

Predictive physico-chemical model for soil quality index in a long-term green manure farming system at tropical conditions, North-eastern Brazil

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Abstract

Soil quality index shed light on soil health and its capacity to sustain high primary production. It also can assist decision-making in farming systems by integrating this valuable product into soil management planning. However, the currently existing models are based on rather local data, and thus, there is a lack of predictive tools to monitor soil quality on farming systems at tropical conditions. We characterized soil physico-chemical properties, plant biomass production under a 6-year experiment in a sandy soil from Tropical ecosystem, using ten treatments: *Brachiaria decumbens*, *Canavalia ensiformis*, *Crotalaria juncea*, *Crotalaria ochroleuca*, *Crotalaria spectabilis*, *Lablab purpureus*, *Mucuna pruriens*, *Neonotonia wightii*, *Pennisetum glaucum*, and *Stilozobium aterrimum*. We found that most of the soil physico-chemical properties were correlated with each other by Pearson's correlation analysis. On the other hand, RDA illustrated that shoot dry biomass was related to soil C stock, K⁺, macro- and microporosity. Soil pH, Al³⁺, Ca²⁺, Mg²⁺, K⁺, Olsen's P, Na⁺, soil C stock, bulk density, microporosity, macroporosity, and permanent wilting point were the main factors driving primary production in our long-term study. Our findings suggest that: 1) a consecutive green manure practice without any input of fertilizers after 6 years changed positively by increasing soil fertility (e.g., Ca²⁺, Mg²⁺, K⁺ and Olsen's P), and improving plant growth and soil quality in tropical savanna climate conditions; and 2) the 33 multivariate predictive models may provide a deeper view about the benefits of using plant species as green manure by creating positive plant-soil feedback thus promoting soil quality.

Introduction

The importance of the green manure farming system as a key management practice of both soil quality and ecosystem processes (e.g., soil organic matter inputs and nutrient cycling) at scales ranging from regional to global have been widely described (He et al. 2020; Khan et al. 2020). Among them, soil physical-chemical properties and net primary production (e.g., shoot and root biomass production) are especially relevant because of their environmental and economic importance (Fernández et al. 2020). Soil physical-chemical properties influence soil organism fitness, plant growth and biomass production (Cardone et al. 2020; Yang et al. 2020), increasing net primary production and creating a positive plant-soil feedback by improving litter deposition and recycling soil nutrients (Chen et al. 2020; Wang et al. 2020; Li et al. 2021). In green manure farming systems, two main effects are widely reported: (i) protecting soil surface thus acting as cover crops; and (ii) increasing soil organic matter when incorporated into soil profile (Gabriel et al. 2021; Torres et al. 2021). From an economic point of view, the use of green manure practice provides important benefits to smallholder farmers by reducing costs with fertilizers and other soil conditioners (Zhou et al. 2020). In fact, this practice reduces in 69% the overall costs with only organic fertilizers in certain regions such as the Brazilian Northeast (Nascimento et al. 2021).

Within this context, it is important to have accurate estimations of soil quality at tropical ecosystem, not only for smallholder farmers to integrate them into soil management planning, but also to comply with the low carbon agriculture requirements proposed by the Brazilian government (Stabile et al. 2020;

Vinholis et al. 2021). Empirical models can contribute to these two tasks by providing quantitative understanding of the impact of several plant species cultivated as green manure on soil ecosystem, allowing to integrate the management of different plant species in existing management practices at the tropics (Sharma et al. 2021). In Brazil, different soil quality models at local and regional scales have been developed so far, mainly considering both soil chemical and biological database (dos Santos et al. 2021). Forstall-Sosa et al. (2020) developed a model for predicting soil quality as a function of abundance of Carabidae, Formicidae and Termitidae, shoot dry biomass, soil pH and available Olsen's P in green manure farming systems of Brazilian Northeast. Later, Kormann et al. (2021) developed similar model as a function of rainfall, soil pH, and abundance of Lumbricidae, Spirobolida and Staphylinidae for agroforestry systems and Mixed Ombrophilous Forest in Brazilian Southern. However, such models require a very trained taxonomist to classify an entire soil biota at Family level (Heydari et al. 2020). On the other hand, there is a lack of models enabling accurate enough prediction of soil quality. The main reason behind this problem is the difficulty to obtain constant quantities of data over long-term experiments, especially if the model considers possible changes in meteorological conditions (Andrade et al. 2020).

In this study, we have used data from a green manure farming system because this experiment is monitored for changes in soil physical, chemical, and biological properties using permanent plots established in tropical environment since 2014. Previous works have shown that cover crops used as green manure are key for improving soil organic carbon, shoot dry biomass production, and soil biota diversity and abundance (Souza et al. 2018; Melo et al. 2019; Forstall-Sosa et al. 2020; Nascimento et al. 2021). Leguminous plant species seem to promote a positive plant-soil feedback as described by Souza and Santos (2019). However, we need to understand the role of root biomass production into soil profile, and how it can contribute to soil quality. Thus, we hypothesized that (i) plant species with high root biomass production over a temporal scale may improve soil quality by promoting some physical and chemical properties as described by Laurindo et al. (2021); and (ii) soil quality index will follow certain soil-plant patterns and, therefore, the variability among plots in relation to plant, soil physical, and soil chemical properties was also studied as proposed by Sánchez-González et al. (2019).

