earth

MDPI

Article

Agrochemicals and Shade Complexity Affect Soil Quality in Coffee Home Gardens

Sophie Manson [1], K. A. I. Nekaris [1,*], Andrew Rendell [2], Budiadi Budiadi [3], Muhammad Ali Imron [3] and Marco Campera [2]

[1] School of Social Sciences, Oxford Brookes University, Oxford OX3 0BP, UK; sophie.manson_2019@brookes.ac.uk
[2] Department of Biological and Medical Sciences, Oxford Brookes University, Oxford OX3 0BP, UK; arrendell@brookes.ac.uk (A.R.); mcampera@brookes.ac.uk (M.C.)
[3] Faculty of Forestry, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia; budiadi@ugm.ac.id (B.B.); maimron@ugm.ac.id (M.A.I.)
* Correspondence: anekaris@brookes.ac.uk

Abstract: Soil quality can directly influence the health, yield, and quality of a particular crop species, and agrochemicals are often used to boost soil micro- and macro-nutrients. The excessive application of agrochemicals, however, is often the cause of imbalances in acidity and nutrient concentration and can cause soil to deteriorate. The presence of multiple shade trees in farmland can positively influence soil quality. Here, we evaluate the effect of agrochemical use (i.e., organic, mixed, and intensive) and shade tree complexity (i.e., sun, low, and high) on soil quality (i.e., pH, macronutrients, and micronutrients) in 56 coffee home gardens in Indonesia. We found that Al, Fe, K, and Mn were significantly higher in farms that used agrochemicals, and pH was more acidic in fields with intensive use of agrochemicals. C:N ratio and Mn were higher in soils with high shade complexity than in sun-exposed soils. The use of agrochemicals, however, is not sustainable as it increases the Al concentration and decreases pH, both of which are associated with poor coffee growth and reduced soil quality. Shade tree removal and the use of invasive, non-native species, such as eucalyptus, can also negatively influence soil quality, and thus the maintenance of complex shade cover with native trees should be prioritised.

Keywords: soil organic carbon; pH; micronutrients; macronutrients; organic; wildlife-friendly; Arabica coffee; potassium; aluminum; Indonesia

Citation: Manson, S.; Nekaris, K.A.I.; Rendell, A.; Budiadi, B.; Imron, M.A.; Campera, M. Agrochemicals and Shade Complexity Affect Soil Quality in Coffee Home Gardens. *Earth* **2022**, *3*, 853–865. https://doi.org/10.3390/earth3030049

Academic Editor: Carmine Apollaro

Received: 31 May 2022
Accepted: 22 July 2022
Published: 28 July 2022

1. Introduction

The global human population is expected to increase to 10 billion by 2050, with demand for food crops exceeding this population inflation [1–3]. As a result, the attention of researchers has turned to the ability of farmers not only to produce enough food to feed the population and meet demand but ensure that generations to come are able to utilize the soils that are left to them. Agroforestry, i.e., the integration of natural forest and farmland, has been suggested as a possible solution to ensure the longevity of smallholder farmland by preserving biodiversity, enhancing ecosystem services and, in turn, securing the livelihoods of farmers [4–6]. Shade trees within farmland provide both habitat for wildlife and a means of income for farmers and enrich soil previously damaged through monoculture farming [7–9]. The quality of soil plays a vital role in providing ideal conditions for crop growth [8,10]. Through the optimal composition of nutrients and minerals, achieved using both artificial and organic inputs, soil can directly influence the health, yield and quality of a particular crop species [11]. Additionally, through interactions between the composition of micro- and macro-nutrients within soil and the diversity of fauna and flora that exist within and around it, soil can influence and benefit entire ecosystems [10,12–14]. By ensuring diversity within soil, farmers allow for the provision of essential ecosystem services, such as pest control and pollination [13,15,16].

The composition of nutrients and minerals within soil that are vital for successful crop harvests may not positively influence the sustainability of the soil. For instance, Arabica coffee (*Coffea arabica*) grows well in acidic soil, ideally between 4.9–5.2 pH [17]. Arabica coffee also requires a finely tuned balance of minerals, namely Al^{3+}, Ca^{2+}, Mg^{2+}, P^{3-}, and K^{+}. [13]. Acidity and mineral application in excess have been shown to reduce the quality of the crop significantly, and, in the long-term, lead to a decrease in cation exchange capability (CEC), an increase in exchangeable acidity and nutrient leaching, and a reduced ability to hold water [10,11]. The excessive application of inorganic agrochemicals, such as chemical fertilizers and herbicides, is often the cause of such imbalances in acidity and nutrient concentration [18]. Therefore, establishing ways in which soil quality can be preserved using organic methods, whilst also ensuring that yield is uncompromised, is of clear importance when discussing the security of economically important food crops.

Arabica coffee is one of the most economically important traded commodities in the world, the demand of which is growing by at least 4–5% per year [19,20]. Indonesia, the fourth largest producer of coffee in the world, is home to 1.2 million ha of coffee plantations and produces 792 kg of coffee beans per hectare per year, providing a means of income for millions of farmers [19]. Therefore, ensuring soil quality and longevity is not only important in terms of keeping up with demand, but is also vital if farmers are to retain a reliable source of income. Due to the strict conditions that Arabica coffee requires (i.e., high altitude, temperate climate, and rich soil), exacerbated by the increasing effects of climate change on environmental variables, farmers often turn to chemical fertilizers to provide the necessary nutrients for growing coffee. In addition to the nutritional content of chemical fertilizers, agrochemicals are often more easily accessible and subsidised by the government due to their (short-term) ability to increase yield [21].

The farming systems of smallholder coffee farmers in West Java, Indonesia vary significantly, moving between entirely organic farms with high shade tree complexity to those that use almost exclusively agrochemicals within a full sun environment. In West Java, coffee farms are planted within a polyculture, agroforest environment, meaning that trees are present within and around farms, providing natural habitats for mammals, birds and invertebrates [5,6,22–24]. Variability exists regarding the extent to which the agroforest environment is present within each farm. Evidence suggests that farms with low shade diversity and continuous coffee cropping suffer from reduced soil pH, microbe populations and organic matter, whilst shade effects positively influence soil quality [8,13,25]. For shade effects to be beneficial, researchers have found that multiple tree species are required [13,25,26].

In this study, we assessed the soil composition of smallholder coffee farms in West Java, Indonesia, and how soil composition varies with regards to agrochemical usage and shade complexity (i.e., high shade complexity equals high shade cover made up of multiple tree species). We aimed to establish the effects of agrochemicals on soil quality and investigate the effectiveness of organic farming practices in providing the nutrients required for coffee to grow. We expected that pH will be higher in farms that use organic farming practices and those with higher shade complexity. Additionally, we expected to see higher concentrations of minerals in farms that use agrochemicals due to the application of chemical fertilizers. Finally, we expected the toxicity of soils to be higher in farms that use agrochemicals, i.e., higher Al concentration. Depending on the outcome of the soil analysis, documenting the success of organic farming practices in producing viable soils without chemical inputs would help in ensuring the sustainability of farmland whilst protecting biodiversity, promoting good quality harvests, and securing livelihoods.

