Danny Dwi Saputra

Soil recovery in cacao and coffee agroforestry systems:

litter, roots, carbon, and water

Propositions

1. Root-derived and aboveground litter are joint determinants of soil carbon storage, but their relative importance depends on context.
(this thesis)

2. Cacao germplasm (implicitly) selected for high root densities improves land use system performance under water-limited conditions.
(this thesis)

3. The 'accepting-what-grows' and 'planting-whatever-there-is' approach by traditional agroforestry smallholders leads to a higher tree diversity and greater resilience than the 'planning' approach of modern agroforestry farmers.

4. Relational and institutional values of nature are both essential for natural resource conservation, but they communicate to different audiences.

5. Excessive shade from a supervisor hinders growth, while insufficient shade risks unhealthy overexposure.

6. Overthinking limits progress of a Ph.D student working with 'process-based' modelling.

7. Proficiency tests to assess the competence of e-bike users, regardless of age, are needed to reduce traffic accidents.

8. Kids' 'why' questions enhance the productive morning work routine of a Ph.D-student couple.

Propositions belonging to the thesis, entitled:

Soil recovery in cacao and coffee agroforestry systems: litter, roots, carbon, and water

Danny Dwi Saputra

Wageningen, 30 October 2023

Soil recovery in cacao and coffee agroforestry systems: litter, roots, carbon, and water

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Thesis

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Abstract

Soil degradation, driven by natural and anthropogenic factors, threatens our ability to support the growing global population and their well-being. Land use systems (LUS) that serve as an interface between 'actors' and 'land cover' can be characterized by GxExM interplay, representing the Genotype (G) by Environment (E) interactions, subject to Management (M). GxExM is a major cause of soil degradation. However, GxExM interactions can also serve as the basis for soil restoration, such as through agroforestry practices that involve retaining, planting, and well-managing (M) the right trees (G) in the right places on farms (E). This thesis investigates the capacity of cacao and coffee-based agroforestry systems in Indonesia to support soil recovery from various disturbances while maintaining their multifunctionality and economic performance. To address this question, a comprehensive approach involving spatial patterns, dynamic processes, and modeling techniques was applied. The thesis started with a focus on the soil recovery of different LUS following deforestation in Southeast Sulawesi, Indonesia. The study compared various LUS, including remnant forest, cacao-based agroforestry systems (simple and complex), cacao monoculture, and annual food crops. The findings revealed that complex agroforestry systems with diverse tree species exhibited higher root density in the upper soil layer, which was positively correlated with soil organic carbon (SOC). The increases in root density and SOC were associated with improved macroporosity, although the impact on aggregate stability and soil infiltration was modest. Furthermore, the thesis explores the multifunctionality and economic performance of cacao-based agroforestry systems using the process-based WaNuLCAS model. Different agroforestry systems involving the companion trees and crops were evaluated against various scenarios, including cacao root densities, soil textures, and climate regimes. The simulation results indicated that cacao agroforestry systems outperformed monoculture in terms of carbon stocks but had limited effects on water-related functions. Additionally, high root density cacao systems demonstrated better resilience to water scarcity, emphasizing the importance of root structure. Integration of cacao with annual crops or fruit trees showed the highest economic performance, with fruit tree combinations being more labor-efficient. However, intercropping cacao with fast-growing trees in water-limited regions was detrimental to multifunctionality and economic performance. The next part of the thesis investigates the impact of volcanic ash deposition on topsoil properties and their recovery in different LUS around Mt. Kelud in East Java, Indonesia. The study compared soil properties before and after the volcanic eruption in remnant forest, coffee-based agroforestry (simple and complex), and annual food crops. Within three years, volcanic ash homogenized soil properties, affecting litter thickness, aggregate stability, and soil infiltration. Although these properties declined initially, they showed signs of recovery after six years. Soil infiltration, in particular, was significantly reduced due to hydrophobicity that may be induced by volcanic ash and surface litter interactions. Additionally, the inclusion of diverse tree species in complex agroforestry systems contributed to higher SOC, aggregate stability, and soil infiltration compared to annual food crops. Furthermore, the thesis explores the interaction between volcanic ash and various organic matter (OM) types in inducing water repellency (WR) and its impact on soil infiltration and hydraulic conductivity. Different OM types, when combined with volcanic ash, resulted in varying levels of WR. The strongest WR was observed with pine litter, followed by durian, mixed OM, and robusta coffee. The application of WR substances on the soil surface significantly reduced hydraulic conductivity, with indications of entrapped air bubbles sustaining the WR effect. Based on the previous findings, a conceptual framework for dynamic SOC models that can be used in modifying the WaNuLCAS model to simulate post-eruption disturbance and recovery under agroforestry practices was then proposed. The last part of the thesis synthesizes the results from the core chapters, highlighting the complementary role of surface litter and roots in facilitating SOC recovery and its associated functions following soil disturbances and degradation. Furthermore, the significance of selecting suitable tree species for the specific environments within the cacao and coffee-based agroforestry systems is emphasized to enhance their multifunctionality and economic performance.

Keywords: soil quality, soil degradation and restoration, agroforestry, multifunctionality, WaNuLCAS model, water repellency

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List of abbreviations

BCR	Benefit and cost ratio
CA	Contact angle
CAF	Complex agroforestry system
CM	Cacao monoculture
CR	Annual crops
CWC	Critical water content
D_{rv}	Dry weight of fine roots per volume of soil
GWR	Groundwater recharge
K_{obs}	Observed long-term hydraulic conductivity
K_{ref}	Reference saturated hydraulic conductivity for given texture and bulk density
K_{sat}	Saturated hydraulic conductivity
LER_{M}	Land equivalent ratio for multifunctionality
LER_{Mcs}	Land equivalent ratio under carbon centric
LER_{Meq}	Land equivalent ratio under equivalent weight
LER_{Mwql}	Land equivalent ratio under water quantity centric
LER_{Mwqt}	Land equivalent ratio under water quality centric
LER_{P}	Land equivalent ratio for productivity
LER_{R}	Land equivalent ratio for regulation services
L_{rv}	Length of fine roots per volume of soil
LUS	Land-use system
MWD	Mean weight diameter
NPV	Net present value
OM	Organic matter
RF	Remnant forests
RtL	Return to labour
SAF	Simple agroforestry system
SOC	Soil organic carbon
SOM	Soil organic matter
SWR	Soil water repellency
VA	Volcanic ash
WDPT	Water drop penetration time
WR	Water repellency
WUE	Water use efficiency
YAE	Year after eruption

CHAPTER 1

Forests, agroforestry, annual crop systems
Asinua Jaya village, Southeast Sulawesi

General Introduction

1.1 Soil degradation and restoration in agricultural lands

A staggering one-third of the Earth's land surface is affected by various forms of soil degradation, necessitating urgent restoration efforts. To support the increasing human population and its wellbeing, the recovery and restoration of degraded agricultural lands are urgent. Restoration efforts contribute to Sustainable Development Goals (SDGs) 2, 6, 13, 15, and 16 dealing with food and water security, climate change mitigadaptation (mitigation + adaptation), life on land, and peace and justice, respectively. In fact, soil restoration interventions have implications across all 17 SDGs (Katila et al. 2019; van Noordwijk et al. 2020).

Depending on the severity of degradation, four intensities of land restoration are: R.I. Ecological intensification within a land use system (LUS), R.II. Recovery/regeneration, within a local social-ecological system, R.III. Reparation/recuperation, requiring a national policy context for co-investment by other parties, and R.IV. Remediation, often requiring (inter)national support and investment (van Noordwijk et al. 2020). In this thesis, I focus on the first two: avoided degradation and recovery/regeneration within a farmer-managed LUS.

LUS, as an interface between 'actors' and 'land cover', can be characterized as GxExM, Genotype (or Germplasm) by Environment interactions, subject to Management (Cooper and Messina 2021; Hajjarpoor et al. 2022). Specific forms of GxExM are the cause of soil degradation, others (e.g., the right trees at the right place and well-managed) form the basis of restoration. It may seem to be attractive to focus the discussion on M, or an E-differentiated account of M, but the specific above- and belowground properties (G) of the plants (crops, trees) used matter. As most of the plants (and the specific varieties) used are selected for harvestable yield, rather than for maintaining or enhancing soil quality, all three parts of the GxExM interaction deserve attention.

Soil degradation processes can become visible at the soil surface by accelerated erosion, but usually start with depleted soil organic carbon (SOC), loss of belowground biodiversity, elemental imbalances, acidification, salinization, and soil compaction (Lal 2015), followed by soil function reduction (**Figure 1.1**). All of these have emerged as critical global issues, particularly prevalent in tropical and subtropical regions (Borrelli et al. 2020). In the tropics, over half a billion hectares of land are impacted by soil degradation. In Indonesia, an estimated 24.3 million hectares of land, where the soil is one of its critical components, have been identified as degraded (UNCCD 2015). This is attributed first to improper land use and soil management. Other sources report an even larger area of approximately 48.3 million hectares as degraded, equivalent to 25% of Indonesia's total land area (Sitorus and Pravitasari 2017), which is predominantly located in sloping areas. Land degradation (loss of desirable vegetation) and soil degradation (loss of functional properties) tend to be poorly separated in such statistics. The bottom-line, however, is clear: avoiding degradation and enhancing soil recovery is a relevant part of sustainability discussions.

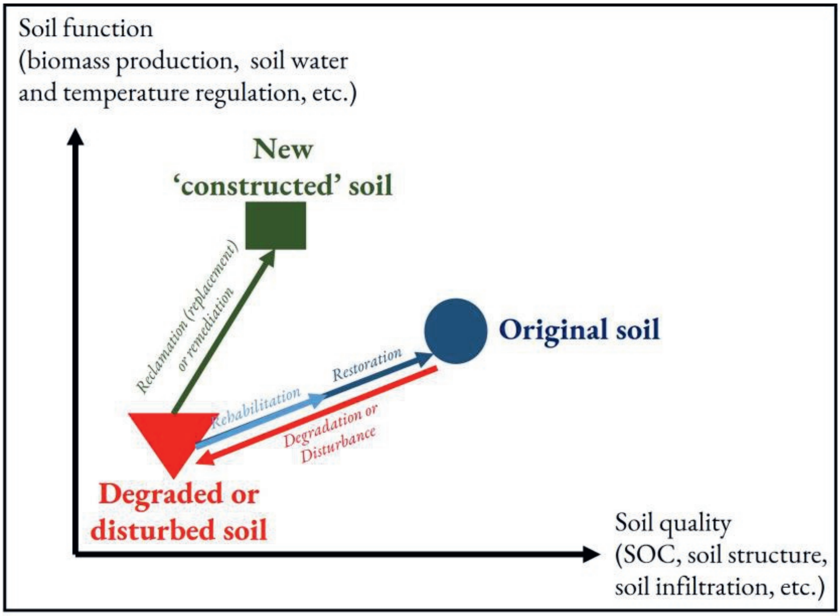

Figure 1.1. Approaches to recover soil quality and functions following soil degradation and soil disturbance (modified from Séré et al. (2008))

The attention given to the restoration of degraded soils in Indonesia differs between lowland and upland systems. Lowland systems, which primarily involve the production of staple crops like rice, receive more focus, with a focus on nutrient supply to the crops, while upland systems are, unfortunately, often neglected, with their additional need to maintain infiltration of rainfall and surface movement of soil particles in an erosion/sedimentation cycle. The paddy rice lowland systems are typically situated in relatively fertile soils, benefiting from terracing and well-maintained irrigation schemes that minimize erosion and associated problems. As a result, soil degradation issues in lowland paddy rice systems are primarily chemical (salinization, nutrient imbalances). In contrast, upland agriculture predominantly relies on rainfed systems located in forest-derived, sloping areas. When used for relatively open and intensive monoculture crop systems, these regions are highly susceptible to soil erosion and other forms of degradation due to their exposure to intense tropical rainfall events, harsh microclimate, inadequate soil protection from the tree canopy and surface litter, and minimum above- and belowground organic matter (OM) input.

1.2 Avoiding soil degradation of tropical-mountainous agriculture landscape

In tropical-mountainous agricultural landscapes, characterized by highly seasonal rainfall and rough terrain, stakeholders have a long-standing debate on the appropriate land use management that effectively supports both productivity and environmental services, particularly those related to water. While "intensive" monocultures have indeed succeeded in boosting agricultural productivity, they often do so at the expense of soil quality and lead to environmental degradation, posing significant sustainability challenges. They also result in the loss of tree and litter cover and deforestation, which is unfavourable for landscape functions. On the other hand, tree-based agricultural systems of agroforestry have emerged as a promising alternative to improve soil quality and its associated functions (Muchane et al. 2020; Schroth et al. 2001; Tscharntke et al. 2011; van Noordwijk 2021), but with the potential drawback of lower staple-food productivity in the short-term (Franzen and Borgerhoff Mulder 2007). Similar issues arise when natural forests of high diversity are replaced by monocultural tree plantations (Widyati et al. 2022).

Despite the economic opportunities offered by intensive crop monocultures, some farmers choose agroforestry systems due to their inherent benefits. As they mature, these systems become self-sustaining and less labour- and input-demanding (Ollinaho and Kröger 2021), a crucial consideration for smallholder farmers limited by production input availability and associated costs. Additionally, agroforestry systems offer income stability and lower financial risk due to their diverse and stable outputs (Ramírez et al. 2001), rendering them more resilient to changing environmental conditions. However, managing agroforestry systems is also challenging, as inappropriately managed agroforestry systems can lead to failure. In contrast, other farmers prefer more intensively managed monocultural systems due to their potential benefits of higher and more rapid economic returns. However, as the soil under monocultures tends to degrade over time, additional inputs often become necessary to sustain the earlier yield levels. The additional expenses burden smallholder farmers financially and in terms of labour, while they aggravate negative environmental impacts and eventually affect their overall livelihood.

The decision on which system to adopt, and then how to manage it, involves a trade-off analysis between economic costs and benefits, and the environmental services involved. Unfortunately, these GxExM interactions are often complex, context-dependent, and occasionally inconsistent (Abdulai et al. 2018a; Mortimer et al. 2018; Schroth et al. 2016). A comprehensive understanding of the effects of trees on agricultural landscapes is essential. The interactions between aboveground crop growth and belowground properties of roots, litter, soil organic carbon, soil structure, and their function in regulating water can be understood as a structure-function-services chain (La Notte et al. 2017). Comparisons between monocultures and mixed systems, as the fundamental differentiators between these systems, need to be carried out and tested under various challenging conditions for performance consistency. This knowledge serves as a focal point for determining the most effective strategies to develop a multifunctional and sustainable LUS.

1.3 Alternate soil degradation and recovery phases through agroforestry

1.3.1 Anthropogenic soil degradation and natural disturbances

Soil, as a complex and dynamic ecosystem, exhibits considerable variability in its composition and properties, giving rise to the concepts of soil quality, and its (inherent and dynamic) functions, and soil degradation. Soil degradation implies a loss of soil quality and its functionality (Lal 2015). Soil quality is described as the capacity of a particular type of soil to function within the limits of natural or managed ecosystems to provide a suitable environment for plant and animal habitation, support its productivity, and improve or preserve the quality of water and air (Karlen et al. 1997). Understanding inherent and dynamic soil quality encompasses a range of measurable properties that contribute to its overall functionality (Bünemann et al. 2018; Gholamhosseinian et al. 2022). However, interpreting these functions and their relative desirability (as implied in 'quality') is inherently subjective, leading to varying perspectives on soil degradation. The improvements in soil quality from one perspective may inadvertently result in degradation from another, highlighting the importance of multiple perspectives for comprehensively evaluating soil functionality and potential degradation. For instance, a high rate of surface runoff is desirable in 'water harvesting' zones but not in production zones. Moreover, perspectives may also depend on time and location, for example: erosion is negative for on-site productivity, but the long-term accumulation of sediments on the move through erosion, has generated some of the world's most productive lowland soils.

