



Soil Degradation Due to Conversion from Natural to Plantation Forests in Indonesia

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Abstract: Soil organic matter (SOM) is a crucial component of soil, through which physical, chemical, and biological characteristics interact in a local context. Within the forest category, the conversion of natural forests to monoculture plantations has raised concerns in Indonesia over the loss of soil functions, similar to conversion to agriculture. In natural forests, SOM can accumulate as part of a closed nutrient cycle with minimal nutrient losses; in plantation forestry, SOM decline and recovery can alternate over time, associated with larger nutrient losses. We reviewed existing studies to quantify how shifts from natural forests to short-rotation plantation forests (SRPF) affect SOM dynamics, soil nutrient contents, and soil-borne pathogens that cause disease. The review combines descriptive and quantitative methods (meta-analysis). The results show that conversion affects the soil C balance, soil structure and water balance, soil nutrient balance, and soil-borne diseases. Contributing factors include the reduced diversity of plant and rhizosphere communities, lower annual litter production, more uniform litter quality, and nutrient removal at the harvest cycle. Conversion from natural to plantation forest conditions also increases plant disease incidence by changing biological control mechanisms.

Keywords: decomposition; disease; litter; nutrient cycles; rhizosphere community; root exudates

1. Introduction

Forests play important roles in the Earth's ecosystem, both ecologically and economically, while they have a specific institutional regime that differs from that for agriculture and other land uses. Ecologically, forests provide a primary home for biodiversity [1], regulate water systems [2], modify the climate [3], and store carbon aboveground in biomass and belowground in roots and in soil organic matter through the production of aboveground litter, root turnover, mycorrhizal hyphae and root exudates [4–6]. Economically, they produce timber and various nontimber forest products, forming a source of income for local communities, businesses, and the government [7]. Institutionally, forests are governed by forest authorities, whose rules vary by country [8]. The 120.5 million hectares of tropical forest, 64% of the country's total land area, make Indonesia the third-largest tropical forest country in the world [9], and make the fate of its forests and its approach to reverse forest and land degradation of global relevance [10].



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). The intersection of land-cover-based and institutional forest cover concepts complicates the meaning of terms such as de- and reforestation in Indonesia [11]. Two types of change in existing forests are important in this respect: institutional de- and re-forestation (taking land out of the forest category, although trees may still be part of subsequent land use; or, bringing land into a forest regulatory regime after returning tree cover, a major drawback for land owners fearing loss of control), and changes in the balance between economic and ecological benefits within the forest category, e.g., by a shift to plantation forestry. Most of the public attention has been on the first ("de/re/af-forestation"), rather than the second type of change ("forest degradation/restoration"), although both are, depending on forest definitions, addressed in the Reducing Emissions from Deforestation and (forest) Degradation (REDD+) and Nationally Determined Contributions (NDC) initiatives of the global climate convention [12–14].

In the last 20 years, institutional deforestation has remained part of Indonesia's chosen development trajectory, as a result of a planned conversion to mining, tree crop plantations, agricultural resettlement programs, food estates and road construction, for example; but changes in forest cover have also occurred outside the legal forest framing as a result of land encroachment in forest areas without effective protection [15]. This second type of deforestation (institutionally considered to be forest degradation) has occurred, especially in (post-logging) secondary forests with weak governance controls [16,17]. While lossof-forest-cover (vegetation-based deforestation) rates were lower than in the preceding decade, Indonesia still reported that in the 2015–2018 period, 0.63 million ha (2015–2016), 0.30 million ha (2016-2017), and 0.46 million ha (2017-2019) was converted to other land uses, legally or illegally [9,18]. An estimated 15%–20% of oil palms in Indonesia grow within what the country considers to be forest lands, without a legal pathway for such presence [19]. As confirmed by a previous study, tropical forests in Asia (including Indonesia) are more vulnerable to land cover changes and forest fragmentation in comparison to other stressors such as climate change [20]. Over time, many programs for returning and improving tree cover have been attempted, both inside and outside institutional forest lands [11,14], but the rate of restoration activities remains much slower than the rate of forest cover loss. For example, the restoration capacity in 2015–2016 was only 0.12 million ha, while forest cover loss affected 0.63 million ha [18].

Conversion of (degraded) natural forests to monocultural plantations, although not included in official deforestation estimates, has significant impacts: while seen as "forest improvement" by the forest industry, it is seen as "forest degradation" by others who care about biodiversity, carbon stocks and forest-based local livelihoods. A substantive literature on the impacts of conversion of natural forest into monoculture plantations in Indonesia has in the past decades focused on oil palm plantations, typically with loss of soil quality in the early phases and potential recovery when the whole life cycle (around 25 years) is considered [21–23]. However, the more than 5 million ha of plantation forests (mostly short-rotation monocultures for industrial use) [9] also deserve to be understood for their impacts on soil properties, including soil organic matter interacting with soil chemical, physical and biological properties. Other estimates of the forest plantation area in Indonesia mention areas over 10 million ha [24], but this may refer to the area of issued permits, rather than achieved forest cover. The establishment of industrial forest plantations has significant impacts on forest functioning, due to the clear-cutting of existing (residual) stands (often followed by the use of woody biomass in pulp and paper mills) and transformation into even-aged monocultural stands. The development of industrial forest plantations is currently crucial to supply wood raw materials to the existing forest industries (that until recently depended heavily on illegal logging to feed its pulp and paper mills); it has advantages in reducing the pressure on natural forests, helps to improve the use of damaged forests, provides jobs and business opportunities, and increases regional and national economic growth [9,25]. However, earlier studies reported that the growth of fast-growing species in monocultures result in reduced soil water content, decreased

nutrient availability, and inhibited undergrowth; therefore, this practice leads to reduced biodiversity, increased soil erosion, and reduced soil fertility [26–31].

