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Coconut-gliricidia mixed cropping systems improve soil nutrients in dry and wet regions of Sri Lanka

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Abstract Agroforestry systems are alternative solutions for production and management of agricultural systems which may improve soil quality. In this study, we evaluated the potential of coconut *Cocos nucifera*-based Gliricidia (*Gliricidia sepium*) systems to improve soil quality of coconut lands in Sri Lanka in dry and wet regions. A three-year field experiment was conducted in a randomized complete block design with three treatments T0, T5 and T20, being respectively the control, five and twenty years aged Gliricidia intercropped coconut-based mixed systems. Three replicates of soil samples were taken at 0–15, 15–30 and 30–45 cm and differences in soil physical and chemical properties were evaluated among treatments and sites. We found significant effects of mixed system treatments on the soil chemical properties. In particular, organic matter, soil exchangeable potassium, total nitrogen and available phosphorus contents showed higher values in most coconut-gliricidia mixed systems' soils, with highest values obtained for T20. Cumulatively for all soil depths, organic matter content (22%) and available phosphorus content (20%) were higher on the wet site, and total

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exchangeable potassium content (69%) higher on the dry site for T20. The pH, bulk density, microbial respiration and electric conductivity did not vary among treatments, but were influenced by the site characteristics, with the dry site showing higher values for pH and the wet site showing higher values for bulk density (5%), microbial respiration (33%) and electric conductivity (2%) in T20 treatment. The study demonstrates that the systems with Gliricidia differed in their soil chemical attributes and had higher levels of soil nutrients when compared to coconut monocrop even at early ages, underlying the potential of Gliricidia for the rehabilitation of coconut growing soils.

Keywords Agroforestry · *Gliricidia sepium* · Intercropping systems · Monoculture · Soil rehabilitation

Introduction

Agroforestry systems are man-made terrestrial ecological landscapes that combine the practice of growing trees and crops and/or animals in spatial and temporal interactive combinations.These systems can be deliberately designed to include trees that can potentially fix atmospheric nitrogen for the benefit of others. In addition, these trees not only absorb nutrients from deeper soil layers, but also produce foliage litter that helps improve the soil quality. Continuous production of perennial crops without external inputs often reduces the availability of soil resources, resulting in low productivity (Osman 2014; Lal 2015; Norris and Congreves 2018); there is increasing support toward considering agroforestry systems among alternative solutions for soil rehabilitation, management of agricultural systems and sustainable production.

Cultivation of green manure crops in intercropping systems can particularly be considered as sustainable solutions for soil quality improvement (Vijayaraghavan and Ramachandran 1989; Atapattu et al. 2017b), especially in regions where farmers are recurrently faced with challenges of soil fertility and application of optimal doses of soil nutrients (Mantiquilla et al. 1994; Martey 2018). Previous studies have reported that green manure shrubs can supply substantial nutrients to the soil (Thomas and Shantaram 1984). Thus, incorporating green manure crops into perennial agroforestry systems can significantly enhance soil fertility and optimize crop production and yield (Kang, 1997; Atangana et al. 2014), as also reported in temperate (Brown et al. 2018) and tropical agroecosystems (Pinho et al. 2012).

Coconut (*Cocos nucifera* L) is a perennial and extremely important crop in the tropics where the rates of soil degradation and loss of soil organic matter are high, due to inceased temperatures, porous light-textured soil and high rainfall (Thomas and Shantaram 1984). In Sri Lanka, it is the second most important food, after rice. It employs some 6.5 million people and occupies nearly 20 percent of the arable lands of the country. Since coconut palms are exploited for more than sixty years on the same land, soil nutrients are progressively depleted from the systems. Further, the invasion of perennial weeds or competitive grasses in the coconut spacing contributes to reducing the soil fertility.

Due to its importance in Sri Lanka, coconut is often grown as a monocrop or as a component of multiple cropping systems with or without livestock (Herath 1993). The multiple cropping systems are intended to facilitate restoration of soil fertility. Accordingly, both leguminous and non-leguminous green manure species have been tested in coconut plantations (Atapattu et al. 2017b; Senarathne et al. 2019), and have proved to supply organic matter (Gama-Rodrigues 2011), recycle plant nutrients (Nair et al. 1999), control erosion (Udawatta et al. 2002), and enhance soil structure, microbial activity and fertility level (Kaur et al. 2000). However, nitrogen-fixing plants that can easily grow within coconut were less studied in coconut-based agro-ecosystems. Further, our ability to recommend practical interventions to restore soil quality can be improved by accounting for the age and suitability of such nitrogen-fixing plants for coconut plantation systems in different climatic and edaphic environments.

In this study, we investigate the potential of *Gliricidia sepium* (Jacq.) Kunth ex Walp. (Fabaceae), a fast-growing leguminous plant, for rehabilitation of soil in coconut plantations in Sri Lanka. *Gliricidia sepium* (hereafter referred to as Gliricidia) is a nitrogen-fixing and multipurpose plant species with significant ecological and economic potential in mixed cropping systems (Atapattu et al. 2017a; Montero-

Solís et al. 2017). While its leaves can serve as forage and green manure (Chamberlain and Galwey 1993; Castrejón-Pineda et al. 2016), the whole plant can be used for constructing living fences and shades for livestock, and maintaining soil fertility (Akinnifesi et al. 2006). Intercropping systems of Gliricidia and annual crops have been proven effective in improving the availability of soil macronutrients (Rothe and Binkley 2001). Given such a potential, Gliricidia can fulfill a number of functions not only in smallholder agricultural production systems but also in large plantations. In addition, considering the greater potential for space and solar radiation in coconut spacing squares, coconut-based Gliricidia agroforestry systems can be highly beneficial intercropping systems, with multiple benefits for coconut growers, mainly as organic manure, fodder, fuelwood, in addition to soil rehabilitation in degraded ecosystems. Yet, there is little information on the species performance under perennials plants like coconut palms, particularly with regards to its soil improvement and rehabilitation potential.