2. Materials and Methods

2.1. Soil Sample Collection

We collected soil samples from 56 coffee home gardens in May 2019 in the municipalities of Cipaganti and Pangauban, West Java (a detailed description of the study site can be found in [5,27]). Soil samples consisted of 15 sub-samples taken by soil probe from 30 cm depth for a total of 1 kg for each home garden. Sub-samples were taken randomly within each home garden, mixed, and stored in one plastic bag labelled with a code of each garden. Before taking soil samples we ensured that the soil was not wet from rain, that the vegetation covering the soil was removed and that the probe was clean from the previous sampling. Once we collected all soil samples, we assessed the shade complexity and agrochemical use within each garden. Agrochemical use (i.e., fertilizer urea and NPK and pesticide Endosulfan) was established through ad hoc interviews with farmers (more details in [6,24]). Following these interviews, we categorised farms into one of three categories detailing their level of agrochemical usage: chemicals (intensive use of chemicals); mixed (used a mix of chemicals and organic methods); and organic (did not use any chemical practices). Shade complexity was calculated using both shade cover and tree species richness. Shade cover was estimated using the Canopeo App that uses photos of the canopy to produce an approximate percentage shade cover [24,28]. We obtained shade tree richness by counting the number of tree species present within and along the perimeter of each farm [24]. Using these data, we then assigned farms a level of shade complexity: sun (less than or equal to 10% shade cover); low shade complexity (above 10% shade cover and less than five tree species present); and high shade complexity (above 10% shade cover and more than or equal to five tree species present). Although there is a relationship between shade farms and organic practices, it is not evenly distributed throughout the study area, and sun farms use a range of agrochemicals and organic alternatives.

2.2. Soil Sample Analysis

We stored the soils sample at room temperature for a maximum of three days after the collection and analyzed them at the Balai Penelitian Tanaman Sayuran (laboratorium penguji terpadu) in Lembang, Bandung. This laboratory follows strict procedures to ensure a high standard of analytical quality control and is accredited ISO/IEC 17025. We calculated: soil pH via by potentiometry (H_2O and KCl); organic carbon (C) as % via the Kumies spectrophotometric method; nitrogen (N) as % via the Kjeldhal method; available potassium (K) as % via the Morgan Venema method; iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) as ppm via the Morgan Venema method; calcium (Ca) and magnesium (Mg) as cmol/kg via Buffer NH4OAC 1 M pH 7; and aluminium (Al) as cmol/kg via the titrimetric method [29].

2.3. Data Analysis

We tested whether soil quality (i.e., soil pH and concentration of individual nutrients) was influenced by agrochemical use and shade complexity via Generalised Linear Models (GLMs). We used the "glmmTMB" package and the "glmmTMB" function to produce the models due to the availability of several fit families within the package [30]. We tested each component within the soil analysis against each family, using the QQ residual plots and residual vs. predicted plots produced via the "DHARMa" package to establish the best fit [31]. We used the "emmeans" package and "emmeans" function to produce estimated marginal means and pairwise ratios for each component [32]. We considered $p < 0.05$ as a significant result and <0.001 as a highly significant result. We used R v.4.2.0 to run all of the analyses [33].

3. Results

3.1. Agrochemical Usage

Al, Fe, K, and Mn were all significantly higher in farms that used agrochemicals, with significant differences observed between organic and chemicals, organic and mixed, and mixed and chemicals (Table 1; Figure 1). Al was particularly affected by chemical usage, exhibiting significant differences between each of the agrochemical use treatments (Table 1; estimated marginal means ratio (95% CI): C:M: 0.895 (0.788–1.017); C:O: 12.13 (2.837–51.8); M:O: 3.02 (0.785–11.6)). In all instances, pH was lower in farms that used agrochemicals, with significant differences observed between those intensively using chemicals and those using organic farming practices (Table 1; Figure 2; H_2O–C:M: 0.928 (0.830–1.038); C:O: 0.888 (0.879–1.042); M:O: 0.957 (0.879–1.042); KCl–C:M: 0.895 (0.788–1.017); C:O: 0.847 (0.755–0.951); M:O: 0.947 (0.860–1.042)).

Table 1. Pairwise ratios of soil components between treatments in relation to agrochemical use (C:M—chemicals:mixed; C:O—chemicals:organic; M:O—mixed:organic) and shade complexity (H:L—high:low; H:S—high:sun; L:S—low:sun) within 56 coffee home gardens in West Java. Data are pairwise ratios from estimated marginal means taken from generalised linear models.

Soil Component	Treatment	Ratio	Standard Error	Lower CL	Upper CL	t-Ratio	*p*-Value
pH (H_2O)	C:M	0.928	0.042	0.830	1.038	−1.653	0.157
	C:O	0.888	0.036	0.803	0.983	−2.980	0.016 *
	M:O	0.957	0.033	0.879	1.042	−1.282	0.206
	H:L	1.019	0.048	0.907	1.15	0.401	0.690
	H:S	0.944	0.046	0.838	1.06	−1.192	0.359
	L:S	0.926	0.030	0.856	1.00	−2.396	0.061
pH (KCl)	C:M	0.895	0.046	0.788	1.017	−2.151	0.055
	C:O	0.847	0.040	0.755	0.951	−3.561	0.003 *
	M:O	0.947	0.037	0.860	1.042	−1.420	0.162
	H:L	1.025	0.055	0.899	1.17	0.471	0.640
	H:S	0.937	0.051	0.819	1.07	−1.190	0.360
	L:S	0.914	0.033	0.836	1.00	−2.485	0.049 *
Al	C:M	4.010	2.350	0.934	17.2	2.373	0.033 *
	C:O	12.130	7.080	2.837	51.8	4.276	<0.001 **
	M:O	3.020	1.640	0.785	11.6	2.041	0.047 *
	H:L	0.520	0.385	0.082	3.29	−0.882	0.574
	H:S	1.610	1.369	0.193	13.4	0.556	0.581
	L:S	3.090	1.610	0.845	11.3	2.166	0.107
Fe	C:M	2.000	0.517	1.057	3.80	2.693	0.014 *
	C:O	2.150	0.502	1.204	3.83	3.270	0.006 *
	M:O	1.070	0.214	0.654	1.76	0.350	0.728
	H:L	0.802	0.219	0.408	1.58	−0.809	0.626
	H:S	1.149	0.325	0.570	2.31	0.491	0.626
	L:S	1.433	0.269	0.899	2.28	1.912	0.185
K	C:M	2.136	0.605	1.059	4.31	2.679	0.030 *
	C:O	1.766	0.456	0.932	3.35	2.204	0.048 *
	M:O	0.827	0.186	0.473	1.44	−0.845	0.402
	H:L	1.178	0.365	0.548	2.54	0.531	0.808
	H:S	0.926	0.291	0.425	2.02	−0.244	0.808
	L:S	0.786	0.162	0.471	1.31	−1.166	0.748
C:N	C:M	1.066	0.041	0.969	1.17	1.664	0.307
	C:O	1.031	0.036	0.946	1.12	0.885	0.380
	M:O	0.967	0.029	0.898	1.04	−1.106	0.380
	H:L	1.070	0.044	0.964	1.18	1.594	0.117
	H:S	1.150	0.049	1.035	1.28	3.278	0.006 *
	L:S	1.080	0.030	1.005	1.15	2.639	0.017 *

