land

Article

Kaleka Agroforest in Central Kalimantan (Indonesia): Soil Quality, Hydrological Protection of Adjacent Peatlands, and Sustainability

Yosefin Ari Silvianingsih [1,2], Kurniatun Hairiah [3], Didik Suprayogo [3] and Meine van Noordwijk [3,4,5,*]

1 Faculty of Agriculture, University of Palangka Raya, Palangka Raya 73111, Indonesia; yosefin_ari@for.upr.ac.id
2 Graduate Studies Program, Faculty of Agriculture, Brawijaya University, Malang 65145, Indonesia
3 Agroforestry Research Group, Faculty of Agriculture, Brawijaya University, Malang 65145, Indonesia; kurniatun_h@ub.ac.id (K.H.); suprayogo@ub.ac.id (D.S.)
4 World Agroforestry, ICRAF, Indonesia Office, Bogor 16155, Indonesia
5 Plant Production Systems, Wageningen University and Research, 6700 AK Wageningen, The Netherlands
* Correspondence: m.vannoordwijk@cgiar.org

Abstract: Increased agricultural use of tropical peatlands has negative environmental effects. Drainage leads to landscape-wide degradation and fire risks. Livelihood strategies in peatland ecosystems have traditionally focused on transitions from riverbanks to peatland forests. Riparian '*Kaleka*' agroforests with more than 100 years of history persist in the peatlands of Central Kalimantan (Indonesia), where large-scale open-field agricultural projects have dramatically failed. Our field study in a Dayak Ngaju village on the Kahayan river in the Pulang Pisau district involved characterizing land uses, surveying vegetation, measuring soil characteristics, and monitoring groundwater during a period of 16 months. We focused on how local practices and farmer knowledge compare with standard soil fertility (physical, chemical, biological) measurements to make meaningful assessments of risks and opportunities for sustainable land use within site-specific constraints. The *Kaleka* agroforests around a former settlement and sacred historical meaning are species-rich agroforests dominated by local fruit trees and rubber close to the riverbank. They function well with high wet-season groundwater tables (up to −15 cm) compatible with peatland restoration targets. Existing soil quality indices rate the soils, with low soil pH and high Al_{exch}, as having low suitability for most annual crops, but active tree regeneration in *Kaleka* shows sustainability.

Keywords: acid soils; agroforestry; fruit trees; groundwater dynamics; land suitability; peatland rewetting; restoration; rubber (Hevea brasiliensis), tree regeneration; water balance

Citation: Silvianingsih, Y.A.; Hairiah, K.; Suprayogo, D.; van Noordwijk, M. *Kaleka* Agroforest in Central Kalimantan (Indonesia): Soil Quality, Hydrological Protection of Adjacent Peatlands, and Sustainability. *Land* **2021**, *10*, 856. https://doi.org/10.3390/land10080856

Academic Editor: Guangju Zhao

Received: 30 June 2021
Accepted: 13 August 2021
Published: 16 August 2021

1. Introduction

Soils of a wide range of physical, chemical and biological soil characteristics can be sustainably used, as long as the vegetation is adapted to the root environment, and if the long-term carbon, nutrient, and water balance is respected by matching inputs to output [1–3]. Soil health and soil quality constrain land use depending on the management applied. The direction of change, interpreted as degradation or restoration, is more relevant to local land users than absolute measurable quantities [4]. Impacts of plot-level change can reach beyond the plot scale of a direct land user and affect ecosystem services 'downstream' [5,6]. Long traditions in 'land evaluation' have informed the locational choice for specific development projects by assessing soil quality in relation to specified requirements of pre-selected (tree) crops [7,8]. In contrast, local people had to deal with and make the best of local conditions through their land use choices, and developed locally calibrated process-level knowledge, spatially explicit indicators, and adjustable management options, even though their site conditions would be considered to be sub-optimal if other choices were available [9,10].

Rather than absolute standards for the value of soil metrics, change relative to soil conditions under a reference land cover type (in many cases the prevailing natural vegetation) provides relevant indications of change that may require adaptive responses by the farmers (land managers) [11,12]. Indicators that have been found to have specific relevance on mineral soils include soil physical ones, such as bulk density (compaction) [13–15] and groundwater levels [16,17], and soil chemical ones, such as C_{org} [18–20], pH and Al saturation [21]. As soil biological indicators of change, earthworms and microbial biomass [22–24] have been shown to respond to pesticide use, crop rotation, and crop residue management [25,26]. On organic soils (peatlands), the depth of water table may well be the single most important indicator of change, as it controls the rate of peat decomposition [27] and, thus, nutrient cycling.

Early studies of tropical peat soils suggested that a depth of groundwater table of 40 cm below the land surface needs to be maintained throughout the year [28] to avoid rapid breakdown of peat with its consequences for subsidence and CO_2 emissions. Subsidence of the land can lead to a self-correcting increase in groundwater tables, but if crops grown do not tolerate this, farmers will be inclined to increase drainage, potentially continuing the process until mineral soil is reached, and all the peat is 'burned up'. Current policy in Indonesia, with its extensive area of tropical peat, is to rewet peatlands until the 40 cm norm can be achieved, using canal blocking. [29,30]. Subsequent land use can focus on (tree) crops or (agro)forest vegetation that tolerate such conditions, including kahui (*Shorea balangeran*) and jelutung (*Dyera costulata*), rather than the widely promoted sengon (*Falcataria moluccana*, also known as *Paraserianthes falcataria*) [31]. Studies of long-term change in soil quality in such landscapes, however, are scarce [32].

A conceptual shift is needed from managing peat soils (as defined in soil taxonomies, typically based on an organic layer of at least 30 cm) to managing peat hydrological units as landscapes that may have non-peat alluvial soils between the peat dome and adjacent rivers. Most of the people living in and using peat hydrological units may live in such riparian fringes of the peat dome, yet their actions impact on the peat dome itself [33,34]. The long, dry season of the 2015 El Niño event showed the vulnerability of human health and social and economic activities to the haze emanating from peat fires, many initiated for land clearing but not sufficiently controlled [35–37]. Our earlier study [38] described long-term land use patterns on the banks of the Kahayan river in Kalimantan (Indonesia), in a priority landscape for the Indonesian Peatland Restoration Agency (BRG), created after the 2015 fires. Here, the gradual transition from alluvial soils based on river sediment to peat domes developed in the interfluvial zone has been the basis of local livelihoods for centuries. Direct use of the core peat domes was limited to opportunistic harvesting of forest products, while a swidden/fallow rotation for the production of rice and other food crops was combined with modified forest ('agroforest') with introduced (including rubber, *Hevea brasiliensis*) and selected local (fruit) trees, such as local durian and forest mango species, as marketable crops for sources of income. These agroforests are locally described as '*Kaleka*', or 'awan uluh bihin', a place where people lived in ancient times. It may have started as a hamlet where only two to three families lived, initially from opening swiddens in the neighborhood and allowing fallows to regenerate after a cropping phase of one or more years. The land directly around the houses became enriched with local fruit trees, and became sacred within the Kaharingan religious tradition, with graves of ancestors. Trees with market potential, such as rubber (Hevea brasiliensis), were planted among the fruit trees. This resulted in a mixed and irregular cropping pattern. New land clearing took place beyond the *Kaleka* agroforests, protected by the local community as fruits can be enjoyed by all residents of the village, while commercial, market-oriented use has more restricted property rights [38]; selling *Kaleka* is considered a taboo and prohibited [39,40]. Historically, the Dayak Ngaju controlled the alluvial–peat soil transitions 2–5 km from the riverbank ('as far from the river as the gong can be heard'), with state forest claims on the peat domes beyond, but harvesting of forest products from these zones part of traditional livelihoods [41]. The Tumbang Anoi Peace Treaty of 1894 recorded 96 customary law provisions related to Dayak heritage, including rules about *Kaleka* 'orchards' [42]. *Kaleka* agroforests occur along the Kapuas river, both upstream and downstream of Palangka Raya [43]; they may, eventually, be abandoned and return to forest conditions [44]. Appreciation of their function as wet ecosystems that protect the peat domes will require an understanding of the socio-ecological drivers of forest degradation in historical context, but also in current policy framing [45,46].

As agroforests, the *Kaleka* have a balance of local fruit trees and rubber, introduced over a century ago, compare well in tree diversity and biomass with well-studied agroforest examples in Indonesia, such as the mixed fruit tree gardens ('simpukng') in East Kalimantan [47], the repong or damar agroforest of Lampung that begins as coffee gardens but becomes dominated by *Shorea* trees that can be tapped for resin with various industrial uses [48], and the rubber agroforests of Sumatra and W Kalimantan [49,50].

Here, we provide a more detailed analysis of soil conditions in the various land uses in relation to groundwater dynamics. Specific question for this research were:

1. How does the groundwater level fluctuate in the various land uses (including *Kaleka*)?
2. What are the soil's physical, chemical, and biological characteristics and the existing soil quality indices in the various land uses?
3. How does botanical composition and vegetation structure of the land uses relate to soil quality, water tables, and internal regeneration as sustainability indicator?

2. Methods

2.1. Location and Period of Study

The research was carried out in the village Henda in the Kahayan watershed, administratively part of Kecamatan Jabiren Raya, Kabupaten Pulang Pisau, in Kalimantan Tengah province, Indonesia (Figure 1).

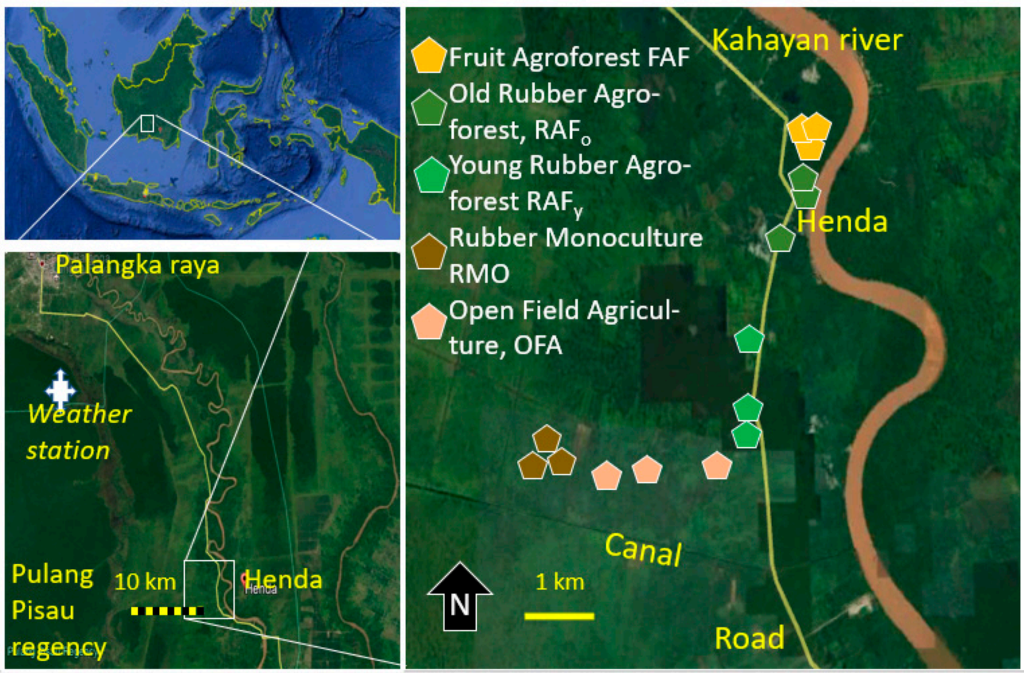

Figure 1. Location of the sample sites in five land uses in the village Henda, Pulang Pisau regency, C. Kalimantan province.

