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Impact of Farm Management on Soil Fertility in Agroforestry Systems in Bali, Indonesia

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Abstract: Expansion and intensification of agricultural land in the tropics increasingly raises environmental concerns and questions about sustainability of production systems. A key parameter to consider when assessing the sustainability of production systems is soil fertility, and of particular interest are macronutrients, pH, electrical conductivity, and microbial communities. To understand which environmental factors influence soil fertility, we studied the abovementioned key parameters in two agroforestry systems (rustic and polyculture) in Bali, Indonesia. Via Generalized Linear Models, we found that agroforestry system, canopy cover, crop richness, tree richness, and yields had differing effects on topsoil (0–5 cm) and subsoil (10–15 cm) properties, including C:N ratios, conductivity, K, organic C, P, and total microbes. We found a higher C:N ratio in topsoil ($p = 0.027$), higher organic carbon content in topsoil ($p = 0.009$) and subsoil ($p < 0.001$), higher total microbes in subsoil ($p = 0.001$), and lower phosphorus levels in topsoil ($p < 0.001$) in rustic than in polyculture systems. Rustic systems may foster conditions conducive to soil fertility, and in our study, canopy cover ($p < 0.001$) and tree richness ($p < 0.001$) emerge as a key positive drivers of the total number of microbes in topsoil. The positive associations observed between crop and tree richness with electrical conductivity and total microbe counts underscore the importance of biodiversity in enhancing soil fertility, emphasizing the need for diversified agricultural systems to promote soil fertility. With soil fertility declining across the world due to global investments in agricultural intensification, it is vital that food production systems divert to the use of systems such as agroforestry in order to ensure soil sustainability and food security for future generations.

Keywords: ecosystem services; agricultural intensification; sustainability; rustic systems; polyculture systems; Indonesia; agroforestry

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1. Introduction

In many tropical regions, due to increased demand for crop commodities and human population increases, there has been an expansion and intensification of agricultural land over the last few decades. This is very apparent in the Indonesian archipelago, the world's fifth most populous country, as there is an increasing demand for domestically produced agricultural produce [1]. Conventional farming practices, with high rates of overfertilization and extensive pesticide use, as seen in many parts of Indonesia, have led to raised levels of environmental and public health concerns [2]. These concerns include loss of biodiversity, pollution, unsustainability, and soil erosion. As a result of these concerns, the long-term sustainability of conventional production methods is questionable, and the potential for organic farming receives increasing attention. Organic farming methods rely on organic inputs and recycling for nutrient supply, emphasize cropping system design and soil biological processes for pest management, and ban applications of synthetic fertilizers and pesticides [3,4].

Crucial in all this is how, in the tropics, farming methods, organic, conventional or other, influence the fertility of the soil. The microbial community is vital in maintaining soil fertility, residue decomposition, nitrogen fixation, nutrient cycling, and carbon sequestration [4]. Carbon (C) and nitrogen (N) are key constituents in soil organic matter, regulating soil structure, microbial growth, moisture retention, and nutrient cycles [5–7]. Phosphorus (P) promotes plant growth, energy transmission, and overall ecosystem health [8–10]. Potassium (K) has important effects on plant health, in particular on stress tolerance and disease resistance [11]. K boosts plant mechanisms that protect plants and dissuade herbivory, such as cell wall thickening and increased production of secondary metabolites [12,13]. Electrical conductivity, which measures the ability of soil to conduct electrical current, indirectly reflects saline levels and mineral content [14] and contributes to soil health and nutrient balance [15].

Agroforestry systems, which integrate trees and shrubs with crops, play a crucial role in maintaining and promoting soil fertility [16]. Trees in these systems contribute organic matter through leaf litter and root decay, enriching the soil with essential nutrients. Additionally, tree roots enhance soil structure and porosity, improving water infiltration and retention, which reduces erosion and nutrient leaching [17]. These processes collectively create a more resilient and fertile soil environment that supports sustainable agricultural productivity.

Beyond enhancing soil fertility, agroforestry systems offer significant benefits in combating climate change. Trees sequester carbon dioxide, storing carbon in their biomass and soil, which helps mitigate greenhouse gas emissions [18]. Moreover, the presence of trees modifies microclimates by providing shade and reducing temperature extremes, which can improve crop yields and reduce heat stress on plants and animals [19]. Agroforestry also increases resilience to extreme weather events; deep-rooted trees stabilize the soil, reducing the impact of heavy rains and winds, while diverse plant species in these systems create a buffer against pest outbreaks and disease, ensuring more stable food production in the face of climate variability [20].

We assessed the soil composition of smallholder farms in West Bali, Indonesia, and how soil composition varies with regards to agricultural practices. We focused on soil fertility, which can be defined as "the function of the soil to act as a mediator of nutrients, water and air for plants and soil life" [21,22]. It is the result of physical, chemical, and biological processes that lead to nutrient release, water, aeration, and stability for plant and soil life, as well as the absence of any substances that may inhibit growth [22]. Soil fertility is closely linked to soil quality. The Soil Science Society of America officially defines soil quality as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" [23]. The most important functions include water flow and retention, solute transport and retention, physical stability and support, retention and cycling of nutrients, buffering and filtering of potentially toxic materials, and maintenance of biodiversity and habitat. A soil may have a high quality for one function but not for other functions [24].

