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Soil Health Impacts of Rubber Farming: The Implication of Conversion of Degraded Natural Forests into Monoculture Plantations

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Abstract: High revenues from rubber latex exports have led to a rapid expansion of commercial rubber cultivation and, as a consequence, the conversion of different land use types (e.g., natural forests) into rubber plantations, which may lead to a decrease in soil health. In this study in Quang Tri Province, Vietnam, we determined: (1) the variation of soil health parameters along a chronosequence of rubber tree stands and natural forests and (2) the relationships and potential feedback between vegetation types, vegetation structures and soil health. Our results revealed that: (1) soil health was higher in natural forests than in rubber plantations with a higher values in higher biomass forests; (2) soil health was lower in younger rubber plantations; (3) soil health depends on vegetation structure (with significantly positive relationships found between soil health and canopy cover, litter biomass, dry litter cover and ground vegetation cover). This study highlights the need for more rigorous land management practices and land use conversion policies in order to ensure the long-term conservation of soil health in rubber plantations.

Keywords: rubber plantations; soil health; land conversion; monoculture crops; farm management

1. Introduction

The rubber tree (*Hevea brasiliensis*) has been one of the most economically valuable trees among global farming systems for the past three decades [1]. Revenues from rubber latex exports have led to financial improvement for thousands of farmers worldwide [2]. Therefore, many farmers have chosen to convert other land use types (e.g., degraded natural forests or timber plantations) into rubber plantations, which has led to the rapid expansion of rubber plantations worldwide [3,4]. In addition to the economic motivations, the ability of rubber trees to grow in diverse eco-regions with a broad diversity of climate conditions, soil types and fertilities has also driven rapid worldwide expansion [5].

Following the introduction of rubber trees to southern Vietnam in 1897 this economically valuable species has also become a major perennial tree in Central and Northern Vietnam [6]. Because of their high economic value, rubber trees have become the priority among targeted trees for the economic development of Vietnam. In 2009 the Vietnamese Prime Minister approved the strategy to expand the rubber industry, which involved expanding the land area dedicated to rubber plantations to 800,000 ha by the year 2020 in order to produce 1.2 million tons of latex and generate approx. USD two billion in new revenue through the increased export of rubber products [7]. To achieve the goals of the revised rubber industry strategy, the conversion of various land use types (e.g., unproductive agricultural land, degraded natural forests and plantations) into rubber plantations was permitted, beginning in 2009 [8].

In Northern Central Vietnam, following the approval of Decision 750/QD-TTg by the Prime Minister in 2009 [9] which permitted the establishment of new rubber plantations on degraded natural forestlands, the region was targeted for planting new rubber plantations (approx. 20,000 hectares) in order to increase the total area in this region dedicated to rubber plantations up to 80,000 hectares [9]. As a result, rubber plantations have expanded rapidly in Northern Central Vietnam with a large proportion of the new rubber plantations established in the region requiring the conversion of degraded natural forests and forest lands [10]. Therefore, the cultivation of rubber plantations is one of the main causes of the loss of the original land cover (i.e., natural forest) in the region [10].

The intensive agricultural practices of rubber plantations are major drivers of soil degradation [5,11], which can lead to long term loss-loss scenarios for farmers when land capacity is reduced and rubber prices decline at the same time [3]. This land capacity reduction may be due to the cultivation of monoculture crops (e.g., rubber, palm oil, coffee), which leads to substantial changes in soil processes and properties that can result in a complete or partial loss of productive capacity [12–14]. Substantial changes in soil processes and properties can also be driven by structural changes to the covering vegetation [15]. While some studies reported the negative impacts of rubber farming on soil properties [12,16–18] other studies reported that the soil properties of rubber plantations were similar to those of natural forests in that only minimal nutrient loss was observed as a consequence of rubber plantation processes [4,16,19]. The inconsistency of these previous studies clearly demonstrates the requirement for further research into the impacts of rubber tree cultivation on soil health.

Moreover, there are interactions among soil parameters and vegetation parameters associated with land use changes [20,21]. Chemical, physical and biological (including microbial) components contributing to soil health maintenance are significantly correlated to each other [22,23]. For example, the assessment of soil porosity permits the determination of soil structure complexity, which is related to the retention and movement of water within the soil and directly affects the proportions of water and dissolved nutrients [24], while soil organic matter directly affects the physical, biological and chemical aspects of the soil and, thus, the capability to support plant growth [25]. Soil microbial populations also play important roles in maintaining nutrient and carbon cycling within the soil [26]; which are susceptible to changes in land use practices [27], and positively correlated with crop yield [28]. Vegetation cover with different tree species, structural complexity and root exudates generates a divergence in soil properties and may impact the soil microbial populations [20]. Due to the comprehensive interaction among soil and vegetation parameters, cultivation is known to generally reduce the amount of soil organic matter, nutrient availability [28], and alter soil microbial communities [29]. Therefore, an understanding of these parameters and their interactions among land uses is important for sustaining short- and long-term land capacity [30,31].

In this study, we hypothesized a strong interaction among soil health indicators, vegetation structure and land uses, and that a simple characterization of vegetation types on different land use categories may not be sufficient to characterize potential soil health changes. We hypothesized that soil health would vary among vegetation types and there is a linkage between vegetation and soil parameters that shape these changes. Hence, the objectives of this study were to determine (1) the variation of soil health parameters along a chronosequence of rubber plantations and natural forests, and (2) the relationships and potential feedbacks between vegetation types, vegetation structure and soil health. Insights obtained from this research can support management practices that aim to minimize soil degradation from land conversion as well as assist farmers and other land owners with improving the productive capacity of their land.