Table 1. *Cont.*

Soil Component	Treatment	Ratio	Standard Error	Lower CL	Upper CL	t-Ratio	*p*-Value
Mn	C:M	1.469	0.272	0.928	2.32	2.076	0.130
	C:O	1.298	0.219	0.856	1.97	1.550	0.191
	M:O	0.884	0.132	0.610	1.28	−0.826	0.413
	H:L	1.390	0.285	0.840	2.31	1.623	0.145
	H:S	1.700	0.350	1.025	2.83	2.598	0.037 *
	L:S	1.220	0.166	0.873	1.71	1.480	0.145
Zn	C:M	1.130	0.228	0.686	1.86	0.610	0.545
	C:O	1.510	0.276	0.959	2.37	2.250	0.087
	M:O	1.330	0.216	0.894	1.99	1.786	0.120
	H:L	0.959	0.212	0.554	1.66	−0.190	0.850
	H:S	0.891	0.199	0.512	1.55	−0.519	0.850
	L:S	0.929	0.137	0.644	1.34	−0.498	0.850
Ca	C:M	0.906	0.143	0.612	1.34	−0.625	0.667
	C:O	0.860	0.123	0.604	1.23	−1.055	0.667
	M:O	0.950	0.113	0.706	1.28	−0.432	0.667
	H:L	0.990	0.163	0.658	1.49	−0.061	0.952
	H:S	0.937	0.159	0.616	1.43	−0.383	0.952
	L:S	0.947	0.105	0.718	1.25	−0.492	0.952
Mg	C:M	1.015	0.187	0.643	1.60	0.081	0.936
	C:O	0.957	0.160	0.632	1.45	−0.266	0.936
	M:O	0.942	0.136	0.659	1.35	−0.411	0.936
	H:L	0.897	0.176	0.551	1.46	−0.554	0.718
	H:S	1.077	0.219	0.651	1.78	0.363	0.718
	L:S	1.200	0.160	0.863	1.67	1.371	0.530
Cu	C:M	0.040	0.203	−0.462	0.542	0.196	0.845
	C:O	0.220	0.184	−0.235	0.674	1.195	0.389
	M:O	0.180	0.157	−0.210	0.570	1.142	0.389
	H:L	−0.202	0.217	−0.738	0.335	−0.930	0.535
	H:S	-6.35×10^{-3}	0.224	−0.560	0.548	−0.028	0.978
	L:S	0.195	0.147	−0.169	0.559	1.329	0.535

* $p < 0.05$; ** $p < 0.001$.

3.2. Shade Complexity

Shade complexity significantly influenced pH, C:N ratio, and Mn concentration (Table 1; Figures 3–5). pH was significantly different between sun and low shade complexity farms (Table 1; Figure 3; estimated marginal means ratio (95% CI): L:S: 0.914 (0.836–1.00)). C:N ratio was higher in farms with low shade complexity, with significant differences observed between high shade complexity and sun farms, and low shade complexity and sun farms (Table 1; Figure 4; estimated marginal means ratio (95% CI): H:S: 1.15 (1.035–1.28); L:S: 1.08 (1.005–1.15)). Mn concentration was reduced with decreased shade complexity, with the only significant difference being between high shade complexity and sun farms (Table 1; Figure 5; estimated marginal means ratio (95% CI): H:S: 1.70 (1.025–2.83)). We found no significant association between shade complexity and agrochemical use ($\chi^2 = 4.29$, $p = 0.368$).

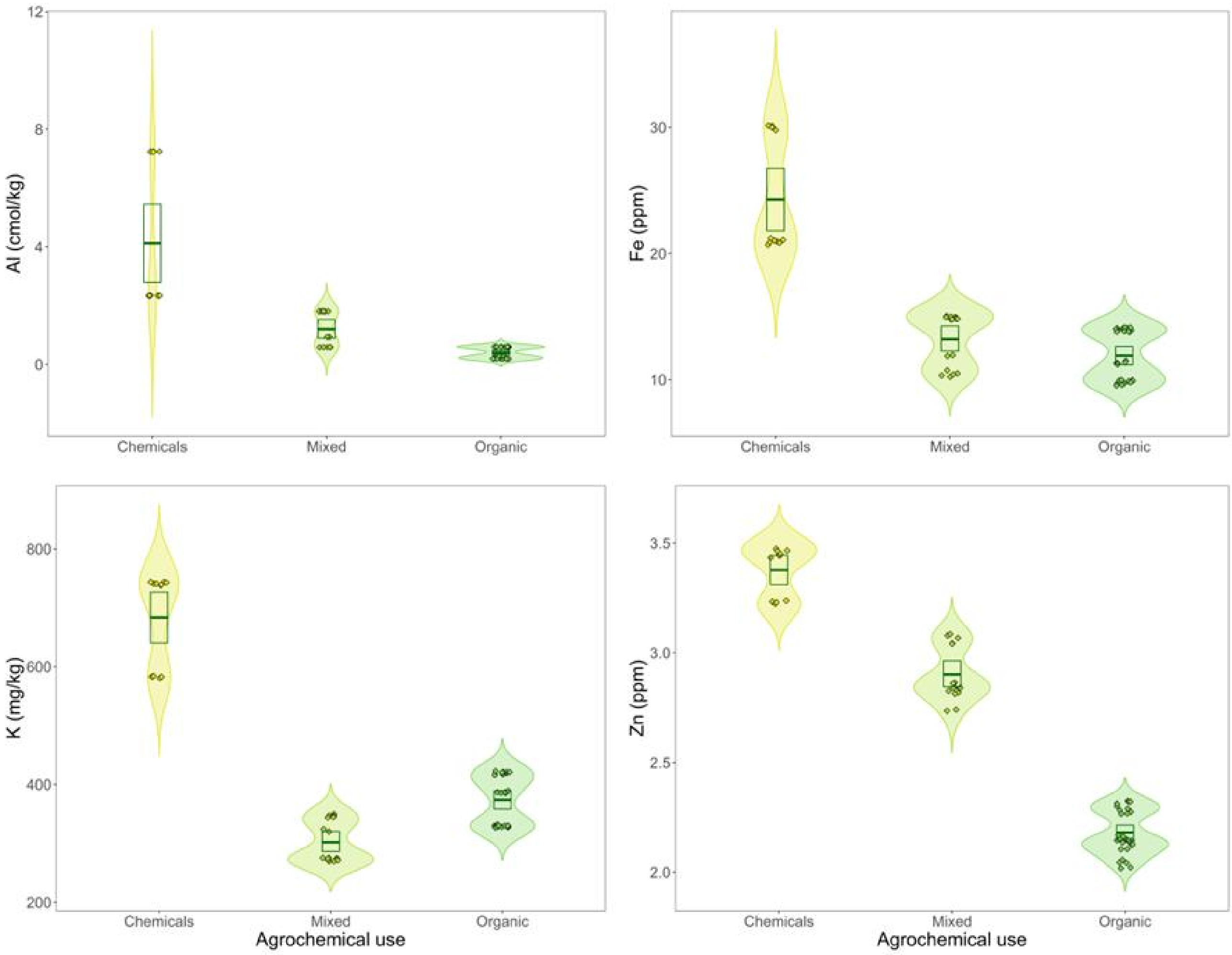

Figure 1. Concentrations of K^+, Al^{3+}, Fe^{3+}, and Zn^{2+} in soil samples from 56 coffee home gardens in West Java in relation to the use of chemicals. Data are model predicted values from generalised linear models, and boxes dictate 95% confidence intervals.