The transition from swidden agriculture to more sedentary systems, coupled with challenging environmental conditions such as steep terrain, high annual rainfall, and warm temperatures, can contribute to a gradual process of anthropogenic soil degradation. This human-induced soil degradation is driven by changes in vegetation composition (tree diversity, density) and management practices (tree and soil), which lead to SOC depletion, thus affecting the soil's physical, chemical, and biological processes, and eventually disrupting the soil's functions. As a consequence of intensive cultivation, agricultural soils have lost up to 75 and 61% of their antecedent store of SOC in the upper 30 cm and 100 cm of soil depth, respectively (Sanderman et al. 2017). The level of degradation often surpasses the current system's capabilities for self-recovery (natural regeneration), making the system unsustainable. However, farmers still have a role to play in promoting system recovery through better LUS management, for example from the Farmer Managed Natural Regeneration (FMNR) program in Sub-Saharan Africa, which has succeeded in improving the soil quality and its functions through agroforestry practices (Chomba et al. 2020; Reij and Garrity 2016).

On the other hand, there comes a point where soil quality and its functionality collapse, marking a critical phase where effective intervention for soil recovery becomes challenging, such as in a condition where the soils have been significantly disturbed due to natural disasters (i.e., forest fire, tsunami, landslide, flood, and volcanic eruption). The concurrent human-induced soil degradation and external shock from the natural disaster could tremendously disrupt soil functions. For Indonesia's context, as a country with 100+ active volcanoes, a sudden and significant soil quality collapse could happen following the topsoil disturbance from the pyroclastic materials (including tephra and volcanic ash) deposition during the volcanic eruption. Newly fresh volcanic ash (VA) contained low SOC when first deposited (Fiantis et al. 2019; Utami et al. 2019), disturbed soil structure, and reduced soil infiltration (Anda et al. 2016; Major and Yamakoshi 2005; Pierson and Major 2014). Nevertheless, depending on its severity level (which is controlled by the adaptive capacity and vulnerability of the LUS), appropriate tree and soil management practices by farmers following the VA deposition could lead to faster system recovery (Craig et al. 2016; Ishaq et al. 2020b; Sword-Daniels et al. 2011; Wilson et al. 2011).

1.3.2 The role of trees in accelerating soil recovery

Swidden-fallow systems, as the origin of nearly all agriculture, commonly involve alternating phases of crop production, leading to soil degradation and recovery in fallow periods (Sanchez 2019). This cycle of net soil degradation and restoration can be prevented by integrating the restorative elements of forests, including the crucial role of trees, into productive agroforestry systems (van Noordwijk et al. 2019b).

The disappearance of natural vegetation's litter layer and protective canopy cover during land clearing for agriculture exposes tropical soils to harsher conditions, including increased sunlight, higher temperatures, lower relative humidity, and reduced soil moisture (Hoffmann 2003). These unfavourable conditions, combined with changes in litter quality and quantity, lead to the rapid disappearance of surface litter due to faster decomposition (Hairiah et al. 2006; Sari et al. 2022). Faster surface litter decomposition, coupled with lower OM input from roots, contributes to SOC depletion and gradual soil degradation.

However, by appropriately integrating trees and managing their canopy cover through agroforestry practices, a favourable microclimate condition and the subsequent benefit of having a positive balance between OM input and output can be achieved. These conditions support the growth of soil organisms such as earthworms, termites, and ants that, together with tree roots, have an essential role as a 'soil ecosystem engineer' actor in supporting soil structure development (Hairiah et al. 2006; Jouquet et al. 2006; Rodríguez et al. 2021).

Tree diversity under 'ecologically intensified' agroforestry systems also provides various rooting patterns and distribution ranges for better exploration of soil resources. Roots also supply organic carbon to the soil when it decays and have been reported to contribute SOC more than aboveground necromass (Hairiah et al. 2020; Kätterer et al. 2011; Rüegg et al. 2019). This ideal combination of above- and belowground properties could accelerate soil quality recovery and its associated functions (**Figure 1.2**) and promote a more sustainable and resilient agriculture system.

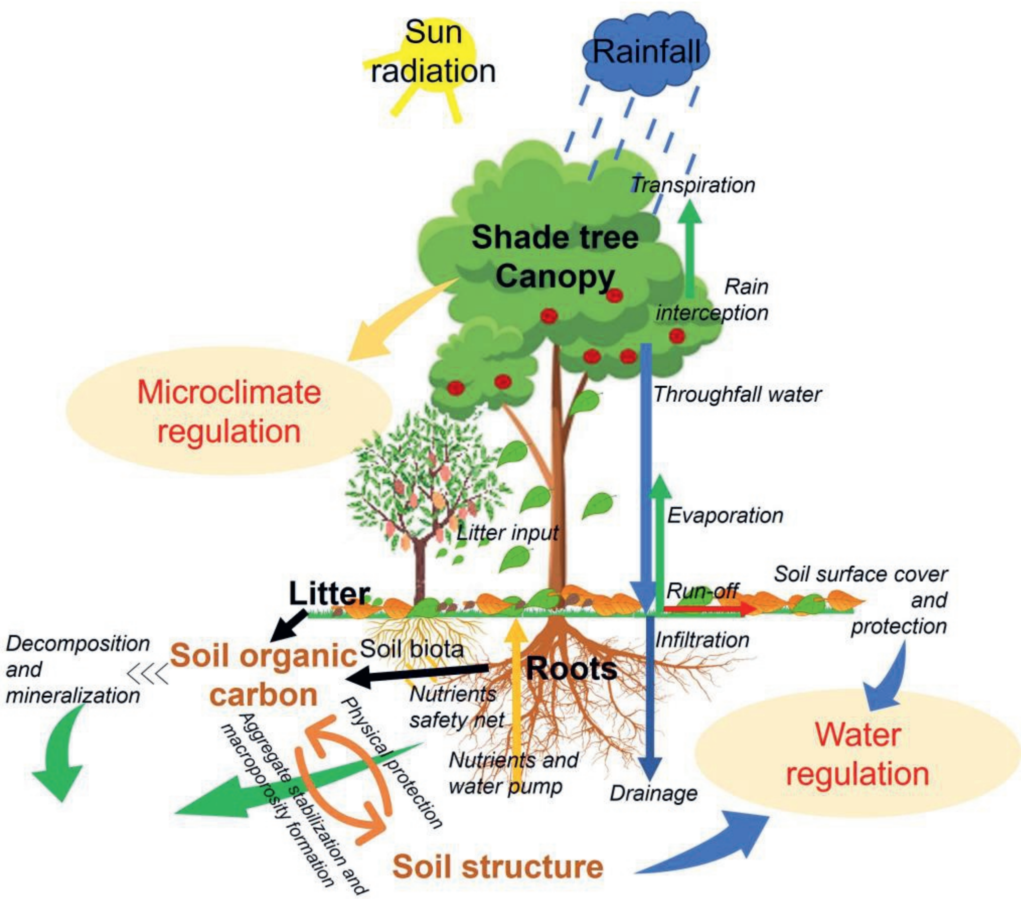

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Figure 1.2. The benefits of integrating trees in agroforestry systems to regulate microclimate, nutrients, and water at the plot scale level

1.4 Cacao and coffee-based agroforestry systems

1.4.1 The dynamics of cacao and coffee as tropical systems

Cacao and coffee, as tropical understorey rainforest species, commonly evolved from mixed multistrata systems resulting from reducing forest tree stands (forest thinning) to a more yield-oriented intensive monoculture (full sun), but now bounce back to a more shaded and diverse agroforestry (Obeng and Aguilar 2015; Tscharntke et al. 2011; Vaast and Somarriba 2014). The reoccurrence of mixed multistrata systems aligns with the ideal shade level requirement of these two commodities (approximately 30-70%) to support good quality and quantity products (Mokondoko et al. 2022; van Noordwijk et al. 2021). A botanically diverse and ecologically complex agroforestry also provides positive impacts on plot and landscape levels of biodiversity conservation, carbon sequestration, soil quality maintenance, and other ecosystem services

(Muchane et al. 2020; Sari et al. 2020; Schroth et al. 2001; Tscharntke et al. 2011; Vanhove et al. 2016). Additionally, from an economic perspective, the tree diversity and their related products also minimize the risk of total loss associated with the price volatility of the two commodities. Therefore, retaining diverse shade trees for smallholder farmers is fundamental to managing the risk, not only in terms of environment-related risk but also an economic risk, as highlighted by Vaast and Somarriba (2014).

1.4.2 Cacao and coffee agroforestry in Indonesia

Although they differ in their introduction timelines, non-native coffee and cacao have become important agricultural commodities in Indonesia. Indonesia emerged as one of the significant countries in maintaining global supply stability for these two commodities. According to FAOSTAT (2023), Indonesia has ranked as the third- and fourth-largest cacao and coffee producer globally in the last three decades. Over 3.7 million smallholder farmers (1.8 million for coffee and 1.6 million for cacao) contributed to over 98% of Indonesia's production of these two valuable commodities (Directorate General of Estates 2022).

In Indonesia, the expansions of coffee- and cacao-based LUS have often been closely associated with lowlands and uplands deforestation (Rajab et al. 2018; Verbist et al. 2005), with coffee grown in a broader range of elevations and climatic conditions than cacao (van Noordwijk et al. 2021). The plantation expansion cycle, as suggested on the common 'intensification hypothesis' framing, often begins with forest clearing or thinning, followed by intensive land use for agriculture until the land becomes degraded and economically not beneficial. The process is followed by abandoning the cultivated land and opening new plantations by cutting down more trees in the forests. In the context of cacao, forest rent theory explains that farmers benefitted from the high soil fertility, low pest and disease attacks, minimum weed pressure, and shade provided by the forest, which are essential for young cacao plants, instead of maintaining their 'exhausted' agricultural land (Clarence-Smith and Ruf 1996; Clough et al. 2009b).

Additionally, the various forms of cacao- and coffee-based LUS and their association with deforestation were also linked to the 'moment of opportunity' available for the farmers. This perspective explains that individual farmers tend to increase their private land ownership (gaining more capital) and livelihood conditions during and after political and security instability (Franzen and Borgerhoff Mulder 2007) and/or due to the attractive price of cacao by claiming the forests. A new private agriculture land claim was often made by planting high economic value trees, such as cacao, coffee, durian, and rambutan, in the forest frontline (**Figure 1.3**). As a result, various forms of cacao- and coffee-based LUS (landscape diversity) emerged, closely intertwined with the country's political history (Lukas 2014; Verbist et al. 2005) and price fluctuation (van Noordwijk et al. 2021).

Figure 1.3. Coffee and cacao planted in the forest margin in East Java (left) and Southeast Sulawesi (right)

1.5 Cacao and coffee-based agroforestry as a multifunctional LUS

The multifunctionality services provided by cacao- and coffee-based LUS, encompassing the land-sharing and land-sparing debate, are important to achieve sustainable systems (Leakey 2014; Lehmann et al. 2020; Tscharntke et al. 2011; van Noordwijk 2021). Multifunctionality is a system's capacity to provide financial incentives through higher productivity and ecosystem functions simultaneously (Blaser et al. 2018; Veldkamp et al. 2023).

Selecting the most suitable genotype (G), creating a favourable environment (E), and implementing proper management practices (M) are crucial for achieving high yields and maintaining environmental services. However, not all these factors can be effectively addressed by smallholder farmers. In the case of coffee and cacao smallholder farmers in Indonesia, they often have limited access to high-genetic quality planting materials. In the case of cacao, smallholder farmers rely on locally available planting materials, which possesses low genetic diversity (Zhang and Motilal 2016). This situation resulted in limited selections and inbreeding over time, which could compromise the crops' potential productivity and resilience to pests and diseases, and climate change (van Noordwijk et al. 2021). Additionally, even if high-quality planting materials are available, they may be unable to reach their full potential due to local environmental incompatibilities. This biophysical mismatch coupled with limited access to high-quality planting materials leave an ample of room for management practices pathway to increase land productivity.

Recognizing the significance of management practices is essential for optimizing productivity and the environment. The central aim is to optimize the design of cacao and coffee agroforestry by selectively choosing shade trees, proper planting distances, and appropriate canopy cover management. Success in achieving this goal could enhance the prominence of coffee and cacao agroforestry systems within farmers' livelihood strategies. As part of its environmental services, it could also contribute to global initiatives on addressing climate change, biodiversity loss, and the degradation of natural resources.

The multifunctionality of agroforestry systems can be quantified through the expanded-Land Equivalent Ratio for Multifunctionality (LER_M) concept proposed by van Noordwijk et al. (2018). LER indicates the relative area under monocropping needed to achieve the same functionality as an area intercropped. Agroforestry functions are grouped under provisioning (or productivity of land) services (LER_P) and regulating services, such as water balance, soil carbon stocks, N leaching, etc. (LER_R). LER_M is quantified by combining these two components of LER_P and LER_R (Khasanah et al. 2020).

1.6 The interactions of roots, litter, soil organic carbon, and soil structure in supporting soil recovery and multifunctionality performance of agroforestry systems

The presence of shade trees in agricultural land, achieved through agroforestry practices, can increase SOC from aboveground and belowground OM sources. From aboveground, litter contributes to SOC when it decays. However, the turnover rate was controlled by the litter quality and quantity, and the surrounding microclimate (Sari et al. 2022). From belowground, tree diversity enhances root biomass and its distribution throughout the soil profile (Rajab et al. 2018). Roots, whether in biomass, root exudates, or rhizodeposits, contributed a significant amount of carbon (up to 75%) to the soil, playing a crucial role in carbon turnover (Austin et al. 2017; Quigley and Kravchenko 2022; Rasse et al. 2005). Roots also have a reciprocal relationship with the development of soil structure (macropores) in their vicinity (rhizosphere) and the entire soil profile (Bengough et al. 2006), as dead roots leave macropores in the soil (legacy root channel). However, the compressing action of growing roots could also reduce soil porosity, but with the overall influence of root penetration on aggregation determined by root architecture (Six et al. 2004).

In various ways, SOC contributes to soil structure from aggregate development and pore space perspectives (Rabot et al. 2018). SOC acts as a bonding agent, facilitating the aggregation of mineral particles into micro-aggregates. Moreover, in collaboration with plant roots and fungal hyphae, SOC turns into a binding agent, contributing to macro-aggregate formation (Hoffland et al. 2020). Higher SOC combined with favourable microclimate conditions under agroforestry systems could boost soil organisms' activities, such as earthworms, that create soil macropores when they move, as reported by Hairiah et al. (2006).

Soil structure development, in turn, could promote the 'carbon stabilization' process directly and indirectly. Soil aggregation directly protects SOC from further decomposition by physically separating it from microbial and enzymatic attacks (Quigley and Kravchenko 2022). While indirectly, soil structure could regulate the micro-environment (water availability and soil aeration) that can effectively control microbial activity (Six et al. 2004). However, under intensive agriculture management that involves frequent soil tillage, soil aggregate destruction triggers SOC destabilization by exposing previously protected C to microbial decomposition, causing SOC loss (Dijkstra et al. 2021).

Finally, the development of soil structure, characterized by the abundance of continuous soil macropores and stable soil aggregation, combined with soil surface protection from surface litter, facilitates faster water infiltration and reduces runoff and soil erosion (Hairiah et al. 2006; Suprayogo et al. 2020). This favourable water balance could support plant productivity while maintaining soil quality and its functions, contributing to sustainable and multifunctional agroforestry systems.