2. Methods

2.1. Study Area

The study was conducted in Vinh Linh district, Quang Tri Province of Northern Central Vietnam (17°04′58.80″ N, 107°00′0.00″ E). The study area (Figure 1) lies within the tropical monsoon zone, which is influenced by the convergent climate of tropical South Vietnam and subtropical North Vietnam. The climate at the study area is relatively harsh with hot dry southwest winds and heavy rainfall. More specifically, the annual average rainfall is approx. 2200–2500 mm, while the annual average temperature is 24–25 °C and average monthly humidity ranges from 85% to 90%. There are two distinct seasons in the study area, a rainy season with heavy rainfall and strong winds, storms and tropical cyclones (October to February), and a dry season with little rain or wind (March to September). The terrain is relatively diverse with four natural geographical regions, including mountainous, midland, plains and coastal. The majority of the local population depends on agriculture for their livelihood; however, annual crop productivity predominantly depends on the climate and, thus, is vulnerable to natural disasters and climate variability. Therefore, there is a high demand among local farmers, with support by local governments to establish farms of climactically robust and economically valuable perennials (e.g., rubber, coffee). The Vinh Linh district, Quang Tri Province is the hotspot area of rubber cultivation with an area of >6775 ha, with this mostly being established by the conversion from degraded natural forests or other agricultural land [32]. Therefore, the Vinh Linh district is a suitable area as a case study to assess the impacts of land use conversion from degraded natural forests to rubber plantations on soil health.

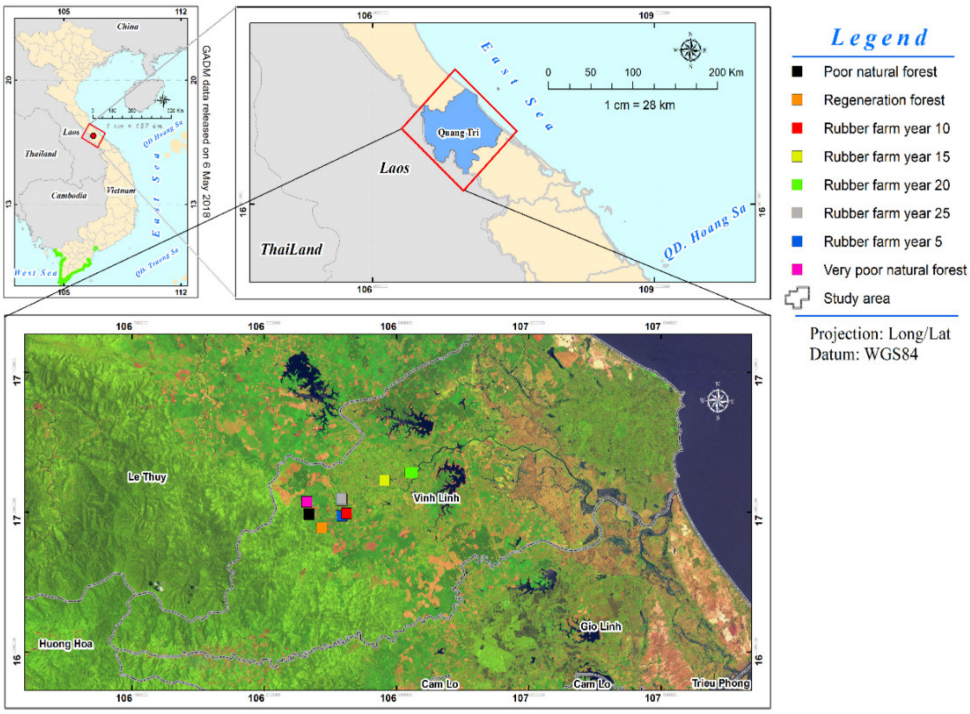

Figure 1. The location of the study area in the Vinh Linh district, Quang Tri Province, Vietnam.

2.2. Field Data Collection and Measurement of Soil Parameters

The study was carried out within rubber plantations of five different ages (five-, ten-, fifteen-, twenty- and twenty-five-years-old) and natural forests of three types (consisting of numerous tropical evergreen broadleaf species that are representative of those permitted by Vietnamese government to be converted into rubber plantations, not the actual forests that were converted into rubber plantations): (1) Moderate volume natural forest (tree volume 101–200 m^3/ha); (2) Low volume natural forest (tree volume from 10 to 100 m^3/ha); (3) Very low volume natural forest (woody trees' average diameter at breast height of less than 8 cm and tree volume of less than 10 m^3/ha) [33]. Nine plots (30 m × 30 m each) were selected for each rubber plantation age (n = 5) and forest of each type (n = 3), with the total number of samples analyzed being n = 72.

In each plot we measured: (1) canopy cover (%) using spherical densitometers [34]; (2) vegetation ground cover (%) and dried leaf litter cover (%), using the Line Intercept Method [35]; (3) leaf litter dry mass (g) after being oven-dried (12 h at 105 °C).

To assess soil health, three top-soil core samples were also randomly collected within each plot (n = 9) at a depth of 0–10 cm. The soil bulk density was calculated as the dry mass of a soil sample in a given volume of soil (without pore spaces occupying the soil). The bulk density soil samples were taken using a soil core sampler with fixed volume of 100 cm^3 [36] and dried (48 h at 105 °C) to determine the dry mass. The soil bulk density (g cm^{-3}) was calculated as the dry mass per a volume unit of the soil (soil solids and pores).

Soil porosity (POR) was calculated from soil bulk density and soil particle density using Equation (1):

$$\text{Porosity}\ (\%) = \left(1 - \frac{\textit{Bulk Density}}{\textit{Particle Density}}\right) \times 100 \quad (1)$$

Soil organic carbon (SOC)was measured using the Walkley–Black method [37]. Following the method, a small amount of soil was mixed with potassium dichromate ($K_2Cr_2O_7$) solution before adding concentrated sulfuric acid (H_2SO_4) to the mixture. The reaction induces oxidation by the acidified dichromate. Then, residual dichromate was back-titrated with additional ferrous sulfate ($FeSO_4$). The comparison with a blank titration determined the percentage of organic carbon in soil, as calculated using Formula (2):

$$\text{SOC}\ (\%) = \text{M} \times \frac{(V1 - V2)}{W} \times 0.3 \times \text{CF} \times 100 \quad (2)$$

where M is the molarity of the $FeSO_4$ solution used for blank titration, $V1$ is the volume (mL) of $FeSO_4$ required in blank titration, $V2$ is the volume (mL) of $FeSO_4$ required in actual titration, W is the mass (g) of the soil sample, and CF is the correction factor (CF = 1.32).