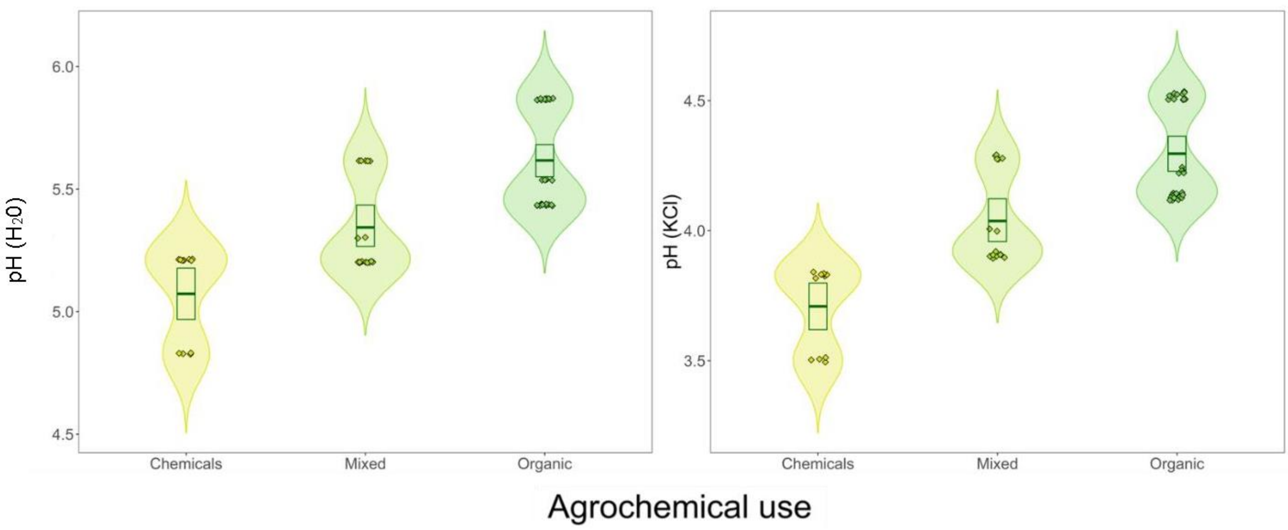

Figure 2. pH of soil samples from 56 coffee home gardens in West Java in relation to the use of chemicals. Data are model predicted values from generalised linear models, and boxes dictate 95% confidence intervals.

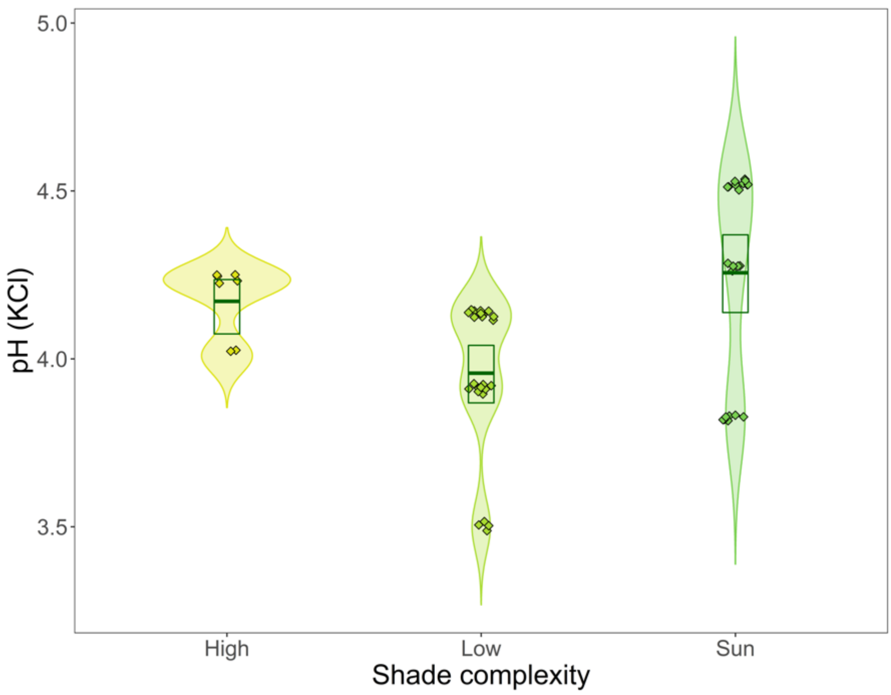

Figure 3. pH of soil samples from 56 coffee home gardens in West Java in relation to shade complexity of gardens (High: >10% shade cover and ≥5 shade tree species; Low: >10% cover and <5 shade tree species; Sun: <10% shade cover). Data are model predicted values from generalised linear models, and boxes dictate 95% confidence intervals.

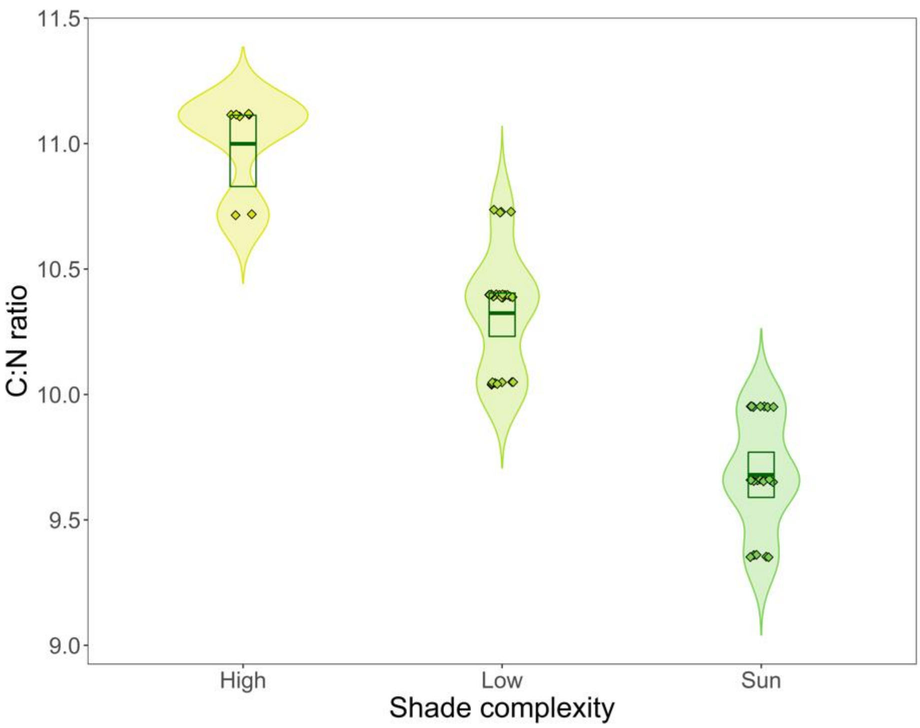

Figure 4. C:N ratio of soil samples from 56 coffee home gardens in West Java in relation to shade complexity of gardens (High: >10% shade cover and ≥5 shade tree species; Low: >10% cover and <5 shade tree species; Sun: <10% shade cover). Data are model predicted values from generalised linear models, and boxes dictate 95% confidence intervals.

