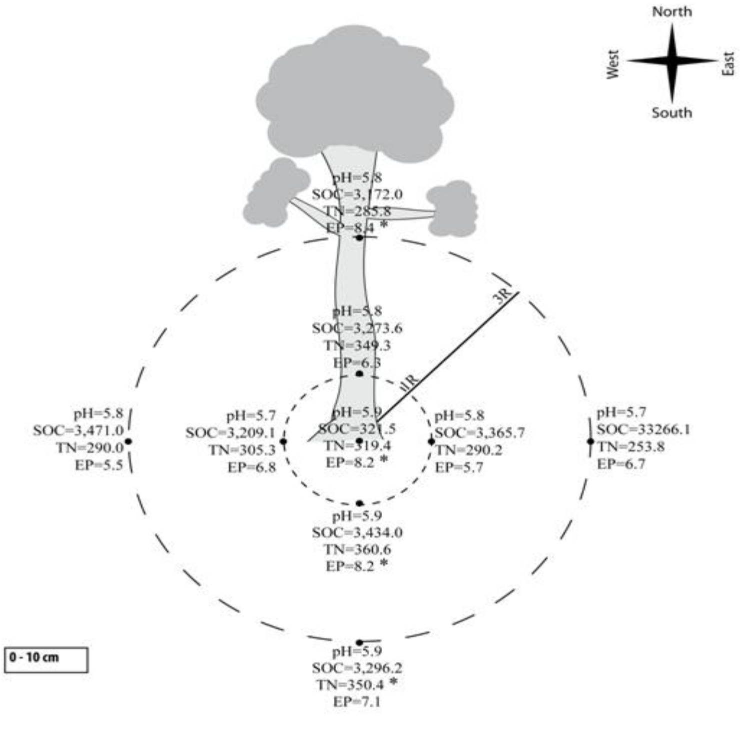

Fig. 1. Spatial distribution of some soil chemical properties beneath and outside the *Guiera senegalensis* at 10-cm depth. Values for pH, soil organic carbon (SOC), soil total nitrogen (TN), or extractible phosphorus (EP), followed by an asterix (*), are significantly different ($P < 0.05$)

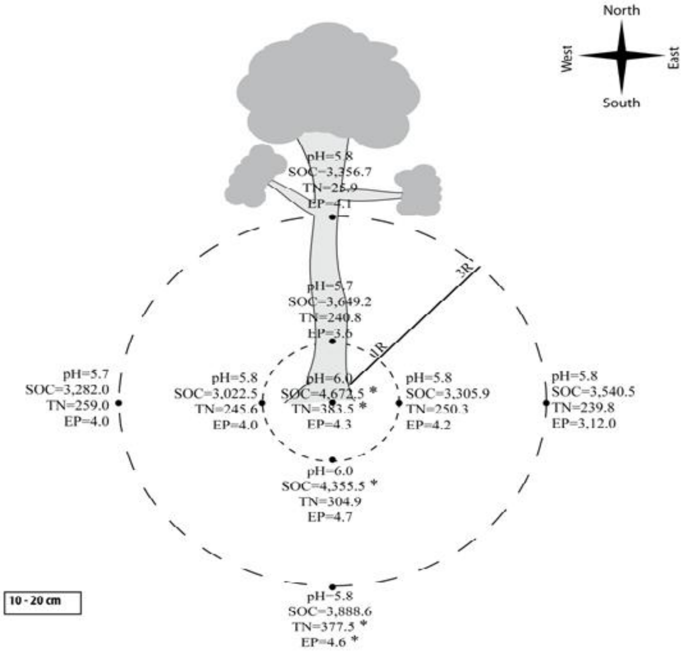

Fig. 2. Spatial distribution of some soil chemical properties beneath and outside the *Guiera senegalensis* canopy at 20-cm depth. Values for pH, soil organic carbon (SOC), soil total nitrogen (TN), or extractible phosphorus (EP), followed by an asterix (*), are significantly different (P < 0.05)