Research on monoculture plantation sites with fast-growing trees, such as *Eucalyptus* spp., *Acacia mangium*, *Acacia crassicarpa*, *Gmelina arborea*, and *Falcataria moluccana*, found that the productivity commonly declines from the second rotation onward due to clear cut harvesting followed by the transportation of wood offsite. In addition, monoculture plantations are reported to absorb large amounts of soil nutrients; hence, a failure to conserve SOM may arise and cause a further decrease in soil fertility, which adversely affects the soil properties and microbial populations [29,32]. Effects of continuous long-term monoculture cultivation may result in the accumulation of high levels of glucose and amino acid compounds that induce the development of soil pathogens to serious levels [33].

This paper presents a meta-review of the alterations in organic matter supply and its consequences due to changes in forest management from natural forests to short-rotation plantation forests (SRPFs) in Indonesia. We followed the systematic review methodology and, on the basis of the literature found, developed a conceptual scheme that represents the current understanding of phenomena (differences between natural and plantation forests), related cause–effect mechanisms (processes) and impacts on the carbon, nutrient and water balance of the soil, and on key soil biological functions.

2. Methods

2.1. PRISMA Systematic Review and Meta-Analysis

A corpus of relevant publications was assembled consisting of journal articles, institutional publications, books, dissertations, and university theses. The literature references were compiled through searches with the Google search engine (Alphabet Inc., Mountain View, CA, USA), and through Google Scholar, Science Direct, ResearchGate, and other relevant databases. This review combined descriptive (compilation) and quantitative (metareview) methods (Figure 1). As in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) technique (PRISMA-P, Canada) [34], the study used explicit steps in (1) identifying keywords to search for relevant articles, (2) screening for duplicates, (3) determining the eligibility of papers, and (4) including subcategories.



Figure 1. Number of references on impacts of the conversion of natural forest into monoculture plantations in Indonesia: (**a**) classification by subtopic; (**b**) screening of publications based on the PRISMA steps.

A descriptive analysis was carried out on the results of the entries, interacting with the development of a conceptual scheme. Based on their dominance, SRPFs based on *Acacia* spp. and *Eucalyptus* spp. could be separately analysed. Data on changes in soil properties over stand age were studied quantitatively, as quantitative methods are especially helpful to conduct a deep analysis of the nutrient dynamics of SRFs monocultures in Indonesia.

2.2. Scheme Linking Characteristics, Processes and Impacts

In interactions with the literature that surfaced in the search, various methods were explored to efficiently represent the summary findings, recognizing the multitude of interacting processes, and the interest in the ecosystem functions that relate to carbon, nutrient and water balances, and to soil biological functions. At the start of the review, our basic understanding of the main characteristics in which plantations differ from natural forests and the underlying processes were as follows.

Natural forests in the tropics, which have a closed nutrient cycle, usually have more fertile soil than forest-derived land cover types. Conversion to monoculture plantations means that forests change their nutrient cycle into an open flow, which results in a decrease in soil nutrients while the soil organic matter (SOM) supply is also affected [35–37]. In forest stands, the main source of SOM is litter (plant roots, debris, leaves, and mulch). The organic matter supplied by forest trees comprises litter, felling residue, and bark, which decompose slowly. The amount of potential litter depends on the type, age, and site conditions. For natural forests, data for Indonesia are typically around 12 tons ha^{-1} (for detailed references see below). Litter productivity in plantation forests is in the range of 3-9 tons ha⁻¹ year⁻¹ [32,38], whereas litter productivity in tropical rainforest ecosystems is significantly different between rainy and dry seasons. Wu et al. [39] synthesized data from tropical rainforests in the southeast Asia region with an asynchronous unimodal method showing an average value of litter in the dry season of circa 6 tons ha^{-1} ; while in the rainy season it produced circa 3 tons ha^{-1} . Macrofauna (soil arthropods, earthworms, etc.), saprophytic fungi, and microorganisms decompose those biomaterials into nutrients that are available to plant absorption. The end product of SOM decomposition is humus. The rate of organic matter decomposition depends on the soil's temperature, moisture, aeration, pH, and nutrient levels [40].

Such generic process-level understanding of tropical forest conditions led to the conceptual scheme (Figure 2) that starts from several of key characteristics in which plantation forests differ from natural forests, considering the various interacting processes and their impacts on overall soil functions. The following text is based on this conceptual scheme.



Figure 2. Conceptual scheme to relate changes in forest characteristics following conversion of natural forest into monoculture plantation, effects on underlying process, and the impacts to soil properties.