The main aim of this study was to develop a predictive physico-chemical model for soil quality index in a long-term green manure farming system, taking into account plant dry biomass (shoot and root), soil pH, soil exchangeable cations (K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Al^{3+}), sum of bases, cation exchange capacity (CEC), soil organic carbon, base saturation, soil bulk density, soil macro- and microporosity, total porosity, soil field capacity, permanent wilting point, available water content, soil aeration capacity, and soil available water capacity as explanatory variables. The predictive model was fitted for all the studied plant species (*Brachiaria decumbens* Stapf. cv. Basilisk, *Canavalia ensiformis* (L.) DC, *Crotalaria juncea* L, *Crotalaria ochroleuca* G. Don, *Crotalaria spectabilis* Roth, *Lablab purpureus* (L) Sweet, *Mucuna pruriens* (L) DC, *Neonotonia wightii* (Wight & Arn.) J.A. Lackey, *Pennisetum glaucum* L, and *Stilozobium aterrimum* Piper & Tracy), based on data from 50 permanent sample plots.

Material And Methods

Sampling design and data collection

The study area was located at the “Chã-de-Jardim” Experimental Station, Agrarian Sciences Centre, Federal University of Paraiba, Areia, Paraiba, Brazil (06°58'12” S, 35°42'15” W, altitude 619 m above sea level). In total 50 permanent plots (24 m² each plot) which were monitored since 2014 have been considered in this study. We have used the same treatments in each studied year (for more details about the studied treatments see Souza et al. 2018, Melo et al. 2019, Forstall-Sosa et al. 2020, Nascimento et al. 2021). Sampling was carried out in each studied year from July to December, and this study shows the results obtained until 2019. The climatic conditions of the study area are classified as tropical with dry-summer characteristics (As-type climate following Köppen-Geiger climate classification), average annual precipitation, and mean air temperature of 1.300 mm and +22.5 °C, respectively (Nascimento et al. 2021). The soil type of the studied site was classified as a Regosol with sandy loam texture (WRB 2006).

All the considered plots have been monitored during growing season (July to December), with data recorded for least 6 consecutive years. The field experiment was arranged in a randomized block design with five blocks and ten treatments (e.g., different plants species following a monocropping system per plot) (Table 1). The size of plots was 6 x 4 meters, with eight lines spaced of 0.5 meters. The seeding was realized rate of 400 seeds m⁻² at 2 cm depth. We have analysed plant dry biomass production (shoot and root), soil physical, and soil chemical properties.

Table 1. Studied plant species (eight Fabaceae species and only two Poaceae species) used as green manure and their characteristics during the field experiment.

Plant species	Family	Flowering (days)	Plant density (plants plot ⁻¹)
<i>Brachiaria decumbens</i> Stapf.	Poaceae	150 - 180	480
<i>Canavalia ensiformis</i> (L) DC	Fabaceae	62 - 70	480
<i>Crotalaria juncea</i> L	Fabaceae	53 – 56	240
<i>Crotalaria ochroleuca</i> G. Don	Fabaceae	52 – 58	240
<i>Crotalaria spectabilis</i> Roth	Fabaceae	72 – 78	240
<i>Dolichos lablab</i> (L) Sweet	Fabaceae	87 – 95	480
<i>Mucuna pruriens</i> (L) DC	Fabaceae	121 - 124	240
<i>Neonotonia wightii</i> (Wight & Arn.) J.A. Lackey	Fabaceae	69 - 75	480
<i>Pennisetum glaucum</i> L	Poaceae	60 - 66	480
<i>Stilozobium aterrimum</i> Piper & Tracy	Fabaceae	119 - 124	480

Plant (shoot and root) dry biomass production

Shoot dry biomass production from each studied plot was recorded for 6 consecutive years and this variable was estimated as described by Forstall-Sosa et al. (2020). Initially, we have selected ten plants per plot with homogenous characteristics of plant height and diameter near soil surface. Subsequently, all plants were harvested at 5-cm above the soil surface and the shoot dry biomass of these ten plants was used to estimate plant biomass production in kg ha^{-1} . For root dry biomass, we used the method to collect soil monoliths ($20 \times 20 \times 20$ cm) as described by Souza and Santos (2018). We collected ten soil monoliths in each studied plot. After that, we wrapped them with plastic film and transported all the monoliths with minimal disturbance until analysis. During our analysis, and to estimate root dry biomass, we collected roots from the soil monoliths. Roots in these layers were washed using a 0.5-mm nylon mesh bag. Shoot and root dry biomass (g) was determined after drying the samples for 48 h at 65°C .

Soil physico-chemical properties

Soil samples with disturbed and undisturbed structure were collected in all plot 90 days after the plant species were incorporated to soil profile. The soil samples with undisturbed structure (e.g., soil samples collected using metallic cylinders with 100 cm^3 each) were used to determine the soil physical properties. While the disturbed samples were used to determine soil chemical properties. The disturbed soil samples were packed separately in plastic bags, air-dried, and passed through a 2 mm mesh sieve (Teixeira et al. 2017). The soil parameters evaluated were soil pH, soil exchangeable cations (K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Al^{3+}), sum of bases, cation exchange capacity (CEC), soil organic carbon, base saturation, soil bulk density, soil microporosity, total porosity, soil macroporosity, soil field capacity, permanent wilting point, available water content, soil aeration capacity, and soil available water capacity. Details of methods used to measure each treatment can be found in Nascimento et al. (2021).