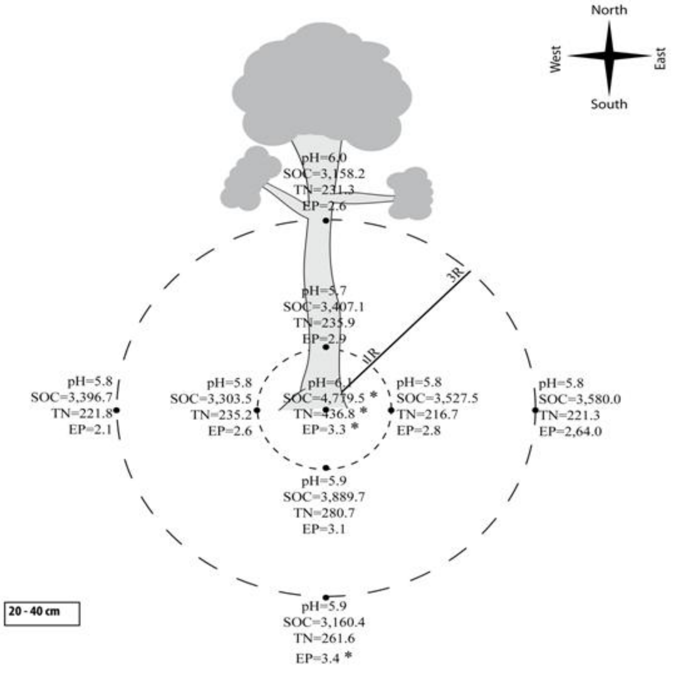

Fig. 3. Spatial distribution of some soil chemical properties beneath and outside the *Guiera senegalensis* canopy at 40-cm depth. Values for pH, soil organic carbon (SOC), soil total nitrogen (TN), or extractible phosphorus (EP), followed by an asterix (*), are significantly different (P < 0.05)

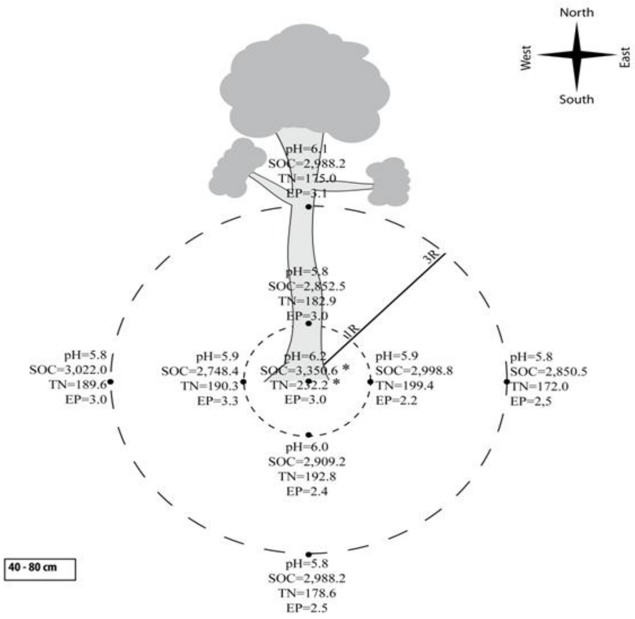

Fig. 4. Spatial distribution of some soil chemical properties beneath and outside the *Guiera senegalensis* canopy at 80-cm depth. Values for pH, soil organic carbon (SOC), soil total nitrogen (TN), or extractible phosphorus (EP), followed by an asterix (*), are significantly different (P < 0.05)