3. Long-Cycle Gap-Level Rejuvenation vs. Short Rotation with Clear-Felling and Replant

In Indonesia there is a major trend from W to E from humid climates where the driest months offer the best opportunities for photosynthesis, to drier climates where the wet season is best for plant growth [39]. This appears to be reflected in the various seasonal patterns of leaf flush and litterfall by tree species: deep-rooted trees that can afford a new flush of leaves in the sunny season complement the phenology of, and interact with litter production via, more shallowly rooted species [41]. Tree phenological diversity is a key feature of natural forests, while variation in tree root architecture means that "soil anchoring" and "soil binding" functions on hill slopes can both be provided [42].

Natural forests have multiple strata, which along with variation in tree species, age and growing stage, create protection for the forest floor from light (and associated temperature variation), and high-energy water droplets, either from the impact of direct rain or dripping from high-level tree canopies. Stratification also occurs belowground where the root architectures of species complement each other in occupying the available space and interacting with water and nutrient resources, promoting overall nutrient absorption efficiency [31]. In monocultural stands, there is significant fluctuation of the soil and surface microenvironment as a result of clear-cutting—planting cycles, as well as at daily scales before tree canopy cover is complete. Tall tree canopies without understory vegetation can induce high-impact rain drops that erode topsoil [43,44]. After clear-fell harvesting, large amounts of residue will decompose on-site (while usable parts are harvested), typically given rapid full sunlight penetration. The resulting nutrient flushes will likely be lost before the newly planted trees have sufficient demand [45]. Hence, there are significant impacts on the local biogeochemical cycle.

Monoculture plantations are known to increase intra-species competition, with plant density chosen to increase tree height in straight boles. Beyond simple light-capturebased interpretations, trees also respond specifically to the presence of surrounding plants, depending on their species [46,47]. Volatile organic compounds aboveground and soluble compounds in the soil around roots can have positive or negative (allelopathic or toxic) impacts [48,49]. Plants compete with their neighbours when growing in both natural and new habitats to acquire above- and belowground resources. Aboveground competition occurs for light and shoot growth space [50], while belowground competition in the soil is more complex because plants not only compete for growing space for their roots but also for water and nutrients [51]. Shallow, medium, or deep root architectures are determined by the genetic traits of each species [52] and modified by environmental context [53]. Heterogeneous forest structures affect the root system and dynamics [54]. On the other hand, in monocultures, all plants have the same root system, so the competition in the area for absorption of nutrients and water is strong [55]. In an intersecting root system, competition for phosphate may also increase [52]. The competition between roots of the same species of plants was found to be three to five times greater than that of different species in a specific study [56]. Another study reported that intra-species competition has increased in a monoculture plantation of *Calliandra calothyrsus* in Indonesia [57].

3.1. Impact on Soil C Balance

Guillaume stated that converting forests to either oil palm or rubber plantations led to a loss of 10 tons C ha⁻¹ in the Ah horizon after about 15 years of conversion. The low vegetation cover directly after conversion caused surface erosion [58]. A small decrease in C content yielded a strong drop in microbial activity [59] which disturbed SOM decomposition processes.

The forest conversion to monoculture plantations changes litter inputs and soil physicochemical properties, such as litter production, lignin content, as well as soil moisture, pH, and ratio of carbon/nitrogen content. These alterations were found to affect soil microbial composition, diversity, and activity [60,61]. Due to the complexity of plant–fungal symbiosis, fungi are thought to be more sensitive to plant changes than bacteria [62]. Changes in vegetation alter soil conditions, such as soil moisture [63], the sizes and forms of soil nutrient pools [64], hence deeply impacting the diversity, structure, and composition of soil fungal communities [65].

Shifts have been reported in soil microbial communities that determine soil enzymatic activities [66]. For example, the activities of two main extracellular enzymes involved in soil carbon (C) and nitrogen (N) cycling and litter decomposition in forest ecosystems, invertase, and urease, have a positive correlation with soil microbial composition [66].

Figure 3 illustrates the bio-chemical process of SOM in multispecies and monoculture forests. Multispecies forests return SOM into the soil as litter and root exudates (RE). Due to the variety in the matter, decomposition occurs in consecutive cycles; hence, SOM can be conserved in soil. These ecosystem conditions are suitable for supporting various soil microbe communities in the rhizosphere, which secrete various growth regulators. In contrast, monoculture forests return homogeneous litter and RE that shape a rhizosphere community characterized by low diversity. The litter sources are identical and, thus, decompose simultaneously; hence, the nutrients can flush (be abundant) for some time or could be in deficit afterward. Coincident harvesting in monoculture plantations results in the removal of nutrients from the site as wood biomass. On the contrary, massive amounts of necromass or waste are produced, which could increase the SOM content. This nutrient imbalance and the excess of RE result in the stands becoming more susceptible to disease (see Section 3.4).



Figure 3. Comparison between natural (**left**) and monoculture (**right**) forests and the consequences to the SOM production, decomposition, nutrient availability, stand productivity, and soil health.

Part of the literature considers whether or not the introduction of exotic species matters beyond the fast growth for which they were selected. While vegetation characteristics such as rooting depth, leaf area index, transpiration rate, tissue biomass, and phenology can be measured [67–69], crediting something as "being a newly introduced exotic" is hard to prove. The most specific aspect of exotic species may be in terms of the microbial flora of the rhizosphere that has not had time to co-evolve; root exudate composition may promote further invasion of exotic plant species [70].