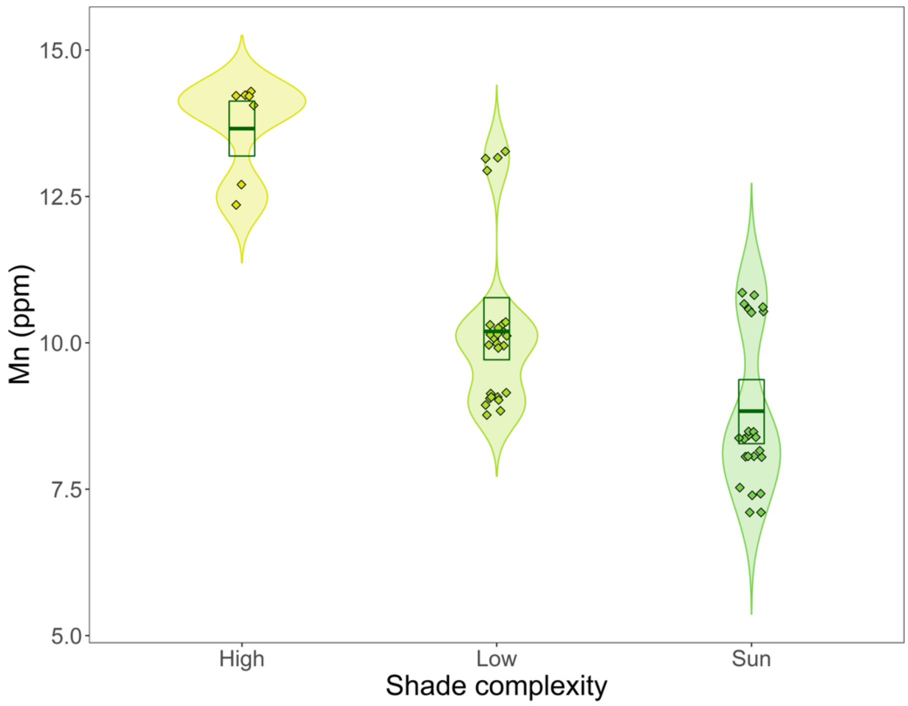

Figure 5. Mn concentration of soil samples from 56 coffee home gardens in West Java in relation to shade complexity of gardens (High: >10% shade cover and ≥5 shade tree species; Low: >10% cover and <5 shade tree species; Sun: <10% shade cover). Data are model predicted values from generalised linear models, and boxes dictate 95% confidence intervals.

4. Discussion

We found that pH was significantly lower in farms that used agrochemicals (both intensive and mixed) than in organic farms, bolstering the extensive published literature documenting the harmful effects of inorganic farming practices on soil pH [10,11,18,34]. The pH of the soil has wide-reaching effects on the soil as an ecosystem, affecting both the life within it and the growing potential of the crops. Soil acidification, caused by the uptake of nitrogen through chemical fertilizers, creates an unfavourable environment for microbial communities to exist and, as a result, harbours fewer nematodes and reduced nematode diversity [13]. In addition to hampering diversity, soil acidification has been found to lead to reductions in yield due to the decrease in soil base cations, Ca^{2+}, and Mg^{2+}, which are essential nutrients for coffee growth, and increases in non-base cations, Fe^{3+}, and Al^{3+} [11,12,35].

Whilst pH was generally lower in sun farms and farms that had lower shade complexity, low pH was also observed in low and high shade complexity farms. This difference will likely be due to the dominating presence of eucalyptus trees (*Eucalyptus* spp.) amongst the shade tree species used at the study site. Eucalyptus trees are often used as shade trees due to their fast growth and income-generating properties [27,36,37]. Numerous studies detail the applicability of eucalyptus trees as shade trees in coffee farms with varying results due to competition for root growth between eucalyptus and crop plants. Competition for root growth has been found to impact the productivity of coffee, although the extent to which productivity is affected seems to vary depending on annual rainfall [36,37]. In addition to affecting yield, eucalyptus trees release a toxin to inhibit the growth of other plants in their vicinity, and this toxin has been proven to cause soil acidification [38]. Therefore, if a farm has high tree species richness yet many of the trees are eucalyptus, acidity is likely to still be higher than in other organic farms. The observed variation in pH in sun farms could be attributed to a wider variation of fertilizers used, both organic and chemical, whereas in high shade complexity farms, farmers use more organic inputs.

We found significantly higher concentrations of Al, Zn, Fe, and K in farms that used agrochemicals intensively and those that used both agrochemicals and organic practices. It is true that these minerals are essential for growing Arabica coffee, yet the significant concentrations of each within farms that use agrochemicals suggests that this is due to the excessive use of chemical fertilizers. Whilst high concentrations of Zn and K have been found to influence coffee cup aroma [26,39], high nutrient concentrations through the application of chemical fertilizers can lead to nutrient leaching and lower CEC, rendering the presence of such nutrients less beneficial due to their impact on the soil's ability to hold them [10,11]. Studies surrounding the nutrients necessary for coffee cup quality (i.e., consistency, freshness, and flavours) are contradictory, with several researchers documenting the opposite effect of Zn [39]. In contrast to the aforementioned nutrients, the toxicity of excessive Al in coffee farms has been well-documented for several decades, with increased Al concentrations associated with poor coffee growth [35]. Not only do increased Al concentrations limit root function and growth, but, similarly to low pH, they have been shown to limit the retention of Ca and Mg [35,40–42]. This is in line with our findings, as Ca and Mg were the only nutrients that were found to be lower in farms that used chemicals.

The C:N ratio of soil samples was significantly higher in farms with high shade complexity, with the C:N ratio decreasing at the same rate between farms with high, low, and sun shade complexity. This difference is due to the increased availability of organic residue from the litter of surrounding shade trees [43]. The fact that C:N ratio was higher in farms with high shade complexity is in line with research by Teixeria et al. [25], who found that increased plant diversity positively influenced soil carbon stocks, showing that it is not just the presence of shade cover that is important, but the diversity of tree species that are used for shade. Whilst shade complexity did positively influence the C:N ratio and soil pH, it was found to be less influential than agrochemical use with regards to soil composition overall. This is in contrast to existing literature reporting the benefits of a diversity of shade tree species for soil quality, with Sauvadet et al. [13] finding that shade complexity was as influential on soil quality as agrochemical use [25]. Our findings are likely due to the presence of eucalyptus trees within our study site affecting soil composition, nutrient retention and soil acidity [36,37].