1.7 Knowledge gaps

Practicing forest-like LUS through agroforestry can serve as a strategy to enhance the resilience of agricultural systems against natural and human-induced soil degradation/disturbance. Numerous studies have highlighted the benefits of agroforestry practices compared to monoculture, emphasizing their positive impact on maintaining soil quality, providing environmental services, and improving economic performance. However, the overall impact of interactions between shade trees and coffee or cacao in agroforestry systems on its multifunctionality is site-specific and context-dependent in ways that are not yet clearly understood (Abdulai et al. 2018b; Blaser et al. 2018; Jezeer et al. 2019; Wartenberg et al. 2017).

Most ExM studies take the existing germplasm (G) as a given. Genetic selection for higher yield potential may have negative consequences for above- and belowground litter production. Moreover, lower investment in roots could lead to a higher vulnerability to drought and climate variability, and yet, there is little quantitative information available on such interactions.

Limited studies have attempted to investigate the role of (natural) trees in accelerating soil recovery following soil disturbance post volcanic eruptions (Ishaq et al. 2020a; Ishaq et al. 2020b). Furthermore, the mechanistic processes underlying the transition from disruption (degradation) to the recovery phase of soil quality and its functions related to the different aboveground and belowground management (as implied in different LUS) post volcanic eruption have received limited attention and without any specific efforts to better understand this event. For example, while the "cemented soil/ash layer" that forms after VA interacts with water has been frequently proposed to explain reduced soil infiltration (Anda et al. 2016; Pierson and Major 2014; Tarasenko et al. 2019), the development of soil water repellency of VA (Berenstecher et al. 2017) interacts with OM (Kawamoto et al. 2007; Neris et al. 2013; Poulenard et al. 2004) may hold the potential to provide further insights into this adversity. However, it remains largely unexplored.

Existing simulation models are challenged by the multitude of spatial and temporal interactions between components of, even simple, agroforestry systems (Luedeling et al. 2016; Tosto et al. 2023), when the interactions of light, water and nutrients are concerned. Yet, further biological interactions (e.g., pests and diseases) may strongly respond to farmer management decisions and influence productivity. Beyond that, soil disturbances (such as from VA deposition on the topsoil) pose a further challenge to realistic modeling of the consequences and management options.

Overall, there is a lack of comprehensive understanding of the alternate natural- and human-induced soil degradation/disturbance - recovery phases related to the interactions between litter, roots, SOC, soil structure, and water in agroforestry systems. Expanding knowledge in these areas is crucial for advancing sustainable cacao- and coffee-based LUS.

1.8 Research objectives, scope and approaches, and thesis outline

1.8.1 Research objectives

The introduction showed that with an appropriate combination of trees and crops, agroforestry plays an important role in accelerating soil recovery due to natural- and human-induced soil degradation/disturbance. However, there is a limited empirical understanding of the best management options for cacao- and coffee-based agroforestry practices toward such role. The general objective of this study was to explore to what extent cacao- and coffee-based agroforestry practices can accelerate soil recovery against natural- and human- induced soil disturbance and degradation. While, at the same time, still maintaining its multifunctionality and economic performance.

The current lack of evidence for the 'internal restoration' hypothesis in agroforestry under various contexts led to the following specific research questions (RQ) and hypotheses (H), which link to the five main research chapters of this thesis:

RQ 1. To what extent can cacao-based agroforestry systems recover soil aggregate stability, porosity, and infiltration by increasing litter, SOC, and fine root density to the local forest reference, compared with cacao monoculture and cropped fields?

H1. Soil structure and its functions, as a critical aspect of soil quality, can be maintained in near-forest conditions by the inclusion of suitable trees in a complex agroforestry system.

RQ2. To what extent can cacao-based agroforestry systems provide stronger multifunctionality and economic performance than monoculture systems under various scenarios?

H2. Agroforestry systems are expected to have stronger multifunctionality and economic performance than monoculture systems.

RQ3. After the soil disturbance due to VA deposition, to what extent can coffee-based agroforestry systems recover soil aggregate stability, porosity, and infiltration by increasing litter and SOC compared with local remnant forests and cropped fields?

H3. The recovery of soil structure and infiltration after soil disturbance can be accelerated by increasing litter and SOC through the inclusion of suitable trees in complex agroforestry systems.

RQ4. Do the types of OM mixed with VA influence water repellency, and how does this surface-level water repellency relate to column-level soil infiltration and hydraulic conductivity?

H4. Soil water repellency inhibits water infiltration and hydraulic conductivity, and its establishment is correlated to the type of OM.

As a follow-on to RQ4, we proposed a conceptual framework to modify the existing tree-soil-crop interaction model of WaNuLCAS so that it could be adapted for the specific challenges of post eruption disturbance and recovery.

1.8.2 Scope and approaches

This thesis focuses on the roles of agroforestry in recovering soil structure and surface hydrological functions after soil degradation caused by different LUS (RQ1) and soil disturbances post VA deposition (RQ3). It also explores the options of system diversification through agroforestry practices to strengthen multifunctionality and economic performance using the process-based model approach (RQ2). In RQ4, a laboratory experiment was designed to better understand the soil surface hydraulic functions disruption post VA deposition concerning soil water repellency development. A range of methods and approaches to address the research questions and test the hypotheses are presented in **Table 1.1.**

The study was conducted in Indonesia: Konawe District, Southeast Sulawesi (RQ1 and 2), and Ngantang Regency, East Java (RQ3 and 4). Measurements were performed in various LUS, including remnant forests (RF), cacao-coffee-based complex agroforestry (CAF), cacao-coffee-based simple agroforestry (SAF), monoculture tree (CM), and annual monoculture crops (CR). As an operational definition for cacao/coffee-simple agroforestry, a relative basal area <80% with five or less other tree species per plot was used, whereas an agroforestry system with a relative cacao/coffee basal area <80% with more than five tree species in a standard 200 m^2 sampling plot is categorized as cacao/coffee-complex agroforestry; otherwise, a system with relative cacao/coffee basal area >80% is defined as a monoculture system. Relative cacao/coffee basal area was calculated based on the total tree basal area and the proportion of this area occupied by cacao/coffee trees (Hairiah et al. 2006; Sari et al. 2020). To measure multiple variables, 20 m x 20 m plots were established, with an age range of 9 to 14 years for cacao and >10 years for coffee. Each LUS was replicated three (3) times.

To answer RQ1, surveys and field measurements were carried out in the Konawe District, Southeast Sulawesi, Indonesia. Based on land use analysis, three villages (Asinua Jaya, Wonuahoa, and Lawonua) were selected to represent the upper-middle, lower-middle, and lower parts of the catchment, respectively, with the parts upstream of Asinua still largely forested. Villages were selected for their opportunity to compare the desired range of land uses and otherwise sample the existing geographical and ecological variation in the catchment.

Table 1.1. The focus of analysis and approaches to address the four questions.

RQs	Focus of analysis	Approaches			
		Survey, field measurement, and other data collection	Lab experiment	Process-based modelling	Life cycle scenario analysis
1	Litter thickness, SOC, root density, soil structure, and infiltration of LUS	■			
2	Multifunctionality and economic performance of cacao-based LUS	■		■	■
3	Litter thickness, SOC, soil structure, and infiltration of various LUS before and after VA depositions	■			
4A	The interactions of VA and various litter type and its effects on column-level soil infiltration and hydraulic conductivity		■		
4B	Conceptual framework to modify the soil C dynamic part of the WaNuLCAS model to facilitate the specific challenges post volcanic eruption disturbance and recovery			■	

Data collected in Chapter 2, and data from various sources were used for the process-based Water Nutrient and Light Capture in Agroforestry System (WaNuLCAS) model (van Noordwijk et al., 1999; van Noordwijk et al., 2011) calibration and validation to answer the RQ2. We developed four different cacao-based agroforestry systems, including cacao + annual crops, cacao + fruit tree, cacao + fast-growing tree, and cacao + slow-growing tree, based on the list of trees preferred by the local farmers as reported by (Sari et al. 2020), and cacao monoculture to be compared. LER_M was used as metric to assess the performance of each system in terms of their provisioning and regulating services. Three economic performance indicators of NPV, BCR, and RtL were also used to assess the economic performance. The consistency of agroforestry performances under two different soil types (sandy and loamy soils), two different cacao root densities (high and low root density), and three climate regimes (tropical rainforest, tropical monsoon, and tropical savannah) were further tested.

To answer RQ3, field measurements of various soil properties were done in four different LUS, including remnant forest (RF), coffee-based complex agroforestry (CAF), coffee-based simple agroforestry (SAF), and annual crops (CR) in the Kali Konto Watershed, Ngantang Regency, East Java, Indonesia. These plots were 13-15 km north of the highly active volcano of Mt. Kelud. To analyse the soil recovery of each LUS, three series of field measurements at the same location (plots) were conducted in 2007/08 (before the 2014 Mt. Kelud eruption), 2016/17 (3 years after the eruption), and 2019/20 (6 years after the eruption).

The result from Chapter 4 (RQ3) indicates that soil water repellency was developed on the soil surface post VA deposition, leading to a significantly lower infiltration rate. This phenomenon has received little attention, with no specific effort to provide quantitative evidence. To answer RQ4, lab experiments by mixing VA with different types of OM (low quality, high quality, mixed quality) and at different water contents were conducted to assess whether their interactions can induce water repellency. Further testing by applying these water-repellent materials on top of the control soil column was done to quantify the effect of the surface water repellency on soil infiltration and hydraulic conductivity. As the follow-on to RQ3 and RQ4, a conceptual framework to modify current SOC dynamics in the current WaNuLCAS model was constructed so that it could be adapted for the specific challenges of post VA disturbance and recovery.

1.8.3 Thesis outline

This thesis consists of six chapters and starts with this general introduction chapter. The subsequent four primary chapters (Chapters 2 – 6) address the four research questions in Section 1.8. The following Chapter 7 discusses the summary of key findings, research limitations, and concluding thought. A framework illustrating the relationship between chapters is presented in **Figure 1.4**.

Chapter 2 reports the field measurement of litter thickness, SOC, root density, and other soil physical properties to answer RQ1. The quantification and analyses provided the pseudo-chronological soil degradation and recovery spectrum of natural forest conversion to monoculture crops and cacao-based LUS in Southeast Sulawesi, Indonesia.

Chapter 3 explores the best management options for cacao-based LUS (RQ2). By using the process-based WaNuLCAS model, the multifunctionality and economic performances of four different cacao-based LUS under various scenarios were compared. This chapter underscores the importance of considering contextual factors when evaluating the multifunctionality and economic performance of agroforestry.