Statistical analysis

All data was analysed with using R statistical software (R Core Team 2018). Pearson's correlation between soil physico-chemical properties and plant fitness (e.g., shoot and root dry biomass production) was tested using the *rcorr* function from the *Hmisc* package to examine the bivariate correlation between soil properties and plant fitness (e.g., shoot and root dry biomass) with data from all the studied years and plots. Next, we arcsin square root transformed all dependent variables to meet assumption of normal distributions. We created predictive models using the *step* function in the *stats* package to verify the effect of individual or combined variables (soil physico-chemical properties, shoot dry biomass, and root dry biomass) on each specific studied variable. We also used treatment (e.g., the studied plant species used as green manure) and the years of their cultivation as fixed effect as described by Rosenfield and Müller (2020). Plots and blocks were included as a random effect in each model.

Soil quality index

An explanatory principal component analysis was performed to explore all variability among years with respect to explore the effects of the studied plant species on soil properties and plant biomass production. The PCA were conducted with *rda* function in the *vegan* package. A soil quality index was calculated using the PCA-LSF-SQIw approach as described by Forstall-Sosa et al. (2020), which combines soil physical and chemical characteristics, and plant biomass production measured at all studied plots. Based on this approach we developed a model (Eq. 1) to determine the soil quality index (SQI). High values of ISQ indicated a high-class soil that provides plant biomass production, soil structure without negative effects to soil ecosystem.

$$\text{Eq.1 SQI} = (53.94 \times N - R) + (27.37 \times N - P) + (5.43 \times N - S) + (3.17 \times N - Ca) + (2.15 \times N - K) + (1,731 \times N - SCS) + 6.22$$

Where: N - R = Normalized values of root dry biomass (g cm^{-3}), N - P = Normalized values of Olsen's available P (mg dm^{-3}), N - S = Normalized values of shoot dry biomass (t ha^{-1}), N - Ca = Normalized values of exchangeable Ca ($\text{cmol}_c \text{ dm}^{-3}$), N - K = Normalized values of exchangeable K ($\text{cmol}_c \text{ dm}^{-3}$), and N - SCS = Normalized values of soil carbon stock (t C ha^{-1}). All normalized values were obtained dividing the mean of each component by their scores obtained in a PCA analysis.

Results

Pearson's correlation showed that most of the soil physico-chemical properties were correlated with each other (Fig. 1). Soil pH was positively correlated with exchangeable Ca ($p < 0.001$), exchangeable Mg ($p < 0.001$), available Olsen's P ($p < 0.001$), sum of bases ($p < 0.001$), soil carbon stock ($p < 0.001$), and bulk density ($p < 0.001$), whereas it was negatively correlated with exchangeable Al ($p < 0.001$), exchangeable Na ($p < 0.001$), $\text{H}^+ + \text{Al}^{3+}$ ($p < 0.01$), shoot dry biomass ($p < 0.05$), root dry biomass ($p < 0.05$), and physical properties ($p < 0.001$) except bulk density and microporosity. Exchangeable Al was positively correlated with exchangeable Na ($p < 0.001$), and $\text{H}^+ + \text{Al}^{3+}$ ($p < 0.001$), whereas it was negatively correlated with exchangeable Ca ($p < 0.001$), K ($p < 0.01$), available Olsen's P ($p < 0.01$), sum of bases ($p < 0.001$), base saturation ($p < 0.001$), root dry biomass ($p < 0.05$), and soil microporosity ($p < 0.05$). Exchangeable Ca was positively correlated with available Olsen's P ($p < 0.001$), sum of bases ($p < 0.001$), CEC ($p < 0.001$), base saturation ($p < 0.01$), root dry biomass ($p < 0.05$), and bulk density ($p < 0.01$), whereas it was negatively correlated with exchangeable Na ($p < 0.001$), soil organic carbon ($p < 0.01$), soil carbon stock ($p < 0.01$), and all physical properties ($p < 0.001$) except bulk density and soil microporosity. Exchangeable Mg was positively correlated with available Olsen's P, sum of bases ($p < 0.001$), CEC ($p < 0.001$), base saturation ($p < 0.001$), and bulk density ($p < 0.001$), whereas it was negatively correlated with exchangeable Na ($p < 0.05$), $\text{H}^+ + \text{Al}^{3+}$ ($p < 0.01$), and all physical properties ($p < 0.001$) except soil microporosity. Exchangeable K was positively correlated with exchangeable Na ($p < 0.01$), base saturation ($p < 0.001$), soil organic carbon ($p < 0.01$), soil carbon stock ($p < 0.001$), shoot dry biomass ($p < 0.001$), and all physical properties ($p < 0.001$) except bulk density and soil microporosity, whereas Exchangeable K was negatively correlated with $\text{H}^+ + \text{Al}^{3+}$ ($p < 0.001$), CEC ($p < 0.01$), root dry biomass ($p <$