Whilst the concentrations of particular nutrients within soil are crucial for successful coffee growth, the importance of a diversity of nutrients has been well documented, with researchers highlighting the benefits of organic farming for maintaining this diversity [10,13,44]. Although farms classified as organic, mixed, and agrochemical were using such practices prior to our study, soil samples were taken during the same year that training for the implementation of high-quality organic practices, such as natural pest control, rabbit manure, and microorganisms (EM4) used to boost plant growth, were implemented [27]. Therefore, it is likely that we were not able to observe the benefits of these practices on nutrient concentration and diversity to the full extent.

By using organic, wildlife-friendly farming practices that promote biodiversity through the use of natural fertilizers and agroforestry, farmers are ensuring the longevity of their farmland through the protection of ecosystem services at all levels [45]. Less acidic soil harbours a diversity of soil microbiota, nematode species, and invertebrates, improving soil structure and plant growth, and, in turn, influencing the presence of birds and mammals [46]. This diversity ensures the direct and indirect provision of ecosystem services, such as pollination, seed dispersal, and natural pest management [5,6,13,15,16,47]. Whilst there is some debate as to whether organic farming practices improve crop yield, researchers have documented decreases in coffee yield under acidic conditions, and in turn, Ca^{2+} and Mg^{2+} depleted soils [8,11,48]. Furthermore, farmers can increase the premium they receive from their crops through organic and environmental certification, with consumers saying they are willing to pay more for products that are pesticide-free and made using organic practices [49]. Finally, by creating a natural optimal environment for coffee, farmers increase their crops' resilience to climate change. Environmental variables, such as temperature, humidity, and altitude, significantly affect coffee growth regardless of agrochemical use and shade complexity [10,50]. Therefore, by tailoring their farms to the needs of coffee through natural interventions, such as adding shade trees to lower temperature, they are increasing the likelihood of successful harvests despite a changing climate [51–53].

5. Conclusions

We aimed to evaluate the effect of agrochemicals and shade complexity on soil quality in coffee home gardens in West Java, Indonesia. We found that both agrochemical use and shade complexity significantly affected soil pH, causing soil to become more acidic in farms that exclusively used agrochemicals and those with low shade complexity. In addition to low soil pH, farms that exclusively used agrochemicals saw higher concentrations of Al, Zn, Fe, and K. Whilst high Al concentrations are directly damaging to coffee growth, the high concentrations of Zn, Fe, and K are due to the excessive application of fertilizers, which will eventually lead to nutrient leaching and low CEC [10,11,34].

Moving forward, we will disseminate the results of this work to farmers from our study site and help promote the ongoing use of high-quality organic practices that will increase pH and decrease Al toxicity, such as the use of rabbit manure and microorganism EM4 [27]. Another way of achieving this is through "liming", where lime calcium oxide, calcium hydroxide, calcium carbonate, or calcium magnesium carbonate are used to reduce the availability of H and Al, leading to a higher pH and reduced Al toxicity [35]. The waste from coffee processing, i.e., coffee husks and pulp, has been found to be effective in liming soil and increasing the presence of Mg and K, helping to reduce waste, reduce costs, and reduce farmers' dependence on chemical substitutes [54,55]. Furthermore, we will promote the use of native fruit tree species as shade trees instead of eucalyptus trees due to the increased micro-organism activity of soil with coffee intercropped with other plant species [56,57]. Although eucalyptus trees are fast-growing and act as a source of income for farmers, as environmental variables begin to fluctuate due to climate change (i.e., fluctuations in rainfall), the long-term sustainability of farmland should be prioritised over short-term gain.