Counts of bacteria (BAC), actinomycetes (ACT) and fungi (FUN) were determined using the serial dilution plate count method [38]. Serial dilutions of 10^{-6} for bacteria, 10^{-3} for fungi and 10^{-5} for actinomycetes were used to plate on selective media with different times of incubation. Bacteria, fungi and actinomycetes were grown out on beef extract–peptone agar, rose bengal agar, and starch–casein agar, respectively. All plates were incubated at 28 °C for 2 days (for bacteria), 4 days (for fungi) and 7 days (for actinomycetes) before counting. The quantities of these microorganisms were counted as the number of organisms per a mass unit of soil (millions of organisms/g of soil).

All analyses were performed by the soil laboratory of the Soil and Fertilizers Research Institute, Tu Liem, Ha Noi, Vietnam.

2.3. Statistical Analyses

The nonparametric Kruskal–Wallis H test was employed to assess the significant differences between soil parameters among vegetation types. Considering the unbalanced sample size in the eight categories, we conducted post hoc Dunn's multiple-comparison tests with adjustments using Bonferroni to compare the significance of variation between the two vegetation types.

Pearson's correlation coefficients were calculated to assess relationships between the measured vegetation attributes and soil properties. We also conducted a principal component analysis (PCA) to identify the main factors controlling soil health parameters and the relationship between soil and vegetation parameters among vegetation types. Only components with eigenvalues >1 were selected to determine the main components. Variables with absolute eigenvector coefficients ≥0.70 were selected and considered significant in each component [39]. All statistical analyses were conducted using R version 3.6.1 [40].

3. Results

Variations in the soil health parameters in different vegetation type categories are displayed in Table 1 and Figure 2. Overall, the means of soil health parameters were higher in natural forests than rubber plantations. Among natural forests, the higher volume forests have generally higher values of soil health indicators, while among rubber plantations, younger plantations had lower values of soil parameters.

Table 1. Kruskal–Wallis H test for the variation of soil health parameters among vegetation types.

	Chi Square	Significant Level (*p* Value)
POR	68.889	$<3.45 \times 10^{-5}$
SOC	170.5	$<2.2 \times 10^{-16}$
BAC	142.71	$<2.2 \times 10^{-16}$
ACT	137.7	$<2.2 \times 10^{-16}$
FUN	79.621	1.65×10^{-14}

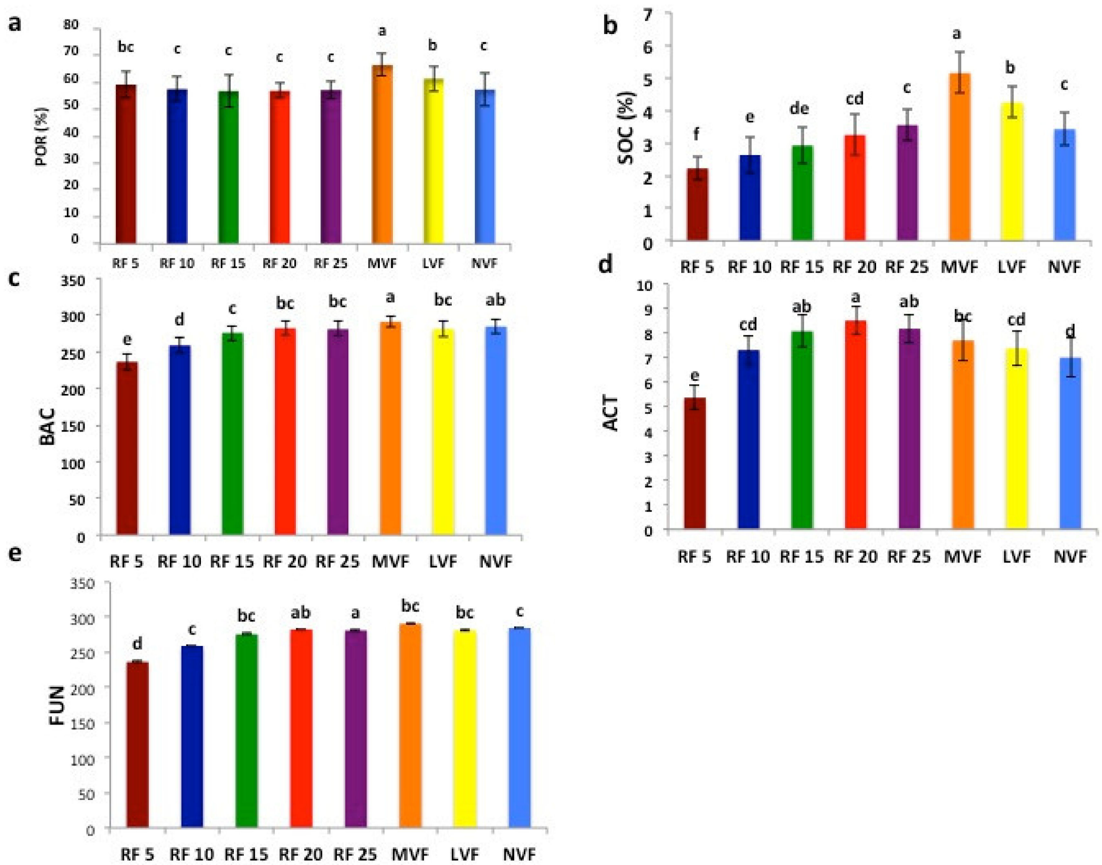

Figure 2. Mean values of key soil health parameters: (**a**). soil porosity (POR), (**b**). soil organic carbon (SOC), (**c**). bacterial counts (BAC), (**d**). fungi counts (FUN) and (**e**). actinomycete counts (ACT). Error bars represent the standard error of the mean (n = 27) for each vegetation type; rubber plantation chronosequence at 5-years-old (RF 5); 10-years-old (RF 10); 15-years-old (RF 15); 20-years-old (RF 20; 25-years-old (RF 25) and natural forests: Moderate volume (MVF); Low volume (LVF); very low forest (NVF)). Differences are significant ($p < 0.05$) when there are different letters above the bars.

Soil porosity (POR) was higher in natural forests than rubber plantations. The highest mean values of POR belonged to the moderate and low volume natural forests (66.5% and 61.4%, respectively). POR means of the very low natural forest and rubber plantations of all ages were lower, ranging from 56% to 59%. There was no significant difference in POR among rubber plantations and the very low natural forest, and between the very low natural forest and the five-year-old rubber plantation.