In this paper, we assessed the potential of coconut-based Gliricidia agroforestry systems to improve soil quality of degraded coconut lands in Sri Lanka at varying climatic conditions. We selected two experimental sites in dry and wet zones, and performed three treatments T0, T5 and T20, T0 being the coconut monocrop while T5 and T20 are respectively 05 and 20 years aged. Gliricidia's leaves and twigs were added annually around each palm in the coconut square. Specifically, we determined whether soil physical and chemical properties varied among treatments, sites and soil depth. The following hypotheses were tested: (i) coconut-gliricidia mixed systems would have characteristics of more improved soils as compared to coconut monocrop, but these effects will vary with sites conditions (wet vs. dry); and (ii) the extent of soil improvement would decrease with the age of Gliricidia plant and soil depth but at different magnitude for both sites (wet vs. dry).

Materials and methods

Study sites

The present study was conducted from January 2016 to December 2018. Experiments were established on two sites with contrasting environmental conditions in Sri Lanka: Pallama Research Station (7°42′54.09″N, 79°57′59.09″E, elevation 40 m) in Puttalam district (dry site) and Walpita Research Station (7°15′52.74″N, 80° 1′58.23″E, elevation 49 m) in Gampaha district (wet site) (Fig. 1). The dry site (Pallama Research Station) is characterized by a bimodal rainfall distribution with an annual precipitation of 1039 mm of which 65% falls between September and February. The temperature varies from 28 to 32 °C (Punyawardena et al. 2003; Punyawardena 2020). The wet site (Walpita Research Station) also has a bimodal rainfall regime and annual mean precipitation above 1900 mm. Approximately 60% of the annual rainfall is recorded from the southwest monsoon (May–September). The average temperature is in the range of 26–30 °C (Punyawardena et al. 2003; Punyawardena 2020). On both sites, the soil is Red Yellow Podzolic with soft or hard laterite (De Alwis and Panabokke, 1972) and slightly acidic. The horizon A of the soil (surface soil: 0–15 cm) is brown in color and has a sandy loam texture.

Experimental design

We used on both dry and wet sites, coconut plantations of 40 years of age, with a stand density of 156 trees/ha, which corresponds to a spacing of 8 m × 8 m or a coconut square of 64 m^2. In between two rows of coconut palms, two rows of Gliricidia cuttings were planted at a spacing of 1 m × 2 m, leaving a distance of 3 m between coconut and Gliricidia plants. These Gliricidia plants were established respectively 05 years and 20 years ago. Our experimental design consisted of six experimental plots, i.e. three plots on each site. Each experimental plot comprised four coconut squares, i.e. 256 m^2. On each site, the three experimental plots corresponded respectively to three treatments: T0, T5 and T20; T0 being the coconut monocrop while T5 and T20 are respectively 05 and 20 years aged, respectively. In the experimentation, for T5 and T20 treatments, Gliricidia leaves and twigs were added twice (in May and November) at a rate of 50 kg/palm/year (60–70% dry weight basis) of around each palm inside the manure circle with the onset of rain, and mature Gliricidia stems were allowed to remain along the rows. All other field management practices were applied following the recommendations of Coconut Research Institute of Sri Lanka.

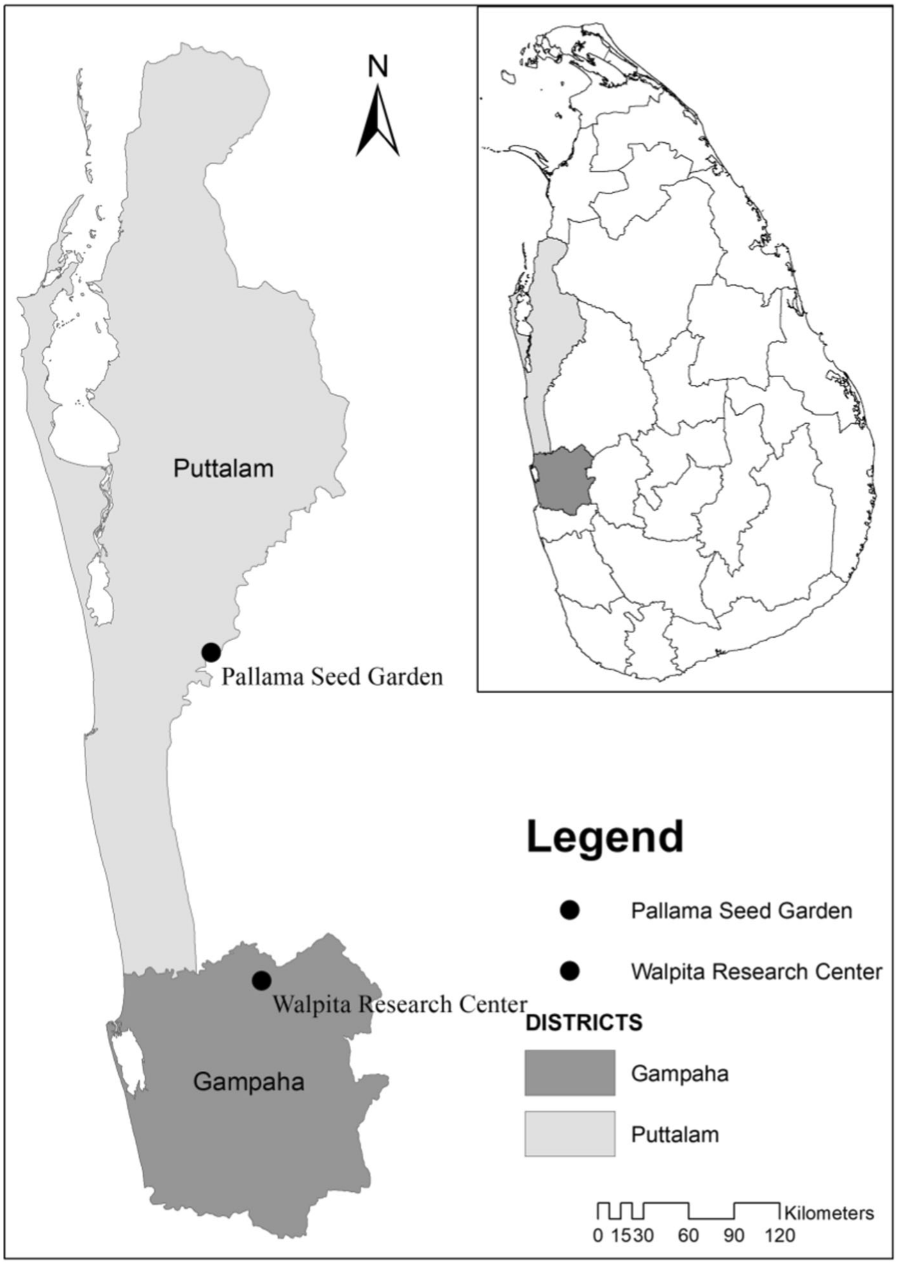


Fig. 1 Map of study sites in Sri Lanka. Solid points represent location of the study sites in research centers of the Coconut Research Institute, Sri Lanka