Description of the vegetation, sampling of earthworms, and collection of soil samples for physical and chemical analysis took place in September–October 2017; groundwater tubes were installed and monitored on a two-weekly schedule until mid-January 2019. Interviews with farmers on their ethnobotanical knowledge and appreciation for various land uses was reported elsewhere [38].

The mean annual rainfall in the area is 3194 mm, with seven humid, three moist, and three dry months, according to the Schmidt–Ferguson criteria used in Indonesian climate statistics [51]. The study area is part of the lower Kahayan River, at 0–5 m above sea level, with still some tidal variation in river flow but no saline intrusion. The peat domes that developed in Central Kalimantan's river deltas are now understood to be part of peat hydrology units (KHG = Kesatuan Hidrologi Gambut).

Kalimantan (the Indonesian part of Borneo Island) is geologically part of the Sunda shelf, dominated by a quaternary geology that reflects fluctuating sea levels and climates in which peat soils could be formed and maintained, alternating with drier and more seasonal climates [52]. The Pulang Pisau district is flat, with the slope on 94% of the land less than 3% and that on 81% less than 1%. As described in the semi-detailed soil map for the district [53], approximately 60% of the area is classified as peat (Histosols): 47.9% ombrotrophic peat that depends on rainfall only rather than river water, and 11.2% peat influenced by rivers on the edges of the interfluvial peat domes. Most of the human activity has historically been in the alluvial deposits (mostly Entisols) by and along a number of rivers (10.2% of the area) and in the coastal zone (13.5% plus 9.5% as fluvio-marine contact zone) with mangroves and associated pyrite concretions in the subsoil that can lead to acid sulphate soil reactions when drained. The remaining 7.7% of the area is tectonic in origin and tends to be used for settlements, such as the city of Palangka Raya; these soils are mostly Inceptisols. A large area (around 440,000 ha) located in the Pulang Pisau Regency became known as 'Block C' in the 'Mega-Rice project' started in the 1990s and abandoned after the government change of 1998 [54]. Of the total area of the Mega Rice Project, 32% consisted of fine-textured mineral soils with a peat layer (histic epipedon) less than 40 cm thick, classified as Sulfaquents (Entisols with a tendency to become acid sulphate soils after drainage), Fluvaquents, Tropaquepts, Dystropepts, and Hapludults.

Henda Village, with an area of 538 km^2 and 648 inhabitants (1.2 km^{-2}) [55], is at the center of the study area (1°32′00–3°28′00 South, 113°30′00–120°00′00 East) of the earlier ethnobotanical study [38]. According to the soil map [53], the soils closest to the river in Henda are Aeric Endoaquepts, followed by Typic Haplosaprist (sapric peat) and Hemic Haplosaprists. As Henda Village is the oldest settlement, has the most extensive land area, and widest range of land uses, it was chosen for more detailed observations. The Dayak Ngaju communities along the Kahayan river interact with various groups of migrants from elsewhere in Indonesia, under the government-sponsored transmigration program as well as spontaneous migrants.

Permission for research was obtained from the village elders, and the first author, with five years' experience in the area, was welcomed in the homes of many villagers, with follow-up interviews in the field, and participation in village events. The results presented here were obtained in parallel with an ethnobotanical study reported elsewhere [38].

2.2. Survey Design for Kaleka as Local Land Use

As a settlement, Henda dates back to at least 1840; it primarily relied on a swidden/fallow rice production system in the riparian zone for food security, with agroforest (farmer-modified forest, with increased presence of preferred species) as source of fruits, medicine, building material, firewood, and marketable 'forest products'. The local name for these agroforests is *Kaleka*, and they can vary in the relative dominance of fruit trees and rubber. When the local population density increased, these riparian, wet agroforests spread further from the riverbanks, but not into deeper peat soils. Privately owned and inherited in the local custom, all these agroforests are owned by Dayak Ngaju families. Based on the local adat history, Henda became a separate village in 1902. Around 1985, 'modern' techniques for rice production were introduced and efforts were made to intensify rubber production as the main income source. The rubber expanded into shallow (<50 cm) peat soils that were made accessible when a paved road connecting Banjarmasin and Palangka Raya (the provincial capitals of S and C Kalimantan) was constructed.

Five land cover types, representing *Kaleka* as the major current land use, were purposely sampled (in three plot-level replicates) around the Henda village (Figure 2).

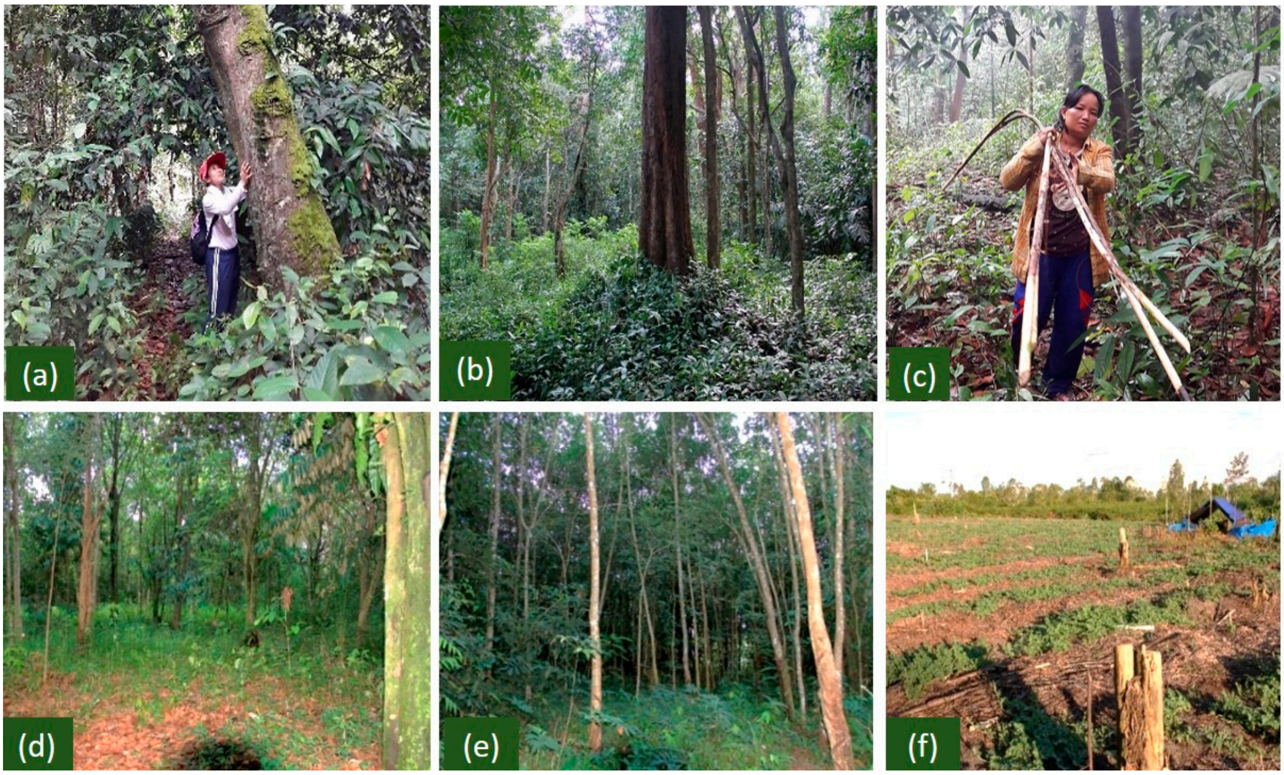

Figure 2. Impressions of the land cover types sampled: (**a**) fruit agroforest (FAF) with rambai (*Baccaurea motleyana*) tree, (**b**) old rubber agroforest (RAF_o), (**c**) collecting rotan vines from RAF_o, (**d**) young rubber agroforest (RAF_y), (**e**) rubber monoculture (RMO), (**f**) open-field agriculture (OFA).

Fruit agroforest (FAF) is closest to the village and what is most likely an older location of the village that shifted slightly to the South. Some of the trees are, according to local sources, at least a hundred years old. Important local fruit trees include 'cempedak' (*Artocarpus integer*), manggis (*Garcinia* sp.), rambai (*Baccaurea motleyana*), langsat (*Lansium domesticum*), and paken (*Durio kutejensis*). There are also rubber (*Hevea brasiliensis*) trees in the plots.

The old rubber agroforest (RAF_o) was planted with rubber approximately 150 years ago and relies on the natural regeneration of these trees within the plot along with local fruit trees, including cempedak, rambai, durian (*Durio* sp.), binjai (*Mangifera caesia*), and rambutan (*Nephelium lappaceum*).

The young rubber agroforest (RAF_y) was planted with rubber approximately 30 years ago (according to local informants) and is similar in tree composition to the RAF_o plots. Local trees include hampalam (*Mangifera* sp.), manggis, rambutan, and sentol (*Sandoricum koetjape*).

The rubber monoculture (RMO), also planted approximately 30 years ago, has a higher rubber density but still contains some local trees, such as durian, rambutan, and cempedak.

The open-field agriculture (OFA) is located in a plot that previously had been rubber agroforest but was opened 5 years before our study. At the time of sampling, watermelon was the main crop planted for selling at markets in the nearby city of Palangka Raya.

Plot-level data were collected on (1) the fluctuations of groundwater levels; (2) soil physical, chemical, and biological characteristics; and (3) vegetation composition and other characteristics. All measurements were coordinated in the sample plot design. The starting point and direction of the plot were randomly selected, with constraints to ensure that the plot would not exit from the land cover type.

In the analysis of variance of the various soil and vegetation characteristics, the five land cover types were treated as main effect and the three sample plots as (pseudo) replicates against a null-hypothesis that all data derived from a single population. Where this null hypothesis was rejected ($p < 0.05$) in an ANOVA in the Genstat 19 software [56], a Duncan test was used to identify significant differences in parameter values (again at $p < 0.05$) between land cover types. This procedure identifies differences between the sites sampled but cannot separate cause–effect relations from locational effects.

2.3. Depth of Water Table

2.3.1. Measurements

To measure the depth of the groundwater table below the plot surface, holes were drilled to a depth of 1.5 m and perforated PVC pipes of 2.5 cm diameter inserted [29]. Manual observations of the depth of groundwater were made at a two-weekly interval for a period of 16 months (September 2017–January 2019).