3.2. Impact on Soil Structure and Water Balance

Monoculture plantations interfere with soil aggregation, and as such can cause soil erosion and degradation, before and after soil cover is established [31]. The application of machines during land preparation before planting and tree harvesting promote soil

compaction that will negatively affect the growth of the understorey. Teak, gmelina and conifer plantations are known to suppress all ground vegetation [71], exposing the soil to high-energy water dripping and soil evaporation rates. The relationship between forest cover and groundwater recharge will depend on a combination of topography, soil types, vegetation and the rainfall regime [2], with critical values differing between mid- and top-slope conditions on a single mountain [72].

Previous studies reported that monoculture plantations caused the depletion of soil moisture and reduced stream flow. *Eucalyptus*, the main genus used in monoculture plantations globally, including in Indonesia, consumes more water than natural forests, which may reduce the water levels in some regions [2,31]. Eucalypts grow fast and have high evapotranspiration rates, hence cultivating this species in monoculture systems may cause risks to the water balance, especially in drier areas [73].

Forest harvesting in monoculture plantations is typically conducted simultaneously at the field-scale, leaving no natural protection for the soils from erosion by wind or rain. Simultaneous harvesting practices in monoculture plantations can result in topsoil loss and eventually loss of soil moisture retention. The application of machines during tree harvesting can promote soil compaction that inhibits rainwater infiltration into the soil and saturated hydraulic conductivity [74]. As a result, the subsequent water availability to plants is reduced, further increasing risks of surface erosion and surface runoff drained through wheel ruts and gouges. Liao et al. found that monoculture plantations increased soil BD by 12.5% [75]. Changes in soil structure and physical properties affect soil nutrient availability due to limited soil water content determining nutrient solubility. It also influences soil microbial community structure. These coinciding changes occurred with soil depths that strongly affect the vertical distribution of aerobic microorganisms [76].

3.3. Impact on Soil Nutrient Balance

In contrast to the natural forest ecosystem, its replacement by monoculture plantation can cause a nutrient imbalance in the soil. Each plant has different needs in terms of what is considered as an appropriate nutrient composition [30]. However, the composition of nutrients required by every type of plant cannot be completely provided by the soil. Hence, in monoculture cultivation, the planted trees may exhaust the most needed nutrients. Intensive monoculture activities over a long period will then result in the depletion of specific nutrients, because plants with the same growth rate in even-aged forests require large amounts of the same nutrients [77], while the sudden release of nutrients in residual biomass at a harvest cycle may exceed concurrent demand and lead to losses. All trees in monocultures release the same root exudates to invite microbes to assist growth and improve fitness. This continuous process negatively impacts soil function and yield sustainability [78].

One of the determining factors for soil nutrient availability in plantation forests is the age of the stand, because the trees consume the nutrients for their growth. The published data collected for analysis of the correlation between nutrient content (N, P, K, Ca, Mg) and stand age are presented from *A. mangium*, *E. pellita* and *E. urograndis* [32,79–92] (presented in Appendix A Table A1). The correlation analysis showed that the soil nutrient content of Ca has a negative correlation with stand age (r = 0.68; p = 0.01); meanwhile, other soil nutrients did not correlate significantly with stand age.

3.4. Impact on Soil-Borne Symbionts and Disease

The root exudates released into the rhizosphere by monoculture exotic species have an unfamiliar composition for the native soil microbes and, as such, affect the structure and function of the rhizosphere community [93–95]. The uniform tree composition and high tree density in monocultures, however, provide food sources and habitats for insects and pathogens, which consequently increase in population size and spread the infection rapidly [31]. Thus, a monoculture is more susceptible to pests and diseases [96].

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Among the rhizodeposits, phenolic acid compounds are essential substances in the allelopathy mechanism [97]; they may change the microbial community in the rhizosphere, increase the growth of soil-borne pathogens and even prevent the growth of beneficial microbes [98]. Critical studies in plantation forestry, however, are scarce. In annual crops, land continuously planted with rye under a monoculture system had a phenolic acid content that was 400% higher than that of a diversified cropping system, associated with a decrease in the Actinomycetes population [99]. One of the important roles of Actinomycetes is to inhibit the growth of several plant pathogens in the rhizosphere [100]. The phenomenon of the emergence of various diseases due to replicated monoculture plantations is known as "replanting diseases" [101,102].

4. Reduced Annual Litterfall

Temporal litterfall patterns in the tropics are more varied than those in temperate zones, where an autumn peak in litter production is common. Litter production is influenced by climate [103], including temperature [104], precipitation [105], solar radiation [106], as well as topography, soil properties, altitude and geographic location; water availability during the growing season can also induce litterfall [103,107]. The conversion from tropical natural forest to monoculture plantation reduced annual litterfall production and caused a more pronounced seasonal pattern [103,108,109]. Yet, where the rate of litter decomposition is reduced by a low litter quality (high ratio of lignin plus polyphenolics over nitrogen) a continuous litter layer protecting the soil can nevertheless be achieved [110].