Soil organic carbon (SOC) content was also highest in the moderate volume natural forest (5.2%) and this was followed by low volume natural forest (4.2%), 25-year-old rubber plantation (3.6%) and very low natural forest (3.4%). SOC was lowest in the youngest rubber plantations, but increased systematically with plantation age; similarly, SOC content increased with increasing volume of the natural forests (Figure 2).

Bacteria counts (BAC) were highest in the three natural forest types and the 20- and 25-year-old rubber plantations compared to the younger rubber plantations. There was no significant difference in BAC found in the three natural forest types and the old rubber plantations (Figure 2). However, actinomycetes counts (ACT) and fungi counts (FUN) were higher in older rubber plantations (years 15, 20 and 25) than the natural forests and younger plantations (years 5 and 10).

Correlations occurred within and among soil health (POR, SOC, BAC, FUN, ACT) and vegetation structure (canopy cover (CAN), vegetation ground cover (VGC), dried litter cover (DLC) and litter biomass (LB)) parameters (Figure 3). Positive correlations were observed among all soil health parameters (r = 0.35–0.8). POR exhibited a stronger positive correlation with SOC, BAC and CAN (r = 0.64, 0.52, and 0.53, respectively) than other soil and vegetation parameters. SOC exhibited a strong positive correlation with BAC as well as CAN, LB and DLC (r = 0.76, 0.77, 0.81 and 0.85, respectively). Microbial population metrics (BAC, FUN and ACT) exhibited strong positive correlations among one another (r = 0.69–0.8) as well as between each microbial population metric and canopy cover (r = 0.7–0.95). BAC also had strong positive correlations with LB and DLC (r = 0.81 and 0.82).

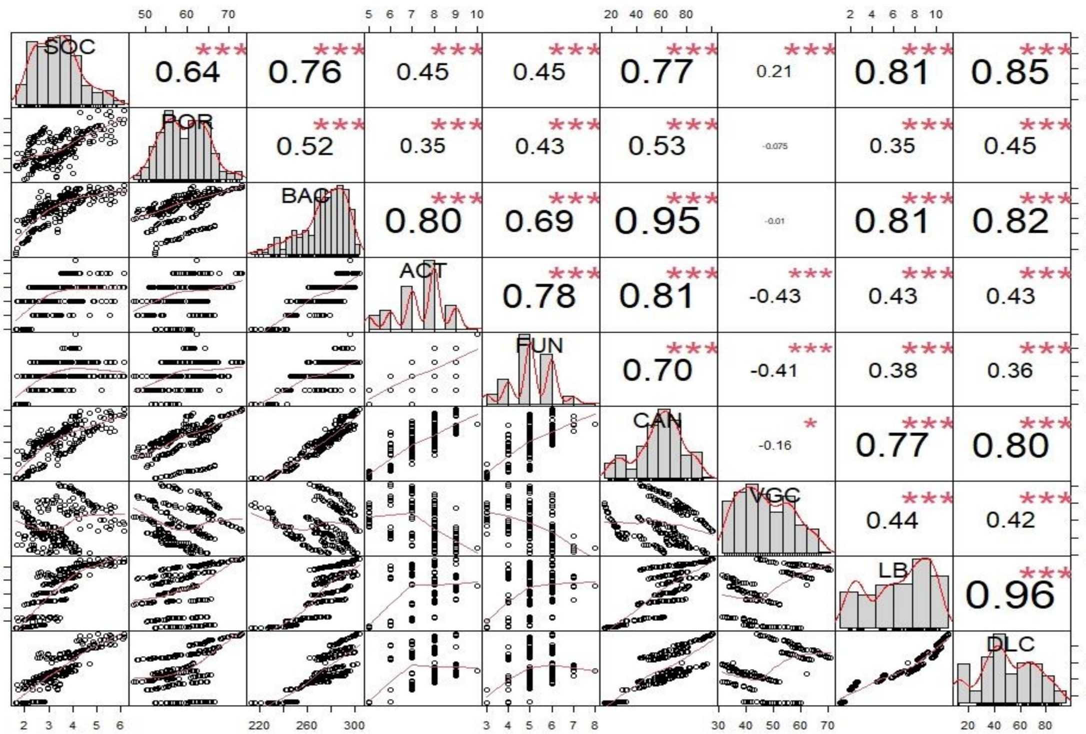

Figure 3. Correlation matrix of the measured soil health parameters (SOC: soil organic carbon (%); POR: soil porosity (%); BAC bacteria counts, ACT: actinomycetes counts, and FUN: fungi counts, in millions organisms/gram soil, respectively) and vegetation parameters (CAN: canopy cover (%); DLC: dried litter cover (%); VGC: vegetation ground cover (%); LB: litter biomass (kg/ha)); r values and * and *** indicate $p < 0.05$, and $p < 0.001$, respectively, in cells.

Among vegetation structure parameters, CAN exhibited strong positive correlations with all soil health parameters except POR (r = 0.70–0.95) as well as with LB and DLC (r = 0.77 and 0.80), but very weak negative correlation with VGC. VGC exhibited a weak positive correlation with SOC (r = 0.21) and weak negative correlations with ACT, FUN and CAN (r = −0.41, −0.43, −0.16, respectively). Litter biomass and dried litter exhibited strong positive correlations with each other and with CAN (r ≥ 0.77), as well as with SOC and BAC (r > 0.8) (Figures 3 and 4).