2.3.2. Simple Water Balance Model

To help in the interpretation of the groundwater data, a simple water balance model (Appendix A) was constructed in which inputs by precipitation (P) are balanced by drainage, evapotranspiration, and changes in groundwater level, with soil porosity modulating the relation between water volume and height change.

2.4. Soil Characteristics

2.4.1. Samples for Physical and Chemical Analysis

Soil samples for each of the three replicates of the five land cover types were composited from five locations in the 20 × 100 m^2 sample plot, for three soil layers 0–10, 10–20, and 20–30 cm depth, respectively (Figure 3).

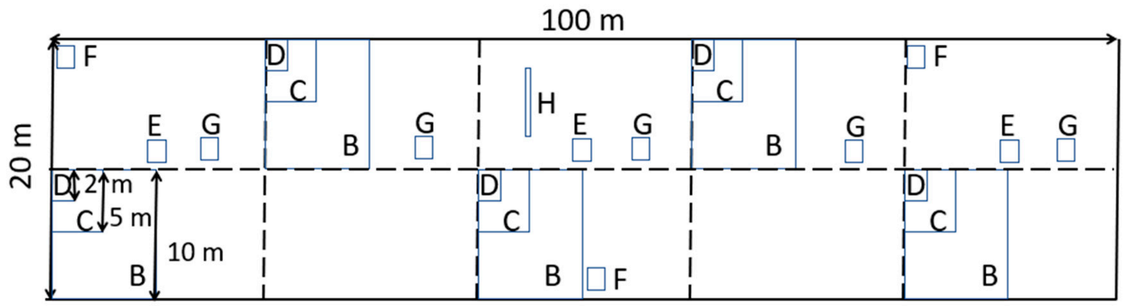

Figure 3. Schematic design of plot-level samples. Legend: A = five sub-plots (20 × 20 m^2) for measurement of trees, classified as medium (20 < DBH < 30 cm) and large (DBH > 30 cm) trees, respectively; B = five sub-plot (10 × 10 m^2) for measurement of poles (10 < DBH < 20 cm) trees; C = five sub-plots (5 × 5 m^2) for measurement of saplings (5 < DBH < 10 cm, height > 1.5 m); D = five sub-plots (2 × 2 m^2) for measurement of understory vegetation below 1.5 m height (including tree saplings, ferns, grass, herbs); E = three monoliths (50 × 50 cm^2) for earthworm counts; F = three undisturbed block sample (20 × 20 × 10 cm^3) for soil bulk density and texture; G = five disturbed soil samples of the 0–10, 10–20, and 20–30 cm soil layers to be aggregated for soil chemical analysis; H = one observation pipe for monitoring groundwater depth.

After drying and sieving, the samples were taken to the laboratory, further ground (to break up aggregates) and analyzed for C_{org} (oxidizable matter in a soil sample based on the dichromate method developed by Walkley and Black [57]), pH(H_2O) and pH(KCl) (1:1 soil:fluid ratio with distilled water or 1 M KCl, respectively) with standard lab methods [58]. Elsewhere in the sampling plots (Figure 3), undisturbed block samples of 20 × 20 × 10 cm^3 were taken with an iron frame to measure bulk density, particle density, and texture at the same three depth intervals. Porosity was calculated from bulk and particle density.

2.4.2. Reference Level for Organic Carbon

To compare the measured C-org concentrations with what can be expected for a mineral soil in the humid tropics of similar texture, pH, and elevation (proxy for temperature), the pedotransfer of [59] for Sumatra as modified for effects of sampling depth in [60] was used to calculate C_{ref} values.

2.4.3. Earthworm Populations

Earthworm populations were sampled in soil monoliths (50 cm × 50 cm; Figure 4) following the methods developed by the tropical soil biology and fertility (TSBF) network [58,61]. The soil, collected at three depths (0–10, 10–20, and 20–30 cm, respectively), was searched, and all earthworms (or cocoons) were collected, rinsed, and preserved in 70% alcohol for identification in the laboratory, followed by drying and weighing. Results were expressed as the number of individuals and dry weight per unit soil area as well as average weight per individual.

Figure 4. Soil monolith sampling for earthworm populations in the *Kaleka* agroforest.

2.4.4. Soil Quality Index

The various measured soil properties were combined into a 'soil quality index' based on a minimum data defined by [62,63] through a Principal Component Analysis (PCA) on datasets for various crops, soil types, and climates. The scores were combined to form a weighted average according to [64–66]:

$$\mathrm{SQI} = \sum_{i=1}^{n} \mathrm{W_i}\, \mathrm{S_i}$$

where, SQI = soil quality index; W_i = factor weight in the PCA; S_i = (normalized) score (0–1) for each indicator i.

2.5. Land Cover Characteristics

2.5.1. Plot Sampling

The sample plots for various components of the vegetation within the 20 × 100 m^2 plots (Figure 3) followed procedures outlined by [67,68] for various size classes of trees and understory vegetation: saplings (5 < DBH < 10 cm, height > 1.5 m), poles (10 < DBH < 20 cm), medium trees (20 < DBH < 30 cm), and large trees (DBH > 30 cm), where DBH is the tree diameter at 1.3 m above the soil surface (with adjustments for trees branched below this height, specified in [68]).

2.5.2. Plant Inventory

All trees, poles, and understory vegetation were identified at species level (with further ethnobotanical detail in [38]). A number of vegetation indices were derived, following [63]:

- Population density (individuals/ha) for the various size classes;
- Species richness = number of species observed in asset of samples;
- INP (%) = Importance index as the sum of KR + FR + DR, where KR is the relative density of a species, expressed as percentage, FR is the relative frequency of sub-plots containing the species, and DR is the relative dominance of the species in terms of basal area (based on DBH measurements);
- Shannon–Wiener diversity index $H' = -\Sigma[(ni/N)Ln(ni/N)]$, where n_i is the number of individuals of a species i and N is the total across all species;
- Basal area = $\sum 0.25\ \pi\ *(DBH^2)$, m^2/ha;
- Estimated aboveground biomass (Mg ha^{-1}), $AGB_{est} = WD * \exp(-1.499 + 2.148 \ln(DBH) + 0.207 (\ln(DBH))^2 - 0.0281 (\ln(DBH))^3)$, where WD is the wood density (g cm^{-3}) according to the ICRAF wood density database [69]. The allometric equation was derived from a large literature base for the humid tropics [70].

3. Results

3.1. Groundwater Levels

The groundwater levels differed clearly and significantly ($p < 0.001$) between the land cover types (locations), with the highest average (−33 cm) in FAF and the lowest (−99 cm) in OFA (Figure 5). The percentage of observations that met the mandated −40 cm groundwater level varied between land uses: 64.7% for FAF, 29.4% for both RAFo and RAFy, 14.7% for RMO, and only 2.9% for AFO.

Across all land cover types, the groundwater depths followed the decreasing rainfall in the February–August period and, with some delay, increased with rainfall in the October–December period (Figure 6). Five parameters for the model were adjusted to match the pattern averaged across the land uses, with three describing an annual pattern in evapotranspirational demand (Epot) (Epotmax: 7 mm day^{-1}; AmplitEpotVar: 0.26; Toffset: −10 day), and two the overall drainage patterns (InterceptEt 0.3; GWdrainfrac: 0.3 per two weeks).

Acceptable fits for this model (given the two-weekly intervals of data collection), were obtained with drain-depths that varied from −40 cm for FAF, RAFo and RAFy, via −60 cm for RMO to −110 cm for OFA (Table 1). The groundwater depth below which tree water uptake will fall short of demand varied less: from 14 cm for FAF to −57 cm for RMO, suggesting that the drain depth at OFA is deeper than what is desirable for plant growth. In OFA, only 22% of rainfall was used for evapotranspiration according to the water balance model, while at the wetter sites, this was 30–51%.

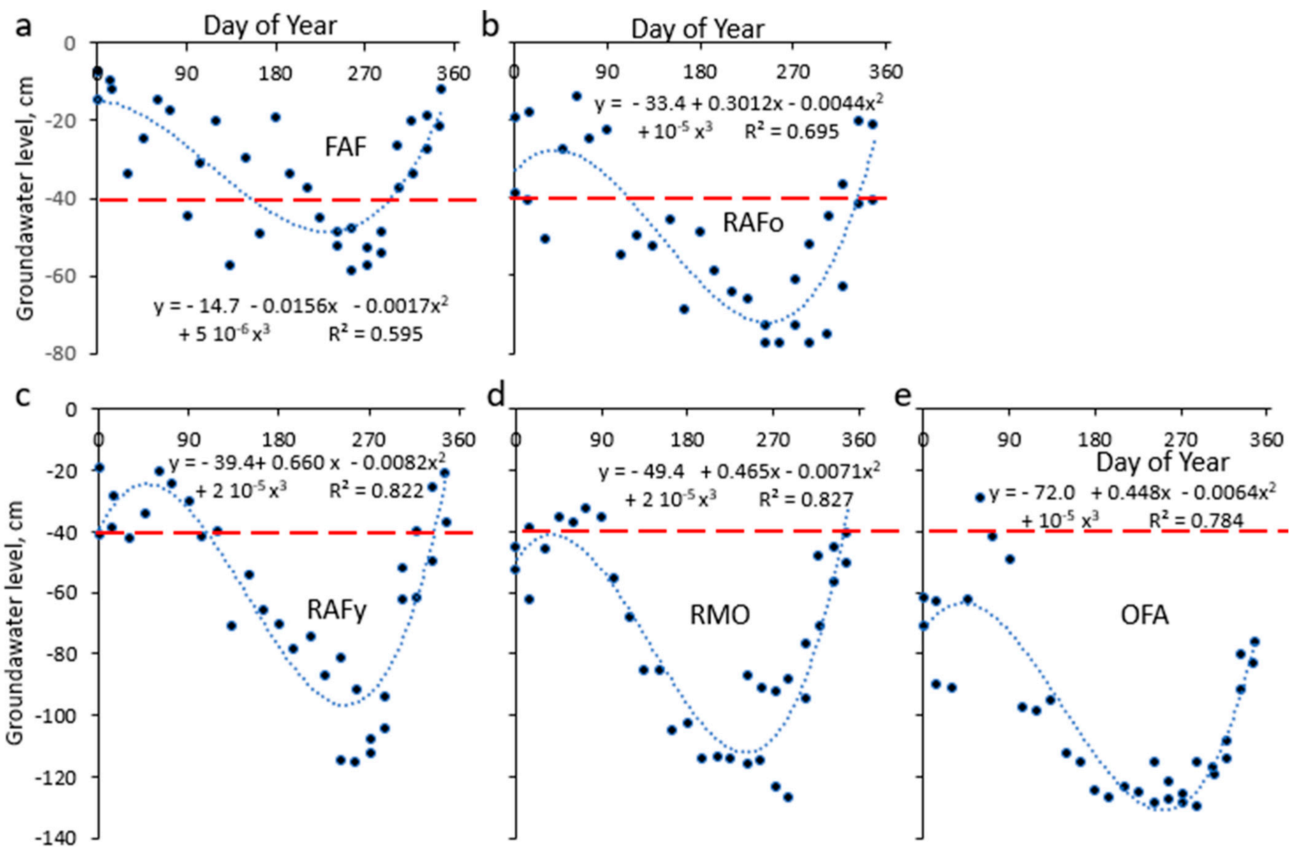

Figure 5. Recorded groundwater levels between 1 September 2019 and 15 January 2019 in the various land uses in relation to the day of year; the red line indicates the mandated groundwater level for peatlands (−40 cm) in all land uses: (**a**) fruit agroforest (FAF), (**b**) old rubber agroforest (RAF_o), (**c**) young rubber agroforest (RAF_y), (**d**) rubber monoculture (RMO), (**e**) open-field agriculture (OFA).