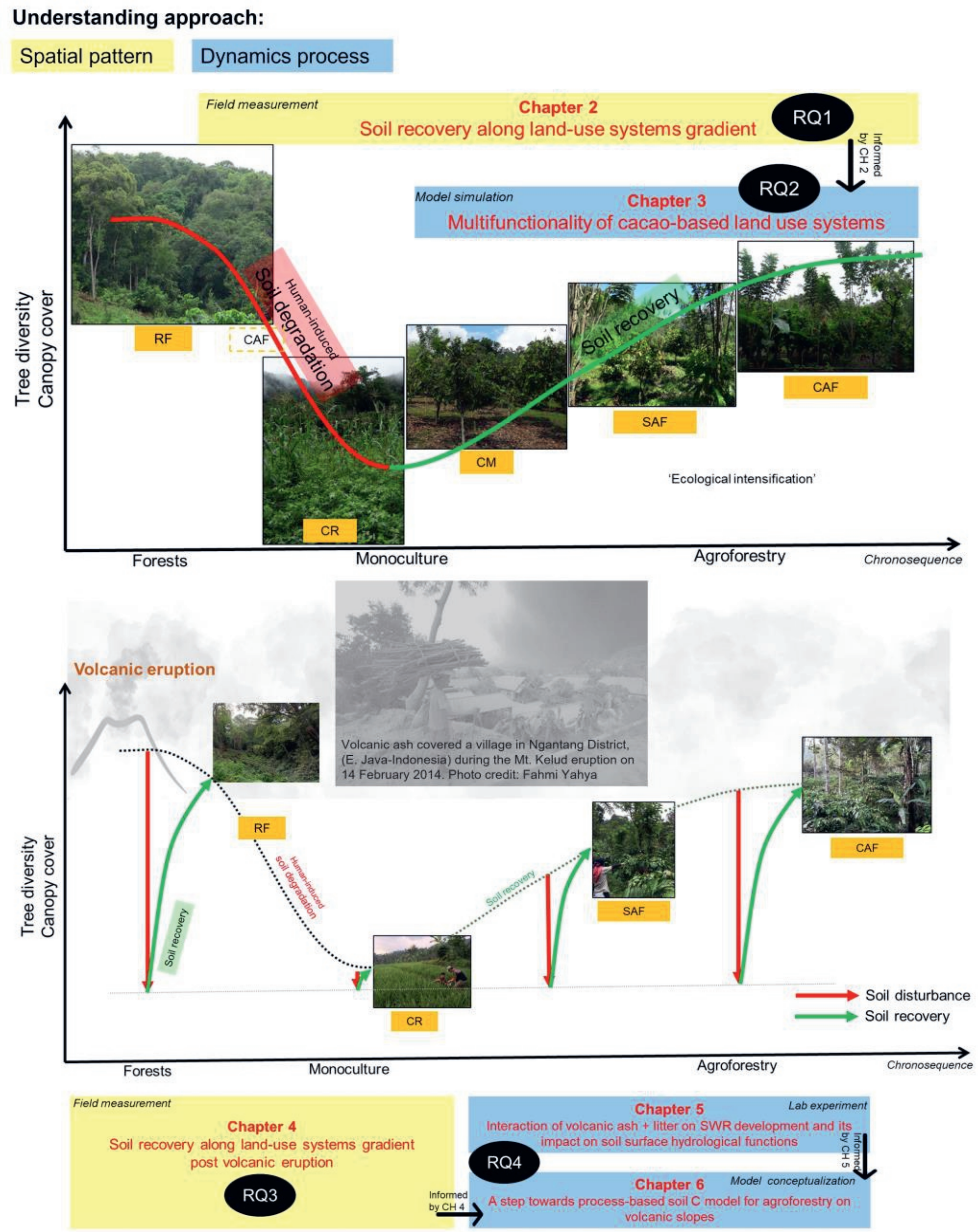


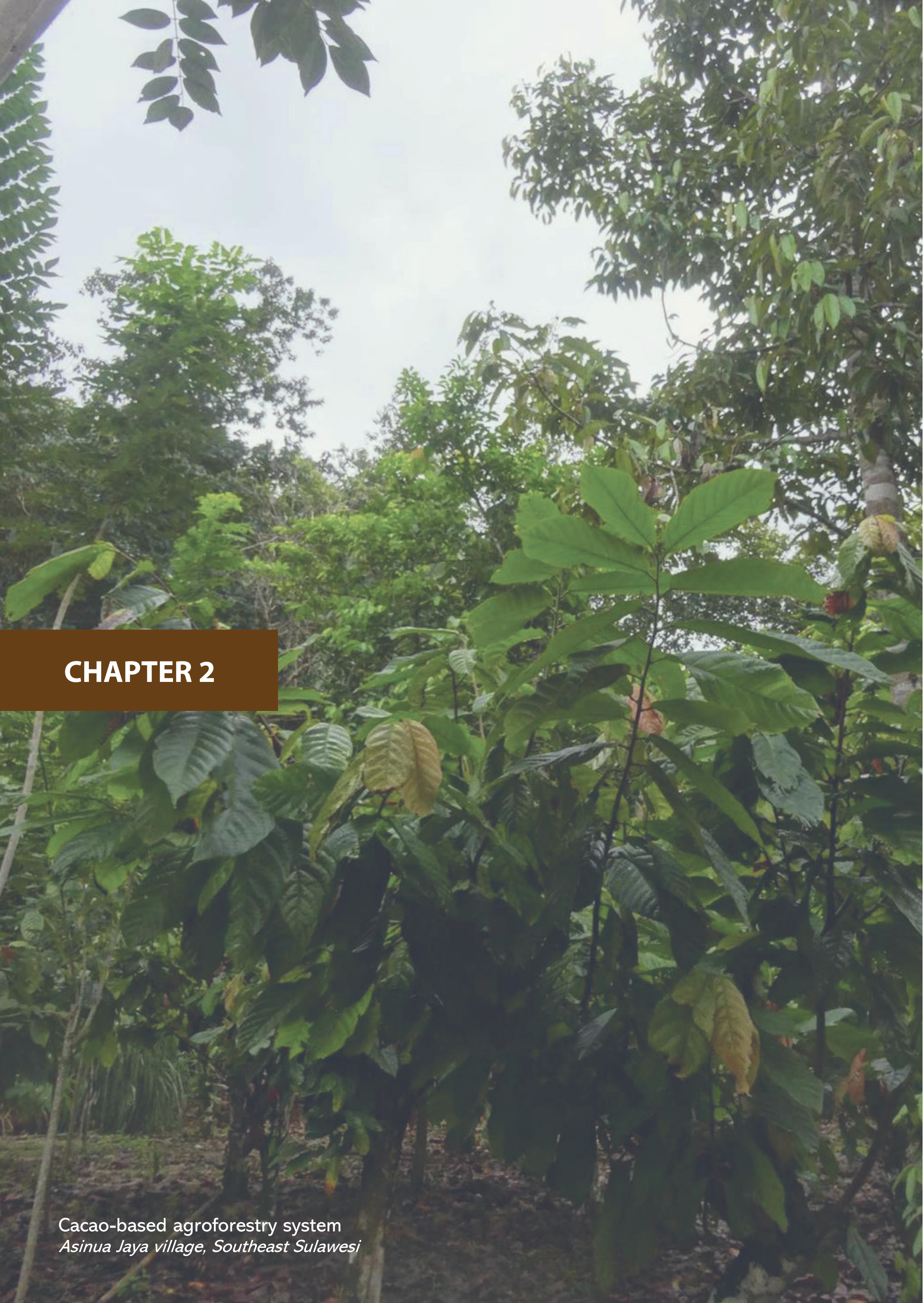
Figure 1.4. Framework illustrating the relationship between the five primary chapters of the thesis mapped above the 'forest transition theory' framing (modified from Dewi et al. (2017)), with a focus on understanding the spatial patterns and dynamic processes involved in the comparative analysis conducted in this research. RF: Remnant forests, CAF: Cacao-coffee-based complex agroforestry, SAF: Cacao-coffee-based simple agroforestry, CM: Cacao monoculture, CR: Annual crops

Chapter 4 discusses the changes in soil surface physical properties of different LUS before and after the soil disturbance from VA deposition (RQ3). This chapter presents the soil surface properties, including litter, SOC, soil structure (aggregate stability and porosity), and infiltration, in a chronological manner from before, three years, and six years after the 2014 Mt. Kelud eruption. The analyses provided the soil recovery rate of each LUS. This chapter also underlines the development of soil water repellency in a new VA-derived soil layer that dramatically reduces soil infiltration and hydraulic conductivity.

Chapter 5 reports the lab experiments on the effect of VA and various OM sources interacting on water repellency and quantifies the consequences for soil infiltration and hydraulic conductivity (RQ4). This chapter underscores those different types of OM influence the degree of water repellency, as indicated by the higher contact angle and longer water drop penetration time. The lipid content of plant litter gives a partial explanation of these effects. The data analysis revealed the negative impact of having a water-repellent layer on the soil surface hydrological functions.

Chapter 6 presents further work on constructing the conceptual model of the process-based soil C model that can be adapted to the volcanic landscape context. This conceptual model facilitates the effects of ash deposition on the soil structure and SOC dynamics on the soil surface post volcanic eruptions.

Finally, the thesis is closed with Chapter 7, which reviews the key findings, general discussion from the integration of chapters 2-6, research limitations and potential future works, and concluding thoughts.



CHAPTER 2

Cacao-based agroforestry system
Asinua Jaya village, Southeast Sulawesi

Can cacao agroforestry restore degraded soil structure following conversion from forest to agricultural use?

This chapter is based on published article:

Saputra DD, Sari RR, Hairiah K, Roshetko JM, Suprayogo D, van Noordwijk M (2020) Can cocoa agroforestry restore degraded soil structure following conversion from forest to agricultural use?

Agrofor Syst 94: 2261-2276
https://doi.org/10.1007/s10457-020-00548-9

Abstract

Alternating degradation and restoration phases of soil quality, as is common in crop-fallow systems, can be avoided if the restorative elements of trees and forests can be integrated into productive agroforestry systems. However, evidence for the hypothesis of 'internal restoration' in agroforestry is patchy and the effectiveness may depend on local context. We investigated to what extent cacao (*Theobroma cacao,* L.) agroforestry can recover soil structure and infiltration in comparison to monoculture systems across the Konaweha Watershed, Southeast Sulawesi.

We compared soil organic carbon, fine root length and weight, soil aggregate stability, macroporosity and infiltration from three soil layers at five land use systems: i.e., remnant forests, 9 to 14 years old of complex-cacao agroforestry, simple-cacao agroforestry, monoculture cacao and 1 to 4 years old annual food crops, all with three replications.

In general, roots were concentrated in the upper 40 cm of soil depth, contained of 70% and 86% of total fine root length and weight. Compared to simple agroforestry and cacao monoculture, complex agroforestry had greater root length and weight in the topsoil, even though it attained only half the values found in remnant forests. Higher root density was positively correlated to soil organic carbon. In upper soil layers, complex agroforestry had slightly higher soil aggregate stability compared to other agricultural systems. However, no significant difference was found in deeper layers. Complex agroforestry had higher soil macroporosity than other agricultural systems, but not sufficient to mimic forests. Remnant forests had two times faster steady-state soil infiltration than agricultural systems tested (13.2 cm h^{-1} and 6 cm h^{-1}, respectively), relevant during peak rainfall events. Compared to other agricultural systems, complex agroforestry improves soil structure of degraded soil resulting from forest conversion. However, a considerable gap remains with forest soil conditions.

Keywords: soil organic matter; root density; aggregate stability; macroporosity; infiltration

2.1 Introduction

Once the litter layer and protective canopy cover of natural vegetation is removed by clearing land for agriculture, tropical soils are exposed to sunshine and harsher micro climatic conditions such as higher temperatures, lower relative humidity and lower soil moisture due to greater insolation (Hoffmann 2003). These unfavourable conditions combined with changes in litter quality and quantity allow the rapid disappearance of any new surface litter. Litter with high quality (low C/N or lignin/N) has faster decomposition rates compared to low litter quality (high C/N or lignin/N) (Chae et al. 2019). Faster litter decomposition combined with a lower root density and turnover could reduce the organic matter (Hairiah et al. 2006), and lead to anthropogenic soil degradation (Lal 2015). The decline of soil organic matter (SOM) is often linked to several soil functions such as presence and activity of soil biota, soil structure, water and nutrient availability (**Figure 2.1**). SOM is also considered to be a key characteristic in judging soil quality (Martinez-Salgado et al. 2010) and land use system (LUS) sustainability (Lal 2015).

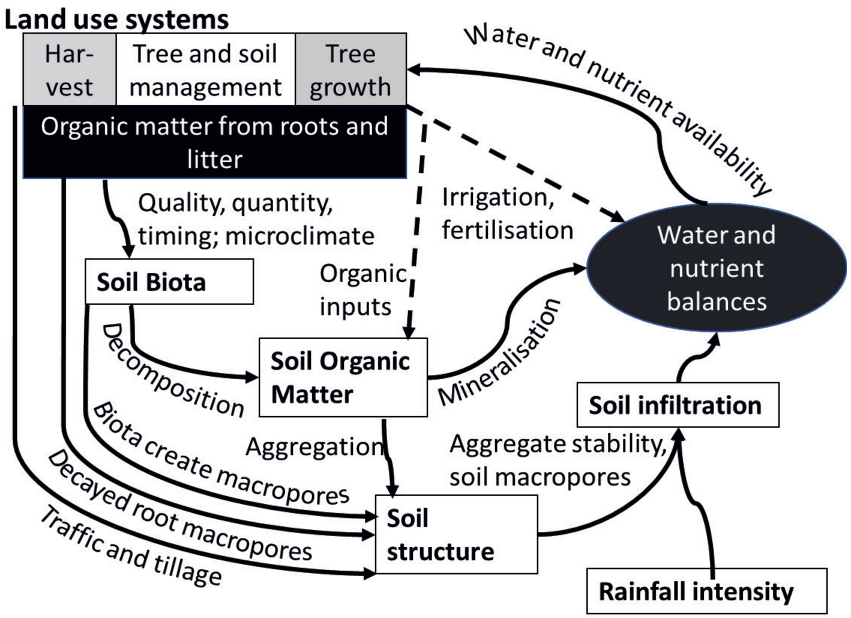


Figure 2.1. Conceptual diagram of soil degradation and restoration caused by different land use systems

In swidden-fallow systems, as the origin of nearly all agriculture, an alternation of crop production, resulting in soil degradation, and soil recovery in a fallow vegetation of lower direct use value is common (Sanchez 2019). However, such alternating net degradation and restoration phases of soil quality can be avoided if the restorative elements of forests can be integrated into productive agroforestry systems (Pinho et al. 2012; van Noordwijk et al. 2019b). Tree diversity can ensure an appropriate range of rooting patterns for better soil exploration, interactions with soil structure and biota, and litter input to provide such functions (Ordonez et al. 2014; van Noordwijk et al. 2015). Nevertheless, the hypothesis on 'internal restoration' in agroforestry has not been widely accepted yet, as the evidence is patchy and remains unclear (Barreto et al. 2010; Norgrove and Beck 2016; Schroth et al. 2001). Effectiveness may depend on local context and circumstances (Arévalo-Hernández et al. 2017; Zamora and Udawatta 2016).

Cacao (*Theobroma cacao* L.), as a neotropical understorey rainforest species, initially planted in the shade of remnant forest trees and subsequently planted with non-native trees such as nitrogen-fixing legume (Rajab et al. 2018) as well as timber and fruit trees in the form of agroforestry. Nevertheless, with progress in selection of 'full-sun' genotypes (Obeng and Aguilar 2015) due to the fear of yield losses caused by competition between crop and shade trees (Tscharntke et al. 2011), cacao is one of the tree crops that mixed agroforestry systems are being replaced by intensive monocultures as a land sparing technique (Vaast and Somarriba 2014). However, negative effects on soil conditions, risks of diseases and greater vulnerability to climate extremes may all point towards a return to partially shaded, mixed agroforestry systems as the more sustainable choice. Therefore, more evidence is needed to judge both the urgency (soil quality decline under monocultures) and opportunities (improvement of soil conditions by inclusion of other trees) in cacao production.

During its top production year of 2010, Indonesia was the worlds' second cacao producing country, behind the Ivory Coast. However, while production in other countries continued to increase, Indonesian production has since declined, with national data for 2010 and 2017 indicating 0.844 and 0.530 M tonnes per year, respectively (FAO 2017). The declines in cacao productivity, quality and consistency in Sulawesi, as the main cacao producer area in Indonesia, are due to several interacting factors (Neilson 2007), including the infestation by pest and diseases, low quality of planting materials, insufficient post-harvest handling and the decline of soil fertility.

The main objective of this study was to investigate whether agroforestry systems can restore degraded soil structure relative to monoculture systems. A comparative study at the plot level was carried out in Konaweha Watershed, where different cacao managements (agroforestry and monoculture), crop monoculture and remnant forests were presented under similar climatic and soil condition. We investigated the vertical distribution of fine root (<2mm), soil organic carbon (SOC), soil aggregate stability and soil macroporosity as well as soil infiltration on the five different LUS. We aimed to test the hypotheses that (1) vertical distribution of fine root increases with increasing tree diversity through agroforestry, (2) increasing fine root distribution results in higher SOC, as fine roots are one of the sources of SOM in the soil after decomposed. We further hypothesized that (3) the higher root distribution and SOC due to more complex LUS results in stronger soil aggregate stability and higher proportion of soil macropore. Finally, we expected that (4) soil infiltration is higher in complex LUS (remnant forests and agroforestry) compared to monoculture cacao and crop systems. This study complements the analysis by Wartenberg et al. (2017) on changes in soil microbial activity and soil fertility, and Sari et al. (2020) on tree diversity and carbon stocks in the same range of LUS.

2.2 Materials and Methods

2.2.1 Description of the study area

The study was conducted in the Konaweha Watershed, located in Konawe District, Southeast Sulawesi, Indonesia. The average annual precipitation is 1500-1900 mm, with the daily temperature 24-31°C (a detailed description of the study area is provided in Sari et al. (2020)). Based on the map provided by FAO-UNESCO (1979), soil in the mountainous area is dominated by weathered *orthic acrisols,* while in the valley and floodplain is dominated by *dystric fluvisols*. On the basis of land use change analysis, three villages including Asinua Jaya, Wonuahoa and Lawonua were selected to represent the whole watersheds. Villages were selected for their opportunity to compare the desired range of land uses and otherwise sample the existing geographical and ecological variation in the catchment.

All field activities such as identification and characterisation of plots, soil and root sampling, and soil infiltration measurement were conducted from March to May 2014. The measurements were made in five LUS with three replications (total of 15 plots). The five selected LUS are as follows: (1) remnant forests (RF) as a control, (2) complex agroforestry (CAF), multistrata cacao with fruit and timber trees as well as nitrogen fixing shade trees (*Gliricidia sepium*), (3) simple agroforestry (SAF), cacao with mainly *Gliricidia sepium* as a shading tree and/or fruit trees, (4) full sun "monoculture" cacao (CM) and (5) annual food crops (CR) of maize (*Zea mays*), groundnut (*Arachis hypogea*), and patchouli (*Pogostemon cablin*). Each cacao-based system was represented by three different farmer's plots, with plots of each cacao treatment located in each of three villages (**Table 2.1**). RF and CR plots were also located in those villages. As a control treatment, we chose 'degraded' RF instead of natural forests due to plot accessibility. In this study we used the FAO term defining the forest degradation as: "changes within the forest which negatively affect the structure or function of the stand or site, and thereby lower capacity to supply products and/or services" (Schoene et al. 2007). In this particular region, RF are relatively open forests mainly resulted from human activities such as overexploitation of forest trees for timber and fuelwood. Degradation results in a reduction in biomass, and changes in tree species composition, structure and productivity compared to natural forest type expected on this site.

As an operational definition for SAF, we used a relative basal area <80%, with five or less other tree species per plot. Whereas gardens with relative cacao basal area <80%, with more than five tree species were categorized as CAF. The gardens with a relative cacao basal area >80% were defined as CM. We calculated relative cacao basal area based on the total tree basal area and the proportion of this area occupied by 'cacao' trees (Sari et al. 2020). To measure research variables, we used plots of 20 m x 20 m with a minimum age of cacao 9 to 14 years and 1 to 4 years old of annual crops. All LUS were replicated three times (fifteen plots in total). All the plots were included in the scope of the 'Agroforestry and Forestry in Sulawesi' (AgFor) project of the World Agroforestry Centre (ICRAF).