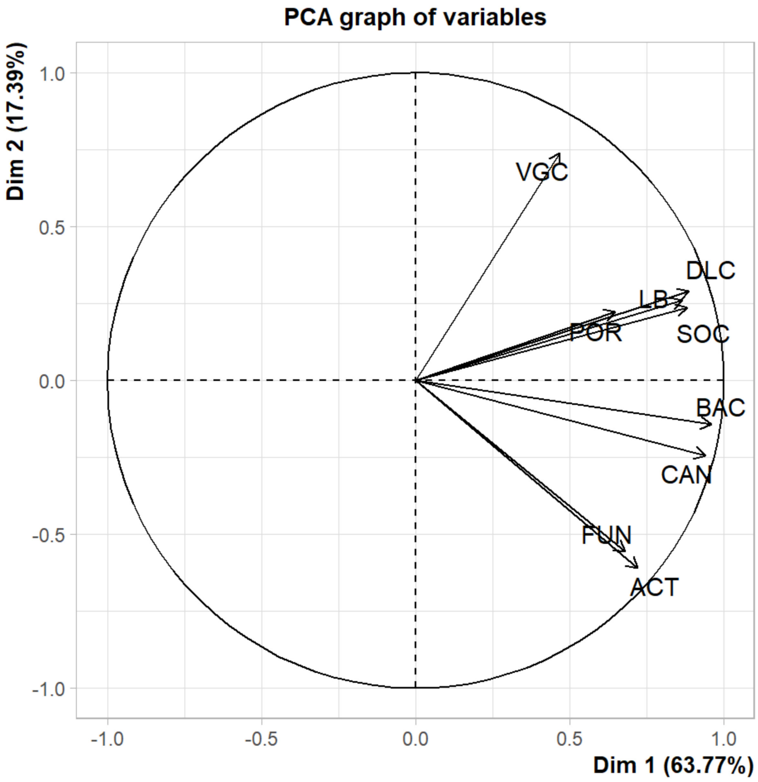

Figure 4. Ordination plot for the principal component analysis. Components 1 and 2 represent 63.8% and 17.4% of the total variance, respectively.

Two principal components explained 81.2% of the observed variation in the soil and vegetation data (Table 2, Figure 4). The first component had high positive loadings for SOC, BAC, ACT, CAN, LB, DLC (Table 2, and it explained 63.8% of the total variance. The second component was dominated by VGC (Table 2). This component accounted for an additional 17.4% of the total variance. These two components reflect the changes in soil parameters due to the variation of vegetation structure.

Table 2. Results of PCA. Variables bolded with absolute eigenvector coefficients ≥ 0.7 are considered significant.

	Rotated Component Matrix	
	Component	
	1	2
POR	0.647	0.223
SOC	**0.881**	0.237
BAC	**0.959**	−0.143
ACT	**0.722**	−0.609
FUN	0.680	−0.557
CAN	**0.940**	−0.244
VGC	0.469	**0.739**
LB	**0.866**	0.261
DLC	**0.888**	0.291
Eigenvalues	5.739	1.565
Variance (%)	63.76	17.39
Cumulative variance (%)	63.76	81.15

4. Discussion

4.1. Variation in Soil Health Parameters by Vegetation Types

Soil health parameters varied among the three types of natural forest and rubber plantations of different ages with overall lower mean values of soil porosity (POR), soil organic carbon (SOC) and bacteria counts (BAC) in rubber plantations. Among the three types of natural forests that are legally allowed to be converted into rubber plantations in Vietnam, the higher volume forests had better soil health indicator values. Similarly, older rubber plantations with bigger trees generally had better soil health. This finding is generally consistent with what has been found in other regions reporting the effects of forest biomass on soil properties [41]. However, our observation that actinomycete counts (ACT) were actually higher in older rubber plantations (15 to 25 years) than any of the natural forest types was entirely unexpected. This could be due to the support of both diversity and the abundance of some microbial populations under intermediate land use intensity conditions that are associated with older rubber plantations [42,43]. This was supported by previous studies indicating that actinomycetes have a preference for physical disturbance [44], and thus higher abundance in agricultural and pasture soils than forested soil [45].

There were significant changes in soil parameters (SOC, BAC, ACT, FUN) between younger and older rubber plantations with an improved trend from younger to older plantations. These observations are consistent with several previous studies that reported improved soil health properties for older rubber plantations due to being less disturbed, given the lack of tillage or plant harvesting [4,46–48]. However, several previous studies reported a lack of significant change in soil health parameters during rubber tree cultivation [19,49] or a decline in soil minerals and soil nutrients over time [50–52].

4.2. Correlations between Soil Health and Vegetation Structure Parameters

Our findings suggest that canopy cover, litter biomass and dried litter cover strongly correlated with soil health parameters and, thus, appear to impact soil health. The impacts of rubber plantation cultivation on soil health appear to be strongest during the first five years after plantation establishment. This could be explained in that, during this early period, rubber trees are small, and the vegetation structure is still simple. However, after five years of establishment, vegetation structure can improve on rubber plantations, which can improve soil parameters. Moreover, older rubber trees with their expanded root systems can lead to greater fine root turnover and higher soil organic carbon [53]. Such correlations between vegetation structure and soil health have also been reported by previous studies [21,48,54]. For example, an increase in canopy cover, leaf litter cover and leaf litter biomass improves soil health in terms of litter, nutrient availability, soil moisture and structure improvement, which, collectively, support healthy soil biota [54]. This could explain the low values of soil health parameters that we observed for young rubber plantations (five years) that becomes less severe (i.e., non-significant) in older rubber plantations where vegetation structure parameters more closely reflect those of natural forests (e.g., 20 to 25 years). However, at this age (≥20 years), the latex production capacity of rubber trees markedly decreases (i.e., they are no longer economically viable) and, thus, rubber trees tend to be cut down after 28 years [55]. As such, the cultivation of rubber plantations poses serious concerns about soil health and conservation, especially when natural forests are converted into rubber plantations because soil health takes approx. 20 years to recover and then becomes degraded again when rubber trees are cut down and replanted only 8 years later (i.e., after 28 years of production). This indicates that the cultivation of rubber trees with an overall restoration trend of soil health over time, due to the improvement of vegetation structure, appears to be difficult to compensate the negative impacts caused by the conversion forests to rubber plantations, which leads to a decline in soil health.

4.3. Implications of Land Conversion Policy and Land Management Practices

The higher values of soil health parameters in natural forests than those in rubber plantations, regardless of the rubber tree age, would suggest that overall soil health declines after forest conversion. The conversion of natural forests into rubber plantations is associated with soil disturbance and changes in vegetation structure, leading to changes in soil properties. These findings are consistent with previous studies that indicated the negative impact on soil health when natural ecosystems (e.g., Indonesian rainforest) were converted into rubber plantations [5,11]. Moreover, the soil health parameters were lower in younger rubber plantations especially in five-year-old rubber plantations. This suggests that the impacts of rubber plantation cultivation on soil health appears to be strongest during the first five years following land use conversion from natural forests due to the replacement of natural vegetation structure with low canopy cover, less ground cover and less leaf litter biomass. In addition, higher volume forests have better soil health, thus indicating that the conversion of higher volume forests would lead to more significant declines in soil health.