In our research, we were particularly interested in how soils differed between rustic agricultural systems, where crops are planted and grown under natural forest tree cover, and polyculture agricultural systems, where one or more crops are planted and grown in the absence of natural forest trees. These two agricultural systems differed in various ways, including the amount of direct sunlight that crops receive, tree cover and tree species richness, as well as agricultural yield. We expected that both pH and the number of microbes would be higher in rustic farms and ones with higher shade complexity. We also expected to see higher concentrations of specific minerals in rustic farms compared to polyculture farms (although this could be reversed by heavier use of fertilizers in the latter). Furthermore, we expected the differences to be more pronounced in the topsoil's upper 5 cm compared to the 15 cm depth (although differences may be more pronounced at greater depths). We had no expectations on how soil composition affects yield as this is additionally dependent on other factors, but we were interested to show this relationship as yields are the main outcome of cropland.

2. Materials and Methods

2.1. Geology and Soils of the Study Region

The island of Bali is Indonesia's smallest province; the main island is 5577 km^2, and it is situated some 8° south of the equator. It is home to some 4.4 million people. The province's main economic driver is tourism, but especially in the areas less frequently visited by tourists, in terms of employment, agriculture provides a livelihood for a significant portion of the Balinese [25]. Agriculture, together with forestry, contributes some 15–17% of Bali's Gross Domestic Product, which is less than tourism but similar to services and transportation and communication [26].

Bali is renowned for its diverse soil types, each with its unique characteristics [27–29]. Bali mainly consists of Quaternary and Late Tertiary volcanic soils, which in certain parts in the northern half of the island combine with calcareous materials from ancient coral reefs. The south consists mostly of limestones with some Tertiary sedimentary rock. Alluvial soils cover only about 5% of the island; these are formed by flooding, and their composition thus depends on the origin of the water source. Bali is dominated, visually and geologically, by the central mountain range, which includes two volcanoes, the inactive Mt. Batukaru in the center of the island and the active Mt. Agung in the east. These are also the highest points on the island, with the former reaching a height of 2276 m above sea level (m.a.s.l.) and the latter 3031 m.a.s.l. Both mountains are sacred for the Balinese. Within this central mountain range are two large volcanic calderas, and for significant parts of the island these are the main source of irrigation.

The westernmost part of Bali, including Jembrana Regency, where our study site is located, comprises a relief barrier of a smaller mountain range, up to 1200 to 1300 m.a.s.l. Here, the volcanoes are dormant. Purbo-Hadiwidjojo [28] gave a clear overview of the geology of Bali, and from this it is evident that Jembrana and our study region are at the intersection of several rock types. At lower elevations in the south, it comprises either alluvial deposits, formed by the depositions of the Yeh Embang and Yeh Buah rivers, amongst others, or a combination of conglomerates, sandstone, ancient reefs, and limestone, known as the Palasari Formation. From the south coast upwards, this Palasari Formation stretches to the upper part of the mountain range but then morphs into more volcanic soils, appropriately named Jembrana Volcanics, comprising lava, breccia, and tuff. Further north, possibly extending into our study area, is a distinct volcanic subtype of lavas and breccias referred to as the Pulari Volcanics. Finally, just northwest of our study area, is the Prapat Agung Formation, comprising limestone, calcareous sandstones, and marts [28] (Figure 1). In Jembrana, the aquifers have low porosity and a rapid runoff of surface water [29].

The soils of Bali are mainly of a medium texture (silt fractions of 0.002 to 0.050 mm), and only areas in the extreme south and offshore islands have areas with a fine (<0.002 mm) or rough (0.05 to 2.0 mm) texture. Macklin [29] presented a modified map of soil composition and distribution for all of Bali, and from this it is evident that, just like its geology, Jembrana is a complex of different soil types. Most of the regency is covered in Brown Latisol and Litosol layers that tend to be very sensitive towards erosion. The lower parts in the south are covered in Grey-Brown Alluvial soils with small areas of Hydromorphic Alluvial soils (the beaches and a narrow strip immediately adjacent to the beaches are covered in Reddish-Brown Latosols and Litosols, but this has little effect on our study area). Within the area of Brown Latisols and Litosols, there are smaller areas of Brown Mediterranean soils.

Latosol soils have undergone an intensive breakdown and developed into advanced soil. They have a pH of 5.5–6.5, with a fine-to-medium texture and a deep permeability. The soil fertility is low-to-medium [30]. Regosol soils are extensively found in the eastern and southeastern part of Bali especially, and these soils are generally rich in Phosphorous and Potassium and poor in Nitrogen; they are less acidic than Lotosols, typically in the region of pH 6.0–7.0.