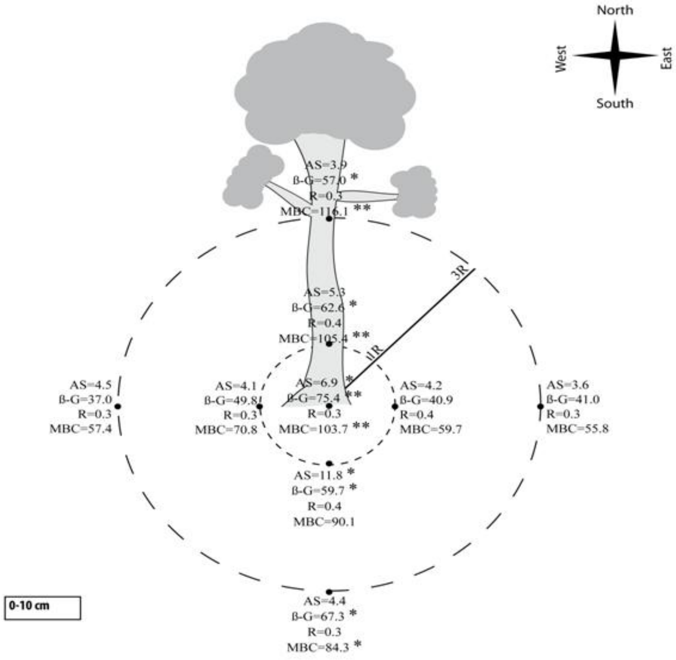

Fig. 5. Spatial distribution of some soil biochemical properties beneath and outside the *Guiera senegalensis* canopy at 10-cm depth. Values for arylsulfatase (AS), ß-glucosidase, (ß-G), soil respiration (R) and microbial biomass carbon (MBC), followed by an asterix (*) are significant (P < 0.05); those with two asterix (**) are highly significant (P < 0.1)

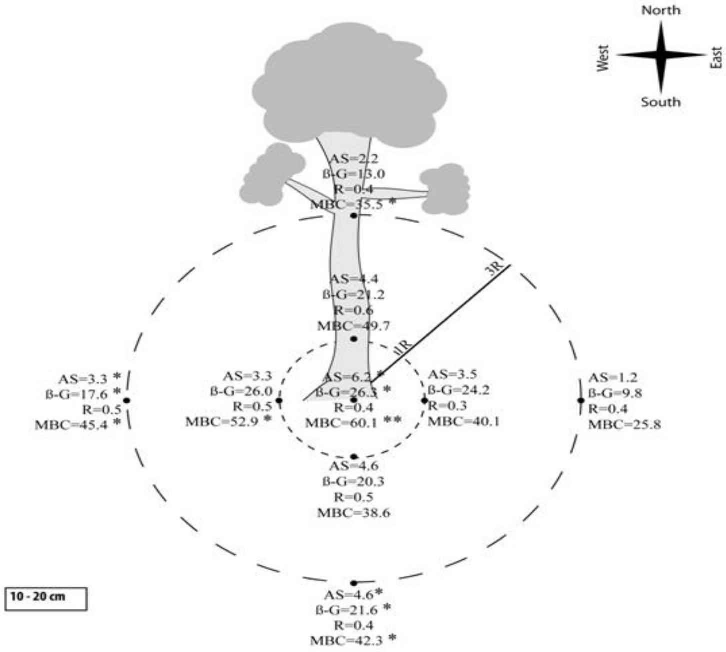

Fig. 6. Spatial distribution of some soil biochemical properties beneath and outside the *Guiera senegalensis* canopy at 20-cm depth. Values for arylsulfatase (AS), ß-glucosidase, (ß-G), soil respiration (R) and microbial biomass carbon (MBC), followed by an asterix (*) are significant ($P < 0.05$); those with two asterix (**) are highly significant ($P < 0.1$)

3.7 Soil Respiration

Under the canopy (1R) Soil respiration (SR) contents did not show any significant difference with depth (0.3-0.4 mg CO_2kg^{-1}) across the directions (0.30 mg CO_2kg^{-1}) in (Figs 5 and 6). The same trend was also observed outside the canopy (3R) with soil depths (0.3-0.4 mg CO_2kg^{-1}) across the directions (0.30–0.4 mg CO_2kg^{-1}). There was no 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 [26].

3.8 Microbial Biomass Carbon

Microbial biomass carbon contents (MBC) presented, under the canopy (Figs. 5 and 6), were highly significantly different 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, MBC values were also highly significantly different (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 observed rather.

It was observed that for all these biochemical properties, with the exception of soi 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 [37], 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%) [37] which produce 1.0–2.0 and 0.7–1.0 Mg crop residue ha^{-1}, respectively [31].

4. CONCLUSION

Existing soil chemical and biochemical properties (likely useful indicators of soil quality), spatially distributed through native shrubs (a source of soil organic carbon), within a physical environment, mainly characterised by wind blowing dominant directions across a landscape, were likely to play an essential 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 to root 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 the soil beneath and outside the shrub canopy have significant implications for restoring and reinforcing lands degraded for sustainable agricultural development.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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