0.05), and bulk density ($p < 0.01$). Available Olsen's P was positively correlated with sum of bases ($p < 0.001$), base saturation ($p < 0.001$), and bulk density ($p < 0.01$), whereas it was negatively correlated with exchangeable K ($p < 0.001$), $H^+ + Al^{3+}$ ($p < 0.001$), soil organic carbon ($p < 0.05$), root dry biomass ($p < 0.01$), and all physical properties ($p < 0.001$), except bulk density and soil microporosity. Exchangeable Na was positively correlated with $H^+ + Al^{3+}$ ($p < 0.05$), soil organic carbon ($p < 0.001$), soil carbon stock ($p < 0.001$), root dry biomass ($p < 0.01$), and all physical properties ($p < 0.001$) except bulk density and soil microporosity, whereas exchangeable Na was negatively correlated with sum of bases ($p < 0.001$), CEC ($p < 0.01$), base saturation ($p < 0.001$), and bulk density ($p < 0.001$). $H^+ + Al^{3+}$ was positively correlated with CEC ($p < 0.001$), root dry biomass ($p < 0.05$), field capacity ($p < 0.05$), and permanent wilting point ($p < 0.01$), whereas it was negatively correlated with sum of bases ($p < 0.01$), base saturation ($p < 0.001$), and soil microporosity ($p < 0.05$). Sum of bases was positively correlated with CEC ($p < 0.001$), base saturation ($p < 0.001$), and bulk density ($p < 0.001$), whereas it was negatively correlated with soil organic carbon ($p < 0.05$), root dry biomass ($p < 0.01$), and all physical properties ($p < 0.001$) except bulk density. CEC was positively correlated with bulk density ($p < 0.01$), whereas it was negatively correlated with shoot dry biomass ($p < 0.05$), and all physical properties ($p < 0.01$), except bulk density. Base saturation was negatively correlated with root dry biomass ($p < 0.01$), all physical properties ($p < 0.01$) except soil microporosity. Soil organic carbon was positively correlated with soil carbon stock ($p < 0.001$), shoot dry biomass ($p < 0.001$), and all physical properties except bulk density, which had a negative correlation with it ($p < 0.001$). Soil carbon stock was positively correlated with shoot dry biomass ($p < 0.01$), and all physical properties ($p < 0.05$) except bulk density, whereas it was negatively correlated with bulk density ($p < 0.05$). Shoot dry biomass was positively correlated with all physical properties ($p < 0.001$) except bulk density which presented a negative correlation with it ($p < 0.05$). Root dry biomass was positively correlated with all physical variables ($p < 0.001$) except bulk density, and soil macro- and microporosity. Bulk density was negatively correlated with all physical variables ($p < 0.001$) except soil microporosity. Microporosity was positively correlated with all physical properties ($p < 0.01$). Finally, the remain physical properties (e.g., soil macroporosity, soil porosity, field capacity, permanent wilting point, available water content, soil aeration capacity, and soil available water capacity) were positively correlated to each other (Fig. 1).

Redundancy analyses (RDA) illustrated that shoot dry biomass was related to soil C stock, exchangeable K (Fig. 2 a), macroporosity, and microporosity (Fig. 2b). All chemical and physical properties could explain 74.26 and 69.59 %, respectively of primary production variation (Monte Carlo permutation test with 999 permutation, $p < 0.001$). Conditional effects show that the main factors driving primary production were soil pH, exchangeable Al, exchangeable Ca, exchangeable Mg, exchangeable K, available Olsen's P, exchangeable Na, soil C stock (Fig. 2a), bulk density, microporosity, macroporosity, and permanent wilting point (Fig. 2b)

Based on the results obtained by stepwise procedure, we created 33 multivariate predictive models to estimate primary production (e.g., shoot and root dry biomass production) and soil physico-chemical properties as a function of plant species (treatments), studied years and the interaction between plant dry

biomass production and changes into soil physico-chemical properties in tropical ecosystem. All the proposed models showed significant differences between treatments and years for several studied variables (Table 2).

Table 2. Predictive models between physico-chemical properties and primary production

Model	F-value	Significance	R ² _{adj}
Soil pH ~ Ca + Mg + K + Na + treatment + year	16.25	< 0.001	0.21
Soil pH ~ Field capacity + Permanent wilting point + SAC + Soil porosity + treatment + year	13.76	< 0.001	0.30
Exchangeable Al ~ Exchangeable Na + (H ⁺ +Al ³⁺) + treatment + year	24.15	< 0.001	0.28
Exchangeable Al ~ Exchangeable Ca + Exchangeable K + Base saturation + Microporosity + treatment + year	18.11	< 0.001	0.36
Exchangeable Ca ~ Olsen's P + CEC + Base saturation + treatment + year	36.81	< 0.001	0.47
Exchangeable Ca ~ Exchangeable Na + SAC + treatment + year	25.91	< 0.001	0.29
Exchangeable Mg ~ Available P + Sum of bases + CEC + Base saturation + treatment + year	27.63	< 0.001	0.47
Exchangeable Mg ~ Exchangeable Na + (H ⁺ +Al ³⁺) + SAC + treatment + year	13.52	< 0.001	0.23
Exchangeable K ~ Exchangeable Na + Base saturation + SOC + Shoot dry biomass + treatment + year	20.09	< 0.001	0.39
Exchangeable K ~ (H ⁺ +Al ³⁺) + Root dry biomass + Bulk density + treatment + year	10.61	< 0.001	0.19
Olsen's P ~ Sum of bases + Base saturation + Bulk density + treatment + year	17.42	< 0.001	0.29
Olsen's P ~ (H ⁺ +Al ³⁺) + Field capacity + treatment + year	29.42	< 0.001	0.32
Exchangeable Na ~ SOC + Soil C stock + Microporosity + Field capacity + SAC + treatment + year	44.50	< 0.001	0.64
Exchangeable Na ~ Sum of bases + CEC + Base saturation + Bulk density + treatment + year	14.30	< 0.001	0.30
(H ⁺ +Al ³⁺) ~ Permanent wilting point + treatment + year	4.72	< 0.05	0.03
(H ⁺ +Al ³⁺) ~ Sum of bases + Base saturation + Microporosity + treatment + year	694.1	< 0.001	0.94
Sum of bases ~ CEC + Base saturation + treatment + year	3306	< 0.001	0.98
Sum of bases ~ SOC + Macroporosity + Microporosity + Permanent wilting point + SAC + treatment + year	26.95	< 0.001	0.52
CEC ~ Bulk density + treatment + year	6.17	< 0.001	0.04
CEC ~ AWC + SAC + treatment + year	18.40	< 0.001	0.22
Base saturation ~ Root biomass + Microporosity +	16.07	< 0.001	0.38