Table 2.1. The general characteristics of remnant forests, cacao systems and annual food crop

Land use systems	Location[a]	Plot age (years)	Tree Density, Trees ha^{-1} [b]	Number of tree species[b]	Shannon index (H)[b]	Dominant/ Codominant tree species[b]	Soil texture
Remnant Forests (RF)	1, 2, 3	-	1275	28	2.36	*Metrosideros petiolata, Homalium foetidum*	Silty clay - silty clay loam
Cacao Complex Agroforestry (CAF)	1, 2, 3	9-14	1317	18	0.93	*Theobroma cacao, Durio zibethinus, Lansium domesticum*	Silt loam - silty clay loam
Cacao Simple Agroforestry (SAF)	1, 2, 3	9-14	1267	4	0.58	*Theobroma cacao, Gliricidia sepium*	Silt loam - silty clay loam
Cacao Monoculture (CM)	1, 2, 3	9-14	900	2	0.24	*Theobroma cacao*	Silt loam - silty clay loam
Annual food crops (CR)	1, 2, 3	1 - 4	-	-	-	-	Silt loam

[a] Lawonua (1), Wonuahoa (2), Asinua Jaya (3)

[b] Sari et al. (2020)

2.2.2 Soil sampling and preparation

We collected disturbed and undisturbed soil samples from three soil layers of soil profile. The soil layer depth in all plots averaged 0-21 cm for the first layer, 21-51 cm for the second layer and 52-90 cm for the third layer. We prefer to use layer boundary, instead of exact soil depth intervals (i.e., 0-10, 10-20, 20-30, and so on) to efficiently access the impact of root distribution on SOM and soil macropore and aggregate stability throughout the soil profile. This approach is based on studies which report that infiltration process is greatly influenced by the existence of soil layers with low permeability that can appear in the deeper of soil profile (Chaplot et al. 2011; Mahapatra et al. 2020; Saito et al. 2016), and are not necessarily correlated to the topsoil characteristics.

In each LUS, we collected two sample points within 400 m^2 plot area. Soil samples from those sample points were mixed to create soil composite. In total, we collected 45 composite soil samples (five LUS with three soil layers and three replications). Composite samples were air-dried at room temperature, grounded and sieved at 2 mm and was analysed in Soil Science Laboratory of Brawijaya University. Disturbed soil samples were used to measure SOC (%) through Walkley and Black method (Anderson and Ingram 1994). Undisturbed soil samples were used to measure soil aggregate stability through wet-sieving methods and were represented as Mean Weight Diameter (MWD, mm) (Carrizo et al. 2015).

2.2.3 Trenching methods for fine root density measurement

Fine root samples were collected by using the 'root trenching' method (Suprayogo et al. 2004). Soil pits of 1 m x 1 m x 1 m were dug, with crosscuts within blocks of 20 cm x 10 cm x 10 cm. To separate root samples from the soil blocks, we placed soil blocks on two sieves, a 2 mm mesh size at top and a 0.5 mm mesh size at the bottom and then flushed the sample with water. The root samples remained between those two sieves was then separated from litter and dead decaying roots by handpicking. Total root length per volume of soil (L_{rv}, cm cm^{-3}) and dried root weight per volume of soil (D_{rv}, g cm^{-3}) were measured by using 'line interception' method of Tennant (van Noordwijk et al. 1997) (**Figure. 2.2**).

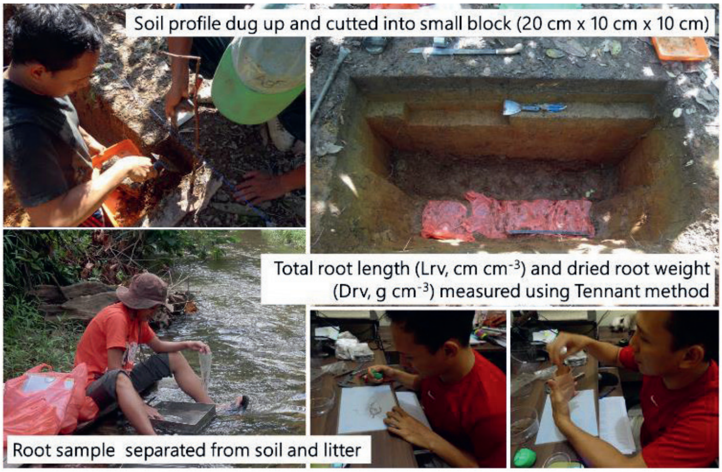


Figure 2.2. Fine root sampling procedure using 'root trenching' method; measuring dried root weight (D_{rv}) and total root length (L_{rv}) per volume of soil using 'line interception' method

2.2.4 Mapping method for soil macroporosity quantification

Surface connected soil macroporosity was measured based on the infiltration pattern of methylene blue liquid. The methylene blue solution (0.35 g l^{-1} of water) was applied over a soil surface area of 1 m x 0.5 m and then allowed to infiltrate overnight. The distributions of methylene blue that appeared on soil profiles (macropore) were traced on plastic sheets for vertical sequence of the soil profiles (Suprayogo et al. 2004). These macroporosity maps were scanned and the total stained area was calculated by using Adobe Portable Photoshop 7.0 program (**Figure 2.3**). Relative area stained was then interpreted as the fraction of surface connected soil macropore within the total soil volume (Hairiah et al. 2006).

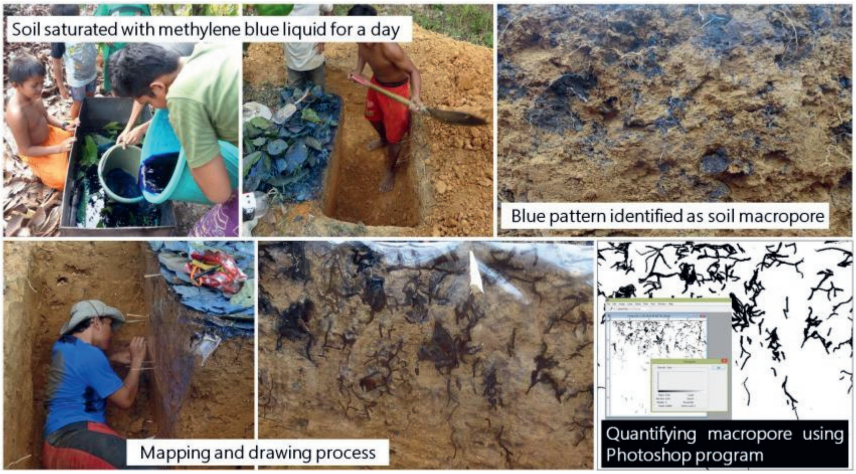


Figure 2.3. Surface connected soil macroporosity quantified based on infiltration pattern of methylene blue dye

2.2.5 Soil Infiltration

Infiltration rate was measured by using a single ring infiltrometer (Sahin et al. 2016). The ring infiltrometer was inserted 15 cm into the soil and filled with water, after which the speed of water infiltration was measured until the infiltration rate reached a constant value (approximately 2-3 h). The infiltration rate was expressed in terms of the volume of water per ground surface and per unit of time (cm h^{-1}). Infiltration rate was determined from three measurement points for each plot (total of 45 measurements in all plots). Steady state infiltrability was afterward estimated by means of curve fitting to Horton's equation using SigmaPlot 2001 v7 software.

2.2.6 Statistical analysis

To evaluate the effect of different LUS, soil depth, and their interaction with various research parameters, we used the general analysis of variance (ANOVA) of Genstat Sixteenth Edition (VSN International Ltd, United Kingdom). An exceptional was the soil infiltration analysis, which was measured only at the soil surface, and therefore the model analysis included only the fixed effect of LUS. Statistical differences were declared significant at $\alpha = 0.05$ level. When an ANOVA test rejected the null hypothesis of homogeneity, the mean parameters values of the various LUS in every soil depth/layer were compared according to the Fisher's Protected LSD ($p < 0.05$). The boxplots were constructed by using 'geom_boxplot' function from 'ggplots2' package in R. To explore the relation between roots and soil characteristics, we performed stepwise regression routines using linear model. Model were fitted using 'lm' function from 'stats' package in R.

2.3 Results

2.3.1 Fine root density

Overall, more than 70% of the total root length (L_{rv}) and 86% of root dry weight (D_{rv}) were concentrated in the upper 40 cm of the soil (**Figure 2.4a, b**). We found a significant difference in L_{rv} between LUS and soil depth, but not with the interaction between LUS and soil depth (**Table 2.2**). The large variation of L_{rv} values found in the first 10 cm of soil did not reveal statistically significant differences between LUS. At a depth of 10-20 cm, RF had the highest L_{rv}, followed by CAF, CR, SAF, and the lowest is in CM. At a soil depth of 20-80 cm, there was no significant difference between the four agricultural systems, while at a depth of 60-70 cm, we observed that CM had a 61% higher L_{rv} compared to other agricultural LUS, even though RF had the highest overall value.

Similarly, results for root length, D_{rv} differed significantly between LUS, soil depth and the interaction between LUS and soil depth (**Table 2.2**). The average D_{rv} in the upper 0-40 cm of RF was 4 times higher than in agricultural systems. Meanwhile, among agricultural systems, CAF had the highest D_{rv}, followed by CR, SAF and CM. At a depth of 60-70 cm, CM had a D_{rv} that was equivalent to that in RF and five times higher than that of other agricultural systems. D_{rv} was higher in CM than in other agricultural systems below a depth of 40 cm. By combining root density and Shannon-Wiener index (*H'*) from Sari et al. (2020), we found a positive correlation among those parameters (**Figure 2.5**).

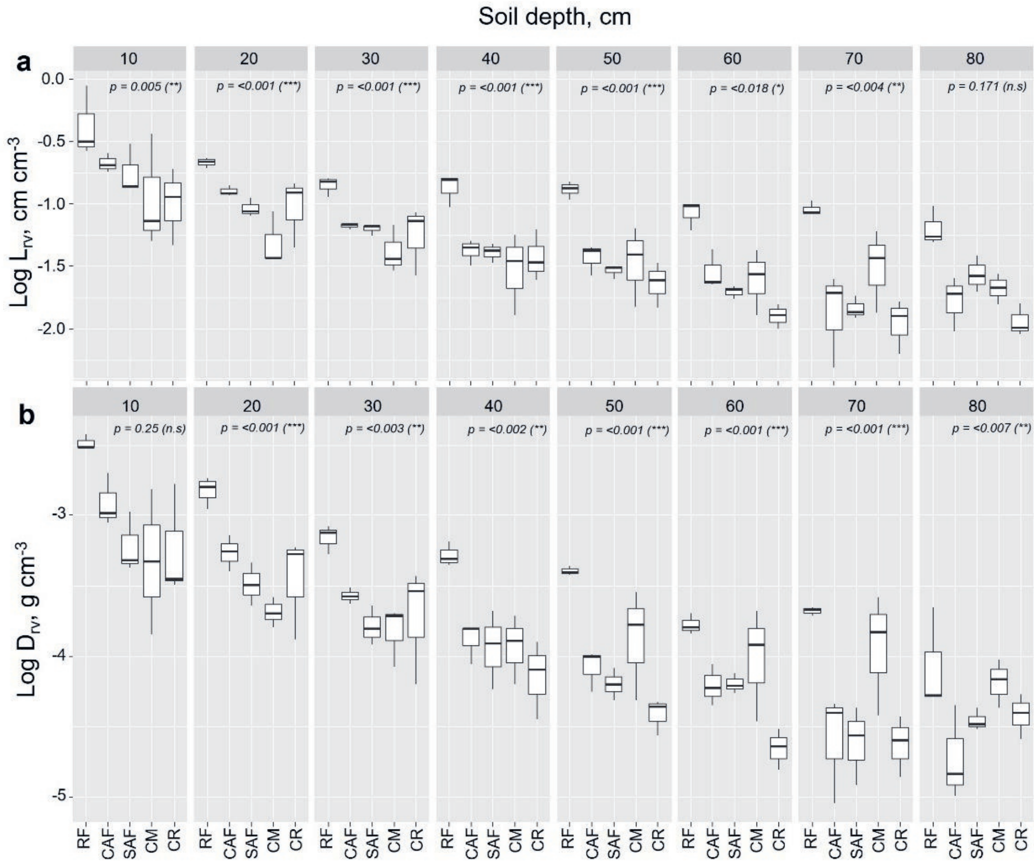


Figure 2.4. Log L_{rv} (a) and log D_{rv} (b) boxplot distribution across remnant forest (RF), complex agroforestry (CAF), simple agroforestry (SAF), cacao monoculture (CM) and annual crop (CR) systems

Table 2.2. Results of a general linear model analysis examining the changes in root and soil parameters in different soil layers among five various land use systems in Southeast Sulawesi, Indonesia

Response variables	Explanatory variables	df	*p* value
L_{rv} (cm cm^{-3})	Reps	2	0.867
	LUS	4	**<.001*** **
	Soil Depth	7	**<.001*** **
	LUS*Soil Depth	28	0.485
D_{rv} (g cm^{-3})	Reps	2	0.947
	LUS	4	**<.001*** **
	Depth	7	**<.001*** **
	LUS*Soil Depth	28	**<.001*** **
SOC (%)	Reps	2	0.24
	LUS	4	0.39
	Soil Layer	2	**<.001*** **
	LUS*Soil Layer	8	0.976
MWD (mm)	Reps	2	0.794
	LUS	4	**0.014* **
	Soil Layer	2	**<.001*** **
	LUS*Soil Layer	8	0.869
Soil macropore (%)	Reps	2	0.174
	LUS	4	**<.001*** **
	Soil Layer	2	**<.001*** **
	LUS*Soil Layer	8	**<.001*** **
Soil infiltration (cm h^{-1})	Reps	2	**0.001** **
	LUS	4	**0.002** **

Note: df (degrees of freedom), L_{rv} (total root per volume of soil), D_{rv} (dried root weight per volume of soil), SOC (soil organic carbon content), MWD (mean weight diameter, is measure of mean soil aggregate size). Significant *p* values are displayed in bold, $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $p < 0.1$

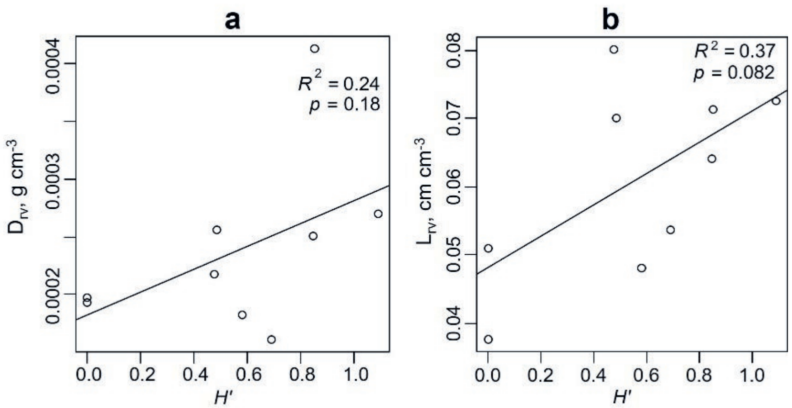


Figure 2.5. Linear regression analysis between Shannon-Wiener diversity index (*H'*) from the same research plots by Sari et al. (2020) with D_{rv} (**a**) and L_{rv} (**b**) confirmed that practicing agroforestry in cacao-based systems could increase root density

2

2.3.2 SOC and its correlation to root density

The average of SOC concentration in the topsoil was 1.1% across LUS, and this number decreased significantly by a third and a half for the second and third soil layer, respectively. However, there were no statistical differences in SOC between LUS and the interaction between LUS and soil layer (**Figure 2.6**, **Table 2.2**). We found a noticeable improvement of SOC in the SAF at all soil layers. Meanwhile, in CAF, SOC was only improved in topsoil layer. We further observed a positive correlation between SOC and L_{rv} and D_{rv} (**Figure 2.8a, b**).