Soil sampling

Soil samples were taken on both sites in 2016 (January) and 2018 (December), from each experimental site and at three soil depths: 0–15 cm (top soil), 15–30 cm (sub soil) and 30–45 cm (deep soil). Before sampling, we removed the surface litter from each soil sampling area, located in the space between Gliricidia rows and 2 m away from each coconut palm. For each experimental treatment and each soil depth, three replicates of soil core samples were extracted from three random soil sampling plots (0.5 m × 0.5 m) using a core sampler. Undisturbed soil samples were also taken for the 0–15 cm layer, for soil bulk density and soil microbial activity determination. Samples were stored in plastic bags, labelled and transported to the Agronomy division of the Coconut Research Institute of Sri Lanka on the same day. After air-drying at room temperature for 48–72 h, debris and gravel were removed from the samples using 2 mm sieve.

Soil physicochemical characterization

Soil laboratory analyses were conducted for determination of soil bulk density, organic matter, nitrogen content, exchangeable potassium, available phosphorus content, pH, electrical conductivity and microbial respiration. Bulk density was determined following Dharmakeerthi (2007). The organic carbon was determined based on Walkley and Black method (Walkley and Black 1934), while total nitrogen contents were measured based on Kjeldahl distillation (Van Ranst et al. 1999). For the soil exchangeable potassium content, we used the method of extraction of ammonium acetate and flame photometry, while for available phosphorus, we employed Bray 1 technique (Bray and Kurtz 1945). pH was determined using a 1:2.5 soil–water ratio (Thomas 1996), and the soil microbial activity following the Chloroform Fumigation Incubation method (Anderson and Ingram 1993).

Statistical analyses

Statistical analyses were performed in the R statistical software version 4.0.0. The experiment was arranged in a randomized complete block design with three replicates. To determine whether coconut-gliricidia mixed systems would have characteristic of more improved soils as compared to coconut monocrop, soil physical and chemical characteristics (soil bulk density, organic matter, nitrogen content, exchangeable potassium, available phosphorus content, pH, electrical conductivity and microbial respiration) were compared between the three treatments using analysis of variance (ANOVA). As site conditions (wet vs. dry) could modulate the effects of coconut-gliricidia mixed systems on soil physical and chemical properties, we performed a two-way ANOVA with interaction effect of site and system types. The ANOVA was performed separately for each soil property. The basic assumptions of normality of residuals and homogeneity of variances were checked using the Shapiro-Wilks test and Levene test, respectively.

To test our second hypothesis, we only used soil properties that revealed significant variations among treatment from the ANOVA. Thus, for each physical and chemical property, we computed the effect size separately for T5 and T20, as the natural log of response ratio (Shi et al. 2018), using T0 as the baseline:

$$ES_i = \ln(\bar{X_i}/\overline{X_0}) \tag{1}$$

where $(\bar{X_i})$ stands for the value of a given soil property in T5 or T20 treatment and $(\overline{X_0})$ is the value of that soil property in the control T0. The effect sizes were compared between T5 or T20 treatments for each soil depth on both sites. The effects sizes were presented graphically for easier interpretation of the results.

Results and discussions

The results of the analyses of variance showed that soil physicochemical properties responded differently to the treatment effects (Table 1). Particularly, we found significant individual and/or interaction (with site) effects of treatments on total nitrogen content, exchangeable potassium and available phosphorus and electrical conductivity ($p < 0.001$; Table 1). Meanwhile, soil organic matter, pH, bulk density and microbial respiration did not vary significantly among treatments ($p > 0.05$; Table 1), but showed significant differences between the two sites ($p < 0.05$; Table 1). Initial soil properties are presented in Figure S1.

Soil organic matter

Soil organic matter (OM) overall differed significantly between sites ($p = 0.037$), with higher values recorded on the wet site (Fig. 2a). However, it did not vary significantly among treatments ($p = 0.094$), although higher values were found on the dry site in the coconut-gliricidia mixed systems, as compared to the monocrop (Fig. 2a).The potential of agroforestry systems for increasing belowground carbon is an important parameter in mitigating soil degradation (Shi et al. 2018; Kay et al. 2019). Contrary to our

Table 1 Summary of the two way analyses of variance testing for significant variations of soil physicochemical properties

Response	Source of variation	DF	Sum of Square	Mean Square	F value	Pr (> F)
SOM	Site	1	0.048	0.048	5.53	**0.037**
	Treatment	2	0.050	0.025	2.90	0.094
	Site: Treatment	2	0.019	0.009	1.08	0.372
N	Site	1	0.000	0.000	0.00	0.974
	Treatment	2	0.008	0.004	42.27	**< 0.001**
	Site: Treatment	2	0.000	0.000	1.22	0.329
P	Site	1	0.162	0.162	34.96	**< 0.001**
	Treatment	2	1.270	0.635	137.23	**< 0.001**
	Site: Treatment	2	0.020	0.010	2.11	0.164
K	Site	1	0.032	0.032	218.85	**< 0.001**
	Treatment	2	0.029	0.014	98.22	**< 0.001**
	Site: Treatment	2	0.012	0.006	41.66	**< 0.001**
pH	Site	1	57.420	57.420	753.38	**< 0.001**
	Treatment	2	0.120	0.060	0.80	0.471
	Site: Treatment	2	0.350	0.180	2.30	0.143
EC	Site	1	169.120	169.120	24.84	**< 0.001**
	Treatment	2	4.970	2.480	0.37	0.702
	Site: Treatment	2	160.410	80.200	11.78	**0.001**
BD	Site	1	0.039	0.039	8.42	**0.013**
	Treatment	2	0.018	0.009	1.98	0.181
	Site: Treatment	2	0.003	0.002	0.34	0.721
MR	Site	1	114.510	114.510	5.89	**0.032**
	Treatment	2	19.990	10.000	0.51	0.611
	Site: Treatment	2	13.750	6.870	0.35	0.709