Author Contributions: Conceptualization, S.M., M.C. and K.A.I.N.; methodology, S.M. and M.C.; software, S.M. and M.C.; validation, M.C. and A.R.; formal analysis, S.M. and M.C.; investigation, M.C. and S.M.; resources, K.A.I.N.; data curation, M.C., S.M. and K.A.I.N.; writing—original draft preparation, S.M.; writing—review and editing, M.C., A.R., B.B., M.A.I. and K.A.I.N.; visualization, M.C.; supervision, K.A.I.N., M.A.I. and B.B.; project administration, K.A.I.N.; funding acquisition, K.A.I.N. and M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Augsburg Zoo, Brevard Zoo, Cleveland Zoo and Zoo Society, Co-lumbus Zoo and Aquarium, Disney Worldwide Conservation Fund, Global Challenges Fund Initiative—Oxford Brookes University, International Primate Protection League, Lee Richardson Zoo, the Leverhulme Trust (RPG084), Mohamed bin al Zayed Species Conservation Fund (152511813, 182519928), Margot Marsh Biodiversity Fund, Moody Gardens Zoo, National Geographic (GEFNE101-13), NaturZoo Rhein, People's Trust for Endangered Species, Primate Action Fund, San Francisco Zoo, and Shaldon Wildlife Trust.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: We thank Indonesia RISTEK for authorizing the study (research permit 24/FRP/E.5/Dit.KI/I/2019). We thank the team members of the Little Fireface Project and Tomas Busina for helping with the data collection.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Tilman, D.; Cassman, K.G.; Matson, P.A.; Naylor, R.; Polasky, S. Agricultural sustainability and intensive production practices. *Nature* **2002**, *418*, 671–677. [CrossRef] [PubMed]
2. Klein, A.M.; Vassière, B.E.; Cane, J.H.; Steffan-Dewenter, I.; Cunningham, S.A.; Kremen, C.; Tscharntke, T. Importance of pollinators in changing landscapes for world crops. *Proc. R. Soc. B* **2007**, *274*, 303–313. [CrossRef] [PubMed]
3. Kemmerling, L.R.; Griffin, S.R.; Haddad, N.M. Optimizing pollination conservation and crop yield among perennial bioenergy crops. *Glob. Chang. Biol. Bioenergy* **2021**, *13*, 1030–1042. [CrossRef]
4. Duffy, C.; Toth, G.G.; Hagan, R.P.O.; McKeown, P.C.; Rahman, S.A.; Widyaningsih, Y.; Sunderland, T.C.H.; Spillane, C. Agroforestry contributions to smallholder farmer food security in Indonesia. *Agrofor. Syst.* **2021**, *95*, 1109–1124. [CrossRef]
5. Campera, M.; Budiadi, B.; Bušina, T.; Fathoni, B.H.; Dermody, J.; Nijman, V.; Imron, M.A.; Nekaris, K.A.I. Abundance and richness of invertebrates in shade-grown versus sun-exposed coffee home gardens in Indonesia. *Agrofor. Syst.* **2022**, *96*, 829–841. [CrossRef]
6. Manson, S.; Nekaris, K.A.I.; Hedger, K.; Balestri, M.; Ahmad, N.; Adinda, E.; Budiadi, B.; Imron, M.A.; Nijman, V.; Campera, M. Flower visitation time and number of visitor species are reduced by the use of agrochemicals in coffee home gardens. *Agronomy* **2022**, *12*, 509. [CrossRef]
7. Ilany, T.; Ashton, M.S.; Montagnini, F.; Martinez, C. Using agroforestry to improve soil fertility: Effects of intercropping on *Ilex paraguariensis* (yerba mate) plantations with *Araucaria angustifolia*. *Agrofor. Syst.* **2010**, *80*, 399–409. [CrossRef]
8. Zhao, Q.; Yiong, W.; Xing, Y.; Sun, Y.; Lin, X.; Dong, Y. Long-term coffee monoculture alters soil chemical properties and microbial communities. *Sci. Rep.* **2018**, *8*, 6116. [CrossRef]
9. Saputra, D.D.; Sari, R.R.; Hairiah, K.; Roshetko, J.M.; Suprayogo, D.; van Noordwijk, M. Can cocoa agroforestry restore degraded soil structure following conversion from forest to agricultural use? *Agrofor. Syst.* **2020**, *94*, 2261–2276. [CrossRef]
10. da Silva Aragão, O.O.; de Oliveira-Longatti, S.M.; de Castro Caputo, P.S.; Rufini, M.; Carvalho, G.R.; de Carvalho, T.S.; de Souza Moreira, F.M. Microbiological indicators of soil quality are related to greater coffee yield in the Brazilian *Cerrado* region. *Ecol. Indic.* **2020**, *113*, 106205. [CrossRef]
11. Castro-Tanzi, S.; Dietsch, T.; Urena, N.; Vindas, L.; Chandler, M. Analysis of management and site factors to improve the sustainability of smallholder coffee production in Tarrazú, Costa Rica. *Agric. Ecosyst. Environ.* **2012**, *155*, 172–181. [CrossRef]
12. Meng, W.A.N.G.; Shanshan, L.I.; Xiaoyue, L.I.; Zhongqiu, Z.H.A.O.; Shibao, C.H.E.N. An overview of current status of copper pollution in soil and remediation efforts in China. *Front. Earth Sci.* **2018**, *25*, 305.
13. Sauvadet, M.; den Meersche, K.V.; Allinne, C.; Gay, F.; de Melo Virginio Filho, E.; Chauvat, M.; Becquer, T.; Tixier, P.; Harmand, J.M. Shade trees have higher impact on soil nutrient availability and food web in organic than conventional coffee agroforestry. *Sci. Total Environ.* **2019**, *649*, 1065–1074. [CrossRef]
14. Medina-Sauza, R.M.; Álvarez-Jiménez, M.; Ortíz-Huerta, Y.; Ruiz-Sayago, E.; Blouin, M.; Villain, L.; Guevara, R.; Sangabriel, W.; Reverchon, F.; Barois, I. Bulk and rhizosphere soil properties under two *Coffea* species influenced by the earthworm *Pontoscolex corethrurus*. *Rhizosphere* **2022**, *21*, 100458. [CrossRef]
15. Armbrecht, I.; Gallego, M.C. Testing ant predation on the coffee berry borer in shaded and sun coffee plantations in Colombia. *Entomol. Exp. Appl.* **2007**, *124*, 261–267. [CrossRef]
16. Escobar-Ramírez, S.; Grass, I.; Armbrecht, I.; Tscharntke, T. Biological control of the coffee berry borer: Main natural enemies, control success, and landscape influence. *Biol. Control* **2019**, *136*, 103992. [CrossRef]
17. Pereira, L.L.; Guarçoni, R.C.; Moreli, A.P.; Pinheiro, P.F.; Pinheiro, C.A.; Moreira, T.R.; Siqueira, E.D.; Caten, C.S. Physicochemical parameters of arabica fermented coffee in different altitudes. *Coffee Sci.* **2021**, *16*, e161877.
18. Barak, P.; Jobe, B.O.; Krueger, A.R.; Peterson, L.A.; Laird, D.A. Effects of long-term soil acidification due to nitrogen fertilizer inputs in Wisconsin. *Plant Soil* **1997**, *197*, 61–69. [CrossRef]
19. Ibrahim, H.W.; Zailani, S. A review on the competitiveness of global supply chain in a coffee industry in Indonesia. *Int. Bus. Manag.* **2010**, *4*, 105–115.
20. DaMatta, F.M.; Rahn, E.; Läderach, P.; Ghini, R.; Ramalho, J.C. Why could the coffee crop endure climate change and global warming to a greater extent than previously estimated? *Clim. Chang.* **2019**, *152*, 167–178. [CrossRef]
21. Oka, I.N. Integrated pest management in Indonesia: IPM by Farmers. In *Integrated Pest Management in the Global Arena*; Maredia, K.M., Dakouo, D., Mota-Sanchez, D., Eds.; CABI Publishing: Wallingford, UK, 2003; pp. 223–237.
22. Imron, M.A.; Campera, M.; Al Bihad, D.; Rachmawati, F.D.; Nugroho, F.E.; Budiadi, B.; Wianti, K.F.; Suprapto, E.; Nijman, V.; Nekaris, K.A.I. Bird assemblages in coffee agroforestry systems and other human modified habitats in Indonesia. *Biology* **2022**, *11*, 310. [CrossRef] [PubMed]
23. Campera, M.; Hedger, K.; Birot, H.; Manson, S.; Balestri, M.; Budiadi, B.; Imron, M.A.; Nijman, V.; Nekaris, K.A.I. Does the presence of shade trees and distance to the forest affect detection rates of terrestrial vertebrates in coffee home gardens? *Sustainability* **2021**, *13*, 8540. [CrossRef]
24. Campera, M.; Balestri, M.; Manson, S.; Hedger, K.; Ahmad, N.; Nijman, V.; Budiadi, B.; Imron, M.A.; Nekaris, K.A.I. Shade trees and agrochemical use affect butterfly assemblages in coffee home gardens. *Agric. Ecosyst. Environ.* **2021**, *319*, 107547. [CrossRef]
25. Teixeira, H.M.; Bianchi, F.J.J.A.; Cardoso, I.M.; Tittonell, P.; Peña-Claros, M. Impact of agroecological management on plant diversity and soil-based ecosystem services in pasture and coffee systems in the Atlantic forest of Brazil. *Agric. Ecosyst. Environ.* **2021**, *305*, 107171. [CrossRef]