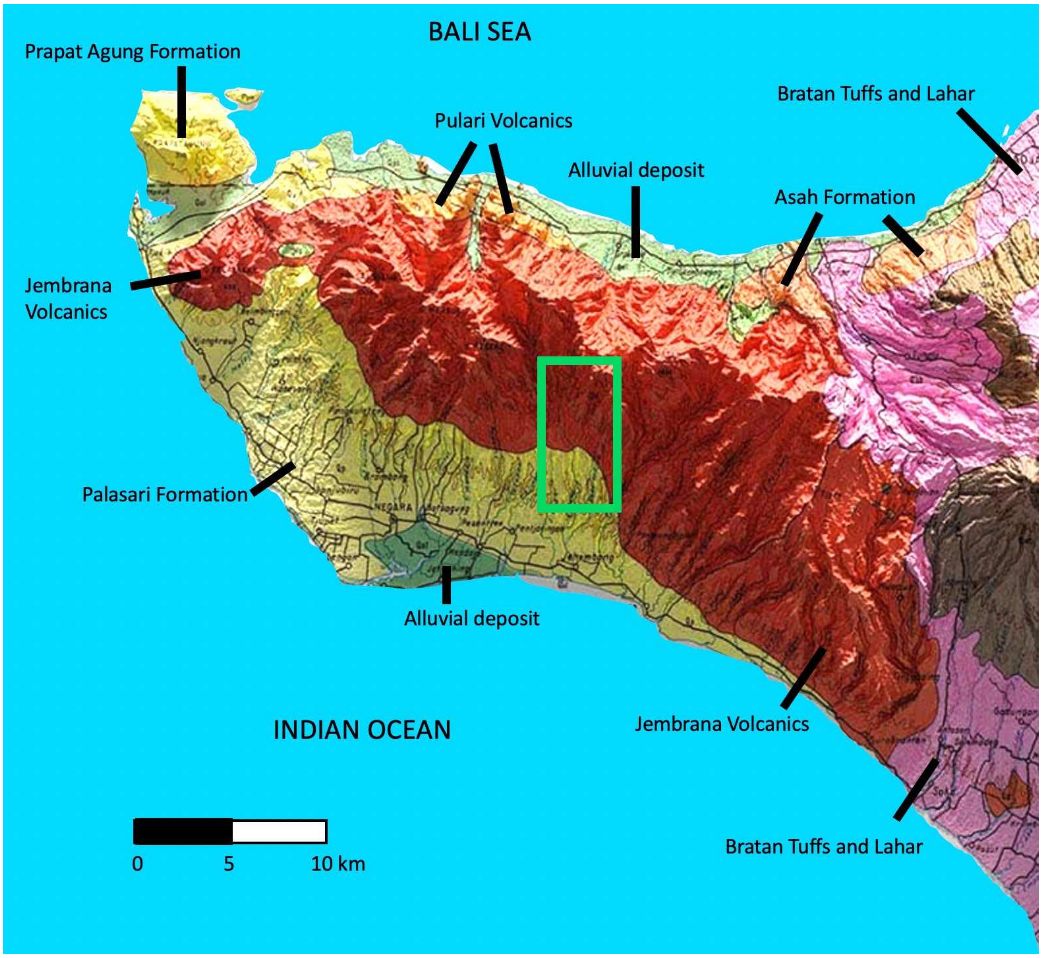

Figure 1. Geology and geography of westernmost Bali, Indonesia, showing the main geological formations; modified after [28]. The study area is indicated by the green box.

As they age, Regosols become more compacted and have a low drainage capacity [31]. They have a low soil fertility (and often require the addition of fertilizer). Brown Mediterranean soils are very weathered and have a pH of 5.5–8.0; they are very permeable and have a medium soil fertility. Alluvial soils are the youngest, and their characteristics (permeability, composition, fertility) depend fully on their origin [32].

2.2. Hydrology and Rainfall

The annual precipitation in the study area is 1010 mm, with a wet season (average of >100 mm rain month^{-1} and 18–22 rainy days month^{-1}) from October until April and a drier season (20–100 mm month^{-1} and 2–13 rainy days month^{-1}) from May until September. Based on the nearby weather station at Yeh Panas, situated closer to sea level, the period between October to May is perhumid (that is, rainfall is over 100 mm month^{-1}), and only during the month of August, and infrequently September, does evaporation exceed precipitation, with the area thus experiencing a dry period [33].

In humid areas, such as Jembrana, soil weathering is more or less continuous because there are no long dry periods. Consequently, dissolved minerals gradually leach away in mature soils to produce acid, kaolinitic, aluminum-rich clays that are unable to hold dissolvable minerals because of the large amounts of rain. Fertility is thus only maintained because of leaf litter and humus in the topsoil layer [34,35]. Many of the soils lower down, in the hillier parts of Bali, are relatively immature and retain moisture better than the mature soils. With higher levels of mineral nutrients, organic matter and phosphorus they are potentially very productive [34].

Jembrana has 40 rivers, but most of them are short (i.e., less than 10 km) with nine of them being 20 km or more in length. But even the longest rivers, Tukad Biluk Poh (29 km) and Tukad Sangiang Gede (25 km), are short [35]. Within the carbon cycle, tropical rivers have a significant influence and are the main drivers for the delivery of inorganic and organic carbon to the coastal plains and the coastal seas. Tropical rivers and streams are thus significant in the global carbon cycle, acting as conduits for organic material and nutrients from seagrass beds, coral reefs, mangrove forests, and estuaries [36–38].

2.3. Data Collection

Data were gathered from May to August 2023 in both polyculture systems and rustic systems adjacent to a natural forest in Yeh Embang Kauh, Jembrana Regency. This was during the dry season in this part of Bali, noting that the average monthly rainfall was still between 60 and 80 mm, and dry conditions (when evaporation exceeds precipitation) were infrequent. Data collection during the dry period had the advantage that it eliminated the potential confounding effects of weather conditions, particularly rainfall.

The study area spans an elevation range of 200 to 500 m.a.s.l. and is rich in biodiversity [33,39]. Crops in this area are cultivated and managed by members of the local community under the farming cooperative Kelompok Tani Hutan (KTH). These crops serve both local consumption and commercial purposes. Most of the polyculture croplands are located near farmers' residences, while the rustic croplands, found within the production forest area, are situated at the base of the protected forest. Permission from the provincial government forestry authority, Kesatuan Pengelolaan Hutan Bali Barat (KPH), allows KTH members to cultivate and harvest crops within the production forest. In the rustic systems, crops include coffee (*Coffea* spp.), cocoa (*Theobroma cacao*), vanilla (*Vanilla planifolia*), durian (*Durio zibethinus*), banana (*Musa* spp.), Siaw nutmeg (*Myristica fragrans*), and clove (*Syzygium aromaticum*). Meanwhile, polyculture farms cultivate clove, coconut (*Cocos nucifera*), cocoa, and coffee.