The litter production potential in a stand is positively correlated with soil organic matter content and soil fertility levels [111,112], although specific mechanisms that transfer organic matters from litter layers to the soil may require further study [110]. On the forest floor, litter buffers the nutrient supply, as immobilization and mineralization phases alternate [113]. The amount of litter productivity of monoculture plantation is much lower compared to that in natural rainforests. Studies in tropical rainforests found rates of litter production of 11.8–12.2 tons ha⁻¹ (Indonesia); 10.3 tons ha⁻¹ (Venezuela), and 8.2 tons ha⁻¹ (Brazil) [114]. Enriching the monoculture stand of the Chinese fir *Cunninghamia lanceolata* with *Michelia macclurei* increased litter production by 23%–79% [115]. The amount of litter produces less litter than either *Eucalyptus* sp. or mixed stands of *Eucalyptus* and *A. mangium* at a 50:50 proportion [115]. In *A. mangium* monoculture forest plantations in Indonesia, the dry season supports higher litter production than the rainy season, with peak litter production in August and September, reaching >0.5 tons ha⁻¹ in a month [116]. Litter production increases and reaches a maximum in the dry season [113].

Plant litter has a dual role in biogeochemical cycles, influencing hydrological processes before, and nutrient supply of forest ecosystems after, decomposition [110,117]. Standing litter stock can be estimated from annual litterfall and "mean residence time", related to the decomposition constant [118].

The litter layer which consists of dead leaves, twigs, and other fragmented organic materials, can be, after the vegetation canopy, the second most significant rainwater redistributor [119]. The litter accumulation between vegetation and soil layer creates a spongy barrier that controls water balance by intercepting and storing rainwater [120], increases water infiltration and restricts soil evaporation and respiration [121], and protects from soil erosion by absorbing the erosive power of the rain and retarding surface runoff [122]. In addition, litter production and decomposition directly or indirectly improve soil structural stability and biological activity in the long term [123], thus enhancing the resistance to rainfall–runoff–erosion processes.

Plant litter also has a key role in reducing soil and water loss. A study on the conversion of tropical forest (TR) to a rubber monoculture (RM) found that the forest conversion reduced average litter thickness from 6.42 cm (TR) to 4.43 cm (RM); it also reduced the maximum water storage capacity of the litter layer from 1.44 mm (TR) to 1.03 mm (RM) [124]. Consequently, the minimum–maximum interception storage capacity of RM was reduced

to a level 77%–80% lower than that of TR. The study concluded that the conversion of TR into RM considerably weakened the hydrological functions of forest litter, such as water storage capacity and rainfall interception, and possibly subsequent erosion control [124]. It is due to the fact that TR litter from miXed species consisted of a larger leaf surface area and higher water affinity, which resulted in a litter interception rate 1.38 times greater (12.3%) than RM litter (8.96%). The accumulation of soil organic matter protects the soil surface more effectively than that of interception by the canopy. A study of *Shorea robusta* plantations showed that raindrop erosion was 9 times higher when litter had been burnt or gathered. Similarly, soil erosion under teak was found to be 2.5–9 times higher than under natural forest [71].

The reduction in litterfall in a plantation compared to a natural forest directly influences the soil nutrient balance. Litter accumulation on the ground (i.e., stand litter) is a key component of forest ecosystems that serves as a temporary sink for nutrients [125].

Some studies reported that natural tropical forests have stronger nutrient cycling than monoculture plantations [103,126]. Concentrations of macro elements in litterfall shifted with forest type. Compared to monoculture plantations, tropical natural forests have higher Ca, Mg and N/P ratios of litterfall. For each forest site, the element concentration ranged in the following order: C > Ca > N > K > Mg > P. In monoculture plantations, nutrient dynamics, C and C return were reduced significantly because of decreased litter production and low variation of aboveground litter [103,127].

5. Diversity in Litter Quality and Timing vs. Single-Source Litter (Aboveground)

Plant species diversity in natural forests produces various litter characteristics, such as broadleaf litter, which absorb more water easily and trigger other species litter decomposition. On the other hand, uniform tree species in monoculture plantation have similar attributes of simultaneously decomposed litter. Zhang et al. [128] found that mixed-species forests have higher litter input and faster decomposition rate than monocultures, due to the differences in litter quantity and quality.

The decomposition rate of leaf litter was slower in monocultures compared to mixedspecies plantations or natural stands [129,130]. Litter from a monoculture decomposed slower than that from a mixed forest [129]. Even-aged stands and a single-layer canopy cover on monoculture plantations did not provide the humidity in the litter layer that modulates decomposition. Interactions among plants and soil are also linked with variations in the quantity and quality of litter, root exudates, associated effects on the neighbours, and soil microbial communities [131]. Variation in tree species affects the levels of root exudates released into the soil and hence determines the weathering of parent materials, mineralization and recycling of soil nutrients [131].

Litter decomposition is influenced by several factors, such as the chemical composition of the litter (litter quality), climate, nutrient availability in the soil, composition of soil organisms, and site-specific factors [132,133]. The lignin content, the number of microbes in the soil, and the C/N ratio influence the rate of litter decomposition. Lignin is a decisive factor in this process when its content exceeds 28% [134]. Above this threshold, lignin inhibits decomposition as it is a complex compound that is difficult for soil microorganisms to degrade [135].