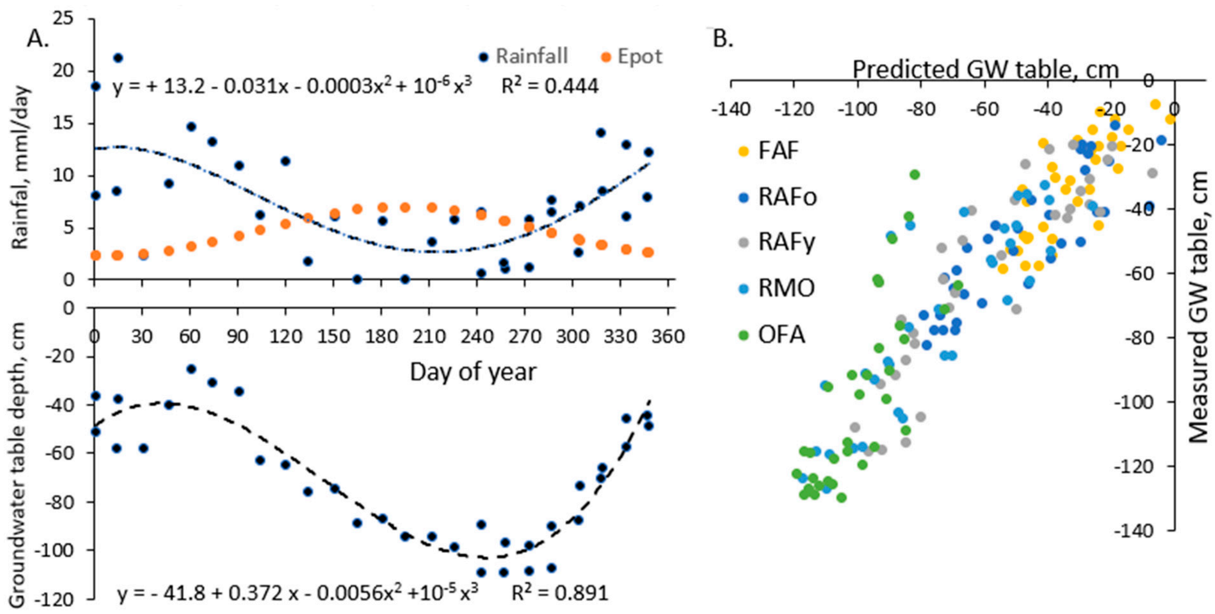

Figure 6. (**A**) Average depth of groundwater table across the five land uses and rainfall data from at the CIMTROP-LAHG weather station in Sebangau, September 2017–January 2019; the estimated potential evapotranspiration is indicated by the dotted orange line; (**B**) predicted versus measured groundwater table depths, based on the simple water balance model with two parameters adjusted per land cover type (location). Land uses: FAF = fruit agroforest, RAFo = old rubber agroforest, RAFy = young rubber agroforest, RMO= rubber monoculture, OFA = open-field agriculture (annual crops).

Table 1. Measured groundwater depths (H_{GW}) and parameters for a simple water balance model adjusted to generic site conditions (the first five parameters), measured soil porosity, and two parameters (H_d and H_{upt}) fitted to obtain an unbiased model.

	FAF	RAFo	RAFy	RMO	OFA
Measured:					
Average H_{GW}	−33.0	−49.6	−59.9	−75.1	−98.9
Standard Deviation	15.9	20.3	30.1	30.3	28.2
Fraction $H_{GW} < -40$	64.7%	29.4%	29.4%	14.7%	2.9%
Parameters adjusted per land use:					
Soil porosity [vol/vol]	0.569	0.556	0.608	0.602	0.541
H_d [cm]	−40	−40	−40	−60	−110
H_{upt} [cm]	−14.3	−30	−47.5	−57	−33
Model performance:					
Slope Predicted: Observed	1.00	1.00	1.00	1.00	1.00
SE slope	0.05	0.04	0.04	0.03	0.03
Fraction of variance accounted for	0.93	0.96	0.95	0.97	0.97
Estimated water balance (2018):					
Drain Fraction	68.2%	55.1%	51.8%	53.7%	76.7%
Evapotranspiration fraction	30.1%	43.2%	50.8%	49.8%	21.8%
Delta ground water storage	1.6%	1.6%	−4.5%	−4.0%	1.6%

Land uses: FAF = fruit agroforest, RAFo = old rubber agroforest, RAFy = young rubber agroforest, RMO= rubber monoculture, OFA = open-field agriculture (annual crops).

3.2. Soil Characteristics

3.2.1. Soil Physical and Chemical Properties

Bulk density, particle density, porosity, texture, C_{org}, and exchangeable Al all differed significantly ($p < 0.01$) between the land covers (locations) (Table 2). Most properties also had significant trends with depth within the 0–30 cm top layer. Nearly all bulk densities were below 1 g cm^{-3} and porosities relatively high at 55–60%, showing no physical limitations to root development and aeration. The soils contained hardly any sand and the clay-to-silt ratio varied from 3:1 in FAF to 1:1 in RMO and OFA.

Table 2. Soil physical and chemical characteristics of plots under various land use systems (s.e.d. = standard error of differences).

	Bulk Density	Particle Density	Porosity	Clay	Silt	Sand	C_{org}	C_{ref}	C_{org}/C_{ref}	pH (H_2O)	pH (KCl)	Al_{exch} cmol kg^{-1}
	g cm^{-3}				%							
Land uses *												
FAF	0.95 b	2.21 c	56.9 a	76.7 a	23.1 a	0	2.04 a	2.58 b	0.72 a	3.63	3.53	7.70 a
RAFo	0.97 b	2.18 c	55.6 a	68.6 a	32.2 ab	0.1	2.76 a	2.55 b	1.03 a	3.64	3.54	8.24 ab
RAF_y	0.85 a	2.17 c	60.8 b	60.9 ab	39.0 bc	0	6.11 b	2.44 a	2.48 b	3.71	3.61	9.79 c
RMO	0.83 a	2.10 b	60.2 b	50.2 bc	49.6 d	0.2	5.43 b	2.36 a	2.21 b	3.66	3.61	10.04 c
OFA	0.94 b	2.04 a	54.1 a	51.1c	48.8 cd	0	5.13 b	2.36 a	2.26 b	3.73	3.61	8.92 b
s.e.d	0.04	0.03	1.66	5.07	4.9	0.1	1.06	0.04	0.44	0.06	0.04	0.38
Soil depth (cm)												
0–10	0.77 a	2.08 a	62.8 c	58.7	41.1	0.1	6.20 b	3.41 c	1.84 a	3.67	3.57	8.47 a
10–20	0.93 a	2.15 b	56.8 a	58.9	40.9	0.1	4.01 a	2.16 b	1.88 a	3.69	3.61	8.84 a
20–30	1.03 c	2.19 b	53.0 a	66.9	33.5	0	2.68 a	1.81 a	1.49 a	3.67	3.57	9.50 b
s.e.d	0.03	0.02	1.29	3.93	3.79	0.1	0.82	0.03	0.34	0.04	0.03	0.23

* Land uses: (a) fruit agroforest (FAF), (b) old rubber agroforest (RAF_o), (c) young rubber agroforest (RAF_y), (d) rubber monoculture (RMO), (e) open-field agriculture (OFA); values not sharing letters differ significantly ($p < 0.05$).

The C_{org} concentrations of RAF_y, RMO, and OFA were more than twice what can be expected as C_{ref} for mineral soils (based on texture, pH, elevation) suggesting a possible history as shallow peat soils. All pH values were in the 3.5–4 range, corresponding with high exchangeable Al concentrations, and a small difference between pH(H_2O) and pH(KCl) suggesting a low buffering of acidity

3.2.2. Earthworms

All earthworms that could be identified (as they had a developed clitellum) belonged to *Pontoscolex corethrurus*. The highest population densities (around 60 m^{-2}) and biomass (around 35 g m^{-2}) and the largest worms (around 0.5 g per individual) were found in the FAF and RAF_o plots, and the lowest and smallest in the OFA plots (Table 3). Differences between land covers (locations) and depths were highly significant ($p < 0.001$), statistically. The largest differences between the soil layers in earthworm presence was found in the wettest (FAF) site.

Table 3. Earthworm population and biomass data for the various sites (land covers) (s.e.d. = standard error of differences).

Depth\Land Use *	FAF	RAFo	RAF_y	RMO	OFA	s.e.d.
Population (individuals m^{-2})						
0–10 cm	64.4 g	54.7 g	35.1 f	18.2 cde	14.7 bcd	
10–20 cm	9.8 abcd	28.0 ef	19.1 de	2.2 a	11.1 abcd	5.07
20–30 cm	0.9 a	10.7 abcd	8.9 abcd	7.1 abc	4.0 ab	
Biomass (g m^{-2})						
0–10 cm	30.8 f	23.8 e	11.3 d	7.1 cd	3.6 abc	
10–20 cm	3.6 abc	11.4 d	6.6 bcd	1.1 abc	3.3 abc	2.58
20–30 cm	0.1 a	5.2 abc	3.0 abc	2.5 abc	0.9 ab	
Size (g/individual)						
0–10 cm	0.49 f	0.42 ef	0.34 def	0.27 bcde	0.20 abcd	
10–20 cm	0.12 abc	0.43 ef	0.31 cdef	0.11 ab	0.20 abcd	0.08
20–30 cm	0.02 a	0.37 def	0.29 bcde	0.13 abc	0.10 ab	

* Land uses: (a) fruit agroforest (FAF), (b) old rubber agroforest (RAF_o), (c) young rubber agroforest (RAF_y), (d) rubber monoculture (RMO), (e) open-field agriculture (OFA); values not sharing letters differ significantly ($p < 0.05$).

3.2.3. Soil Quality Indicators

Combining nine measured soil attributes into a single 'soil quality index' (Table 4) showed low values of 0.21–0.25 on a 0–1 scale. Soil quality at the FAF, RAF_o, and RAF_y sites is considered to be higher than that at the RMO and OFA sites.