We established plots measuring 25×25 m^2 (26 in the rustic system, 21 in the polyculture system), chosen based on local farmers' expertise regarding crop locations within the systems (Figure 2). These 47 plots were categorized as either "rustic" or "polyculture" depending on the presence or absence of native forest trees. In rustic plots, various types of cropping trees coexisted with native tree species, whereas in polyculture plots, multiple cropping trees were grown without native forest trees. We did not set up random plots, as most of the areas are not accessible due to steep slopes, and we decided to follow the network of pre-existing trails set up by farmers. The plots were thus set in areas with low slopes, these being the areas that are preferred and selected by farmers as well. The elevation range of plots was from 229 to 439 m.a.s.l (mean: 299 m.a.s.l.). To maintain adequate spacing between plots, we ensured a minimum distance of 50 m, linking our soil data to environmental data [34]. Production forests are delineated as a political land zoning measure, which may not always align with practical land use. Ideally, production forests should sustainably utilize forest resources without removing forest trees. Although the production forest in our study area is largely intact, some areas have been cleared in the past and no longer support native forest trees. Consequently, five plots were categorized as polyculture systems despite being situated within the production forest area.

To assess the shade cover of each plot, we utilized the Canopeo application, which analyzes the shaded area from photographs [40]. Within each plot, we captured four random and independent photographs, computing the average value for each plot [40]. To maintain consistency, we ensured a minimum distance of 5 m between photo points and a 5 m buffer from the field edge [41]. Our calculations were carefully conducted to avoid bias, excluding understory canopy elements such as banana leaves [33]. Additionally, we recorded the richness of crop species ("crop richness" henceforth) and tree species ("tree richness" henceforth) within each plot. Subsequently, we estimated (1) the productivity of each crop plant per year based on local knowledge, (2) the overall yields per year for each crop in every plot, and (3) the comprehensive productivity of each plot.

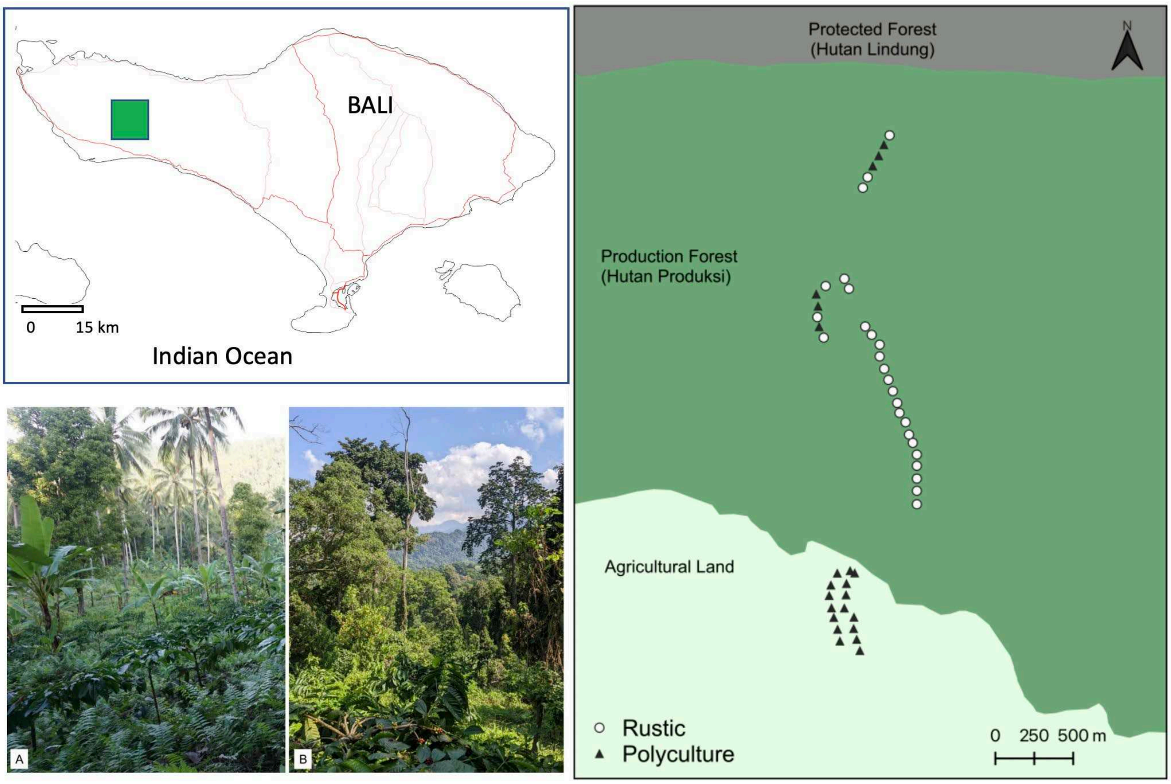

Figure 2. Study design in the western part of the island of Bali, Indonesia (**top left**), with rustic and polyculture plots in agricultural land and in production forests (**right**) and photographs of polyculture (**A**) and rustic (**B**) agroforestry systems. Note that five plots in the production forest area were classified as polyculture plots as they had no cover from forest tree species due to past forest clearance.