The decomposition rate is determined by species, age and habitat [136]. The main limiting factor in the litter decomposition process of *A. mangium* plantation is its low phosphorus content. This species can quickly translocate P compounds toward the tips; hence, *A. mangium* litter tends to have low P levels, particularly in P-poor growing habitats [137]. The proportion of lignin components in *A. mangium* litter also affects the decomposition rate [138]. The difficulty in breaking down lignin compounds in *A. mangium* litter is further compounded by the high availability of N in the litter and soil [139]. The N-rich litter of *A. mangium* plays a role in slowing the process of lignin degradation and carbohydrate lignification in the subsequent decomposition [140,141]. The low content of water-soluble compounds in *A. mangium* litter compared to other species such as *Eucalyptus* sp. is also

indicated as one of the factors affecting the low activity of decomposing microorganisms associated with the decomposition residues of *A. mangium* [142].

In an *A. mangium* plantation, soil decomposers are dominated by fungi, mostly Ascomycota (62%) and Basidiomycota (28%). Basidiomycota fungi are generally able to decompose more complex compounds found in litter, such as lignin and holocellulose, and are generally referred to as ligninolytic fungi [143]. Meanwhile, *Ascomycota* fungi generally decompose relatively simple compounds. The dominance of *Ascomycota* fungi as decomposers of *A. mangium* was expected to be the cause of the low decomposition rate of *A. mangium* litter. Meanwhile, *Eucalyptus* sp. plantation has a higher proportion of Basidiomycota (75%) fungi than *Ascomycota* (19%), that decomposes the litter [143]. It is reported that *A. mangium* stands support a lower microbial biomass than that of *Eucalyptus* sp. stands [115]. Measurements in an *A. crassicarpa* plantation on organic soils (also known as peatlands) showed slow litter decomposition due to a high lignin content (36%–39%), low P and N content (P < 0.25% and N < 2.5%), and unfavourable soil environment, microclimate conditions [144], and a poor soil microbe population [145]. In (agro)forests on the fringe of a peat dome, wet conditions slowed decomposition, but not enough to induce peat formation [146].

The slower rate of litter decomposition under a monoculture can also be caused by less effective glucosinolates (GSLs) that are susceptible to being decomposed when plant tissue is damaged, i.e., due to harvesting; GSLs will be hydrolysed by myrosinase enzymes to form isothiocyanates, nitriles, thiocyanates, and other biologically active compounds [147]. Many of these hydrolysis products kill a range of arthropods, microbes, and nematodes [148], and hence will disturb the decomposition process of SOM. Simultaneous harvesting affects the GSLs and then influences ecosystem engineer populations.

6. Diversity of Rhizosphere, Mycorrhiza and Other Symbiont Relations Interacting with Root Turnover vs. Single-Source Rhizosphere Processes

Plant species diversity affects the soil chemical properties and the structural and functional microbial community. In return, variations of soil properties affect the complexity of forest cover types. The structural and functional properties of soil microbial communities are strongly controlled by abiotic (climate zone, ecosystem type, physical and chemical properties of soil) and biotic factors (plant species identity and specificity) [131]. Diversity in the tree species composition of the natural forest also has an advantage in controlling sunlight penetration, which enhances the spatial heterogeneity of soil fertility [149]. The over-storey constructs under-storey species diversity that consists of woody and herbaceous plant species. The biomass characteristics (quality and quantity) of under-storey influence energy flow and nutrient cycling in forest ecosystems [149]; hence, it determines the nutrient availability in soils.

Each species has a specific root exudate concentration and composition with special purposes in helping plants to access nutrients, meet their needs, and protect themselves [131]. It was found that the chemical compounds, which are produced by roots belonging to the same or a different genetic lineage, have different effects on root branching [150]. The earlier studies found that the abundance, composition, and diversity of soil microbes, involved mycorrhiza, are strongly determined by plant species [151,152]. The specificity of root exudate production is known as plant species identity, while the effectiveness of symbiosis is determined by microbes, either from the native habitats or brought by plants, and depends on the purpose, prevalence, and strength of the symbiotic interactions [94]. Changes in plant composition from poly- to monoculture alter the chemical and biological properties of the rhizosphere, hence altering the rhizosphere community [153]. It controls the main biogeochemical cycles in the habitat [99]. The variation of plant species identity also affects the mineral weathering of parent materials, and the mineralization of Ca in soils [131]. Subsequently, litter attributes, Ca content, and soil pH affect C and N cycling, soil biomass, soil respiration and net N mineralization in the soil ecosystems [154,155].

Continuous monoculture cultivation determines the mycorrhizal status of plant species, which may affect the abundance of AMF propagules in soils [46,99,156]. Different plant species vary in the quantity and quality of their root exudates. This indicates that root exudates are under phylogenetic control and fit within an exploitative root nutrient uptake strategy, high rates of root exudation are linked to root characteristics, especially root diameter [157]. Exudation stimulates an ecosystem response to a changing environmental condition [157]. Conversion of natural forest into monoculture plantation changes the root exudation process in soil, and hence affects the root colonization with mycorrhizal fungi. Consequently, microbial relationships of native plant species of forest ecosystems may be vulnerable to disruption through the novel biochemistry of exotic mono plants [131].