SOM soil organic matter, *N* total nitrogen content, *P* available phosphorus content, *K* soil exchangeable potassium, pH, *EC* electrical conductivity, *BD* bulk density and *MR* microbial respiration among treatments (T0—monocrop, T5—five years old and T20—twenty years old mixed cropping systems) and sites (dry and wet)

Probability values in bold indicate significant variations ($P < 0.05$) of soil physicochemical properties

expectations that Gliricidia planted fields would increase the level of soil organic matter, we observed that the latter not vary significantly among treatments. Further, given the nonsignificant interaction between site and treatment (Table 1), separate ANOVAs were performed (Table S1), and revealed on the dry site only, significantly higher values in the coconut-gliricidia mixed systems, as compared to the monocrop (Fig. 2a). Thus, the potential influence of trees on soil organic matter was confirmed only on our dry study site, corroborating previous findings that coconut-gliricidia mixed systems increased soil organic matter fractions in dryer agricultural system (Beedy et al. 2010). This is probably because of natural returns of senesced leaves and stalks on the surface soil promoting more organic matter in the soils of Gliricidia grown systems, as compared to the monocropping system. Although the organic matter did not vary among treatments on the wet site, we observed generally higher values on the wet site, as compared to the dry site may be due to the higher biomass production in wet sites. These values in the wet site were also in most cases, higher than the suggested threshold value of 1.0% organic carbon for coconut soils (Mancot et al. 1979). This finding suggests that the humid conditions in the wetter site might have favored accumulation of organic matter even in the mono-cropping systems owing to higher biomass production. Compared to the drier site, the humid conditions would facilitate rapid decomposition of litter coupled with lower soil respiration due to lower temperatures, which could improve the soil organic matter.

Total nitrogen content

Total nitrogen content did not differ significantly between sites ($p = 0.974$; Table 1). However, it varied significantly among treatments ($F = 42.27$; $p < 0.001$), with significantly higher values for the 20 years aged Gliricidia based systems followed by the 05 years aged Gliricidia based systems (Fig. 2c). These results were confirmed by the significant values of the effect size expressed as changes in total nitrogen in coconut-gliricidia mixed systems' treatments (T5 and T20) compared to the mono-cropping system (Fig. 3). However, the effect size was generally higher for the 20 years aged Gliricidia based systems in the 0–15 and 15–30 cm layers for the dry site and in the 15–30 and 30-45 cm layers of the wet site (Fig. 3).

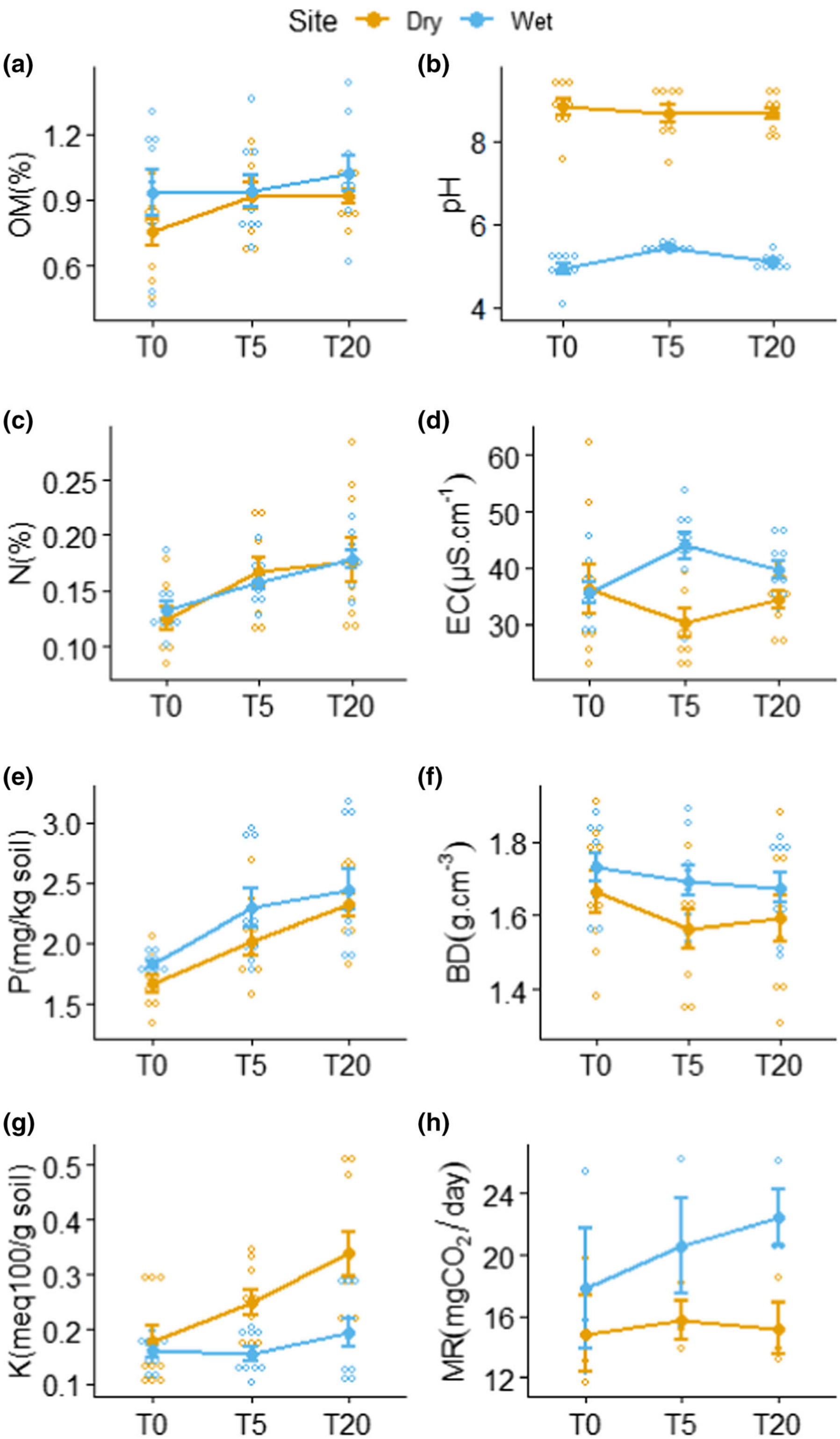
The higher values of nitrogen content in T5 and T20 (Fig. 2c) indicate the potential of Gliricidia to increase the nitrogen availability in the soils with time through the fixation process. This was expected given that *G. sepium* is a leguminous and nitrogen-fixing plant. In a previous study by Kaba et al. (2019), Gliricidia trees were shown to fix the atmospheric nitrogen in mixed-stand agroforestry systems with cocoa. As a legume, *G. sepium* is able to take advantage of the association with rhizobial symbionts to fix N (Bordeleau and Prévost 1994), not only to fulfill the N needs of their growing shoots (Kaba et al. 2019), but also to transfer part of the fixed N to co-existing non-leguminous plants (Temperton et al. 2007). As such, coconut-gliricidia mixed systems will be highly beneficial for N-limited soils like coconut grown soils, reducing the need for N fertilizers for coconut palms.