2.4. Soil Sample Collection and Analysis

Soil samples were taken by means of a soil probe from two layers, one at 0 to 5 cm depth and one at 10–15 cm depth. These two different layers give a good representation of the soil variables [42] (see also our Discussion) and have been shown to differ significantly in terms of chemical characteristics and microbes in agroforestry systems [43]. Samples were taken randomly within each plot, mixed, and stored in one plastic bag labelled with a plot code [44]. 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. We stored the soils sample at room temperature for a maximum of two days after the collection and analyzed them at the Udayana University, Denpasar, about a 100 km distance from our study area. This laboratory follows strict procedures to ensure a high standard of analytical quality control. Serial dilution was utilized to examine the complete microbial population. Soil samples were analyzed in quantities of 10 g, submerging the soil sample in a physiological solution for 30 min with continuous stirring. The agitated sample was then diluted by adding 1 mL of media from the agitated physiological solution to the subsequent 9 mL of physiological solution (sodium chloride 0.85%). The pour-plate method was used to separate microorganisms. Precisely 0.1 mL of the diluted solution was placed into a cup and thereafter evenly dispersed over the whole surface area of the Petri plate. The media that had been mixed with the dilution suspension was placed in an incubator and the number of bacterial colonies that grew were counted. We used an electrical conductivity meter for measuring EC (mS/cm).

We calculated soil pH via potentiometry (H_2O); organic carbon (C) as a % via the Walkley and Black method; nitrogen (N) as a % via the Kjeldhal method; and available phosphorus (P) and potassium (K) as ppm via the Bray-1 method [45] (Table 1).

Table 1. Parameters, extraction methods, and measurements for soil analysis for establishing soil fertility at two agricultural systems in Bali, Indonesia.

Parameter	Extraction	Measurement
Available P (ppm)	Bray-1 method	Spectrophometry UV-VIS
Available K (ppm)	Bray-1 method	Atomic Absorption Spectrophotometer
pH soil	H_2O	pH meter
Total N (%)	Kjeldhall method	Titration
Organic Carbon (%)	Walkley and Black method	Spectrophometry UV-VIS
Conductivity (mS/cm)	See text	EC meter
Total microbes		

2.5. Ethics and Permissions

The study was conducted as part of a collaborative effort involving Oxford Brookes University in the United Kingdom, Universitas Warmadewa in Bali, and Bumi Lestari Conservana, a for-profit social enterprise specializing in processing non-timber forest products from Indonesian forests. Approval for the research, particularly involving non-Indonesian researchers, was obtained from Indonesia's National Research and Innovation Agency in Jakarta (Badan Riset dan Inovasi Nasional—BRIN).

2.6. Data Analysis

We employed generalized linear models to determine the dissimilarities of soil structure and yields between the topsoil (0–5 cm) and subsoil (15 cm) between the polyculture and rustic systems. We utilized the "emmeans" package to compute estimated marginal means. Profits from yields were determined by obtaining average selling prices for each crop from farmers in Indonesian Rupiah and converting them to US dollars using a conversion rate of IDR 15,625 to USD 1. Generalized linear models were employed to analyze the impact of the agroforestry system (rustic vs. polyculture), canopy cover, crop richness, tree richness, and yields (fixed effects) on topsoil properties (including C:N ratio, conductivity, K, organic C, P, and total microbes) and subsoil properties (C:N ratio, conductivity, K, N, organic C, P, pH, and total microbes) as response variables.

For model fitting, we utilized the "glmmTMB" function from the "glmmTMB" package in R version 4.3.1, which offers various fit families suitable for count data analysis. Selection of the fit family and consideration of including or excluding a zero-inflation term was based on diagnostics such as QQ plot residuals and residual vs. predicted plots from the "DHARMa" package. We then used the "step" function to automatically select the best combinations of factors to include in the model based on the Akaike Information Criterion. In the results, we only reported the parameters included in the selected model. We accept significance when $p < 0.05$ in a two-tailed test; occasionally we report trends when $p < 0.10$.

3. Results

The two different agricultural systems' soil characteristics are presented in Table 2; it is clear that there are similarities and differences between systems and that this depends on the depth of where the samples were taken (i.e., in the upper topsoil layer, or lower into the subsoil).

Table 2. Soil characteristics at different depths (topsoil and subsoil) in two agroforestry systems (rustic, 26 plots and polyculture, 21 plots) in western Bali, Indonesia. Mean and standard deviation were used.

Variables	Rustic		Polyculture	
	Topsoil 0 to 5 cm	**Subsoil 10 to 15 cm**	**Topsoil 0 to 5 cm**	**Subsoil 10 to 15 cm**
pH	6.56 ± 0.11	6.59 ± 0.12	6.59 ± 0.15	6.51 ± 0.19
Conductivity (mS/cm)	0.61 ± 0.033	0.44 ± 0.19	0.77 ± 1.43	0.36 ± 0.18
Organic C (%)	3.17 ± 0.81	2.59 ± 0.57	2.46 ± 1.08	1.97 ± 0.71
Total N (%)	0.17 ± 0.08	0.17 ± 0.05	0.19 ± 0.06	0.15 ± 0.04
C:N ratio	32.34 ± 39.08	17.17 ± 7.62	13.66 ± 6.05	13.52 ± 6.17
Available P (ppm)	2.53 ± 2.84	2.61 ± 2.33	12.46 ± 13.36	14.83 ± 13.83
Available K (ppm)	174.04 ± 73.53	173.93 ± 71.17	244.76 ± 70.68	238.37 ± 73.58
Total microbes (x million)	88.50 ± 194.07	110.35 ± 204.92	5.79 ± 13.00	9.52 ± 20.44

The descriptive statistic for the other fixed factors is illustrated in Table 3. Please note the presence of outliers in the variable total microbes (Figure A1), which required the use of a distribution for highly skewed data (i.e., Tweedie) in the generalized linear model.