3.3. Vegetation

3.3.1. Tree Populations, Basal Area, and Tree Biomass

All agroforest plots showed active natural regeneration with an abundance of saplings and poles. Across all trees, the basal area was 25–35 m^2 ha^{-1} for the FAF and RAF_o plots and around 20 m^2 ha^{-1} for RAF_y and RMO (Table 5), with the difference mostly caused by larger populations of trees with DBH > 30 cm (around 100 trees ha^{-1}). Aboveground tree biomass was approximately 300 Mg ha^{-1} in FAF and RAF_o plots, and approximately 145 Mg ha^{-1} in RAF_y and RMO. Aboveground biomass is related to basal area, but also depends on wood density and the share of large trees, as the allometric relation involves powers for the stem diameter above 2.0.

Table 4. Soil quality index (SQI) rating (0–1) for the various parameters in the land use systems and classification (L = low, VL = very low, M = medium) of the various metrics based on [71].

Soil Indicator	SQI									
	FAF		RAFo		RAF_y		RMO		OFA	
Bulk density	0.35	L	0.39	L	0.35	L	0.49	M	0.56	M
Particle density	0.12	VL	0.10	VL	0.23	VL	0.25	L	0.13	VL
C_{org}	0.06	VL	0.11	VL	0.31	L	0.27	L	0.25	L
Clay + silt	0.13	VL	0.14	VL	0.13	VL	0.13	VL	0.13	VL
pH	0.13	VL	0.13	VL	0.15	VL	0.13	VL	0.15	VL
Porosity	0.12	VL	0.10	VL	0.19	VL	0.18	VL	0.07	VL
Water table	0.56	M	0.46	M	0.39	M	0.29	L	0.15	VL
Al_{exch}	0.44	M	0.38	L	0.23	L	0.20	L	0.31	M
Earthworms	0.37	L	0.47	M	0.31	L	0.12	VL	0.13	VL
Total	2.28		2.28		2.27		2.05		1.87	
Average	0.25	L	0.25	L	0.25	L	0.23	L	0.21	L

FAF had a higher calculated biomass and lower basal area than $RAF_{O,}$ for example, as rubber has a medium wood density (0.48 g cm^{-3}), and many of the fruit trees have higher values, such as durian (0.61 g cm^{-3}), manggis (0.79 g cm^{-3}), and rambutan (0.80 g cm^{-3}).

FAF had a higher calculated biomass and lower basal area than RAF^O, for example, as rubber has a medium wood density (0.48 g cm^{-3}), and many of the fruit trees have higher values, such as durian (0.61 g cm^{-3}), manggis (0.79 g cm^{-3}), and rambutan (0.80 g cm^{-3}).

Table 5. Population densities of seedlings, saplings, poles, and small and large trees in the various land cover types (s.e.d. = standard error of differences).

Land Use *	Understory	Saplings	Poles	Medium Trees	Large Trees	Basal Area	Aboveground Tree Biomass
	Individuals ha^{-1}					m^2 ha^{-1}	Mg ha^{-1}
FAF	24,167 a	107	320 b	142 b	87 b	26.8 bc	299 c
RAFo	28,000 a	533	347 b	127 b	102 b	34.4 c	281 c
RAF_y	32,833 a	373	527 c	132 b	28 a	20.2 b	144 b
RMO	37,000 a	293	320 b	217 c	40 a	20.8 b	148 b
OFA	79,667 b	0	0 a	0 a	0 a	0.0 a	0 a
s.e.d	13,671	202	76	27.75	19.08	3.71	42.7

* Land uses: RAFo = old rubber agroforest, FAF = fruit agroforest, RAFy = young rubber agroforest, RMO = rubber monoculture, OFA = open-field agriculture (annual crops); values not sharing letters differ significantly ($p < 0.05$).

3.3.2. Species Composition

Ranked by importance index, rubber (*Hevea brasiliensis*) dominated among the large trees, with cempedak locally known as *mangkahai* (*Artocarpus integer)* and kecapi (*Sandoricum koetjape*) leading among local fruit trees (Table 6).

3.3.3. Diversity Indices

Across the various stages (from seedlings to trees), the highest species richness (32 woody species) was found in RAFo, followed by FAF and RAFy (both 25 species), with the RMO at 10 species but still meeting the 'monoculture' definition of >85% of basal area in the dominant species (Figure 7). The Shannon–Wiener (H') diversity indices were highest for the seedlings and saplings in the understory vegetation (0.45–1.70), followed by the small tree stage (0.0–1.51).

Table 6. Importance index (INP% on a 0–300 scale) of plant species across the five land covers.

Scientific Name	Local Name	Under-Story	LCs	Saplings	LCs	Poles	LCs	Medium Trees	LCs	Large Trees	LCs
Hevea brasiliensis	Karet	132.7	2,3,4	300	1,2,3,4	226	1,2,3,4	287	2,3,4	300	2,3,4
Artocarpus integer	Mangkahai	0	0	194	4	82	1,3,4	133	1,3	158	1,3
Sandoricum koetjape	Katapi	37.4	1	0	0	0	0	31	3	164	3
Durio sp.	Dahuyan	0	0	101	4	0	0	0	0	70	1
Mangifera caesia	Binjai	0	0	0	0	0	0	0	0	59	2
Baccaurea mottleyana	Rambai	0	0	62	2	41	2	0	0	49	1
Artocarpus nitidus	Tampang	0	0	0	0	0	0	70	2	0	0
Lansium domesticum	Langsat	0	0	0	0	0	0	65	1	0	0
Nephelium lappaceum	Rambutan	30.6	4	0	0	240	1	47	1,4	0	0
Peronema canescens	Sungkai	0	0	0	0	0	0	41	2	0	0
Calophyllum hosei	Jinjit	42.6	1,2	0	0	38	2	0	0	0	0
Garcinia sp.	Manggis	0	0	300	1	0	0	0	0	0	0
Vitex pubescens	Kalapapa	0	0	300	3	0	0	0	0	0	0
Parkia speciosa	Petai	0	0	168	1	0	0	0	0	0	0
Mezzettia parviflora	Kambalitan	0	0	55	2	0	0	0	0	0	0
Mangifera odorata	Kweni	0	0	49	3	0	0	0	0	0	0
Dillenia sp.	Simpur	79.5	3	0	0	0	0	0	0	0	0
Pteris sp.	Hawuk	67.2	5	0	0	0	0	0	0	0	0
Guazuma ulmifolia	Kalanduyung	44.7	5	0	0	0	0	0	0	0	0
Stenochlaena palustris	Kalakai	43.1	4	0	0	0	0	0	0	0	0
Calamus sp.	Rotan	36.4	2	0	0	0	0	0	0	0	0
Citrullus lanatus	Semangka	36.1	5	0	0	0	0	0	0	0	0
Coffea canephora	Kopi	36.1	3	0	0	0	0	0	0	0	0

LCs = Land covers. 1: FAF = fruit agroforest, 2: RAFo = old rubber agroforest, 3: RAFy = young rubber agroforest, 4: RMO= rubber monoculture, 5: OFA = open-field agriculture (annual crops).

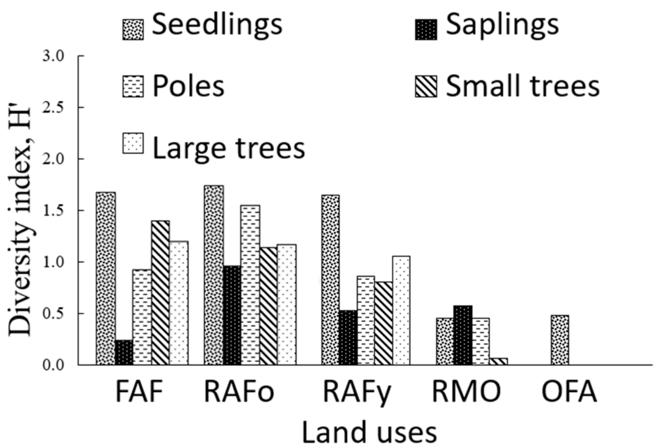

Figure 7. Shannon–Wiener diversity index (H’) for trees in five growth stages (seedlings, sapling, poles, and small and large trees) in the five land uses.

4. Discussion

4.1. Groundwater Level Fluctuations

Probably the most salient result for peatland rewetting and restoration is the confirmation that the *Kaleka* agroforest, in either its fruit tree or rubber dominated forms is compatible with a wet peatland hinterland, as it functions at high groundwater tables itself. The fruit agroforest functioned at an average groundwater level of −33 cm, and measurements indicated that, 55 percent of the time, it exceeded the −40 cm level that is mandated for peatlands. The old rubber agroforest had an average groundwater depth of −50 cm and demonstrated that rubber trees can function well under wet conditions.

This form of land management through agroforest, developed as part of Dayak Ngaju traditions, is thus compatible with the hydrological goals of rewetting peatland landscapes, understood as hydrological units and including non-peat soils. When peatlands are to be successfully restored, rewetting the peat domes will need to be accompanied by land uses around the peat dome that maintain high groundwater levels.

The estimates of the plot-level water balance based on groundwater fluctuations suggested that drainage dominated over evapotranspiration for most land covers; however, in the May–October period, evapotranspiration exceeded rainfall and groundwater levels dropped. In this period, however, lateral interactions in the landscape are reduced to aboveground (mesoclimatic) effects via air humidity, and, if they occur, fires spreading through dry ground vegetation. Hydrologically, the high groundwater levels in the wet season are directly relevant to the drainage of the hinterland.

4.2. Soil Quality

The low pH values (3.5–4) and high exchangeable Al concentrations indicate that the soil, in its current state, would be suitable only for crops with high Al tolerance, or that a high dosage of lime would be needed to allow open-field agriculture to thrive.

The relatively high C-org concentrations for a mineral soil could point at a history as shallow peat soils. Interestingly, the C_{org}/C_{ref} ratio was above two for the three land covers with a shorter use history (RAFy, RMO, and FAF) and at or below one for the oldest Kaleka (FAF and RAFo) plots, suggesting that, over time, there may be a convergence of conditions in mineral soils elsewhere.

The association of earthworms with the most forest-like land covers, rather than with the highest C_{org} concentrations, may be due to the continued and diverse litter layer in these systems that provides food for earthworms [72,73]. Earthworm diversity in these agroforests is, however, lower than that reported elsewhere [74]. Pontoscolex corethrurus is a species with a wide distribution, often associated with agriculture and replacing a more diverse forest fauna [75].

The low soil quality in the peat zones and surrounding mineral soils was known at the time the Mega Rice Project was planned [76], and has subsequently contributed to the failure of large-scale rice production. Tree crops tolerant of acid-soil and wet conditions, such as rubber, are to be preferred on the alluvial soils.

4.3. Botanical Composition and Vegetation Structure

The most salient observations here are that the *Kaleka* agroforests are rejuvenating through natural regeneration, giving the farmers a choice of local fruit (and/or timber) trees that they want to retain and let grow to maturity. The tree species selected for retention and/or cultivation are generally locally adapted, as is the case with studies [77,78] in agroforestry of local communities in Sumatra and Central Kalimantan or the Moluccas [79].