The increasing demand for rubber production worldwide has created economic incentives for rubber plantation expansion in marginal environments. This requires the conversion of other land use types into rubber plantations. The current state of knowledge regarding soil health impacts due to rubber tree cultivation is unclear. This lack of clarity could be due to the impacts of rubber tree cultivation on soil health being dependent on the land use type that was converted into a rubber plantation (e.g., moderate, low or very low forests). To meet the demands of economic development, the Vietnamese government permitted degraded natural forestlands (e.g., moderate, low or very low forests) to be converted into new rubber plantations as of 2009. Given the difference in severity of soil health impacts, depending on what type of natural forest is converted into a rubber plantation, changes could be made in forest conversion policy decisions. For example, the 2009 policy could be amended to exclude moderate volume natural forests from legal conversion to rubber plantations in an effort to avoid a long-term reduction in productive capacity due to degraded soil health.

Furthermore, it is critical to address land management practices for young rubber plantations (5 to 10 years), because the impacts of rubber cultivation on soil health are the most significant during this initial period of establishment. The significant correlation observed in this study between soil health and vegetation structure indicates that land owners can design an agroforestry system that incorporates the necessary level of canopy cover to minimize soil health degradation when rubber trees are small (i.e., during the first 5–10 years of farm establishment). Moreover, the incorporation of woody trees with an understory of smaller trees during the early establishment periods of rubber plantations can create a sustainable agroforestry systems with improved land functionality (i.e., improved soil health conservation; [56]). Agroforestry trees have the potential to promote positive changes in soil nutrients, soil structure and soil organisms [57]. For example, intercropped plants (e.g., leguminous trees) in alley cropping systems can increase soil nitrogen by as much as 358 kg per hectare [58]. However, for rubber plantations, further research is needed to determine how much canopy cover and litter cover is required to conserve soil health during the early stages of rubber plantation establishment without harming development (i.e., conserve soil health without impacting economic viability).

5. Conclusions

This study confirmed that the Northern Central Vietnam natural forests have higher values of soil health than that in rubber plantations. Among the rubber plantations of different ages, soil health was lowest in the youngest (five-years-old) rubber plantation, but it improved as the rubber trees got older due to improved canopy cover, ground cover, and leaf litter biomass. The extent to which rubber tree cultivation impacts soil health also depends on the type of land use that was replaced. The conversion of higher biomass ecosystems (e.g., moderate volume forest (101–200 m^3/ha)) to rubber plantations may result in a more severe decline in soil health parameters compared to the conversion of lower biomass ecosystems (e.g., low volume forest (10–100 m^3/ha)) and the very low forest. Taken together, our data suggest that moderate natural forests should be considered for exclusion from the land use types that are legally permitted to be converted into rubber plantations in Vietnam. Moreover, the observations presented here and elsewhere suggest that plantation management should use cultivation techniques that minimize soil health degradation. Future studies are encouraged to determine the ideal parameters for this and other agroforestry systems that inherently conserve soil health.

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References

1. Arjunan, T.R.J.; Radha, G.K.; Karumankandathil, R.; Sankaran, S.; Parukuttiyamma, K.J.; Sreedharan, S.K.; Alikunju, S.; Perumal, V. Rubber Tree. In *Compendium of Transgenic Crop Plants*; Blackwell Publishing Ltd.: Hoboken, NJ, USA, 2019; pp. 117–139.
2. Guo, Z.; Zhang, Y.; Deegen, P.; Uibrig, H. Economic Analyses of Rubber and Tea Plantations and Rubber-tea Intercropping in Hainan, China. *Agrofor. Syst.* **2006**, *66*, 117–127. [CrossRef]
3. Antje, A.P.; Hollingsworth, M.H.; Alan, D.Z.; Jefferson, M.F.; Huafang, C.; Yufang, S.; Jianchu, X. Current trends of rubber plantation expansion may threaten biodiversity and livelihoods. *Glob. Environ. Chang.* **2015**, *34*, 48–58.
4. N'Dri, J.K.; Guéi, A.M.; Edoukou, E.F.; Yéo, J.G.; N'Guessan, K.; Lagerlöf, J. Can litter production and litter decomposition improve soil properties in the rubber plantations of different ages in Côte d'Ivoire? *Nutr. Cycl. Agroecosyst.* **2018**, *111*, 203–215. [CrossRef]
5. Blagodatsky, S.; Xu, J.C.; Cadisch, G. Carbon balance of rubber (Hevea brasiliensis) plantations: A review of uncertainties at plot, landscape and production level. *Agric. Ecosyst. Environ.* **2016**, *221*, 8–19. [CrossRef]
6. Aso, M. *Rubber and the Making of Vietnam: An Ecological History, 1897–1975*; The University of North Carolina Press: Chapel Hill, NC, USA, 2018; pp. 1–426.
7. Phuc, T.X.; Nghi, T.H. *Rubber Expansion and Forest Protection in Vietnam*; Tropenbos International Viet Nam: Hue, Vietnam, 2014.
8. Ministry of Agriculture and Rural Development (MARD). *Circular 127/2008/TT-BNN Dated 31 December 2008 Providing Guidance on Planting Rubber Trees on Forestland*; Ministry of Agriculture and Rural Development (MARD): Ha Noi, Vietnam, 2008.