Two forms of nitrogen available for the plants are ammonium and nitrate (Aczel 2019). The availability and concentrations of these forms fluctuate based on the rate of biological activity, which directly depends on the temperature and moisture availability. As such, nitrate is often leached or washed off from the soil of sites with high rainfall or excessive irrigation (Lehmann and Schroth 2009) and therefore that might be a reason for the nonsignificant effect size observed for T5 and T20 treatments on the wet site (Fig. 3) and the lower total nitrogen contents in the topsoil layer (Table S1). It follows that the lack of significant effect of the site could suggest that nitrogen dynamic seemed to be affected by humid conditions at the top soil layers. Further, soil nitrogen supply is known to be related to the soil organic fractions; interestingly, in this study, organic matter and nitrogen contents showed strong correlation (r = 0.6) on the dry site and very weak correlation on the wet site (r = 0.16), suggesting that nitrogen and organic matter patterns vary with sites conditions, including soil type (Malhotra et al. 2017). Appropriate C:N ratio is critical for the rate of the decomposition of organic matter, and therefore the amount of nitrogen available in the system also could vary with these decomposition processes even if high amount was added to the soil via *G. sepium*.

Available phosphorus content

Unlike nitrogen content, soil available phosphorus content differed significantly between sites (F = 34.96; $p < 0.001$; Table 1), with higher values recorded in the wet site (Fig. 2e). Phosphorus content also varied significantly among treatments (F = 137; $p < 0.001$) as the 20 years aged Gliricidia based systems followed by the 05 years aged Gliricidia based systems exhibited significantly higher values for both sites (Fig. 2e). However, these treatment effects did not vary with the site ($p = 0.164$ for the interaction term; Table 1). On both sites and across layers, the effects sizes were greater for the 20 years aged Gliricidia based treatments (Fig. 3).

The significant site effect suggests that environmental variability between two different locations creates different influences on the phosphorus dynamics in the soils. In coconut growing areas of Sri Lanka, soils are generally deficient in active as well as available forms of P (Wijebandara and Somasiri 1994). Because plants and coconut palms would require P for root development and growth, the higher phosphorus content recorded for the Gliricidia based treatments (and more so with the 20 years aged Gliricidia based treatment) suggests that, in addition to improve soil nitrogen content, Gliricidia trees play a vital role in rehabilitating soil P content. As such, the P limitation of the coconut grown soils and palms offers a suitable opportunity for Gliricidia to play a complementary additional role in these systems. Previous studies reported that P fertilization increases the nodulation activities of leguminous (Magadlela et al. 2016; Pérez-Fernández et al. 2017) in P deficient soils. Therefore, the significantly higher values of P in the mixed Gliricidia-coconut systems soils (as compared to the control) is also beneficial for the nodulation and N fixation by Gliricidia, which can further increase as the phosphorus increases, as also shown for *Virgilia divaricate*, a legume tree in nutrient-poor Mediterranean-type ecosystems (Magadlela et al. 2016).


Site
Dry
Wet
(a)
OM(%)
1.2
0.9
0.6
T0
T5
T20
(b)
pH
8
6
4
(c)
N(%)
0.25
0.20
0.15
0.10
(d)
EC(μS.cm⁻¹)
60
50
40
30
(e)
P(mg/kg soil)
3.0
2.5
2.0
1.5
(f)
BD(g.cm⁻³)
1.8
1.6
1.4
(g)
K(meq100/g soil)
0.5
0.4
0.3
0.2
0.1
(h)
MR(mgCO2/day)
24
20
16
12

◀**Fig. 2** Organic matter (OM, **a**), pH (**b**), Total nitrogen content (N, **c**), Electrical conductivity (EC, **d**), Available phosphorus content (P, **e**), Bulk density (BD, **f**), Soil exchangeable potassium (K, **g**) and Soil microbial respiration (MR, **h**) between treatments (T0—monocrop, T5—five years old and T20—twenty years old mixed cropping systems) for dry and wet site

Soil exchangeable potassium

Soil exchangeable potassium varied significantly with sites, treatments and their interactions effects ($p < 0.001$; Table 1). Greater values of K were observed on dry sites than wet sites (Fig. 2g). Treatments effects were shown by significantly increased K content for the two treatments, with 20 years aged Gliricidia-coconut mixed systems showing high values (Fig. 2g).

These results further demonstrated that coconut-gliricidia systems also have positive effects for the soil exchangeable potassium (K), when compared to coconut monocultures on both sites. The significantly higher values in T5 and T20 coconut systems might be due to deep soil nutrient uplift by the tap root system, continuous addition and decomposition of nutrient-rich litter, leaves and stalks (Atapattu et al. 2017b), as also reported for *Gliricidia sepium* intercropped in a maize system in Malawi (Beedy et al. 2010). According to Primo et al. (2018), potassium content of Gliricidia leaves and twigs with 1 cm thickness is approximately 21 g/kg, and according to Agyeman et al. (2013), it was 0.66% in Gliricidia leaves. More soil exchangeable potassium on the dry site could be explained by the local environmental conditions, particularly high rainfall, as the potassium content of the soils may differ according to the rates of crop removal and leaching (Zörb et al. 2014). The interaction effects revealed that the positive effects of the treatments increased with the age of Gliricidia plants, and were even greater for the dry site than for the wet site (Fig. 2g), as also shown by the higher effect sizes on dry site compared to the wet site (Fig. 3), indicating that not only environmental conditions but also the age of Gliricidia plants, modulate the dynamic of exchangeable potassium.