The measured tree diversity indices in the *Kaleka* plots were comparable to those measured in agroforests in Tumbang Nusa (C. Kalimantan) (1.64; [80]) but much lower than measurements in natural forest elsewhere in Kalimantan: 3.54 in W. Kalimantan [81], 4.17 in Barito Hulu [82], and 6.05 in the primary forest in Besiq Bermai [83]. The data fit the pattern described by [84], that, in agroforestry, tree species richness is approximately proportional to tree biomass (or carbon stocks).

The active regeneration of a wide range of species within the *Kaleka* agroforests is in contrast with current efforts for peatland rewetting in burnt peatlands where initial species richness remains low [80]. Beyond rewetting the peat domes and blocking existing canals [85], vegetation tolerating high groundwater levels is needed surrounding the peat area as such. As the fire ban applied to both peat and mineral soils has de facto forced an 'outsourcing' of rice as staple food [38], local livelihoods have little choice but to follow a pattern that emerged voluntarily elsewhere [86].

4.4. Sustainability

As absolute interpretation of soil quality can be done with reference to specific crops but not across the full range of land use options, considerations of sustainability need to include a time dimension. The *Kaleka* agroforest may have started when there was still a shallow peat layer on top of the mineral soil, as the soil map for the surrounding landscape indicate, but this cannot be ascertained at the level of sample points. In the transition from sapric peat to an organic matter-rich mineral soil, the C_{org}/C_{ref} ratio was lower in the older than in the younger agroforest sites. So far, however, losses of soil carbon relative to a natural vegetation reference state are not affecting productive use of the land under the agroforest management regime. Most importantly, the mineral soil shows little signs of subsidence and can drain excess water at high groundwater levels without excessive flooding, beyond the tolerance levels of the tree species used. The ability of tree root systems to survive fluctuating and high groundwater levels, probably based on internal aerenchyma, is an important functional trait [87] not shared by species currently promoted by the forestry industry in the area [31].

As indicated in an overview of agroforestry-based ecosystem services [88], the benefits that wider society derives from a well-functioning agroecosystem (the definition of ecosystem services) need to be understood at the level of interacting zones and land uses rather than as standard value per unit area multiplied by the area involved. Maintaining viable and culturally embedded wet land use in the riparian transition zone of peat domes makes it possible to hydrologically restore the peat domes that are threatened by networks of drainage canals constructed with unrealistic expectations of agricultural intensification of the area. By maintaining a diverse and healthy tree population at plot-level, the *Kaleka* agroforests contribute to a healthy peat hydrological unit, as target of current management. More explicit recognition of the current relevance of these agroforests is needed.

5. Conclusions

Data on groundwater dynamics and soil quality corroborate results of a recent ethnobotanical study on the indicator and use values of plants in *Kaleka* agroforests that grow on the riverbank with peat domes as their hinterland. Especially in the oldest fruit agroforest and the old rubber agroforests that may be a century old, internal rejuvenation allows a permanent tree cover and uneven age distribution of trees that mimics a natural forest and contrasts with even-aged plantations. The fruit agroforest functioned at an average groundwater level of −33 cm and measurements indicated that 55 percent of the time it exceeded the −40 cm level that is mandated for peatlands. The old rubber agroforest had an average groundwater depth of −50 cm and demonstrated that rubber trees can function well under wet conditions. This form of land management through agroforest, developed as part of Dayak Ngaju traditions, is thus compatible with the hydrological goals of rewetting peatland landscapes, understood as hydrological units and including non-peat soils. The low pH values (3.5–4) and high exchangeable Al concentrations indicate major constraints to common agricultural crops and suggest that major interventions such as liming would be needed to allow open-field agriculture to thrive. When peatlands are to be successfully restored, rewetting the peat domes will need to be accompanied by land uses around the peat dome that maintain high groundwater levels. The *Kaleka* agroforests described here have played that role successfully for at least a century. They deserve further attention and recognition.

Author Contributions: Conceptualization, Y.A.S., K.H., D.S., and M.v.N.; methodology, Y.A.S., K.H., D.S., and M.v.N.; investigation, Y.A.S. and M.v.N.; writing—original draft preparation, Y.A.S.; writing—review and editing, M.v.N.; visualization, Y.A.S. and M.v.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the PhD scholarship for first author from the Indonesian Ministry of Research, Technology and Higher Education. APC was supported by the Agroforestry Research Group of Brawijaya University.

Institutional Review Board Statement: Beyond consent from village elders and approval of the research proposal by the Graduate School, no institutional review was required within existing regulations.

Informed Consent Statement: Before its onset, informed consent was obtained from village elders and subsequently from all persons involved in the study.

Data Availability Statement: Basic data will be made available upon acceptance by the journal.

Acknowledgments: (not implying endorsement or responsibility for perspectives presented here) Our deep gratitude to the people in Henda villages, especially to the Lambung and Dillin family (Alo Lambung and Susana), and Cimtrop (Center for International Co-Operation in Sustainable

Management of Tropical Peatland) who helped to process this research. Pordamantra assisted in the research survey activities. Bapak Mazwar helped in the initial survey sharing his knowledge of soil types, Bapak Cahyo Prayogo and Ibu Yayuk Yuliati commented on early stages of the design of the research, and Bapak Salampak shared his deep understanding of peatland ecosystems in Central Kalimantan.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1. Simple Water Balance Model

The main equations (inExcell format) were:

DailyEpotMax = EpotMax*(AmplitEpot + (SIN(PI()*(DoY + T_{offset})/365))^2)/(1 + AmplitEpot), with EpotMax (mm day^{-1}), AmplitEpot (dimensionless) and T_{offset} (days) as parameters;

Eact = DailyEpotMax*MIN(1;$H_{upt}/H_{gw}(t-1)$), with H_{upt} (cm) is groundwater height below which plant water use is reduced, Hgw(t − 1) as the groundwater height (cm) at time t − 1;

RainInfiltrated = (1 − InterceptEt)*Rainfall(t), with InterceptEt (dimensionless) as parameter and Rainfall(t) (mm day^{-1}) as input per observation period;

Drained = GWdrainfrac*MAX(0;$H_{gw}(t-1) - H_d$), with GWdrainfrac (dimensionless) as parameter and Hd as the depth (cm) below which no drainage occurs

$H_{gw}(t) = H_{gw}(t-1)$ + Period*(0.1/SoilPorosity)*(RainInfiltrated − Drained − Eact), with Period as the average number of days between measurements (15.1 days) and Soil-porosity (fraction, v/v) as site parameter.

Appendix A.2. Relationship between Groundwater Levels and Preceding Rainfall

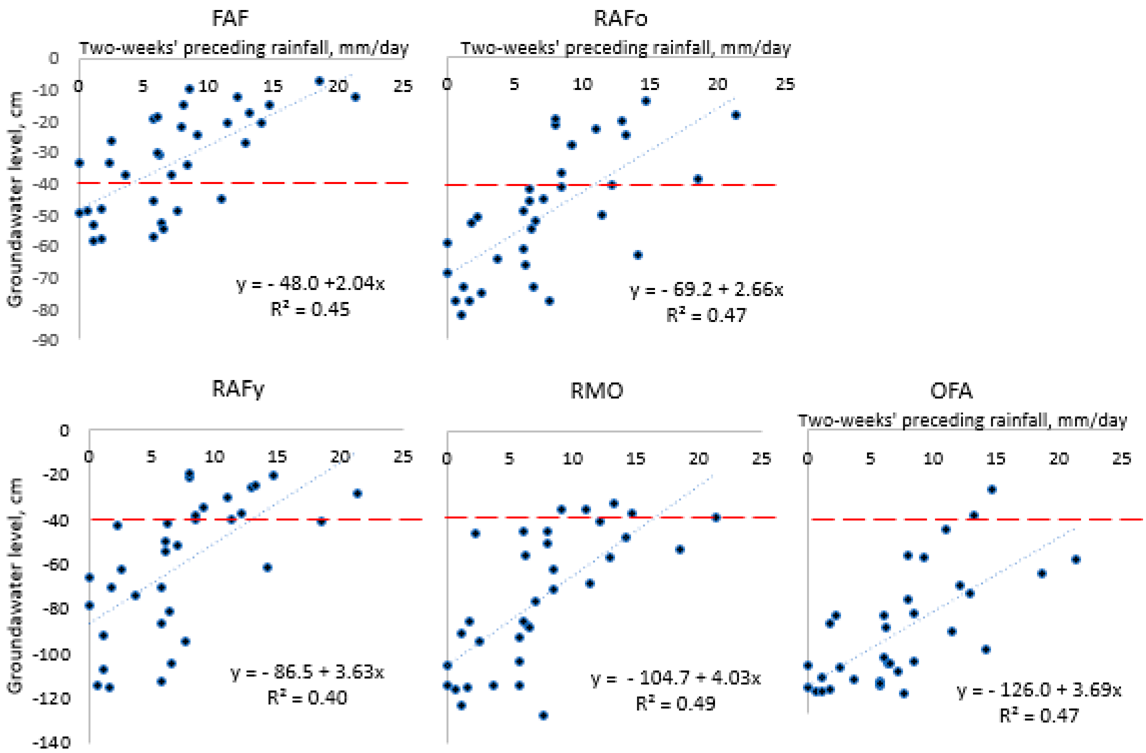

Figure A1. Recorded groundwater levels between 1 September 2019 and 15 January 2019 in the various land uses in relation to the average rainfall in the preceding two weeks at the CIMTROP-LAHG weather station in Sebangau; the red line indicates the mandated groundwater level for peatlands (−40 cm).