9. The Government of Vietnam (GOV). *Decision No. 750/QD-TTg of June 3, 2009, Approving the Planning on Development of Rubber Tree up to 2015, with a Vision toward 2020*; The Government of Vietnam, Ed.; The Government of Vietnam (GOV): Ha Noi, Vietnam, 2009.
10. Ministry of Agriculture and Rural Development (MARD). *Emission Reductions Program Document (ER-PD)*; Ministry of Agriculture and Rural Development (MARD): Ha Noi, Vietnam, 2017.
11. Schneider, D.; Engelhaupt, M.; Allen, K.; Kurniawan, S.; Heinemann, M.; Krashevska, V.; Nacke, H.; Wijayanti, M.; Meryandini, A.; Corre, M.D.; et al. Impact of Lowland Rainforest Transformation on Diversity and Composition of Soil Prokaryotic Communities in Sumatra (Indonesia). *Front. Microbiol.* **2015**, *6*, 1339. [CrossRef]
12. Singh, D.; Ferry Slik, J.W.; Jeon, Y.S.; Tomlinson, K.W.; Yang, X.; Kerfahi, D.; Porazinska, D.L.; Adams, J.M. Tropical forest conversion to rubber plantation affects soil micro- & mesofaunal community & diversity. *Sci. Rep.* **2019**, *9*, 5893.
13. Pauli, N.; Donough, C.R.; Oberthür, T.; Cock, J.H.; Verdooren, R.; Rahmadsyah; Abdurrohim, R.; Indrasuara, K.; Lubis, A.; Dolong, T.; et al. Changes in soil quality indicators under oil palm plantations following application of 'best management practices' in a four-year field trial. *Agric. Ecosyst. Environ.* **2014**, *195*, 98–111. [CrossRef]
14. Velmourougane, K. Impact of Organic and Conventional Systems of Coffee Farming on Soil Properties and Culturable Microbial Diversity. *Scientifica* **2016**, *2016*, 3604026. [CrossRef] [PubMed]
15. Teixeira, H.M.; Cardoso, I.M.; Bianchi, F.J.J.A.; da Cruz Silva, A.; Jamme, D.; Peña-Claros, M. Linking vegetation and soil functions during secondary forest succession in the Atlantic forest. *For. Ecol. Manag.* **2020**, *457*, 117696. [CrossRef]
16. Peerawat, M.; Blaud, A.; Trap, J.; Chevallier, T.; Pascal, A.; Gay, F.; Thaler, P.; Spor, A.; Sebag, D.; Choosai, C.; et al. Rubber plantation ageing controls soil biodiversity after land conversion from cassava. *Agric. Ecosyst. Environ.* **2018**, *257*, 92–102. [CrossRef]
17. Allen, K.; Corre, M.D.; Tjoa, A.; Veldkamp, E. Soil Nitrogen-Cycling Responses to Conversion of Lowland Forests to Oil Palm and Rubber Plantations in Sumatra, Indonesia. *PLoS ONE* **2015**, *10*, e0133325. [CrossRef]
18. Kotowska, M.M.; Leuschner, C.; Triadiati, T.; Meriem, S.; Hertel, D. Quantifying above- and belowground biomass carbon loss with forest conversion in tropical lowlands of Sumatra (Indonesia). *Glob. Chang. Biol.* **2015**, *21*, 3620–3634. [CrossRef] [PubMed]
19. Guillaume, T.; Holtkamp, A.M.; Muhammad, D.; Brümmer, B.; Kuzyakov, Y. Soil degradation in oil palm and rubber plantations under land resource scarcity. *Agric. Ecosyst. Environ.* **2016**, *232*, 110–118. [CrossRef]
20. Chandra, L.R.; Gupta, S.; Pande, V.; Singh, N. Impact of forest vegetation on soil characteristics: A correlation between soil biological and physico-chemical properties. *3 Biotech* **2016**, *6*, 188. [CrossRef] [PubMed]
21. QuynhAnh, P.T.; Gomi, T.; MacDonald, L.; Mizugaki, S.; Van Khoa, P.; Furuichi, T. Linkages among land use, macronutrient levels, and soil erosion in northern Vietnam: A plot-scale study. *Geoderma* **2014**, *232–234*, 352–362.
22. Trivedi, P.; Delgado-Baquerizo, M.; Anderson, I.C.; Singh, B.K. Response of Soil Properties and Microbial Communities to Agriculture: Implications for Primary Productivity and Soil Health Indicators. *Front. Plant Sci.* **2016**, *7*, 990. [CrossRef]
23. Franzluebbers, A.J. Stratification of Soil Porosity and Organic Matter. In *Encyclopedia of Agrophysics*; Horabik, J., Lipiec, J., Eds.; Springer: Dordrecht, The Netherlands, 2011; pp. 858–861.
24. Dexter, A.R. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. *Geoderma* **2004**, *120*, 201–214.
25. Biancalani, R.; Petri, M.; Bunning, S.; Salvatore, M.; Tubiello, F.N. The use of soil organic carbon as an indicator of soil degradation. *Energ. Ambiente e Innov. 4* **2012**, *5*, 73–78.
26. Izquierdo, I.; Caravaca, F.; Alguacil, M.M.; Hernández, G.; Roldán, A. Use of Microbiological Indicators for Evaluating Success in Soil Restoration after Revegetation of a Mining Area under Subtropical Conditions. *Appl. Soil Ecol.* **2005**, *30*, 3–10. [CrossRef]
27. Masto, R.E.; Chhinkar, P.K.; Singh, D.; Patra, A.K. Changes in soil quality indicators under long-term sewage irrigation in a sub-tropical environment. *Environ. Geol.* **2009**, *56*, 1237–1243. [CrossRef]
28. Bennett, L.T.; Mele, P.M.; Annett, S.; Kassel, S. Examining links between soil management, soil health, and public benefits in agricultural landscapes: An Australian perspective. *Agric. Ecosyst. Environ.* **2010**, *139*, 1–12.