PH

Soil acidity plays an important role in plant growth as it controls the availability of nutrients and regulates microbial processes. The pH values did not vary significantly ($p = 0.471$; Table 1) among treatments, but instead differed between sites, with the dry site showing more acidic conditions (Fig. 2b). These results suggest that growing Gliricidia in coconut squares has no considerable effect on the soil acidity. While coconut palm can adapt to a wide range of soil acidity and can be cultivated in the soil pH range of 5 to 8 (Mancot et al. 1979), it is important to note that increased soil acidity may reduce the availability of nitrogen, phosphorus, and potassium to the plants as a result of a low decomposition rate of organic matter due to low microbial activity especially bacteria in acidic or alkaline pH levels.

Electrical conductivity

Electrical conductivity did not differ between treatments but showed significant responses to site effects and its interaction with treatments (Table 1). The site effect was shown by higher values of EC at wet site, and more so for the Gliricidia based treatments (Fig. 2d) while lower values were observed for the Gliricidia based treatments of the dry site. Electrical conductivity is basically a measure of the amount of salts in the soil, and is expected to be higher in dry areas. However, in this study, the dry site showed lower level of EC, which decreased with the 05 years aged Gliricidia based treatment, and increased with the 20 years aged Gliricidia based treatment.

Bulk density and soil microbial respiration

Both bulk density and soil microbial respiration were significantly higher on the wet site than on the dry site (Table 1; Fig. 2), possibly as a result of prevailing humid conditions favoring microbial activities. However, bulk density and soil microbial respiration did not vary significantly among treatments (Table 1; Fig. 2), although there was a significant difference for bulk density in 15–30 cm depth on dry site and 0–15 cm depth on wet site, with highest values for the control on both sites (Table S2). Due to the addition of organic matter continuously, root penetration and distribution in *G. sepium* in coconut mixed cropping

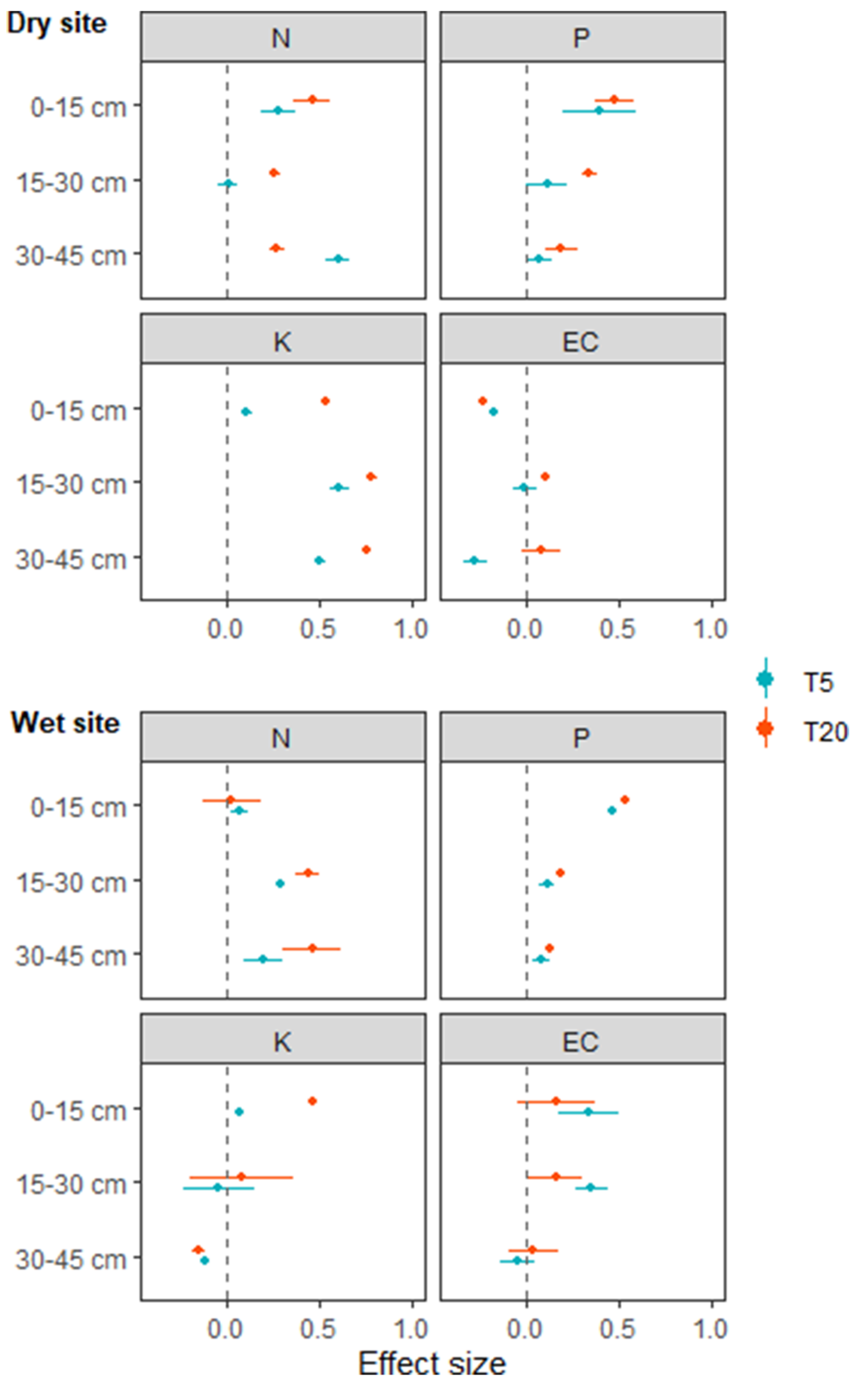


Fig. 3 Effect sizes expressed as changes of soil physicochemical parameters. Total nitrogen content (N), Available phosphorus content (P), Soil exchangeable potassium (K) and Electrical conductivity (EC) in intercropping treatments (T5—five years old and T20—twenty years old mixed cropping systems) compared to the control (mono-crop) across both sites (dry and wet) and soil depths. Effect sizes were computed only for variables that showed significant variations (Table 1)

systems, reduction of bulk density was visible. Similar results were obtained by Vidhanaarchchi and Liyanage (1996), and according to them, the effect of this fragmentation by *G. sepium* roots significantly reduced the bulk density.