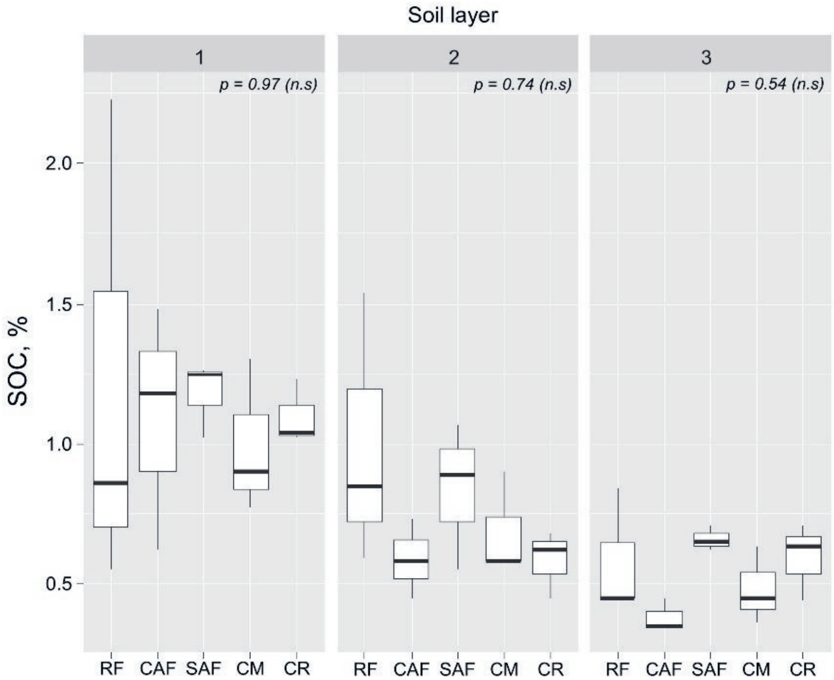


Figure 2.6. Soil organic carbon (SOC) boxplot distribution across remnant forest (RF), complex agroforestry (CAF), simple agroforestry (SAF), cacao monoculture (CM) and annual crop (CR) systems at three soil layers

2.3.3 Soil aggregate stability and macroporosity and its correlation to SOC

Overall, the MWD of aggregates in the topsoil layer was 59% higher than that in the second and third soil layers (**Table 2.2**). Differences of MWD across all LUS were statistically significant only in the topsoil layer. MWD in RF was 31% to 52% higher than that of CR, CM, SAF and CAF (**Figure 2.7a**).

We found a significant different on soil macroporosity between LUS, soil layers and the interaction between LUS and soil layers (**Table 2.2**). The average of surface connected soil macroporosity was 80% higher in the topsoil (14.5%) than in the lowest soil layer (3.2%). Differences in plot management had a significant effect on soil macroporosity in the first and third soil layer. In the topsoil, RF had a 32%, 54%, 66% and 67% higher soil macroporosity than what were found in CAF, CR and CM, and SAF, respectively (**Figure 2.7b**). Meanwhile in the third soil layer, CAF had a higher macroporosity compared to other agricultural systems, and even equal to RF. We found that the increase of shade tree diversity in CAF could produces 5.6 times higher macroporosity in deeper soil layer compared to other agricultural systems. Furthermore, we observed a positive relation between SOC and MWD and macroporosity (**Figure 8c, d**).

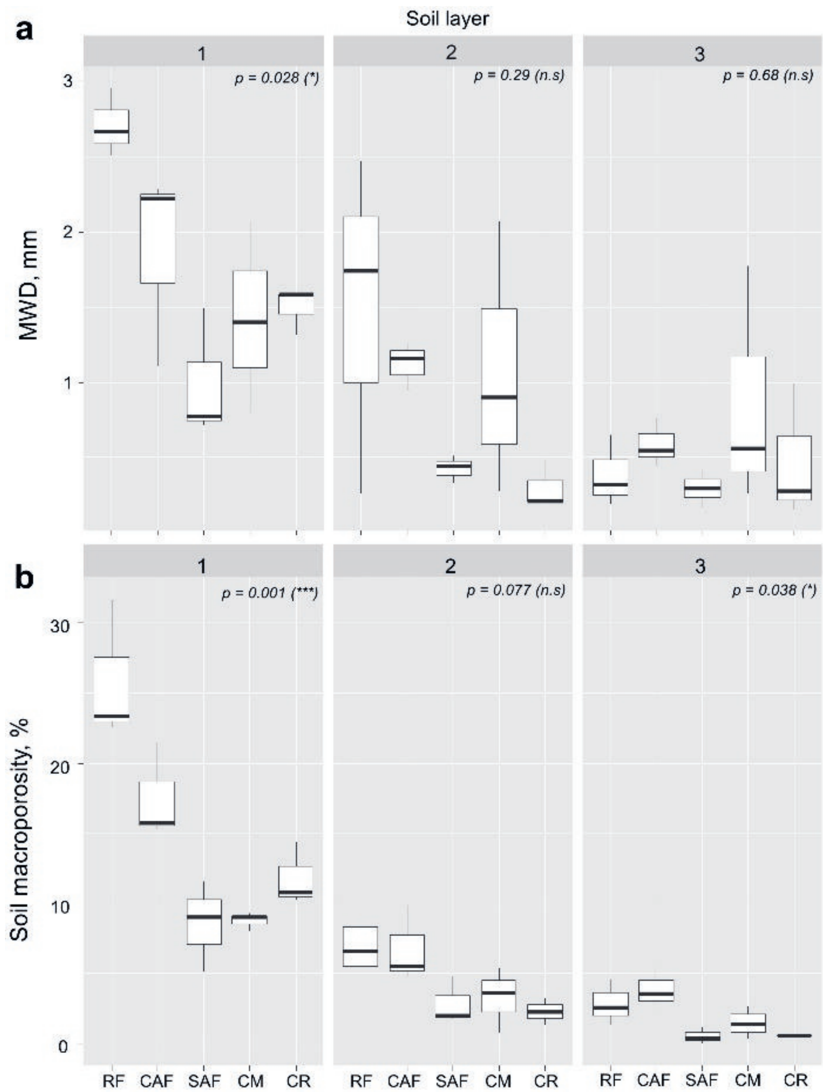


Figure 2.7. Mean weight diameter (MWD) boxplot distribution of soil aggregate (**a**) and surface connected macroporosity (**b**) across remnant forest (RF), complex agroforestry (CAF), simple agroforestry (SAF), cacao monoculture (CM) and annual crop (CR) systems

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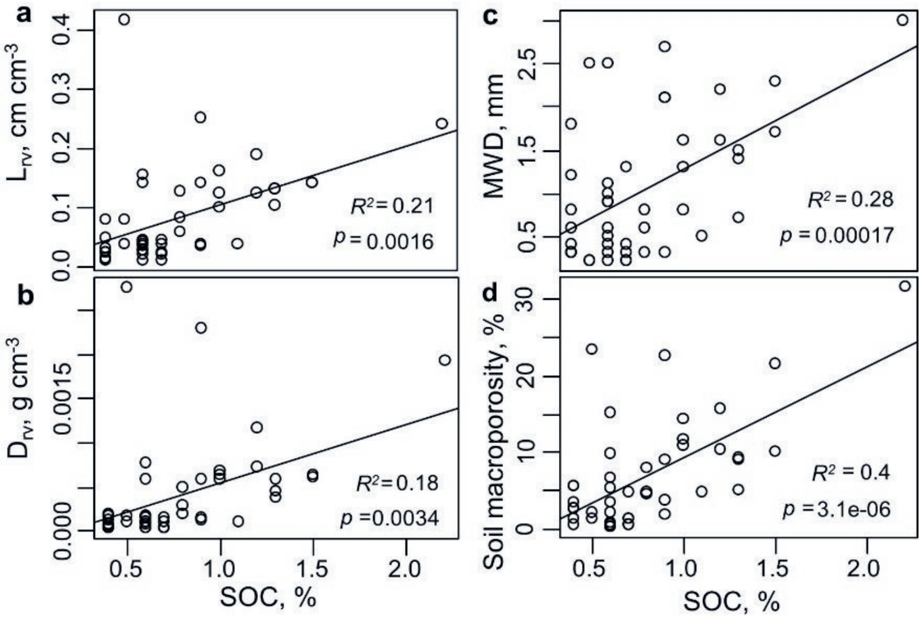


Figure 2.8. Linear regression analysis between SOC and L_{rv} (**a**), D_{rv} (**b**), MWD (**c**) and soil macroporosity (**d**)

2.3.4 Soil infiltration and its correlation to soil aggregate stability and macroporosity

We created the infiltration curves using the soil infiltration field data after fitting the data in the Horton equation. The infiltration curves of each LUS show similar patterns (**Figure 2.9**). The infiltration rates started to plummet from the initial time measurement and began to show a constant rate after 30 minutes. The difference of LUS had a significant effect on steady state soil infiltration, with RF having the highest rate (**Figure 2.10**, **Table 2.2**). Across agricultural systems, however, the infiltration rate was not significantly different with average of 6 cm h^{-1}. We found that integrating more tree species through CAF only slightly improved the soil infiltration. Linear regression analysis has found a significant positive impact of increasing macroporosity (**Figure 2.11b**) to soil infiltration, but not with MWD (**Figure 2.11a**).

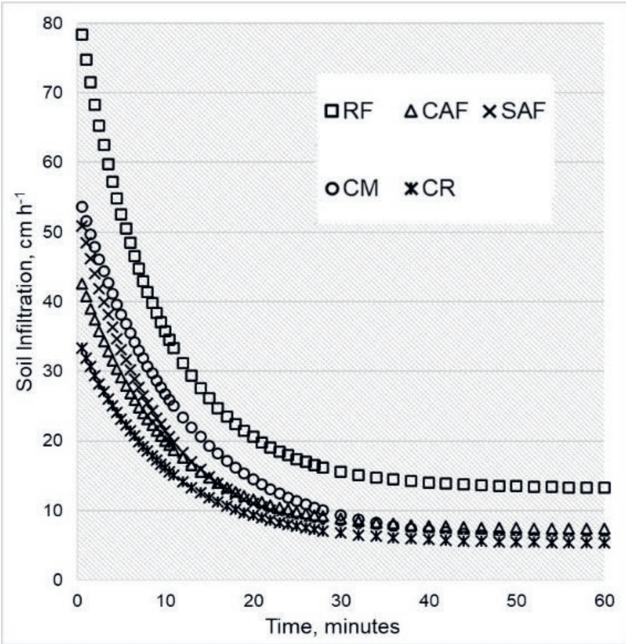


Figure 2.9. Soil infiltration curve across remnant forest (RF), complex agroforestry (CAF), simple agroforestry (SAF), cacao monoculture (CM) and annual food crop (CR) systems. The infiltration curve derived from the average of field measurements data after fitted in Horton equation

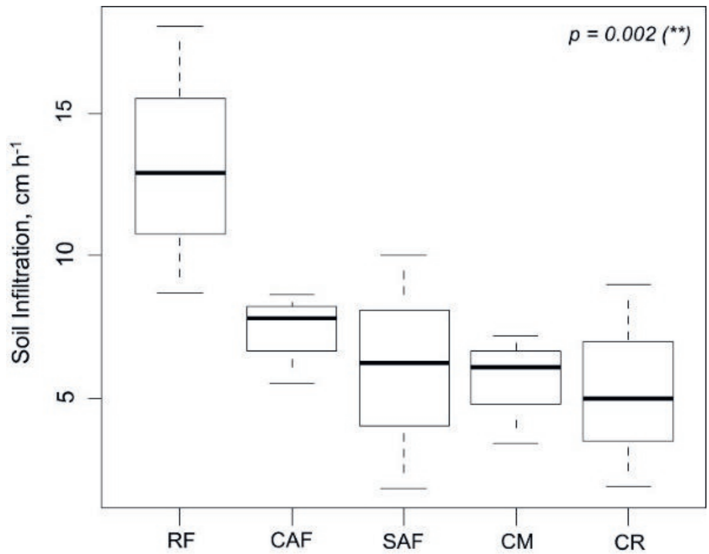


Figure 2.10. Boxplot distribution of steady state infiltration across remnant forest (RF), complex agroforestry (CAF), simple agroforestry (SAF), cacao monoculture (CM) and annual food crop (CR) systems

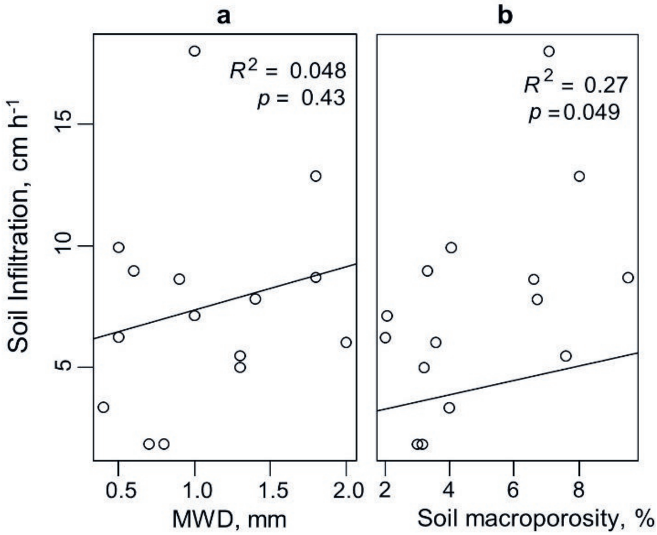


Figure 2.11. Linear regression analysis between soil infiltration and MWD (**a**) and soil macroporosity (**b**)

2.4 Discussion

2.4.1 Incorporating shading trees through agroforestry increases fine root density

In our first hypotheses, we expected that the increase of tree diversity through agroforestry could improve the vertical distribution of fine root. Indeed, by combining tree diversity index from the same sampling sites from Sari et al. (2020) and current root data, we found that incorporating shade trees through CAF and SAF were positively associated to L_{rv} ($R^2 = 0.37$) and D_{rv} ($R^2 = 0.24$) (**Figure 2.5a, b**). This assertion supported by Rajab et al. (2018) which explained that the presence of shade trees in agroforestry systems resulted in higher stem densities and aboveground biomass which could increase root biomass over unshaded monocultures.

However, the low coefficients of determination in **Figure 2.5a, b** indicated that higher tree diversity was not the sole influencing factor for higher root density. We assumed that high organic deposit at topsoil in agroforestry systems originating from aboveground sources (leaf litter and understorey) and belowground sources (root turnover and soil organism activity) could improve the nutrient availability after decomposition. The abundance of nutrients in the topsoil in mixed systems could trigger competition among trees for resources acquisition, and as a mitigation effort, trees will localize the root growth as well as increase its rate resulting in higher L_{rv} and D_{rv}. This might also explain the slight decreases gradient of root density on CM along with the soil depth as a complementarity form of these systems in acquiring limited nutrients at topsoil. Borden et al. (2019) found that cacao fine root distribution in mixed systems with *Entandrophragma angolense* and *Terminalia ivorensis* was concentrated in shallow soils compared to CM. However, at the fine scale of individual roots it was not easy to separate competitive (resource depletion) and facilitative (organic deposition) effects in monospecific and mixed stands (Borden et al. 2019; Mommer et al. 2016).

On the other hand, the average of fine root density (L_{rv} and D_{rv}) produced by the CR was not significantly different from that of cacao-based systems which concentrated in the upper soil layers and decreases with soil depth. This condition was in line with research by Gao et al. (2010) which found that the fine root lengths of maize and soybean plants were mainly distributed in the 0-30 cm of the soil layer and continue to decrease with soil depth. However, this does not mean that the total root biomass produced was equal, as the root class observed in this study was only fine roots (d < 2 mm), whereas with trees large roots (d = 2-5 mm) and coarse root (d > 5 mm) were excluded.

2.4.2 Increasing fine root distribution positively correlated to SOC

Even though the increasing of shading trees in cacao based system did not have a significant effect on SOC, as it was found in this research as well as in the study of Wartenberg et al. (2017), the increasing of fine root distribution alongside with tree diversity was positively correlated to SOC (**Figure 2.8a, b**). The combination of cacao with *Gliricidia sepium* in SAF were associated with a noticeable increase of SOC in deeper soil layer compared to other cacao-based systems. Similarly, the increasing of tree diversity (combinations of fruit and timber trees) in CAF slightly improved SOC at topsoil, but with no effect on deeper soil layers. This result was agreed with that by Rajab et al. (2018) which stated that the fine root turnover of the *Gliricidia sepium* shade trees in agroforestry system was high particularly in the deeper soil layers and significantly exceeded the turnover rate of cacao trees. In contrast, the shade trees in the cacao multi plot had an only slow fine root turnover, which was significantly less than that of the cacao trees.