Table 3. Descriptive statistics of the continuous fixed factors considered in this study.

Factor	Mean	Std	Minimum	Maximum
Canopy cover (%)	29.2	19.0	0.5	71.9
Crop richness (n)	4.7	1.5	2.0	9.0
Tree richness (n)	2.1	2.2	0.0	7.0
Yields (USD/plot)	300.9	324.7	14.7	1844.3

The results from the analysis of topsoil (0–5 cm) and subsoil (10–15 cm) properties unveil several significant associations between various factors and soil characteristics. In the topsoil layer, the agroforestry system demonstrates a notable impact on several properties, with rustic systems showing higher C:N ratios, Organic C, and P levels compared to polyculture systems.

The results of the topsoil (0–5 cm) show that rustic plots had a significantly higher C:N ratio ($Z = 2.12$, $p = 0.027$) compared to polyculture plots, indicating potential differences in organic matter decomposition rates. Crop richness positively influenced conductivity ($Z = 2.67$, $p = 0.008$), suggesting that more diverse crop plantings may enhance soil conductivity. Tree richness negatively affected K levels ($Z = -4.34$, $p < 0.001$), implying that higher tree richness might reduce soil potassium content. Rustic plots exhibited higher organic C levels ($Z = 2.62$, $p = 0.009$), indicating greater organic carbon content compared to polyculture plots. Rustic plots also had lower phosphorus levels ($Z = -3.36$, $p < 0.001$) than polyculture plots, suggesting differences in nutrient availability. Canopy cover positively influenced total microbe counts ($Z = 3.43$, $p < 0.001$), indicating that more canopy cover may foster a greater number of microbes in the soil (Table 4).

The results for subsoil (10–15 cm) show that crop richness negatively impacted the C:N ratio ($Z = -2.58$, $p = -0.010$), implying that greater crop richness may lead to a lower C:N ratio in subsoil. Rustic plots had higher conductivity ($Z = 2.81$, $p = 0.005$) than polyculture plots. Canopy cover negatively affected K levels ($Z = -1.99$, $p = 0.047$), suggesting that increased canopy cover might reduce soil potassium content in the subsoil. Both crop richness ($Z = 2.31$, $p = 0.021$) and tree richness ($Z = 2.56$, $p = 0.010$) positively influenced nitrogen levels, indicating that higher agroforestry system complexity may enhance nitrogen availability in subsoil. Rustic plots exhibited higher organic C levels ($Z = 3.42$, $p < 0.001$), indicating greater organic carbon content in the subsoil.

Canopy cover positively influenced phosphorus levels (Z = 2.17, $p = 0.030$), suggesting that increased canopy cover may enhance phosphorus availability in subsoil. Tree richness positively affected pH levels (Z = 2.11, $p = 0.035$), indicating that higher tree richness may lead to more neutral pH levels in the subsoil. Both crop richness (Z = 2.60, $p = 0.009$) and rustic systems (Z = 7.06, $p = 0.001$) positively influenced total microbe counts, indicating higher number of microbes in soils with greater crop richness and in rustic systems.

Table 4. Results of the Generalized Linear Models after a stepwise model selection. Only the factors included in the best model after model selection are included.

Response	Factor	Beta	Std Error	Z Value	p Value
		Topsoil (0–5 cm)			
C:N ratio	Agroforestry system [a]	18.68	8.44	2.12	0.027
Conductivity	Crop richness	0.14	0.05	2.67	0.008
	Tree richness	0.51	0.07	7.03	<0.001
K	Tree richness	−19.03	4.39	−4.34	<0.001
Organic C	Agroforestry system [a]	0.70	0.27	2.62	0.009
P	Agroforestry system [a]	−0.13	0.04	−3.36	<0.001
	Yields	-1.57×10^{-4}	0.318×10^{-4}	−5.03	<0.001
Total microbes	Canopy cover	0.04	0.01	3.43	<0.001
	Tree richness	0.45	0.12	3.63	<0.001
	Yields	-2.0×10^{-3}	0.3×10^{-3}	−6.24	<0.001
		Subsoil (10–15 cm)			
C:N ratio	Crop richness	−1.70	0.66	−2.58	0.010
Conductivity	Agroforestry system [a]	0.28	0.10	2.81	0.005
	Yields	-1.86×10^{-4}	0.80×10^{-4}	−2.33	0.020
K	Canopy cover	−1.10	0.55	−1.99	0.047
	Tree richness	−11.54	4.70	−2.45	0.014
N	Crop richness	1.01×10^{-2}	0.44×10^{-2}	2.31	0.021
	Tree richness	7.68×10^{-3}	2.99×10^{-3}	2.56	0.010
Organic C	Agroforestry system [a]	0.62	0.18	3.42	<0.001
P	Canopy cover	2.05×10^{-3}	0.94×10^{-3}	2.17	0.030
	Crop richness	-1.80×10^{-2}	0.72×10^{-2}	−2.50	0.013
	Tree richness	3.38×10^{-2}	1.64×10^{-2}	2.07	0.039
	Yields	-4.81×10^{-5}	2.35×10^{-5}	−2.05	0.040
pH	Tree richness	0.02	0.01	2.11	0.035
Total microbes	Crop richness	0.37	0.14	2.60	0.009
	Agroforestry system [a]	2.99	0.42	7.06	0.001

[a] agroforestry system: rustic set as reference category.