Carbon and nitrogen-rich plant materials provide better substrates to the microorganism, and therefore, the number of microbes and the rate of decomposition should be higher than in the soils with less organic matter. Presence of a higher number of microbial populations increases the rate of nutrient cycling through the decomposition of leaf litter. However, in this study microbial respiration was not significantly influenced by the treatment on both sites.

Conclusion

From the results of this study, we conclude that *Gliricidia sepium* has a greater potential for improving poor soil characteristics, particularly in dryer agroecosystems. Further, this study demonstrates that coconut-based Gliricidia systems can be effectively used to rehabilitate the degraded coconut growing soils. Among the selected parameters, soil organic matter content, soil exchangeable potassium content, total nitrogen content and available phosphorus content, showed significant or comparatively higher values in *G. sepium* and coconut mixed cropping systems than coconut monocrop on both sites. Thus this study demonstrates that coconut-based Gliricidia system is an effective tool for rehabilitation of degraded coconut growing soils in both dry and humid areas.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

References

Aczel MR (2019) What is the nitrogen cycle and why is it key to life? Front Young Minds. https://doi.org/10.3389/frym.2019.00041

Agyeman K, Berchie JN, Gaisie E, Adomako J (2013) Synchronization of nutrient release from *Gliricidia sepium* with nutrient uptake by Maize through biomass decomposition. Int J Sci Adv Technol 3:49–57

Akinnifesi FK, Makumba W, Kwesiga FR (2006) Sustainable maize production using gliricidia/maize intercropping in southern malawi. Exp Agric 42:441. https://doi.org/10.1017/S0014479706003814

Anderson J, Ingram JSI (1993) Tropical soil biology and fertility: a handbook of methods, 2nd edn. CAB International, Wallingford

Atangana A, Khasa D, Chang S, Degrande A (2014) Tropical agroforestry. Springer, Dordrecht

Atapattu AAAJ, Raveendra SAST, Pushpakumara DKNG, Rupasinghe WMD (2017a) Regeneration potential ofGliricidia Sepium (Jacq.) Kunthex Walp. as a fuelwood species. Indian J Plant Sci 6:32–39

Atapattu AAAJ, Senarathne SHS, Raveendra SAST et al (2017b) Effect of short-term agroforestry systems on soil quality in marginal coconut lands in Sri Lanka. Agric Res J 54:324. https://doi.org/10.5958/2395-146X.2017.00060.6

Beedy TL, Snapp SS, Akinnifesi FK, Sileshi GW (2010) Impact of Gliricidia sepium intercropping on soil organic matter fractions in a maize-based cropping system. Agric Ecosyst Environ 138:139–146. https://doi.org/10.1016/j.agee.2010.04.008

Bordeleau LM, Prévost D (1994) Nodulation and nitrogen fixation in extreme environments. Plant Soil 161:115–125. https://doi.org/10.1007/BF02183092

Bray RH, Kurtz LT (1945) Determination of total, organic, and available forms of phosphorus in soils. Soil Sci 59:39–46. https://doi.org/10.1097/00010694-194501000-00006

Brown SE, Miller DC, Ordonez PJ, Baylis K (2018) Evidence for the impacts of agroforestry on agricultural productivity, ecosystem services, and human well-being in high-income countries: a systematic map protocol. Environ Evid 7:24. https://doi.org/10.1186/s13750-018-0136-0

Castrejón-Pineda FA, Martínez-Pérez P, Corona L et al (2016) Partial substitution of soybean meal by *Gliricidia sepium* or *Guazuma ulmifolia* leaves in the rations of growing lambs. Trop Anim Health Prod 48:133–137. https://doi.org/10.1007/s11250-015-0932-2

Chamberlain JR, Galwey NW (1993) Methods of identifying genetic diversity in *Gliricidia* species for biomass production. Exp Agric 29:87. https://doi.org/10.1017/S0014479700020433

De Alwis K, Panabokke C (1972) Handbook of the soils of Sri Lanka (Ceylon). J Soil Sci Soc 2:1–97

Dharmakeerthi R (2007) Manual of soil sampling and analysis. In: Dharmakeerthi R, Indraratne S, Kumaragamage D (eds) Special publication no. 01. Science Society of Sri Lanka, pp 19–21

Gama-Rodrigues AC (2011) Soil organic matter, nutrient cycling and biological dinitrogen-fixation in agroforestry systems. Agrofor Syst 81:191–193. https://doi.org/10.1007/s10457-011-9372-9

Herath A (1993) Appropriate intercropping systems for coconut small holders: an application of multi-period linear programming technique in coconut-based farming systems. Sri Lankan J Agric Econ 1:26–45

Kaba JS, Zerbe S, Agnolucci M et al (2019) Atmospheric nitrogen fixation by gliricidia trees (*Gliricidia sepium* (Jacq.) Kunth ex Walp.) intercropped with cocoa (*Theobroma cacao* L.). Plant Soil 435:323–336. https://doi.org/10.1007/s11104-018-3897-x

Kang BT (1997) Alley cropping—soil productivity and nutrient recycling. For Ecol Manag 91:75–82. https://doi.org/10.1016/S0378-1127(96)03886-8

Kaur B, Gupta SR, Singh G (2000) Soil carbon, microbial activity and nitrogen availability in agroforestry systems on moderately alkaline soils in northern India. Appl Soil Ecol 15:283–294. https://doi.org/10.1016/S0929-1393(00)00079-2

Kay S, Rega C, Moreno G et al (2019) Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. Land Use Policy 83:581–593. https://doi.org/10.1016/j.landusepol.2019.02.025