Soil porosity + Permanent wilting point + SAC + treatment + year			
SOC ~ Soil C stock + Bulk density + Shoot biomass + Field capacity + AWC + treatment + year	1269.09	< 0.001	0.98
Soil C stock ~ Bulk density + Shoot biomass + Microporosity + Field capacity + AWC + treatment + year	8.56	< 0.001	0.24
Shoot biomass ~ Bulk density + Field capacity + Permanent wilting point + SAC + treatment + year	8.87	< 0.001	0.20
Root biomass ~ Permanent wilting point + AWC + SAC + treatment + year	7.51	< 0.001	0.14
Bulk density ~ Microporosity + Soil porosity + SAC + treatment + year	37.66	< 0.001	0.48
Microporosity ~ Macroporosity + Soil porosity + Field capacity + treatment + year	1383.00	< 0.001	0.97
Macroporosity ~ SAC + treatment + year	106.4	< 0.001	0.46
Soil porosity ~ SAC + treatment + year	318.1	< 0.001	0.72
Field capacity ~ Permanent wilting point + AWC + treatment + year	9251.00	< 0.001	0.99
Permanent wilting point ~ AWC + SAC + treatment + year	924.7	< 0.001	0.93
AWC ~ SAWC + CAS + treatment + year	8223.02	< 0.001	0.99
SAWC ~ SAC + treatment + year	1221.02	< 0.001	0.91

Soil biological quality index was reduced when *C. juncea*, *C. ochroleuca*, and *P. glaucum* plants were cultivated in our experiment. We found the highest values of soil biological quality index on the plots where *N. wightii* was cultivated (628.65 ± 109.57). There were no significant differences between *C. ensiformis*, *C. spectabilis*, *D. lablab*, *M. pruriens*, and *S. aterrimum* on soil quality index. Overall, the soil biological quality index was affected positively by all the studied plant species after 6 years of their cultivation and incorporation into soil profile (Fig. 3).

Discussion

Our results emphasize the long-term influence of different plant species used as green manure on soil physico-chemical properties, plant biomass production (e.g., shoot and root), and soil quality in a Tropical ecosystem. Essentially, we wanted to understand how the biomass incorporation of green manure into soil profile created a positive plant-soil feedback by improving soil properties without any input of fertilizers or soil conditioners on soil quality. Our results revealed significant correlations between all studied variables including soil ecosystem (represented by soil physico-chemical properties) and

primary production (represented by shoot and root dry biomass production). Accordingly, to the studies done by Souza et al. (2018) and Melo et al. (2019), plant species used as green manure such as leguminous plant species can promote positive changes in soil physico-chemical properties by increasing soil C stock, nutrient cycling, soil water infiltration, and soil aeration capacity, especially when their plant residue is fully incorporated into soil profile (Austin et al. 2017, Demir and Işık, 2019; Ashworth et al. 2019). In our study, we found that plant species used as green manure, such as *N. wightii*, that showed in all studied years high root biomass production, and have improved soil available P, Ca²⁺, K⁺, and soil C stock through its biomass incorporation into soil profile. These results agree with previous studies done by Nascente and Stone (2018), Souza et al. (2018), and Mortensen et al. (2021), which reported that soil ecosystems with constant nutrient-rich organic amendments may increase soil physico-chemical properties (e.g., soil organic carbon, Ca²⁺, available P, bulk density, and soil porosity).