29. Rodrigues, J.L.M.; Pellizari, V.H.; Mueller, R.; Baek, K.; da C Jesus, E.; Paula, F.S.; Paula, F.S.; Hamaoui, B.M., Jr.; Tsai, S.M.; Feigl, B.; et al. Conversion of the Amazon rainforest to agriculture results in biotic homogenization of soil bacterial communities. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 988–993.
30. Angers, D.A.; Caron, J. Plant-Induced Changes in Soil Structure: Processes and Feedbacks. In *Plant-Induced Soil Changes: Processes and Feedbacks*; Van Breemen, N., Ed.; Springer: Dordrecht, The Netherlands, 1998; pp. 55–72.
31. Lal, R. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science* **2004**, *304*, 1623–1627. [CrossRef] [PubMed]
32. Quang Tri online. Vinh Linh: Rubber Production in 2018 Reached Nearly 8.000 tons 2019. Available online: http://baoquangtri.vn/Th%C6%A1%CC%80i-s%C6%B0%CC%A3/modid/445/ItemID/136590 (accessed on 1 May 2020).
33. Ministry of Agriculture and Rural Development (MARD). *Circular 34/2009/TT-BNNPTNT Dated 10 June 2009 on Criteria of Forest Classification and Identification*; Ministry of Agriculture and Rural Development (MARD): Ha Noi, Vietnam, 2009.
34. Lemmon, P.E. A Spherical Densiometer For Estimating Forest Overstory Density. *For. Sci.* **1956**, *2*, 314–320.
35. Canfield, R.H. Application of the Line Interception Method in Sampling Range Vegetation. *J. For.* **1941**, *39*, 388–394.
36. Grossman, R.B.; Reinsch, T.G. 2.1 Bulk Density and Linear Extensibility. In *Methods of Soil Analysis*; Soil Science Society of America: Madison, WI, USA, 2018; pp. 201–228.
37. Walkley, A.; Black, I.A. An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* **1934**, *37*, 29–38. [CrossRef]
38. Susan, I.; Jennings, D. *Microbial Culture*; Bios Scientific: London, UK, 1995.
39. Wotling, G.; Bouvier, C.; Danloux, J.; Fritsch, J.-M. Regionalization of extreme precipitation distribution using the principal components of the topographical environment. *J. Hydrol.* **2000**, *233*, 86–101. [CrossRef]
40. Team, R.C. *R: A language and Environment for Statistical Computing Computer Program*, version 3.6.1; R Core Team: Vienna, Austria, 2019.
41. Soong, J.L.; Janssens, I.A.; Grau, O.; Margalef, O.; Stahl, C.; Van Langenhove, L.; Urbina, I.; Chave, J.; Dourdain, A.; Ferry, B.; et al. Soil properties explain tree growth and mortality, but not biomass, across phosphorus-depleted tropical forests. *Sci. Rep.* **2020**, *10*, 2302. [CrossRef]
42. Tardy, V.; Spor, A.; Mathieu, O.; Eque, J.; Terrat, S.; Plassart, P.; Regnier, T.; Bardgett, R.; Putten, W.; Roggero, P.P.; et al. Shifts in microbial diversity through land use intensity as drivers of carbon mineralization in soil. *Soil Biol. Biochem.* **2015**, *90*, 204–213. [CrossRef]
43. Bouchez, T.; Blieux, A.L.; Dequiedt, S.; Domaizon, I.; Dufresne, A.; Ferreira, S.; Godon, J.J.; Hellal, J.; Joulian, C.; Quaiser, A.; et al. Molecular microbiology methods for environmental diagnosis. *Environ. Chem. Lett.* **2016**, *14*, 423–441. [CrossRef]
44. Hill, P.; Krištůfek, V.; Dijkhuizen, L.; Boddy, C.; Kroetsch, D.; Van Elsas, J.D. Land use intensity controls actinobacterial community structure. *Microb. Ecol.* **2011**, *61*, 286–302. [CrossRef] [PubMed]
45. Shange, R.S.; Ankumah, R.O.; Ibekwe, A.M.; Zabawa, R.; Dowd, S.E. Distinct soil bacterial communities revealed under a diversely managed agroecosystem. *PLoS ONE* **2012**, *7*, e40338. [CrossRef] [PubMed]
46. Guo, H.; Wang, W.-B.; Luo, X.; Wu, X. Variations in rhizosphere microbial communities of rubber plantations in Hainan island China. *J. Rubber Res.* **2013**, *16*, 243–256.
47. de Blécourt, M.; Hänsel, V.M.; Brumme, R.; Corre, M.D.; Veldkamp, E. Soil redistribution by terracing alleviates soil organic carbon losses caused by forest conversion to rubber plantation. *For. Ecol. Manag.* **2014**, *313*, 26–33. [CrossRef]
48. Zhou, Y.-J.; Li, J.-H.; Ross Friedman, C.; Wang, H. Variation of Soil Bacterial Communities in a Chronosequence of Rubber Tree (Hevea brasiliensis) Plantations. *Front. Plant Sci.* **2017**, *8*, 849. [CrossRef] [PubMed]
49. Umami, I.M.; Kamarudin, K.N.; Abe, S.; Hermansah, H. Does Soil Fertility Decline under Smallholder Rubber Farming? The Case of a West Sumatran Lowland in Indonesia. *Jpn. Agric. Res. Q.* **2019**, *3*, 279–287. [CrossRef]
50. Aweto, A.O. Physical and nutrient status of soils under rubber (Hevea brasiliensis) of different ages in south-western Nigeria. *Agric. Syst.* **1987**, *23*, 63–72. [CrossRef]

51. Liu, C.; Jin, Y.; Liu, C.; Tang, J.; Wang, Q.; Xu, M. Phosphorous fractions in soils of rubber-based agroforestry systems: Influence of season, management and stand age. *Sci. Total Environ.* **2017**, *616-617*, 1576–1588. [CrossRef]
52. Cheng, C.; Wang, R.; Jiang, J. Variation of soil fertility and carbon sequestration by planting Hevea brasiliensis in Hainan Island, China. *J. Environ. Sci.* **2007**, *19*, 348–352. [CrossRef]
53. Lehmann, J.; Kleber, M. The contentious nature of soil organic matter. *Nature* **2015**, *528*, 60–68. [CrossRef]
54. Ogunkunle, C.; Awotoye, O. Soil Fertility Status under Different Tree Cropping System in a Southwestern Zone of Nigeria. *Not. Sci. Biol.* **2011**, *3*, 123–128. [CrossRef]
55. Food Agricuture Organization (FAO). *The Rubber Tree*; Better Farming Series; Food Agricuture Organization (FAO): Rome, Italy, 1977; pp. 1–31.
56. Raj, A. Role of Trees and Woody Vegetation in Soil Fertility Enrichment and Food Security in Dryland Agroforestry as a Climate-Smart Agriculture Strategy. *Int. J. Trop. Agric.* **2017**, *35*, 1147–1161.
57. Barrios, E.; Sileshi, G.W.; Shepherd, K.D.; Sinclair, F. Agroforestry and Soil Health: Linking Trees, Soil Biota, and Ecosystem Services. In *Soil Ecology and Ecosystem Services*; Oxford University Press (OUP): Oxford, UK, 2012; pp. 315–330.
58. Palm, C.A. Contribution of agroforestry trees to nutrient requirements of intercropped plants. *Agrofor. Syst.* **1995**, *30*, 105–124. [CrossRef]