4. Discussion

4.1. Effect of Agricultural Practices on Soils

Our aim was to assess the effect of agricultural practices on soil qualities and soil microbial communities. The analysis of topsoil (0–5 cm) and subsoil (10–15 cm) properties unveils intriguing insights into the intricate relationships between various factors and soil characteristics [46]. In the topsoil layer, the type of agroforestry system emerges as a significant determinant of soil properties, with rustic systems exhibiting distinct attributes, such as higher carbon-to-nitrogen ratios, organic carbon content, and lower phosphorus levels compared to polyculture systems [9]. This suggests that rustic systems may foster conditions conducive to soil fertility, but potentially with a lower input of macronutrients. Moreover, canopy cover emerges as a key driver of the total number of microbes, highlighting its crucial role in shaping soil fertility [47]. This can also be a consequence of the fact that plots under high canopy cover do not need inputs of agrochemicals that are a major cause of reduction in soil microbe abundance [48,49]. The positive associations observed between crop and tree richness with conductivity and total microbe counts underscore the importance of biodiversity in enhancing soil fertility, emphasizing the need for diversified agricultural systems to promote soil fertility [35].

Other studies have found that shade cover, crop richness, and tree richness significantly impact soil fertility and microbial communities. For instance, canopy cover can moderate soil temperature and moisture levels, creating a more stable environment that supports diverse microbial populations [50]. This stable microclimate reduces stress on soil microorganisms, allowing for higher microbial abundance and diversity [51]. Additionally, higher crop and tree richness contribute to varied root exudates and litter inputs, enriching the soil organic matter and promoting nutrient cycling [52]. The diversity of plant species also fosters symbiotic relationships between plants and soil microbes, enhancing nutrient availability and soil structure [53]. These findings reinforce the importance of maintaining diverse and well-covered agricultural landscapes to boost soil fertility.

Additionally, it is essential to consider the historical use of agrochemicals in polyculture farms, even if we could investigate this factor, since most of the farmers were not using agrochemicals in the study area. Agrochemical residues can significantly impact soil fertility and microbial communities. Studies have shown that prolonged use of pesticides and synthetic fertilizers can lead to the accumulation of harmful substances in the soil, which may reduce microbial diversity and soil fertility [54]. For instance, high levels of agrochemicals can disrupt the natural nutrient cycles and decrease the abundance of beneficial microorganisms that are crucial for soil fertility and plant growth [55]. Therefore, transitioning to organic or reduced-chemical farming practices is critical for maintaining soil biodiversity and long-term fertility in these systems [56].

Conversely, the negative association of yields with certain soil attributes in the topsoil layer suggests potential trade-offs between agricultural productivity and soil fertility [57]. Specifically, higher yields correlate with reduced carbon-to-nitrogen ratios and total number of microbes, indicating the need for careful management practices to balance productivity goals with soil conservation efforts. In the subsoil layer, similar trends are observed, with type of agroforestry system, canopy cover, crop richness, tree richness, and yields exerting significant influences on various soil properties [58]. The contrasting effects of canopy cover on potassium levels and phosphorus availability further underscore the complexity of managing soil fertility in agricultural landscapes. These findings underscore the multifaceted nature of soil–plant interactions and highlight the importance of holistic land-management approaches to ensure sustainable agricultural production while preserving soil fertility and biodiversity.

To compare data from our organic agroforestry system, we extracted data on soil organic carbon and soil pH from Gomez et al. [59], who compiled a global dataset. We selected data from agroforetsry systems in Indonesia and data for the 0–10 cm top layer (occasionally 0–5, 0–15, or 0–20 cm) (Table 5).

From this, we calculated the mean soil organic carbon, expressed as g/kg or as a percentage, and calculated the mean pH. We only included studies that presented both soil organic carbon and topsoil pH. We obtained data from 12 studies that were conducted in Indonesia (Sumatra, Borneo, Java, Sulawesi, and Bali) in an agroforesty system and that reported on soil organic carbon in the topsoil and topsoil pH (Table 5). The amount of soil organic carbon averaged 36 g/kg (range 15–79 g/kg) and 2.5% (range 1.1–3.7%). The pH averaged 5.2 (range 3.7–6.6).

It is important to note the importance of having natural shade trees in croplands for organic carbon availability both in the topsoil and subsoil. This indicates that the potential for regrowth of plants and restoration is higher if forest trees are kept. In the rustic systems investigated, the presence of large native trees is often linked with traditional beliefs, and the tree species that is mostly kept is *Ficus* sp. We also want to highlight that Indonesia's agricultural productivity is significantly influenced by its geography and climate. The combination of rainfall and temperature patterns can lead to impoverished soils, through erosion, weathering, and leaching of nutrients, which may drive farmers to clear forests in search of soils suitable for cutivation.

Table 5. The amount of soil organic carbon and pH of the topsoil in relation to management regime from different studies conducted in Indonesia (data selected from [59]).

Management Regime, Island	Depth (cm)	Soil Organic Carbon (Mean, g/kg)	Soil Organic Carbon (Mean, %)	pH Soil (Mean)	References
Agroforestry, Sumatra	0–5	44.20		6.10	[60]
Agroforestry, Sulawesi	0–10	20.95		5.67	[61]
Agroforestry, Java	0–10	78.77		6.07	[62]
Agroforestry, Sulawesi	0–10	15.13		4.18	[63]
Agroforestry, Sumatra	0–10	21.34	2.06	4.98	[64]
Agroforestry, Sumatra	0–15		1.57	5.13	[65]
Agroforestry, Sumatra	0–20	37.23		4.20	[66]
Agroforestry, Sulawesi	0–20		1.60	3.95	[67]
Agroforestry, Borneo	0–30		3.64	3.66	[68]
Agroforestry, Bali	0–5		2.85	6.57	This study
Agroforestry, Bali	10–15		2.31	6.55	This study
Agroforestry, Java	0–30		3.45	5.34	[41]

4.2. Study Limitations, Caveats and Suggestions for Further Research

Agroforestry has the potential to be benefitial to both the farmers (in terms of crop yields, crop quality, sustainability, and stabilizing effects on incomes) and the environment (including soil fertility and biodiversity). In Indonesia, proper assessements on how this indeed works out in practice have been conducted relatively sparsely, with a strong bias towards the island of Java [69]. We here focused on Bali, geographically close to Java and geologically similar, but with very different population numbers.