In fact, the green manure practice has the ability to change both soil physical and chemical soil properties due to the high biomass production on soil surface (e.g., at this point the green manure plants act as cover crops protecting soil surface from erosion) and their biomass incorporation into soil profile (e.g., here promoting rhizodeposition, nutrient cycling), thus resulting in a healthy soil environment from the subsequent annual plant species (Pacheco et al. 2017; Hirte et al. 2018; Çerçioğlu et al. 2019; Oliveira et al. 2020; Hu and Chabbi, 2021; Liu et al. 2021; Mortensen et al. 2021). Our results highlight the importance of considering the green manure practice as an alternative way to input organic resources (Haruna et al. 2020). It may act as a driver for improving the soil physical-chemical properties as we have found in our predictive models especially if we are considering the effect of the green manure practice over the years (in our study 6 years of continuous use of the green manure). Our results showed that microporosity, macroporosity, soil C stock and exchangeable Al were strongly correlated with root dry biomass. Plant species with high root biomass production (e.g., *N. wightii* and *B. decumbens*) can improve rootability (e.g., by releasing exudates and H⁺), create biopores, thus influencing soil microbial activity and soil porosity (Restovich et al. 2019), also these plant species may affect the rhizodeposition around the rhizosphere by the allocation of N- and C-rich compounds as described by Redin et al. (2018). According to the study done by Rossi et al. (2020), plant roots may influence the input of soil organic carbon into soil profile, for example, Poaceae presents high fine roots production (e.g., lignin and cellulose rich) which are slowly decomposed by soil organisms, while Fabaceae presents faster fine roots production and decomposition (Jo et al. 2020; Forstall-Sosa et al. 2020). For shoot dry biomass, we found significant correlation with bulk density, Olsen's P, and soil pH. These results may be related with the high both plant residue deposition and incorporation which may change the soil bulk density and lead to improve the soil aeration capacity, soil structure, and soil nutrient contents (Adekiya et al. 2019; Islam et al. 2019; Zhang et al. 2019).

For soil quality index, the Fabaceae plant species showed highest values for green manure when compared with Poaceae plant species. Fabaceae plant species produce nitrogen inputs, thus improving biogeochemical cycles (Pereira et al. 2018). Besides that, legume green manures (e.g., Fabaceae species) contributes to the nutrient balance and consequent restore crop productivity. Their capacity to fix

atmospheric nitrogen decreases the C:N ratio, resulting in faster residue decomposition and consequent release of N, P and K to the soil. The P release occurs in a labile form that enhances P nutrition of succeeding crops. Therefore, the Fabaceae green manure increase soil fertility levels over time. (Karuku et al. 2019). *N. wightii* is one of the most representative in Fabaceae Family in our long-term study. We found that *N. wightii* provided the highest values for soil quality index (Jain et al. 2018). In our plots, we observed that *N. wightii* developed a very dense perennial root system during the six years of our experiment, in addition this plant species showed an extraordinary regrowth capacity (Xavier and Vieira et al. 2018). These factors make the species more advantageous, reflecting in a high soil quality index. The highest values of *N. wightii* for soil quality index also relates to production a high quantity of fine roots since the principal predictor of soil quality index was the fine roots production. The nitrogen accumulation for legumes green manure varies according with soil fertility, soil water availability and legumes species (Armstrong et al. 2018, Wang et al. 2018, Dayoub et al. 2017), which may explain the low values of soil quality index for *C. juncea*. The low dry matter accumulation provided by *P. glaucum* reflected for low soil quality index for this species (Teófilo et al. 2020).

Conclusions

The green manure practice over a long-term experiment determined positive changes in soil physico-chemical properties and plant biomass production in a tropical ecosystem. The use of *N. wightii* showed the highest soil quality index by improving root biomass production, available P, Ca²⁺, K⁺, and soil C stock on a tropical sandy soil under field conditions. Our findings suggest that these plant species have positive effects on soil fertility, soil hydraulic properties, and primary production as described by the thirty-three proposed predictive models. The results of our study highlight the importance of considering plant species from both Poaceae and Fabaceae family used as green manure as soil conditioner, and thus creating a positive plant-soil feedback. Thus, long-term experiments considering our models may exploit all the correlation between all soil physico-chemical variables, primary production, soil hydraulic properties, and soil quality.

Declarations

Author's contributions

We declare that all the authors made substantial contributions to the conception, design, acquisition, analysis, and interpretation of the data. All the authors participate in drafting the article, revising it critically for important intellectual content; and finally, the authors gave final approval of the version to be submitted to Journal of Soil and Sediments through transfer desk service.

Compliance with ethical standards

The authors declare that they have no conflict of interest.