Multiple effects of mycorrhizal fungi on vegetation and soil influence the soil structure directly and indirectly. In the direct process, the mycelial networks modify the soil structure in the mycorrhizosphere through the physical and chemical binding of soil particles by extraradical hyphae, thus leading to changes in soil aggregation, pore size distribution, and bulk density [158]. The hyphae networks play roles in the formation of stable soil aggregates, building up a macroporous soil structure that facilitates water and air penetration into the soil and prevents erosion [159]. In the indirect process, mycorrhizal-induced changes in SOM content and soil structure then affect the relationship of water to soil [160], the capacity of soil infiltration and soil-water retention, and the soil hydraulic conductivity [161]. It is well established that the arbuscular mycorrhiza fungi (AMF) and the ectomycorrhiza (ECM) greatly enhance the uptake of immobile soil nutrients such as P and water by plant root hosts in exchange for carbohydrates supplied by the host plant [162]. The different mode of nutrient transmission is also recognized for improving soil properties [163]. The water and nutrient transfer in AMF are accomplished intracellularly by the extra-radical mycelia that extend directly into the soil beyond plant rhizosphere-depletion zones through intracellular arbuscules [164]. Transformation in the ECM occurs both via intercellular Hartig net hyphal networks surrounding the epidermal, cortex cells and extra radical mycelia outside the mantle, which create broad nutrient-absorbing networks in the soils, as well as improved protection to soil-borne pathogens [163,165]. To increase nutrient availability, some mycorrhizal fungi produce extracellular enzymes catalysing the hydrolysis of N- and phosphorus (P)-containing compounds in the SOM [166,167]. These enzymes' activities are closely related to SOM and microbial biomass, and the decomposition rate of SOM also affects the soil physicochemical property transformation [64,168].

7. Diversity-Based Biological Control vs. Opportunities for Build-Up of Specialized Soil-Borne Diseases

Soil ecosystems in natural forests can suppress the development of pathogens [169], through several mechanisms, such as antibiosis, parasitism, predation, and competition [170]. Thus, microbial composition and diversity play important roles in determining the level of suppressive capacity [170–173].

The disease suppressive capacity in natural soil ecosystems is generally higher than that in monoculture plantations [173,174]. In Indonesia there are limited reports of plant disease outbreak incidence in the natural forest. However, in the monoculture industrial forest plantation, outbreaks of root rot and heart rot diseases by *Ganoderma* and *Ceratocystis* on *A. mangium* were reported in Sumatra and Kalimantan which caused significant yield losses [175–181] (Table 1). Consequently, acacia is no longer recommended for multi-cycle forest plantations in Indonesia [182].

The loss of disease suppressive capacity in monoculture plantations caused by allelopathic mechanisms [48,49,101,183]. Allelopathic compounds inhibit not only the growth of plants but also the proliferation of soil microbes [48]. Each plant produces certain allelochemical compounds with different control mechanisms [49]. Plants that are uniformly cultivated in monocultures release the same compounds, resulting in autotoxicity [48,101], where plants are poisoned by the same compounds produced by themselves [48,183]. An

Host	Disease	Pathogen	Reference
	Root rot, heart rot	Ganoderma philippii	[175-177]
Acacia mangium	Brown root rot	Phellinus spp.	[178]
	Wilt disease	Ceratosystis spp.	[179]
Eucolumtus pollita	Stem and branch cancer	Botryosphaeria spp.	[180]
Еисигургиз решии	Wilt disease	Ralstonia pseudosolanacearum	[181]

earlier study found that auto-toxicity conditions lead to plants being more vulnerable to disease [184].

Tab	le 1.	Some t	the disease	outbrea	ks in	Indonesia	in p	lantation	forest.
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Among the secondary metabolites produced by plants are glucosinolates (GSLs), with a special function in defence against herbivores [185], as well as fungicidal, bactericidal, and nematocidal properties [186]. Indole GSLs play a role in pathogen defence and provide resistance to phloem-feeding insects and microbes [187]. This increases the evidence of disease in the following rotation of the plantation. The content of GSLs in plants depends on the plant genetic background [188]. The kinds and concentrations are closely related to the taxonomic groups of the host plants [186]; hence, more diverse plants will produce a greater variety of GSLs, which may improve the resistance of the forest stands [189].

8. Nutrient Removal in Harvest Cycles

For several decades, foresters have been substantially changing the stand ecological conditions by cutting and removing trees, with consequences for biodiversity and ecosystem fluctuation (Figure 3). Cutting trees results in direct and independent changes to the soil microclimate [190] and litter quality and quantity, decreasing the soil organic carbon and nutrient availability [191]. After harvesting, in the open land, fluctuations in soil temperature, soil moisture, and the availability of organic matter occur, which affect the soil microbial community and enzyme activity.

When woody stems were harvested as logs, nutrients were also removed from plantation sites, because nutrients had accumulated in the tree biomass. A study in Tanzania reported that *Pinus patula* plantations led to annual removals of N (40 kg ha⁻¹), P (4 kg ha⁻¹), K (23 kg ha⁻¹), Ca (25 kg ha⁻¹), and Mg (6 kg ha⁻¹), due to log harvesting [71]. The harvesting practices cause nutrient loss due to biomass yielding. A study conducted on eucalypts in Australia showed that an amount of 3–4 kg ha⁻¹ P was removed per cycle based on typical forest harvesting systems. The depletion would not be solely from the more available pools because there is an equilibrium between the various soil phosphorus components [192]. It is predicted that at least four forest rotations (which is about 320 years) would be required before any change to be detectable within forest communities [193]. A similar depletion estimate was calculated for the potentially most vulnerable cation, e.g., Ca. The other nutrient cations, such as Mg and K, had considerably larger supplies. The monoculture plantation was less efficient in preserving nutrients because fewer roots exist near the surface, which may further lead to remarkable nutrient loss from the harvest sites. In addition, some tree genera, such as eucalypts and *Gmelina*, can acidify soils [31].