Lal R (2015) Restoring soil quality to mitigate soil degradation. Sustainability 7:5875–5895. https://doi.org/10.3390/su7055875

Lehmann J, Schroth G (2009) Nutrient leaching. Trees, crops and soil fertility: concepts and research methods. CABI, Wallingford, pp 151–166

Magadlela A, Vardien W, Kleinert A et al (2016) Variable P supply affects N metabolism in a legume tree, *Virgilia divaricata*, from nutrient-poor Mediterranean-type ecosystems. Funct Plant Biol 43:287. https://doi.org/10.1071/FP15262

Malhotra S, Maheswarappa S, Selvamani V, Chowdappa P (2017) Diagnosis and management of soil fertility constraints in coconut (Cocos nucifera): a review. Indian J Agric Sci 87:711–726

Mancot R, Ollagnier M, Ochs R (1979) Mineral nutrition and fertilization of the coconut around the world Part I, Oleagineux, 34 (11)

Mantiquilla J, Canja L, Margate R, Magat S (1994) The use of organic fertilizer in coconut (A research note). Philipp J Coconut Stud 19:8–13

Martey E (2018) Welfare effect of organic fertilizer use in Ghana. Heliyon 4:e00844. https://doi.org/10.1016/j.heliyon.2018.e00844

Montero-Solís FM, López-López MÁ, Jiménez-Casas M et al (2017) *Gliricidia sepium* and fertilization affect growth, nutrient status, and incidence of *Hypsipyla grandella* in a *Cedrela odorata* plantation. Agrofor Syst. https://doi.org/10.1007/s10457-017-0175-5

Nair PR, Buresh R, Mugendi D, Latt C (1999) Nutrient cycling in tropical agroforestry systems. In: Buck LE, Lassoie JP, Fernandes ECM (eds) Agroforestry in sustainable agricultural systems. CRC Press, London

Norris CE, Congreves KA (2018) Alternative management practices improve soil health indices in intensive vegetable cropping systems: a review. Front Environ Sci. https://doi.org/10.3389/fenvs.2018.00050

Osman KT (2014) Soil degradation, conservation and remediation. Springer, Dordrecht

Pérez-Fernández MA, Calvo-Magro E, Rodríguez-Sánchez J, Valentine A (2017) Differential growth costs and nitrogen fixation in *Cytisus multiflorus* (L′Hér.) Sweet and *Cytisus scoparius* (L.) Link are mediated by sources of inorganic N. Plant Biol 19:742–748. https://doi.org/10.1111/plb.12599

Pinho RC, Miller RP, Alfaia SS (2012) Agroforestry and the improvement of soil fertility: a view from Amazonia. Appl Environ Soil Sci 2012:1–11. https://doi.org/10.1155/2012/616383

Primo DC, Menezes RSC, De Oliveira FF et al (2018) Timing and placement of cattle manure and/or gliricidia affects cotton and sunflower nutrient accumulation and biomass productivity. An Acad Bras Cienc 90:415–424. https://doi.org/10.1590/0001-3765201820150841

Punyawardena BVR (2020) Climate. In: Mapa R (ed) The soils of sri lanka. World Soils Book Series. Springer, Cham, pp 13–22

Punyawardena BV, Bandara TMJ, Munasinghe MAK, Jayaratne Banda M, Pushpakumara SMV (2003) Agro-ecological regions of sri lanka. Natural Resources Management Center, Department of Agriculture, Peradeniya

Rothe A, Binkley D (2001) Nutritional interactions in mixed-species forests: a synthesis. Can J For Res 31:1855–1870. https://doi.org/10.1139/x01-120

Senarathne SHS, Atapattu AJ, Raveendra T et al (2019) Biomass allocation and growth performance of *Tithonia diversifolia* (Hemsl.) A. Gray in coconut plantations in Sri Lanka. Agrofor Syst 93:1865–1875. https://doi.org/10.1007/s10457-018-0290-y

Shi L, Feng W, Xu J, Kuzyakov Y (2018) Agroforestry systems: meta-analysis of soil carbon stocks, sequestration processes, and future potentials. Land Degrad Dev 29:3886–3897. https://doi.org/10.1002/ldr.3136

Temperton VM, Mwangi PN, Scherer-Lorenzen M et al (2007) Positive interactions between nitrogen-fixing legumes and four different neighbouring species in a biodiversity experiment. Oecologia 151:190–205. https://doi.org/10.1007/s00442-006-0576-z

Thomas G (1996) Soil pH and soil acidity. In: Bigham J, Bartels J (eds) Methods of soil analysis. Part 3. Chemical methods. ASA-SSSA, Madison, pp 475–490

Thomas GV, Shantaram MV (1984) In situ cultivation and incorporation of green manure legumes in coconut basins. Plant Soil 80:373–380. https://doi.org/10.1007/BF02140044

Udawatta RP, Krstansky JJ, Henderson GS, Garrett HE (2002) Agroforestry practices, runoff, and nutrient loss. J Environ Qual 31:1214–1225. https://doi.org/10.2134/jeq2002.1214

Van Ranst E, Verloo M, Demeyer A, Pauwels J (1999) Manuals for the soil chemistry and fertility laboratory: analytical methods for soils and plants equipment, and management of consumables. University of Gent, Belgium

Vidhanaarchchi L, Liyanage M de S (1996) Role of *Gliricidia sepium* on physical improvement of gravelly soil. COCOS 11:40–52

Vijayaraghavan H, Ramachandran TK (1989) Effect of in situ cultivation and incorporation of green manure crops on the yield of coconut. COCOS 7:26–29. https://doi.org/10.4038/cocos.v7i0.2061

Walkley A, Black IA (1934) An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci 37:29–38. https://doi.org/10.1097/00010694-193401000-00003

Wijebandara DMDI, Somasiri LLW (1994) Comparison of routine laboratory methods for the estimation of plant available phosphorus in soils of the low country intermediate zone of Sri Lanka. Trop Agric Res 6:211–222

Zörb C, Senbayram M, Peiter E (2014) Potassium in agriculture: status and perspectives. J Plant Physiol 171:656–669. https://doi.org/10.1016/j.jplph.2013.08.008