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Figures

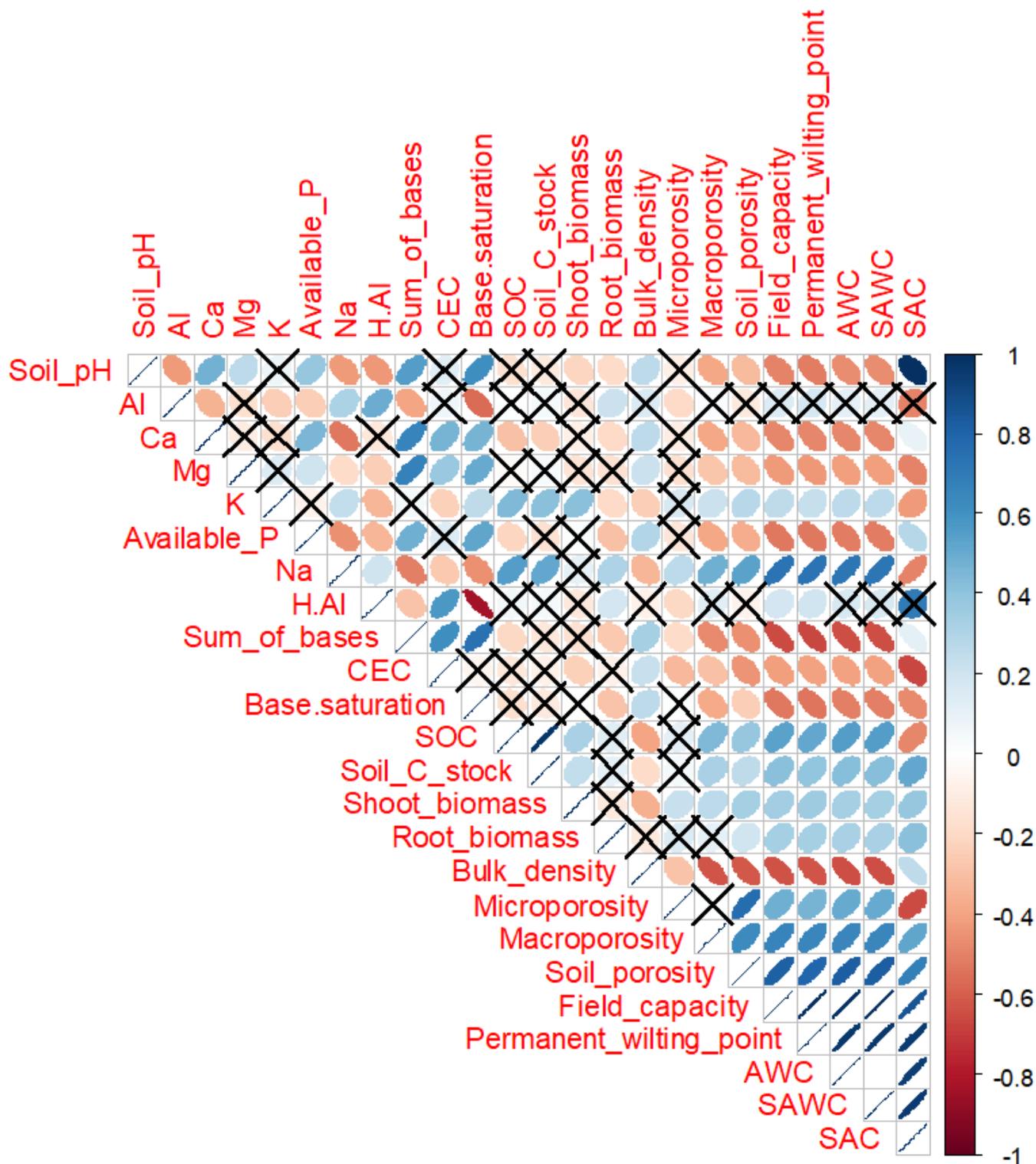


Figure 1

Correlation among the soil properties of plant species used as green manure in tropical ecosystem, Areia, Paraíba, Brazil. Data = Mean \pm SD. No-significative effect are represented by x. SOC = Soil organic carbon; AWC = available water content; SAWC = soil available water capacity; and SAC = soil aeration capacity.