Nutrient removals in harvested timber are substantial when whole-tree harvesting is practiced. A study in an old upland black spruce stand showed that elements of N, P, K, Ca, and Mg in bolewood and bark amounted to 43, 12, 25, 98, and 8 kg ha⁻¹, respectively [194]. Another study of a jack pine stand in the same group reported that harvested woods exported 185, 14, 93, 132, and 20 kg ha⁻¹, of N, P, K, Ca, and Mg, respectively [195]. The difference between the tree species was directly related to differences in biomass, as nutrient concentrations did not vary significantly. Nitrogen deficiency in most forest types indicated that nitrogen removals by cutting should be the greatest concern in terms of nutrient balance [193].

Tree-felling diminishes the photosynthetic carbon (C) flow from trees into the soil, and influences the population of root-associated microbes [196]. The direct impact of tree-

cutting led to a low-resource environment and to a change in soil microbial physiology [190]. However, at harvest time, a flush of biomass waste and debris is released into the soil environment, where it brings about challenges to the microbial community. This peak–trough substrate availability pattern is a selection process for SOM degrading microbes [78].

Nutrient removal from timber harvesting in the monoculture plantation also affects soil-borne symbionts and diseases. After plants were harvested, litter, rhizo-deposits, microbes communities, and soil-borne pathogens remain in the soils; these will determine the growth of subsequent plants in the next rotation (plant–soil feedback); such effects are commonly called "legacy effect" [197]. The kind of soil-transferred legacy effects varies depending on numerous parameters, such as the previous plants, soil attributes, and climate conditions [198]. Legacy effects are strongly defined by the amount and type of transmitted-persistence residue in the soil when the previous crop is removed [199].

9. Some Limitations of Existing Literature

Despite the intentions to reduce bias in the way literature reviews can be carried out using established "systematic review" procedures, the selection of which phenomena are studied and reported in publications shifts over time [200] and implies a bias that cannot be avoided when efforts are made to include all published sources. With a limited number of studies that addressed the specific processes after conversion from natural to plantation forestry in Indonesia, we had to include studies with a broader geographic range and a wider set of tree-based land cover types to fill gaps. A major limitation of most studies is that they compare existing land cover types in a single landscape (e.g., remaining natural forest and plantations), but cannot safely assume that land use change is random relative to soil properties. For example, surveys of soil carbon stocks found higher values in rubber agroforests in Jambi (Sumatra) than in adjacent natural forests, but these results could be accounted for by higher clay contents close to the river where conversion to rubber agroforests dominated; application of a "pedotransfer" function that relates soil carbon to soil texture could change the interpretation from excess to a loss of carbon in comparison with what could be expected for a natural forest on the same soil [201,202]. Similar corrections are still not normally performed where land cover types are compared as such.

Conclusions about the actual conditions in plantation forests in Indonesia compared with what the original natural forests would have been in the same location are further limited by the likelihood that a forest degradation phase due to logging and possibly fire may have preceded the plantation development, with unknown effects on soil properties.

10. Conclusions

The review found evidence for alterations in soil C balance, soil structure and water balance, soil nutrient balance, and soil-borne diseases due to the conversion of natural forests to monoculture plantations. The identified alteration process varies among plant composition and harvesting practices, annual litter reduction, variety of litter quality, diversity of rhizosphere communites, variability of biological control, and nutrient removal at the harvest cycle. Evidence exists that the soil C balance, soil structure and water balance, soil nutrient balance, and soil-borne diseases are strongly determined by plant composition variation and harvesting practices, litter quality, diversity of rhizospher communites, and nutrient removal in the harvest cycle. However, conversion from natural to plantation forest led to the emergence of plant disease caused by the change in biological control mechanism. Consequently, land productivity is reduced in line with the repetitive plantation practice, without the use of rotational diversity as is common in annual crops. The problems are aggravated by species selection that favours short rotation species with low investments in long-term soil processes. **Author Contributions:** Each author (E.W., H.S.N., H.L.T., N.M., Y.L., D., L.A., M., D.O., D.P., H.H.R., S., N.E.L., W.D., M.W., T.K., Y. and M.v.N.) equally contributed as main contributors to the design and conceptualization of the manuscript, conducted the literature reviews, performed the analysis, prepared the initial draft, and revised and finalized the manuscript. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Table A1. Research works related to soil organic matter on SRPFs and their corresponding publication year.

Year of	Ν	Source				
Publication	A. mangium	E. pellita	E. urograndis	Age (Year)	Source	
1997	9			5-8	[79]	
1998	16			2, 5, 8, 11	[80]	
2000	10			9	[81]	
	1			n.a	[82]	
2004	4			1–4	[83]	
	8			5–8	[84]	
	5	5		4,6	[85]	
2005	6			2–6	[86]	
2006	8			1–3	[87]	
	15			1–5	[88]	
2008	7			17	[89]	
	3			5–8	[90]	
	10			8	[91]	
2011			15	1–5	[32]	
2019		15		2, 4, 6	[92]	

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