The total SOC in CM was as high as that in other tree-based systems. Even though the aboveground biomass from tree, as one of the primary sources of organic matter (OM), was only 12%, 67% and 65% relative to RF, CAF and SAF, respectively (Sari et al. 2020). Obalum et al. (2017) suggested fractionation of SOC could reveal more subtle differences in active fractions where total organic carbon is dominated by stable fractions. In the long run, the decline in total biomass production (aboveground and belowground) after forest conversion to agricultural systems may have the potential to reduce SOC. However, among the agriculture systems, the total biomass production of agroforestry (SAF and CAF) proved to be higher than monoculture systems (CM and CR) so that over time SOC could incrementally increase or at least be maintained.

2.4.3 Higher SOC improves aggregate stability and soil macroporosity

The level of soil aggregate stability and macroporosity are related to root distribution and SOC due to different land use management (third hypotheses). Our result showed that the different MWD across all LUS was only significant in the topsoil with the ranges of 0.9 mm to 2.72 mm. This numbers were relatively high compared to Wartenberg et al. (2017), where the range values were 0.9-1 mm for forests and 0.7 for cacao-based systems. This might be caused by the different number of samples as well as the different land use ranges between the studies. However, both studies confirmed that MWD particularly at topsoil across cacao-based system was lower compared to forests. This results were also supported by Le Bissonnais et al. (2018) which stated that soil aggregate stability was affected by land use changes only in surface layers where roots were most abundant and organic C inputs from leaf litterfall, and root litter were at the greatest amount.

The difference in LUS had a significant effect on soil macroporosity for the first and third soil layers, where average soil macroporosity in the topsoil was 80% higher compared to the deeper soil layer. The range of soil macroporosity in this research was 14.5% to 3.2%, and it 2.6 times higher compared to Hairiah et al. (2006) that measured the topsoil macroporosity of forests and coffee-based agroforestry in Lampung, Indonesia. The macroporosity at the agricultural system in Sumberjaya only reached 30% relative to the forests while in this study the difference in macroporosity was reached 50%.

Practising SAF did not significantly improve soil aggregate stability and macroporosity, even though it provided high SOC concentrations. The combination of trees with slow litter decomposition rate (which could help to protect the soil surface and create a better soil microclimate) and trees with the deep root system (which could create macroporosity when decomposed) in CAF was probably the best option to improve the soil physical condition (Hairiah et al. 2006).

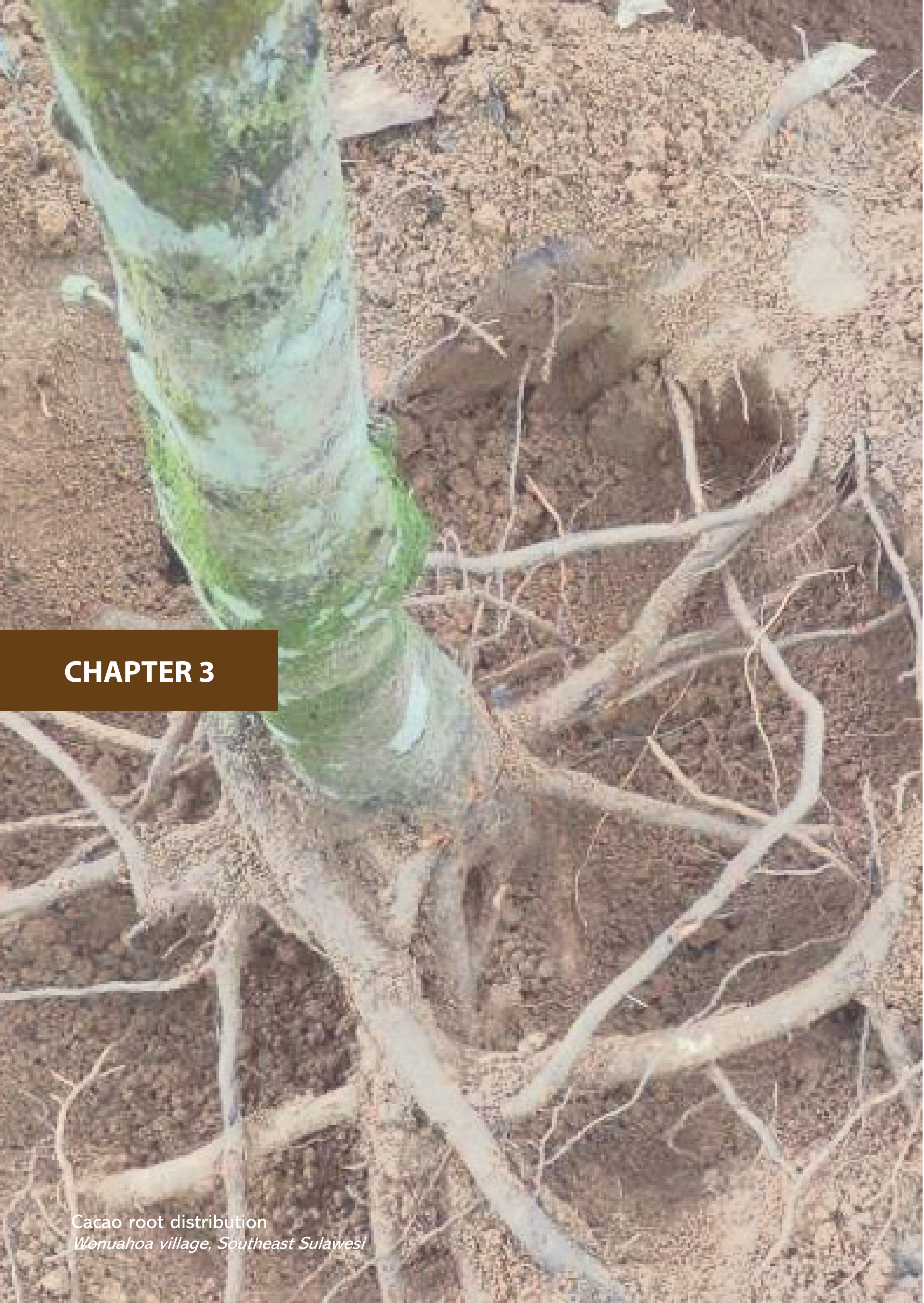
2.4.4 Increasing root density, SOC, aggregate stability and soil macroporosity through agroforestry only slightly improves soil infiltration

Our measurement confirmed that different LUS resulted in different infiltration rates. RF had soil infiltration rates two times faster compared to agricultural systems (**Figure 2.10**). Dense, diverse and evenly distributed root system in RF soil produced more recalcitrant root litter that slowly decomposed (Prieto et al. 2016), which increased the accumulation of SOC (Schmidt et al. 2011) leading to the formation and stabilization of soil transmission pores and higher infiltration (Vignozzi et al. 2019). The existence of shade trees in cacao-based agroforestry did only provide a slightly higher soil infiltration compared to CM. Similar result was found by Benegas et al. (2014), where well-managed coffee monoculture in Turrialba, Aquiares, Costa Rica provided the same function as agroforestry systems with respect to the formation of macroporosity and infiltration. However, research conducted in Copan River, Honduras (in the same publication) concluded that the existence of trees in agroforestry systems was positively correlated to macroporosity, preferential flow and infiltrability. Another factor possibly responsible for lower soil infiltration rates in agriculture systems might be related to the existence of surface crusting in agriculture systems due to weak soil aggregate stability (Gucci et al. 2012) which merits further investigation.

The slight improvement of soil quality and infiltration provided by cacao agroforestry systems compared to monoculture might be correlate to the plot age after conversion to cacao-based systems. The early stage of this cacao-based systems (9-14 years old cacao) in this research were unable to restore the soil quality equal to the condition of RF. The recovery of soil quality in agriculture systems, indeed, is a slow process. Several studies on management changes found that the loss of SOC was faster than SOC restoration (asymmetric response), due to the differences in OM input between restoration and degradation managements (Jensen et al. 2020). A study by Dawoe et al. (2014) revealed that soil quality deteriorated significantly in 3 year old cacao systems, but only started to improve in 15 and 30 year old cacao systems. Based on the positive trend showed on **Figure 2.10**, however, the application of CAF, with time, potentially could provide a faster soil infiltration compared to other agriculture systems. Further study should investigate the long-term effect of agroforestry practices on soil quality, environmental services and land productivity.

2.5 Conclusions

Compared to SAF and CM, integrating a diverse combination of tree species in CAF significantly improved root density in the topsoil layer, even though only half of that in RF. Practicing SAF significantly increased the SOC, particularly in deeper soil layer, whereas CAF only marginally improved SOC at topsoil compared to CM. Soil aggregate stability in RF was higher compared to CR and SAF; while in CAF, soil aggregate stability in topsoil was within the confidence interval of measurement in RD. Our study also highlighted that CAF recovered soil macroporosity better compared to other agricultural systems and impressively equal to RF, particularly in the subsoil. Hence, CAF had slightly higher infiltration compared to other agricultural systems, even though still unable to achieve the soil infiltration rates of RF.



CHAPTER 3

Cacao root distribution
Wonuahoa village, Southeast Sulawesi

Roots for multifunctionality of cacao production systems across climatic zones and avoidance of tree-site mismatching

This chapter is based on submitted article:

Saputra DD, Khasanah N, Sari RR, van Noordwijk M. Roots for multifunctionality of cacao production systems across climatic zones and avoidance of tree-site mismatching.

Under review

Abstract

Protective roles of shade trees for climate-resilient cacao appear to depend on tree-site matching while agroforestry practices involve a wide range of context-specific management options, which can be complex and pose challenges due to trade-offs. Setting out to assess the benefits and drawbacks, across a range of contexts, of various cacao-based land use systems practices on multifunctionality and economic performance, a process-based model was used as tool.

We used the process-based Water, Nutrient and Light Capture in agroforestry systems (WaNuLCAS) model to simulate five cacao-based land use systems (cacao monoculture, cacao + annual crops, cacao + fruit tree, cacao + fast-growing tree, and cacao + slow-growing tree), in three climate regimes (tropical rainforest, monsoon, and savannah). Two soil textures were compared, interacting with two sets of cacao root density data (based on Indonesian versus West African studies). Several metrics quantified the performance of each land use system, including the Land Equivalent Ratio (LERP) for production or multifunctionality (LERM), and Net Present Value (NPV), Return to Labour (RtL), and Benefit-Cost Ratio (BCR) as economic performance indicators.

Simulated cacao production per tree, positively or negatively influenced by intercrops, responded to the number of days cacao grew under water-limited conditions. Good cacao root development supported LERP values (1.15 versus 0.95 on average); in the savanna, the LERP difference became 0.27. Among the agroforestry systems, cacao + annual crops had a LERP of 1.13, followed by cacao + slow-growing trees (1.09), and a lowest result (0.98) for cacao + fruit trees; they were higher for the rainforest zone 1.08, and lowest for savanna climates (1.01); soil texture had no effect on the average LERP across other main factors. Agroforestry systems had a higher time-averaged carbon stock than monocultures or systems with annual crops, but effects on other aspects of environmental performance, averaged over a 20-year life cycle, were modest, and variation in LERM was small. Economic performance indicators diverged, with the highest NPV for cacao + annual crops or cacao with fruit trees, the highest BCR for cacao + fruit trees and the highest RtL for cacao + fruit trees followed by cacao + slow-growing trees.

Our study highlights that the potential benefits of cacao-based agroforestry practices depend on strong root development by the cacao trees. In selecting for high yields in monocultures, the benefits of intercropping may be forfeited, especially when used in drier climates.

Keywords: *Theobroma cacao*; root density; agroforestry; land equivalent ratio; environmental services; net present value

3.1 Introduction

Cacao production has become a hot topic at the interface of rural development, environmental conservation and global trade (Boeckx et al. 2020; Wainaina et al. 2021). Global demand for *Theobroma cacao* (cacao) is expected to keep growing, especially in Asia and Africa, where chocolate consumption increases with growing middle-class consumption patterns. Due to stagnating productivity (Vanhove et al. 2016) and unsustainable cacao production systems (Schroth et al. 2016), area expansion and continued forest conversion (Clough et al. 2009a) are a major source of concern, including in Indonesia (Rajab et al. 2018). Yield gaps, where the achieved land productivity is less than the potential, indicate, when calculated for monocultures, that the Land Equivalent Ratio (LER) is less than one; for mixed systems (land sharing), cacao yield gaps can still allow efficient (LER>1; 'land sparing') land use (Khasanah et al. 2020; van Noordwijk et al. 2018). Cacao expansion outside the humid tropics can reduce pressure on areas of high biodiversity value but may make the crop more vulnerable to climate change. Both rejuvenation and restoration of existing cacao stands are urgent but require guidance on how to increase, rather than decrease, sensitivity to climate change (Somarriba et al. 2021). There is considerable scope for combining biodiversity and productivity in cacao agroforests (Clough et al. 2011), but some of the experience with a two-component simple cacao agroforestry and a fast-growing tree has been negative.

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Two contrasting views have been documented on the climate sensitivity of cacao production: literature from West Africa suggests a high climate sensitivity, and in some studies, a negative impact of shade trees in agroforestry on cacao resilience (Abdulai et al. 2018b). A high vulnerability to ENSO (El Nino Southern Oscillation) events has also been reported for Brazilian cacao agroforests in the Northeastern state of Bahia, where cacao is grown, somewhat beyond its climatic limits, in wildlife-friendly agroforests (Gateau-Rey et al. 2018). On the other hand, experiments of artificially inducing drought in Sulawesi (Indonesia) showed a surprisingly slow response to an experimentally imposed drought on six-year-old cacao grown with six-year-old Gliricidia shade. Excluding 78% of the local rainfall over 13 months (about 3000 mm rain in that period) caused only a 10% loss in cacao yield during the rainfall exclusion, though a further 45% reduction was recorded after the end of the drought; no cacao tree mortality was observed (Schwendenmann et al. 2010).

While the specific evidence for West Africa of negative impacts of shade trees by Abdulai et al. (2018b) has been challenged (Wanger et al. 2018) as a basis for the generalizations made, a remarkable aspect of the data in their case study is that drought-induced cacao mortality occurred with an abundance of groundwater 50 cm below the surface, as both cacao and the fast-growing timber tree were shallowly rooted on the soil of the experiment. Generalizations of the protective or risk-enhancing impacts of cacao agroforestry, compared to open-field monocultures, may depend on the combination of climate soil, tree spacing and root development, beyond what current literature recognizes. Beyond rooting depth, the relative root length densities of intercropped trees matter for the competition outcomes (van Noordwijk et al. 2004; van Noordwijk and Lusiana 1998). We used a generic, process-based simulation model of water, nutrient and light capture in agroforestry systems (WaNuLCAS 4.0) that is explicit in belowground interactions to explore the internal consistency of the way climate, soil, and root characteristics interact with aboveground system design and tree architecture that can account for both the West African and Indonesian experience with the crop in response to rainfall.