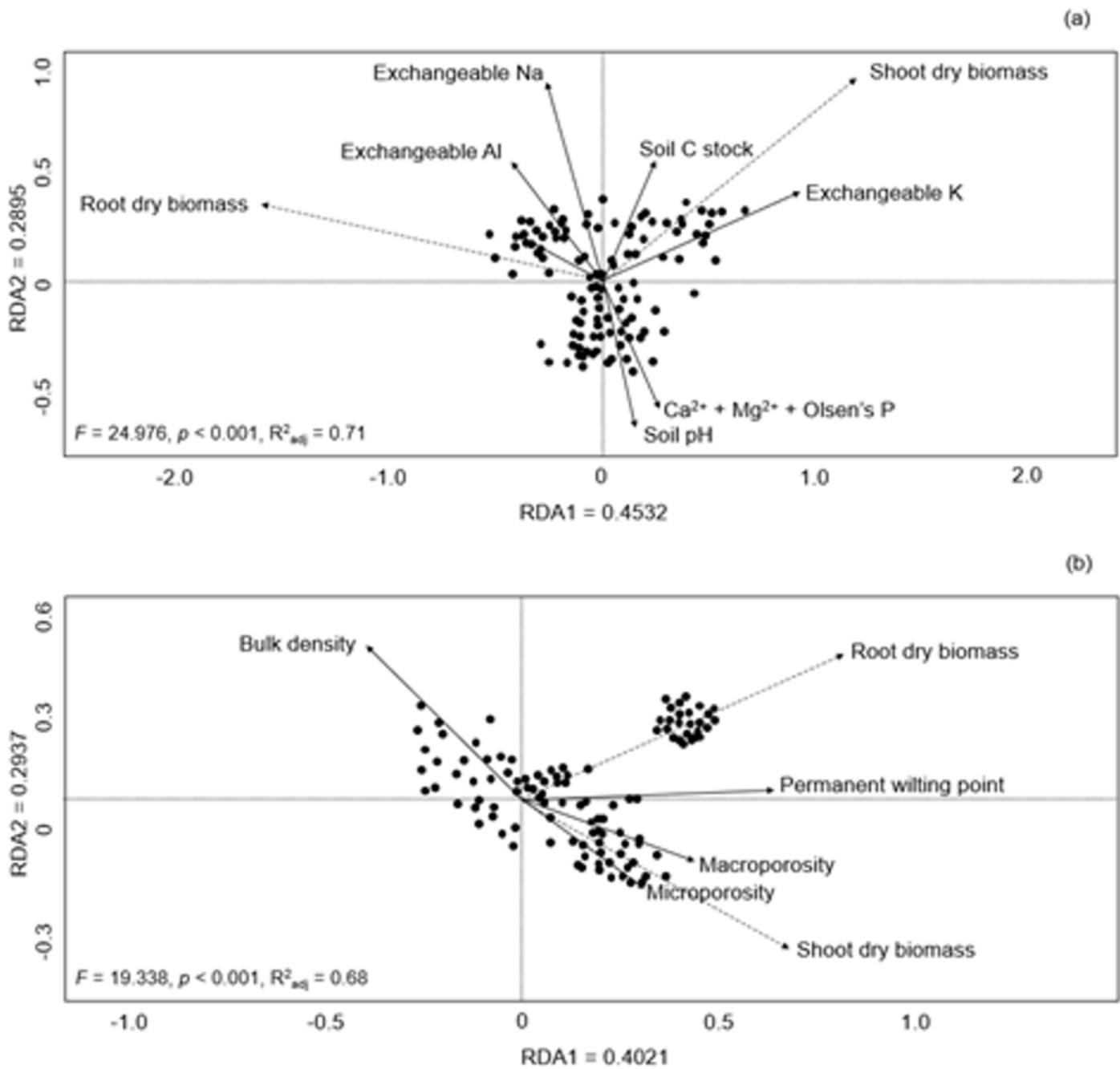


Figure 2

Redundancy analyses (RDA) ordination diagram for the relationship between primary production (shoot and root dry biomass) and soil chemical (a) and physical (b) properties.

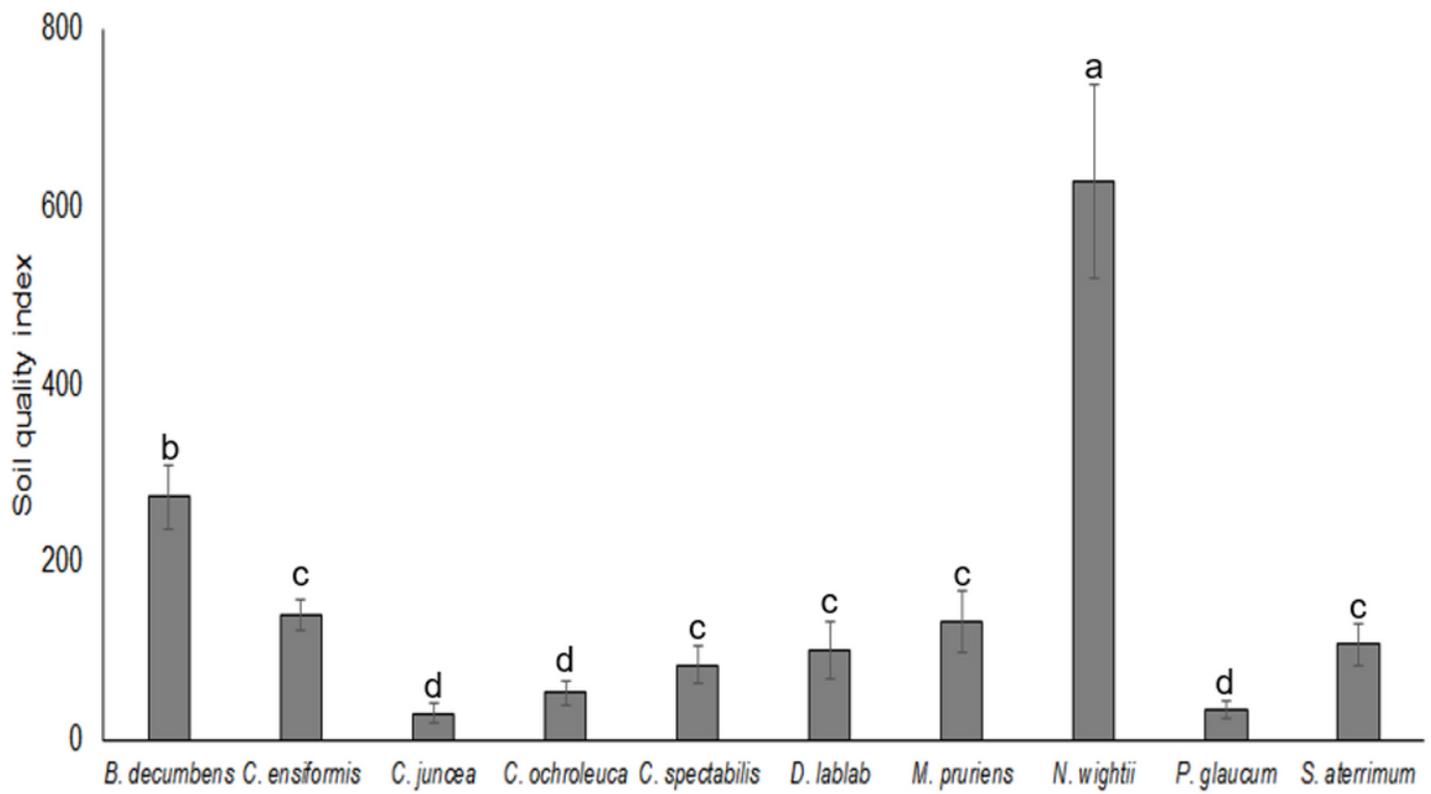


Figure 3

Soil biological quality index of different green manure plant species from the Brazilian semi-arid