References

1. Sanchez, P.A. *Properties and Management of Soils in the Tropics*, 2nd ed.; Cambridge University Press: Cambridge, UK, 2019; p. 666.
2. Doran, J.W.; Zeiss, M.R. Soil health and sustainability: Managing the biotic component of soil quality. *Appl. Soil Ecol.* **2000**, *15*, 3–11. [CrossRef]
3. Van Noordwijk, M. Nutrient cycling in ecosystems versus nutrient budgets of agricultural systems. In *Nutrient Disequilibria in Agro-Ecosystems: Concepts and Case Studies*; Smaling, E.M.A., Oenema, O., Fresco, L.O., Eds.; CAB International: Wallingford, UK, 1999; pp. 1–26.
4. Shepherd, K.D.; Shepherd, G.; Walsh, M.G. Land health surveillance and response: A framework for evidence-informed land management. *Agric. Syst.* **2015**, *132*, 93–106. [CrossRef]
5. Power, A.G. Ecosystem services and agriculture: Tradeoffs and synergies. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 2959–2971. [CrossRef]
6. Van Noordwijk, M.; Poulsen, J.; Ericksen, P. Quantifying off-site effects of land use change: Filters, flows and fallacies. *Agric. Ecosyst. Environ.* **2004**, *104*, 19–34. [CrossRef]
7. Dent, D.; Young, A. *Soil Survey and Land Evaluation*; George Allen & Unwin: London, UK, 1981.
8. Mantel, S.; Wösten, H.; Verhagen, J. *Biophysical Land Suitability for Oil Palm in Kalimantan, Indonesia*; Report 2007/01; ISRIC—World Soil Information, Alterra, Plant Research International, Wageningen UR: Wageningen, The Netherlands, 2007.
9. Joshi, L.; Shrestha, P.K.; Moss, C.; Sinclair, F.L. Locally derived knowledge of soil fertility and its emerging role in integrated natural resource management. In *Below-Ground Interactions in Tropical Agro-Ecosystems: Concepts and Models with Multiple Plant Components*; van Noordwijk, M., Ong, C.K., Cadisch, G., Eds.; CAB-International: Wallingford, UK, 2004; pp. 17–39.
10. Barrios, E.; Coutinho, H.L.; Medeiros, C.A. *InPaC-S: Participatory Knowledge Integration on Indicators of Soil Quality: Methodological Guide*; World Agroforestry Centre (ICRAF): Nairobi, Kenya, 2012.
11. Rousseau, G.X.; Deheuvels, O.; Arias, I.R.; Somarriba, E. Indicating soil quality in cacao-based agroforestry systems and old-growth forests: The potential of soil macrofauna assemblage. *Ecol. Indic.* **2012**, *23*, 535–543. [CrossRef]
12. Plaas, E.; Meyer-Wolfarth, F.; Banse, M.; Bengtsson, J.; Bergmann, H.; Faber, J.; Taylor, A. Towards valuation of biodiversity in agricultural soils: A case for earthworms. *Ecol. Econ.* **2019**, *159*, 291–300. [CrossRef]
13. Hossain, M.F.; Chen, W.; Zhang, Y. Bulk density of mineral and organic soils in the Canada's arctic and sub-arctic. *Inf. Process. Agric.* **2015**, *2*, 183–190. [CrossRef]
14. Jim, C.Y.; Ng, Y.Y. Porosity of roadside soil as indicator of edaphic quality for tree planting. *Ecol. Eng.* **2018**, *120*, 364–374. [CrossRef]
15. Fu, Y.; Tian, Z.; Amoozegar, A.; Heitman, J. Measuring dynamic changes of soil porosity during compaction. *Soil Tillage Res.* **2019**, *193*, 114–121. [CrossRef]
16. Jaenicke, J.; Wösten, H.; Budiman, A.; Siegert, F. Planning hydrological restoration of peatlands in Indonesia to mitigate carbon dioxide emissions. *Mitig. Adapt. Strateg. Glob. Chang.* **2010**, *15*, 223–239. [CrossRef]
17. Takeuchi, W.; Hirano, T.; Roswintiarti, O. Estimation Model of Ground Water Table at Peatland in Central Kalimantan, Indonesia. In *Tropical Peatland Ecosystems*; Springer: Tokyo, Japan, 2016; pp. 445–453.
18. Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil* **2002**, *241*, 155–176. [CrossRef]
19. Huang, B.; Sun, W.; Zhao, Y.; Zhu, J.; Yang, R.; Zou, Z.; Su, J. Temporal and spatial variability of soil organic matter and total nitrogen in an agricultural ecosystem as affected by farming practices. *Geoderma* **2007**, *139*, 336–345. [CrossRef]
20. Lal, R. Sequestering carbon in soils of agro-ecosystems. *Food Policy* **2011**, *36*, S33–S39. [CrossRef]
21. Hairiah, K.; Utami, S.R.; Suprayogo, D.; Sunaryo, S.; Sitompul, S.M.; Lusiana, B.; Mulia, R.; van Noordwijk, M.; Cadisch, G. *Pengelolaan Tanah Masam Secara Biologi. Refleksi Pengalaman Dari Lampung Utara*; International Centre for Research in Agroforestry: Bogor, Indonesia, 2000.
22. Chan, K.Y.; Baker, G.H.; Conyers, M.K.; Scott, B.; Munro, K. Complementary ability of three European earthworms (*Lumbricidae*) to bury lime and increase pasture production in acidic soils of south-eastern Australia. *Appl. Soil Ecol.* **2004**, *26*, 257–271. [CrossRef]
23. Velásquez, E.; Lavelle, P.; Andrade, M. GISQ, a multifunctional indicator of soil quality. *Soil Biol. Biochem.* **2007**, *39*, 3066–3080. [CrossRef]
24. Fründ, H.C.; Graefe, U.; Tischer, S. Earthworms as bioindicators of soil quality. In *Biology of Earthworms*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 261–278.
25. Jongmans, A.G.; Pulleman, M.M.; Balabane, M.; Van Oort, F.; Marinissen, J.C.Y. Soil structure and characteristics of organic matter in two orchards differing in earthworm activity. *Appl. Soil Ecol.* **2003**, *24*, 219–232. [CrossRef]
26. Jouquet, P.; Blanchart, E.; Capowiez, Y. Utilization of earthworms and termites for the restoration of ecosystem functioning. *Appl. Soil Ecol.* **2014**, *73*, 34–40. [CrossRef]
27. Guo, X.; Du, W.; Wang, X.; Yang, Z. Degradation and structure change of humic acids corresponding to water decline in Zoige peatland, Qinghai-Tibet Plateau. *Sci. Total Environ.* **2013**, *445*, 231–236. [CrossRef]
28. Wösten, J.H.M.; Clymans, E.; Page, S.E.; Rieley, J.O.; Limin, S.H. Peat–water interrelationships in a tropical peatland ecosystem in Southeast Asia. *Catena* **2008**, *73*, 212–224. [CrossRef]
29. Ritzema, H.; Limin, S.; Kusin, K.; Jauhiainen, J.; Wösten, H. Canal blocking strategies for hydrological restoration of degraded tropical peatlands in Central Kalimantan, Indonesia. *Catena* **2014**, *114*, 11–20. [CrossRef]

30. Dohong, A.; Tanika, L. Hydrological Management Practices. In *Tropical Peatland Eco-Management*; Springer: Singapore, 2021; pp. 567–593.
31. Nuroniah, H.S.; Tata, H.L.; Mawazin, M.; Martini, E.; Dewi, S. Assessment on the suitability of planting non-native peatlands species *Falcataria moluccana* (Miq.) Barneby & Grimes in rewetted peatlands. *Sustainability* **2021**, *13*, 70152021. [CrossRef]
32. Page, S.; Hosciło, A.; Wösten, H.; Jauhiainen, J.; Silvius, M.; Rieley, J.; Ritzema, H.; Tansey, K.; Graham, L.; Vasander, H.; et al. Restoration ecology of lowland tropical peatlands in Southeast Asia: Current knowledge and future research directions. *Ecosystems* **2009**, *12*, 888–905. [CrossRef]
33. Cattau, M.E.; Harrison, M.E.; Shinyo, I.; Tungau, S.; Uriarte, M.; DeFries, R. Sources of anthropogenic fire ignitions on the peat-swamp landscape in Kalimantan, Indonesia. *Glob. Environ. Chang.* **2016**, *39*, 205–219. [CrossRef]
34. Dohong, A.; Aziz, A.A.; Dargusch, P. A review of the drivers of tropical peatland degradation in South-East Asia. *Land Use Policy* **2017**, *69*, 349–360. [CrossRef]
35. Huijnen, V.; Wooster, M.J.; Kaiser, J.W.; Gaveau, D.L.; Flemming, J.; Parrington, M.; Van Weele, M. Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997. *Sci. Rep.* **2016**, *6*, 268862016. [CrossRef]
36. Miettinen, J.; Shi, C.; Liew, S.C. Fire distribution in Peninsular Malaysia, Sumatra and Borneo in 2015 with special emphasis on peatland fires. *Environ. Manag.* **2017**, *60*, 747–757. [CrossRef] [PubMed]
37. Khakim, M.Y.N.; Bama, A.A.; Yustian, I.; Poerwono, P.; Tsuji, T.; Matsuoka, T. Peatland subsidence and vegetation cover degradation as impacts of the 2015 El niño event revealed by Sentinel-1A SAR data. *Int. J. Appl. Earth Obs. Geoinf.* **2020**, *84*, 1019532020. [CrossRef]
38. Silvianingsih, Y.A.; Hairiah, K.; Suprayogo, D.; van Noordwijk, M. Agroforests swiddening and livelihoods between restored peat domes and river: Effects of the 2015 fire ban in Central Kalimantan (Indonesia). *Int. For. Rev.* **2020**, *22*, 382–396. [CrossRef]
39. Galudra, G.; Van Noordwijk, M.; Suyanto, S.; Sardi, I.; Pradhan, U.; Catacutan, D. Hot spots of confusion: Contested policies and competing carbon claims in the peatlands of Central Kalimantan, Indonesia. *Int. For. Rev.* **2011**, *13*, 431–441. [CrossRef]
40. Rahu, A.A.; Hidayat, K.; Ariyadi, M.; Hakim, L. Ethnoecology of *Kaleka*: Dayak's agroforestry in Kapuas, Central Kalimantan Indonesia. *Res. J. Agric. For. Sci.* **2013**, *1*, 5–12.
41. Suyanto, S.; Khususiyah, N.; Sardi, I.; Buana, Y.; van Noordwijk, M. *Analysis of Local Livelihoods from Past to Present in the Central Kalimantan Ex-Mega Rice Project Area. Working Paper 94*; World Agroforestry Centre: Bogor, Indonesia, 2009; 70p. Available online: http://apps.worldagroforestry.org/sea/Publications/files/workingpaper/WP0124-10.pdf (accessed on 25 July 2021).
42. Lubis, Z.B. *Social Mapping of Access to Peat Swamp Forest and Peatland Resources. Working Paper*; Indonesia-Australia Forest Carbon Partnership: Jakarta, Indonesia, 2013. Available online: http://simlit.puspijak.org/files/buku/Social_Mapping_of_Access_to_Peat_Swamp_Forest-Eng_PP3.pdf (accessed on 28 June 2021).
43. Jemi, R.; Joni, H.; Toni, H.; Aguswan, J.; Triyadi, A.; Putir, P.E.; Lusiana, H. *Kaleka* Lapetan Agroforestry Masyarakat Dayak di Desa Bahu Palawa Kabupaten Pulang Pisau. In Proceedings of the conference SEMIRAT Bidang Ilmu Pertanian BKS PTN Barat, Palangka Raya, Indonesia, 14–15 November 2015.
44. Rahu, A.A.; Hidayat, K.; Ariyadi, M.; Hakim, L. Management of *Kaleka* (Traditional Garden) Dayak community in Kapuas, Central Kalimantan. *Int. J. Sci. Res.* **2014**, *3*, 205–210.
45. Medrilzam, M.; Dargusch, P.; Herbohn, J.; Smith, C. The socio-ecological drivers of forest degradation in part of the tropical peatlands of Central Kalimantan, Indonesia. *Forestry* **2014**, *87*, 335–345. [CrossRef]
46. Jewitt, S.L.; Nasir, D.; Page, S.E.; Rieley, J.O.; Khanal, K. Indonesia's contested domains. Deforestation, rehabilitation and conservation-with-development in Central Kalimantan's tropical peatlands. *Int. For. Rev.* **2014**, *16*, 405–420. [CrossRef]
47. Mulyoutami, E.; Rismawan, R.; Joshi, L. Local knowledge and management of simpukng (forest gardens) among the Dayak people in East Kalimantan, Indonesia. *For. Ecol. Manag.* **2009**, *257*, 2054–2061. [CrossRef]
48. Torquebiau, E. Man-made dipterocarp forest in Sumatra. *Agrofor. Syst.* **1984**, *2*, 103–127. [CrossRef]
49. Van Noordwijk, M.; Tata, H.L.; Xu, J.; Dewi, S.; Minang, P.A. Segregate or integrate for multifunctionality and sustained change through rubber-based agroforestry in Indonesia and China. In *Agroforestry—The Future of Global Land Use*; Springer: Dordrecht, The Netherlands, 2012; pp. 69–104.
50. Lawrence, D.C. Trade-offs between rubber production and maintenance of diversity: The structure of rubber gardens in West Kalimantan, Indonesia. *Agrofor. Syst.* **1996**, *34*, 83–100. [CrossRef]
51. BMKG: Badan Meteorologi, Klimatologi dan Geofisika. Available online: Dataonline.bmkg.go.id/data_iklim (accessed on 15 August 2021).
52. MacKinnon, K.; Hatta, G.; Mangalik, A.; Halim, H. *The Ecology of Kalimantan*; Periplus Editions: Hong Kong, China, 1996.
53. BBSDLP. *Atlas Peta Tanah Semi Detail Skala 1:50,000*; Ministry of Agriculture: Jakarta, Indonesia, 2016. Available online: www.litbang.pertanian.go.id (accessed on 25 July 2021).
54. Notohadiprawiro, Y. Mega-project of Central Kalimantan Wetland Development Project for Food Crop Production: Belief and Truth. 1998. Available online: http://faperta.ugm.ac.id/download/publikasi_dosen/tejoyuwono/1991/1998%20mega.pdf (accessed on 25 July 2021).
55. Badan Pusat Statistik (BPS). *Kecamatan Jabiren Raya Dalam Angka*; National Bureau of Statistics: Jakarta, Indonesia, 2018.
56. *Genstat 64-Bit Release 19.1*; (PC/Windows 8), Copyright 2018; VSN International Ltd.,; University of Brawijaya: Malang, Indonesia, 2018.