26. Tassew, A.A.; Yadessa, G.B.; Bote, A.D.; Obso, T.K. Influence of location, elevation gradients, processing methods, and soil quality on the physical and cup quality of coffee in the Kafa Biosphere Reserve of SW Ethiopia. *Heliyon* **2021**, *7*, e07790. [CrossRef] [PubMed]
27. Campera, M.; Budiadi, B.; Adinda, E.; Ahmad, N.; Balestri, M.; Hedger, K.; Imron, M.A.; Manson, S.; Nijman, V.; Nekaris, K.A.I. Fostering a wildlife-friendly program for sustainable coffee farming: The case of small-holder farmers in Indonesia. *Land* **2021**, *10*, 121. [CrossRef]
28. Patrignani, A.; Ochsner, T.E. Canopeo: A powerful new tool for measuring fractional green canopy cover. *Agron. J.* **2015**, *107*, 2312–2320. [CrossRef]
29. Sparks, D.L.; Page, A.L.; Helmke, P.A.; Loeppert, R.H.; Soltanpour, P.N.; Tabatabai, M.A.; Johnston, C.T.; Sumner, M.E. *Methods of Soil Analysis, Part 3–Chemical Methods*; Soil Science Society of America Inc.: Madison, WI, USA, 1996.
30. Brooks, M.E.; Kristensen, K.; van Benthem, K.J.; Magnusson, A.; Berg, C.W.; Nielsen, A.; Skaug, H.J.; Maechler, M.; Bolker, B.M. glmmTMB balances speed and flexibility among packages for zero-inflated Generalized Linear Mixed Modeling. *R J.* **2017**, *9*, 378–400. [CrossRef]
31. Hartig, J. DHARMa: Residual Diagnostics for Hierarchical (Multi-Level/Mixed) Regression Models. Available online: https://cran.r-project.org/web/packages/DHARMa (accessed on 30 May 2022).
32. Lenth, R. Emmean: Estimated Marginal Means, Aka Least-Squares Means. R Package Version 1.3.4. 2019. Available online: https://cran.r-project.org/package=emmeans (accessed on 30 May 2022).
33. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2018.
34. Kwiatkowski, C.A.; Harasim, E. Chemical properties of soil in four-field crop rotations under organic and conventional farming systems. *Agronomy* **2020**, *10*, 1045. [CrossRef]
35. Parecido, R.J.; Sorattio, R.P.; Perdona, M.J.; Gitari, H.I.; Dognani, V.; Santos, A.R.; Silveira, L. Liming method and rate effects on soil acidity and Arabica coffee nutrition, growth, and yield. *J. Soil Sci. Plant Nutr.* **2021**, *21*, 2613–2625. [CrossRef]
36. Schaller, M.; Schroth, G.; Beer, J.; Jiménez, F. Species and site characteristics that permit the association of fast-growing trees with crops: The case of *Eucalyptus deglupta* as coffee shade in Costa Rica. *For. Ecol. Manag.* **2003**, *175*, 205–215. [CrossRef]
37. Latini, A.O.; Silva, D.P.; Souza, F.M.L.; Ferreira, M.C.; de Moura, M.S.; Suarez, N.F. Reconciling coffee productivity and natural vegetation conservation in an agroecosystem landscape in Brazil. *J. Nat. Conserv.* **2020**, *57*, 125902. [CrossRef]
38. del Moral, R.; Muller, C.H. Fog Drip: A Mechanism of toxin transport from *Eucalyptus globulus*. *Bull. Torrey Bot. Club* **1969**, *96*, 467–475. [CrossRef]
39. Yadessa, A.; Burkhardt, J.; Bekele, E.; Hundera, K.; Goldbach, H. The role of soil nutrient ratios in coffee quality: Their influence on bean size and cup quality in the natural coffee forest ecosystems of Ethiopia. *Afr. J. Agric. Res.* **2019**, *14*, 2090–2103.
40. Kopittke, P.M.; Blamey, F.P.C. Theoretical and experimental assessment of nutrient solution composition in short-term studies of aluminium rhizotoxicity. *Plant Soil* **2016**, *406*, 311–326. [CrossRef]
41. Auler, A.C.; Caires, E.F.; Pires, L.F.; Galetto, S.L.; Romaniw, J.; Charnobay, A.C. Lime effects in a no-tillage system on Inceptisols in Southern Brazil. *Geoderma Reg.* **2019**, *16*, e00206. [CrossRef]
42. Takala, B. Ameliorative effects of coffee husk compost and lime amendment on acidic soil of Haru, Western Ethiopia. *J. Soil Water Sci.* **2020**, *4*, 141–150.
43. Nuddin, A. The role of tree crops on nutrient availability, and production of coffee agroforestry. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *270*, 012049.
44. Thomazini, A.; Mendonça, E.S.; Cardoso, I.M.; Garbin, M.L. SOC dynamics and soil quality index of agroforestry systems in the Atlantic rainforest of Brazil. *Geoderma Reg.* **2015**, *5*, 15–24. [CrossRef]
45. Jose, S. Agroforestry for ecosystem services and environmental benefits: An overview. *Agrofor. Syst.* **2009**, *76*, 1–10. [CrossRef]
46. Medina-Sauza, R.M.; Alvarez-Jimenez, M.; Delhal, A.; Reverchon, F.; Blouin, M.; Guerrero-Analco, J.A.; Cerdan, C.R.; Guevara, R.; Villain, L.; Barois, I. Earthworms building up soil microbiota, a review. *Front. Environ. Sci.* **2019**, *7*, 81. [CrossRef]
47. Plaas, E.; Meyer-Wolfarth, F.; Banse, M.; Bengtsson, J.; Bergmann, H.; Faber, J.; Potthoff, M.; Runge, T.; Schrader, S.; Taylor, A. Towards valuation of biodiversity in agricultural soils: A case for earthworms. *Ecol. Econ.* **2019**, *159*, 291–300. [CrossRef]
48. Matsuyama, N.; Saigusa, M.; Sakaiya, E.; Tamakawa, K.; Oyamada, Z.; Kudo, K. Acidification and soil productivity of allophanic andosols affected by heavy application of fertilizers. *Soil Sci. Plant Nutr.* **2006**, *51*, 117–123. [CrossRef]
49. Herring, M.W.; Garnett, S.T.; Zander, K.K. From boutique to mainstream: Upscaling wildlife-friendly farming through consumer premiums. *Conserv. Sci. Pract.* **2022**, *4*, e12730. [CrossRef]
50. Grüter, R.; Trachsel, T.; Laube, P.; Jaisli, I. Expected global suitability of coffee, cashew and avocado due to climate change. *PLoS ONE* **2022**, *17*, e0261976. [CrossRef]
51. Borron, S. *Building Resilience for an Unpredictable Future: How Organic Agriculture Can Help Farmers Adapt to Climate Change*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2006.
52. Scialabba, N.E.; Müller-Lindenlauf, M. Organic agriculture and climate change. *Renew. Agric. Food Syst.* **2010**, *25*, 158–169. [CrossRef]
53. Rahn, E.; Läderach, P.; Baca, M.; Cressy, C.; Schroth, G.; Malin, D.; van Rikxoort, H.; Shriver, J. Climate change adaptation, mitigation and livelihood benefits in coffee production: Where are the synergies? *Mitig. Adapt. Strateg. Glob. Chang.* **2013**, *19*, 1119–1137. [CrossRef]

54. Kasongo, R.K.; Verdoodt, A.; Kanyankagote, P.; Baert, G.; Van Ranst, E. Coffee waste as an alternative fertilizer with soil improving properties for sandy soils in humid tropical environments. *Soil Use Manag.* **2010**, *27*, 94–102. [CrossRef]
55. Dzung, N.A.; Dzung, T.T.; Khanh, V.T.P. Evaluation of coffee husk compost for improving soil fertility and sustainable coffee production in rural central highland of Vietnam. *Resour. Environ.* **2013**, *3*, 77–82.
56. Guimarães, N.D.; Gallo, A.D.; Fontanetti, A.; Meneghin, S.P.; de Souza, M.D.B.; Morinigo, K.P.G.; da Silva, R.F. Biomass and soil microbial activity in different systems of coffee cultivation. *Rev. Fac. Cienc. Agrar.* **2017**, *40*, 34–44.
57. Henrique, N.S.; Maltoni, K.L.; Faria, G.A. Soil quality in two coffee crop systems in the Amazon biome. *Rev. Bras. Eng. Agric. Ambient.* **2020**, *24*, 379–384. [CrossRef]