In our study, we aimed to effectively assess the impact of two distinctly different agricultural practices on soil fertility, utilizing a carefully designed approach. However, it is important to acknowledge potential limitations in our methodology. Firstly, our soil sampling method may have underestimated the true variation within plots. Increasing the number of samples taken from individual plots could have mitigated this limitation. Additionally, we focused on two specific soil layers, the topsoil and subsoil, measured at depths of 0–5 cm and 10–15 cm, respectively, leaving a gap between these layers. While this approach provides clear delineation between layers, an alternative method could involve sampling at finer intervals (e.g., every 5 cm up to 20 or 30 cm) and classifying soil types based on observed differences. If not limited by budget constraints, we could have also considered to sample deeper strata of the soil (e.g., up to 1 m depth) to have a better idea of the variability in the whole soil profile. In addition, with the method used for estimating total microbes (i.e., serial dilution) it is only possible to count visible culturable microorganisms that are only a small fraction of the total microorganisms available (~1%) [70]. Still, on a comparative term, we think there is value in showing predictors of visible microorganisms. Furthermore, although our sampling was spatially extensive, all samples were collected at a single time point, during the onset of the dry season in the Bali region. It is conceivable that certain soil parameters reported may be influenced by factors such as rainfall and evaporation.

In gradual comparison, we can draw insights from studies that have examined the effects of weather on soil variables. Research by Smith and Brown [20] found that variations in precipitation patterns influenced soil moisture content, which in turn affected nutrient availability and the total number of microbes. Similarly, Johnson and colleagues [47] observed fluctuations in temperature impacting soil pH levels and organic matter decomposition rates. These findings suggest that weather dynamics play a significant role in shaping soil properties over time, highlighting the importance of considering temporal variability in soil studies. These issues can be addressed in future studies.

Other factors such as slope and elevation have been shown to influence soil parameters [71,72] but were not considered in this study since there was limited variability in those parameters. A study from Tegallalang in central Bali shows that slope had a clear lowering effect on soil fertility, but only when the slope was more than 25%, whereas in those areas that were flat or undulating, like in our study site in Yeh Buah, this was decisively less [70]. We also need to note that other soil parameters (e.g., soil temperature, moisture, granulometry, and enzymes) could have been taken into consideration to have a better understanding of soil fertility [73–75].

5. Conclusions

From this study, and the extensive associated literature, we show that agroforestry systems, such as Yeh Embang Kauh, can positively influence soil fertility and thus provide benefits for farmers while at the same time helping to conserve biodiversity. Our findings indicate that more rustic systems may foster conditions conducive to soil fertility, with canopy cover emerging as a key driver of the total number of microbes. The positive associations observed between crop and tree richness with conductivity and total microbe counts underscore the importance of biodiversity in enhancing soil fertility, emphasizing the need for diversified agricultural systems to promote soil fertility. Agroforestry systems are capable of increasing the resilience of ecosystems against climate change through carbon sequestration, the creation of microclimates for temperature-sensitive crops, and physically bolstering environments against the increased likelihood of extreme weather events. From a farmer's perspective, good quality soils increase yields, precluding the necessity for applying (costly) fertilizer, and may stabilize agricultural output and income. With soil fertility declining across the world due to global investments in agricultural intensification, it is vital that food production systems divert to the use of systems such as agroforestry in order to ensure soil sustainability and food security for future generations.

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Appendix A

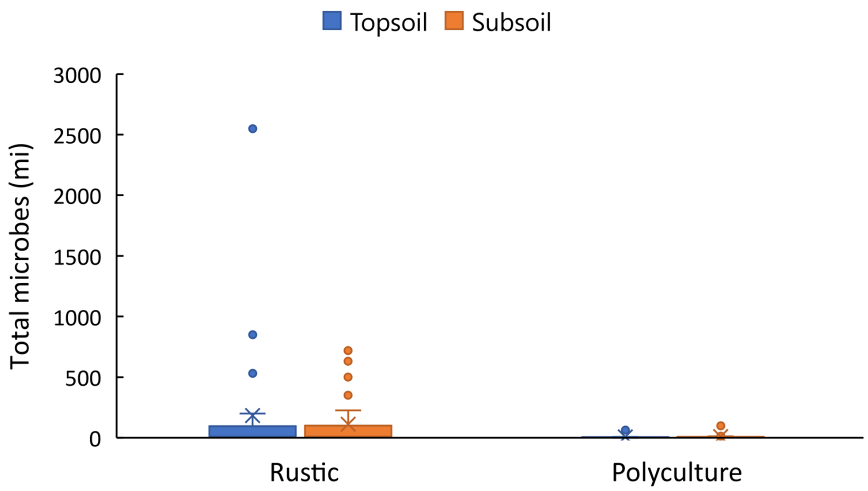

Figure A1. Boxplots with outliers of the total microbes (million) in topsoil (0–5 cm) and subsoil (10–15 cm) samples in two agroforestry systems (rustic, 26 plots and polyculture, 21 plots) in western Bali, Indonesia.

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