57. Walkley, A.; Black, I.A. An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid tritation method. *Soil Sci.* **1934**, *37*, 29–38. [CrossRef]
58. Anderson, J.M.; Ingram, J.S.I. *Tropical Soil Biology and Fertility. A Handbook of Methods*, 2nd ed.; CAB International: Wallingford, UK, 1993.
59. Van Noordwijk, M.; Woomer, P.L.; Cerri, C.; Bernoux, M.; Nugroho, K. Soil carbon dynamics in the humid tropical forest zone. *Geoderma* **1997**, *79*, 187–225. [CrossRef]
60. Hairiah, K.; van Noordwijk, M.; Sari, R.R.; Saputra, D.D.; Widianto, W.; Suprayogo, D.; Kurniawan, S.; Prayogo, C.; Gusli, S. Soil carbon stocks in Indonesian (agro)forest transitions: Compaction conceals lower carbon concentrations in standard accounting. *Agric. Ecosyst. Environ.* **2020**, *294*, 106879. [CrossRef]
61. Baretta, D.; Brown, G.G.; James, S.W.; Cardoso, E.J.B.N. Earthworm populations sampled using collection methods in Atlantic forests with *Araucaria angustifolia*. *Sci. Agric.* **2007**, *64*, 384–392. [CrossRef]
62. Vasu, D.; Singh, S.K.; Ray, S.K.; Duraisami, V.P.; Tiwary, P.; Chandran, P.; Anantwar, S.G. Soil quality index (SQI) as a tool to evaluate crop productivity in semi-arid Deccan plateau, India. *Geoderma* **2016**, *282*, 70–79. [CrossRef]
63. Rahmanipour, F.; Marzaioli, R.; Bahrami, H.A.; Fereidouni, Z.; Bandarabadi, S.R. Assessment of soil quality indices in agricultural lands of Qazvin Province, Iran. *Ecol. Indic.* **2014**, *40*, 19–26. [CrossRef]
64. Biswas, S.; Hazra, G.C.; Purakayastha, T.J.; Saha, N.; Mitran, T.; Roy, S.S.; Mandal, B. Establishment of critical limits of indicators and indices of soil quality in rice-rice cropping systems under different soil orders. *Geoderma* **2017**, *292*, 34–48. [CrossRef]
65. Nusantara, R.W.; Aspan, A.; Alhaddad, A.M.; Suryadi, U.E.; Makhrawie, M.; Fitria, I.; Rezekikasari, R. Peat soil quality index and its determinants as influenced by land use changes in Kubu Raya District, West Kalimantan, Indonesia. *Biodiversitas J. Biol. Divers.* **2018**, *19*, 535–540. [CrossRef]
66. Sharma, K.L.; Mandal, U.K.; Srinivas, K.; Vittal, K.P.R.; Mandal, B.; Grace, J.K.; Ramesh, V. Long-term soil management effects on crop yields and soil quality in a dryland Alfisol. *Soil Tillage Res.* **2005**, *83*, 246–259. [CrossRef]
67. Kusmana, C. *Metode Survey Vegetasi*; Insitut Pertanian Bogor Press: Bogor, Indonesia, 1997.
68. Hairiah, K.; Ekadinata, A.; Sari, R.R.; Rahayu, S. *Pengukuran Cadangan Carbon: Dari Tingkat Lahan ke Bentang Lahan. Petunjuk Praktis*, 2nd ed.; World Agroforestry Centre, ICRAF: Bogor, Indonesia, 2011.
69. ICRAF. Wood Density Database. Available online: http://db.worldagroforestry.org/ (accessed on 25 June 2021).
70. Chave, J.; Andalo, C.; Brown, S.; Cairns, M.A.; Chambers, J.Q.; Eamus, D.; Folster, H.; Fromard, F.; Higuchi, N.; Kira, T.; et al. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* **2005**, *145*, 87–99. [CrossRef] [PubMed]
71. Nortcliff, S. Standardisation of soil quality attributes. *Agric. Ecosyst. Environ.* **2002**, *88*, 161–168. [CrossRef]
72. Eriksen-Hamel, N.S.; Speratti, A.B.; Whalen, J.K.; Légère, A.; Madramootoo, C.A. Earthworm populations and growth rates related to long-term crop residue and tillage management. *Soil Tillage Res.* **2009**, *104*, 311–316. [CrossRef]
73. Feijoo, A.; Carvajal, A.F.; Zúñiga, M.C.; Quintero, H.; Fragoso, C. Diversity and abundance of earthworms in land use systems in central-western Colombia. *Pedobiologia* **2011**, *54*, S69–S75. [CrossRef]
74. Mulia, R.; Hoang, S.V.; Dinh, V.M.; Duong, N.B.T.; Nguyen, A.D.; Lam, D.H.; Thi Hoang, D.T.; van Noordwijk, M. Earthworm diversity, forest conversion and agroforestry in Quang Nam province, Vietnam. *Land* **2021**, *10*, 36. [CrossRef]
75. Topoliantz, S.; Ponge, J.F. Burrowing activity of the geophagous earthworm Pontoscolex corethrurus (Oligochaeta: Glossoscolecidae) in the presence of charcoal. *Appl. Soil Ecol.* **2003**, *23*, 267–271. [CrossRef]
76. Wijaya Adhi, I.P.G.; Subiksa, I.G.M.; Kasdi, S.D.; Ardi, S. Pengelolaan Tanah dan Air Lahan Rawa: Suatu Tinjauan Hasil Penelitian Proyek Swamps II. In *Review Hasil–Hasil Penelitian Proyek Swamps II di Bogor, 19–20 February 1993*; Badan Penelitian dan Pengembangan Pertanian; Departemen Pertanian: Bogor, Indonesia, 1993; p. 22.
77. Khasanah, N.M.; van Noordwijk, M. Subsidence and carbon dioxide emissions in a smallholder peatland mosaic in Sumatra, Indonesia. *Mitig. Adapt. Strateg. Glob. Chang.* **2019**, *24*, 147–163. [CrossRef]
78. Tata, H.L. Mixed farming systems on peatlands in Jambi and Central Kalimantan provinces, Indonesia: Should they be described as paludiculture? *Mires Peat* **2019**, *25*, 1–17.
79. Kaya, M.; Kammesheidt, L.; Weidelt, H.J. The forest garden system of Saparua island Central Maluku, Indonesia, and its role in maintaining tree species diversity. *Agrofor. Syst.* **2002**, *54*, 225–234. [CrossRef]
80. Tata, M.H.L.; Pradjadinata, S. Regenerasi alami hutan rawa gambut terbakar dan lahan gambut terbakar di tumbang nusa, kalimantan tengah dan implikasinya terhadap konservasi. *J. Penelit. Hutan Dan Konserv. Alam* **2013**, *10*, 327–342. [CrossRef]
81. Budiharta, S. Floristic composition at biodiversity protection area in Lubuk Kakap, District of Ketapang, West Kalimantan. *Biodiversitas J. Biol. Divers.* **2010**, *11*, 3. [CrossRef]
82. Brearley, F.Q.; Prajadinata, S.; Kidd, P.S.; Proctor, J. Structure and floristics of an old secondary rain forest in Central Kalimantan, Indonesia, and a comparison with adjacent primary forest. *For. Ecol. Manag.* **2004**, *195*, 385–397. [CrossRef]
83. Sofiah, S.; Metusala, D.; Trimanto, T.; Nurfadilah, S. Flora diversity, composition and ecology in Besiq Bermai tropical forest of Damai District, East Kalimantan. *BIOTROPIA Southeast Asian J. Trop. Biol.* **2018**, *25*, 85–94.
84. Sari, R.R.; Saputra, D.D.; Hairiah, K.; Rozendaal, D.; Roshetko, J.M.; van Noordwijk, M. Gendered species preferences link tree diversity and carbon stocks in Cacao agroforest in Southeast Sulawesi, Indonesia. *Land* **2020**, *9*, 108. [CrossRef]
85. Noor, M. *Lahan Gambut: Pengembangan, Konservasi, dan Perubahan Iklim*; Gadjah Mada University Press: Yogyakarta, Indonesia, 2010.

86. Van Noordwijk, M.; Bizard, V.; Wangpakapattanawong, P.; Tata, H.L.; Villamor, G.B.; Leimona, B. Tree cover transitions and food security in Southeast Asia. *Glob. Food Secur.* **2014**, *3*, 200–208. [CrossRef]
87. Van Noordwijk, M.; Martikainen, P.; Bottner, P.; Cuevas, E.; Rouland, C.; Dhillion, S.S. Global change and root function. *Glob. Chang. Biol.* **1998**, *4*, 759–772. [CrossRef]
88. Van Noordwijk, M. Agroforestry-Based ecosystem services: Reconciling values of humans and nature in sustainable development. *Land* **2021**, *10*, 699. [CrossRef]