Cacao in Indonesia and West Africa have had different trajectories of germplasm selection. Cacao came to Indonesia from the Philippines (early post-Columbus Spanish connections) and was primarily grown in Central Java. Data from 1950 indicated that 91% of the cacao plantations in Indonesia at that time were in either Pekalongan or Semarang, both in Central Java, with a research station in Getas (Salatiga) as the primary centre for selection and propagation (Balai Penjelidikan Perkebunan 1953). Three characteristics that may have contributed to a strong root development of selected clones were: the climate with a pronounced dry season, the focus on cacao planting in previous coffee gardens or abandoned swiddens, rather than following primary or secondary forest conversion, and the practice of first establishing shade trees and shrub vegetation, before planting cacao in partially cleared rows. In contrast, West African cacao takes its genetic origin from Amelonado cacao, introduced from Bahia, Brazil, to the Central African Coast, Ghana and Nigeria in the 19th century (Hervé and Albanie 2021). Further selection took place in coastal research locations on more recently converted forest soils, in a more humid climate, and focused on monocultures without shade trees. The resulting West African germplasm has a higher yield potential but is more sensitive to climate change. In Indonesia, the primary strategy for yield improvement has been grafting on local rootstock (Baharuddin et al. 2022) rather than selected seed sources. This strategy may have led to problems of poor root development when successful clones were propagated as whole plants in a national cacao intensification program that failed dramatically (van Noordwijk et al. 2021). Beyond a direct resource limitation, literature also asserts a critical role for cacao pollination, with ongoing efforts to clarify the habitat requirements for effective pollinators; pollinators may depend on the field-level presence of banana stumps and a litter layer (Bos et al. 2007; Groeneveld et al. 2010; Toledo-Hernández et al. 2023). The current simulation models (e.g. Zuidema et al. (2005)) do not include such interactions at the process level.

There is a parallel debate on the trees used as companion trees for cacao. These can be of three origins: remnant trees of previous vegetation, where cacao was planted under shade, trees planted as a (simple or complex) cacao agroforestry system, or trees that were established (or were transplanted) after the cacao started (Ordonez et al. 2014). A substantial part of timber currently harvested from cacao agroforest is of the first type, while future harvests will be of the third type, while the success rate of the second may be lower than expected (Kouassi et al. 2023). Climate change is likely to shift the optimum allocation of growth resources to roots (van Noordwijk et al. 1998).

This study aimed to assess the benefits and drawbacks of agroforestry systems on their multifunctional services and economic performances. As direct field trials are scarce for obvious reasons of time, labour, and finances, process-based models are an alternative to test the internal consistency of assumptions. In this study, the Water, Nutrient and Light Capture (WaNuLCAS) model, which focuses on productive trade-offs between trees and crops, and environmental services such as carbon sequestration, nutrient and water balances (Luedeling et al. 2016; Paul et al. 2017), was used to assess these systems on a daily process basis, extended to 25-year system life cycle (Hussain et al. 2016).

To assess the trade-off between provisioning and regulating functions among management options in the cacao-based land use systems (LUS) in different scenarios such as soil texture, cacao root architecture and climate region, we used several metrics, including Land Equivalent Ratio (LER) for its multifunctionality services (LER_M), and Net Present Value (NPV), Return to Labour (RtL), and Benefit Cost Ratio (BCR) for its economic performance. Our specific questions were:

1) How do above- and belowground architecture and functional traits of potential cacao agroforestry components relate to expected cacao yields simulated under different climate, soil and root scenarios?
2) To what degree can cacao agroforestry systems be a strategy to reduce land hunger through the improvement of LER above 1 on land multifunctionality services (LER_M) – which are indicated by higher LER for cacao production (LER_P) and environmental services (LER_R)?
3) How are various production systems' economic performance indicators (NPV, RtL, and BCR) reflecting the farmer risk and potential benefits in agroforestry systems compared to cacao monoculture?

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with as corresponding hypotheses:

1) Agroforestry systems are expected to have higher cacao productivity per tree compared to cacao monoculture but have lower total cacao production per hectare
2) Cacao agroforestry is expected to have LER_M above 1. Thus, it can be a promising strategy to reduce forest conversion to a new cacao cultivation area
3) Cacao agroforestry is expected to have lower farmer risk and higher potential benefits, as indicated by better economic performance indicators (NPV, RtL, BCR) compared to cacao monoculture

3.2 Materials and methods

3.2.1 WaNuLCAS model

The Water, Nutrient and Light Capture in Agroforestry System (WaNuLCAS) model is a tree-soil-crop interaction representation of above and belowground interactions in agroforestry systems (van Noordwijk and Lusiana 1998; van Noordwijk et al. 2011). We chose this process-based model for its flexibility in representing tree-soil-crop management options and its ability to directly estimate economic and environmental impacts (Khasanah et al. 2015; Khasanah et al. 2020). Data produced from this model simulation were used for analysing the productive trade-off study (Paul et al. 2017), a fundamental factor to consider in agroforestry system feasibility analysis.

The model has a daily time step and spatial resolution at the plot scale, featuring a four-layer soil profile and four spatial zones. It allows for flexible trees and/or crop placement in any zone. The model considers three primary component resources: light availability for aboveground resources, water and nutrient availability (nitrogen and phosphorus) for belowground resources, and belowground architecture and phenology (Khasanah et al. 2015). These component interactions are interpreted in different modules, including cropping management options (van Noordwijk and Lusiana 1998; van Noordwijk et al. 2011).

WaNuLCAS model has been previously used for numerous agroforestry studies with various tree-crop combinations, such as teak- maize system (Khasanah et al. 2015; Paul et al. 2017), oil palm – cacao system (Khasanah et al. 2020), *Jatropha curcas* and *Moringa oleifera* (Noulèkoun et al. 2018), Maize- chilli - *Leucaena leucocephala* systems (Hussain et al. 2016), *Eucalyptus* – maize (Magcale-Macandog 2014), sorghum – *Parkia biglobosa*, *Vitellaria paradoxa*, *Adansonia digitata* (Coulibaly et al. 2014).

3.2.2 WaNuLCAS parameterization, calibration, validation and evaluation

3.2.2.1 Model parameterization, calibration and validation

We explored tree and crop growth and production and its consequences on the environmental services of different LUS using data produced by WaNuLCAS. Prior to using the model output, we performed a series of model calibrations and validation to test the model's validity. The general workflow of this study started from model input parameterization and calibration, model performance evaluation, scenarios simulation, and output analysis, presented in **Figure 3.1**.

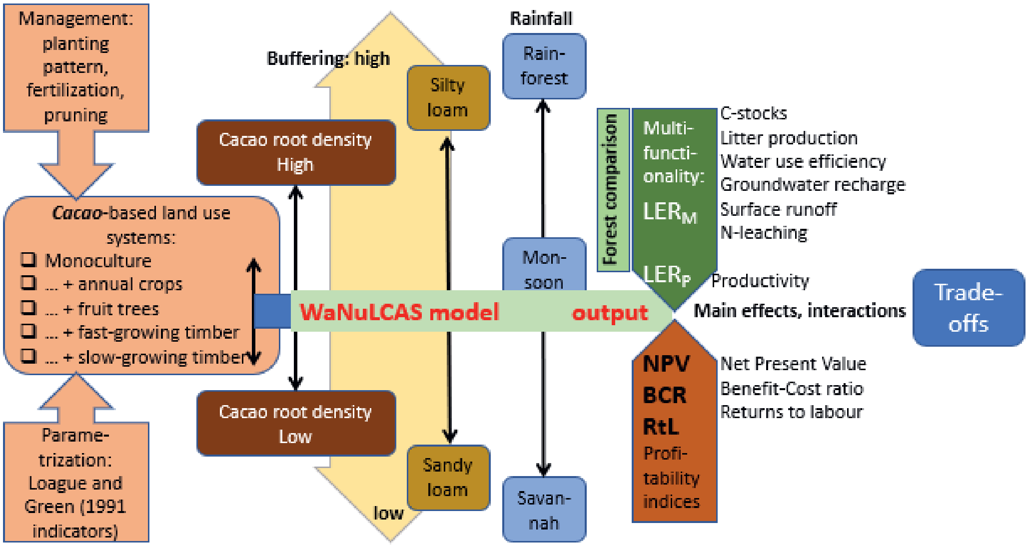

Figure 3.1. Study workflow consisted of WaNuLCAS model input parameterization, model performance evaluation, simulation scenarios, and output analysis

3

The input data for the WaNuLCAS model includes weather, soil parameters, and crop and tree management. We utilized monthly rainfall and temperature data from BMKG (2021) as the input for the WaNuLCAS model to generate daily rainfall and potential evapotranspiration. Climate, tree and soil data from Southeast Sulawesi (tropical rainforest region) were used for cacao and *Pogostemon cablin* model parameterization and calibration. However, for other trees species such as *Durio zibethinus, Tectona grandis, and Falcataria mollucana*, we used climate data from East Java (tropical monsoon region), as the parameters used for model evaluation were obtained from studies conducted in Java Island. Detailed information regarding the weather data used for model parameterization is presented in **Figure 3.3.**

Aboveground data on tree density was adapted from Sari et al. (2020), while belowground data such as soil organic carbon (SOC), soil texture, pH, bulk density, and other soil characteristics were based on Saputra et al. (2020) and Khasanah (2021). We used the Hodnett and Tomasella (2002) pedotransfer function (PTF) in the WaNuLCAS model excel sheet to generate the soil hydraulic properties. The reference value of initial soil nitrogen, phosphorus concentration, and Cation Exchange Capacity (CEC) were derived from (Khasanah 2021). These soil properties were set according to the four vertical layers of the WaNuLCAS model that correspond to the three layers observed in the field; therefore, layer 3 and 4 of the model has identical value except for soil pH (**Table 3.1**). The cacao management database that consists of farmers' tree preferences, pruning and fertilizer application schedule were collected in 2015 through the farmer interview (for farmers' tree preferences, please see Sari et al. (2020). The detailed fertilizer application schedule and dosage are available in Supplementary Information 3.1 (**SI 3.1**). These datasets were also used to generate farm budgets and profitability metrics.

Table 3.1. Soil properties data used to parameterize the pedotransfer module (PTF) of the WaNuLCAS model

Parameter	Soil layer, cm			
	0-20	20-50	50-75	75-100
Clay (%)	24.8	20.0	20.9	20.9
Silt (%)	61.2	61.3	60.0	60.0
Sand (%)	14.0	18.7	19.1	19.1
SOC (%)	0.99	0.69	0.48	0.48
BD (g cm^{-3})	1.37	1.38	1.35	1.35
CEC (cmol kg^{-1})*	16.0	10.2	10.2	10.2
pH H_2O	4.21	4.16	3.92	3.88
N total (%)*	0.12	0.16	0.16	0.16
P (mg kg^{-1})*	5.38	5.56	5.56	5.56
K_{sat} (cm day^{-1})**	14.8	27.2	30.7	30.7

Note: SOC: soil organic carbon, BD: bulk density, CEC: cation exchange capacity, P: available phosphorus, K_{sat}: saturated hydraulic conductivity. *(Khasanah 2021), ** estimated from pedotransfer function from Hodnett and Tomasella (2002)

3.2.2.2 Model performance evaluation

We evaluated the model performance for cacao by comparing the measured and simulated data of tree biomass, litterfall and dry weight cacao production. Dry weight cacao production was referred to Khasanah (2021). Tree biomass and litter production were referred to Sari et al. (2020) and Sari et al. (2022). Meanwhile, for patchouli and other trees (*Durio zibethinus, Tectona grandis and Falcataria mollucana*) model performance evaluation, we use parameters such as tree diameter, height, and yield from various references (see references used in section **3.3.1, Figure 3.4**). We tested the model accuracies using the statistical indicator proposed by Loague and Green (1991) (**Table 3.2**).

Table 3.2. Statistical criteria for model performance evaluation as proposed by Loague and Green (1991)

Criteria	Symbol	Calculation formula	Min	Max	Opt
Maximum error	ME	$Max\,\lvert P_i - O_i \rvert_{i=1}^{n}$	0		0
Root mean square error	RMSE	$\left(\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{n}\right)^{\frac{1}{2}} x \frac{100}{O_{mean}}$	0		0
Coefficient of determination	CD	$\frac{\sum_{1=1}^{n}(O_i - O_{mean})^2}{\sum_{1=1}^{n}(P_i - O_{mean})^2}$	0		1
Modelling efficiency	EF	$\frac{(\sum_{1=1}^{n}(O_i - O_{mean})^2 - \sum_{1=1}^{n}(P_i - O_{mean})^2)}{\sum_{1=1}^{n}(O_i - O_{mean})^2}$		1	1
Coefficient of residual mass	CRM	$\frac{(\sum_{1=1}^{n}O_1 - \sum_{1=1}^{n}P_i)}{\sum_{1=1}^{n}O_1}$		1	0

Note: P_i = predicted value; O_i = observed value; n = the number of samples; O_{mean} = the mean of the observed data. Min: minimum limit, Max: maximum limit, Opt: optimum value

3.2.3 Simulation scenarios

Different cacao-based LUS were simulated to identify the best possible management options based on the farmers' chosen tree species. These included annual crops, fast-growing timber tree, slow-growing timber tree and fruit trees, as adapted from Sari et al. (2020). The detailed combination of tree and crop management options is presented in **Table 3.3**. The characteristics of shading trees used in the simulation concerning the aboveground and belowground architecture characteristics are presented in **SI 3.2.**

Table 3.3. The combination of cacao and crop/trees under different cacao-based LUS

LUS	Intercropped species (IS)	Spacing (m)		Tree density (tree ha^{-1})		
		Cacao	IS	Cacao	IS	Total
Cacao	-	3 x 3	-	1111	-	1111
Cacao + annual crops	*Pogostemon cablin*	3 x 3 x 6	1 x 11	733	-	733
Cacao + fast-growing timber tree	*Falcataria mollucana*	3 x 3 x 8	5 x 11	600	450	1050
Cacao + slow-growing timber tree	*Tectona grandis*	3 x 3 x 8	5 x 11	600	450	1050
Cacao + fruit tree	*Durio zibethinus*	3 x 3 x 11	8 x 14	467	70	537

Note: LUS: land use system, IS: intercropped species

3

The consistency of agroforestry system on its multifunctionality related to the different soil textures was tested by simulating the management options under the sandy loam soil texture (2 and 4 scenario – please see **Table 3.4**) as this soil has lower buffer capacity than the silt loam soil used during the first and third scenario. Furthermore, we explored the effect of different cacao root densities on the performance of the LUS (**Table 3.4**). Cacao in Sulawesi has been known for its rather dense and evenly distributed fine root density from the well-established (old variety) cacao rootstock, at least up to 1 m depth of soil profile as reported by Saputra et al. (2020) and Moser et al. (2010), compared to more recent cultivar (hybrid) cacao that widely cultivated in Ghana as reported by Borden et al. (2019), similar to the measured root density of 1.02 cm cm^{-3} in the 0-15 cm depth layer in Bahia (Brazil) (Kummerow et al. 1981). Therefore, we used these distinct root densities for our high- and low-root-density scenarios. The summary of all scenarios is presented in **Figure 3.1**.

Table 3.4. Soil texture, hydraulic conductivity, and root density used for simulation scenarios

Parameter	Soil layer thickness, cm			
	0-20	20-50	50-75	75-100
Silt loam soil for scenarios 1 and 3				
Clay (%)	25	20	21	21
Silt (%)	61	61	60	60
Sand (%)	14	19	19	19
K_{sat} (cm day^{-1})	15	27	31	31
Sandy loam soil for scenarios 2 and 4				
Clay (%)	16	12	12	12
Silt (%)	18	30	30	30
Sand (%)	66	58	58	58
K_{sat} (cm day^{-1})	96	47	55	55
Root density (cm cm^{-3})				
High root density for scenarios 1 and 2	2.1	0.4	0.4	0.6
Low root density for scenarios 3 and 4	1.0	0.4	0.2	0.1

Note: K_{sat}: saturated hydraulic conductivity

Ultimately, those cacao-based scenarios were simulated under three different climate regions of tropical rainforest (TR), tropical monsoon (TM) and tropical savannah (TS) (**Figure 3.2**). These climate-related settings were developed to test the sensitivity of shade tree options on the multifunctionality of agroforestry systems toward different annual rainfall and potential evapotranspiration, and therefore water availability. The annual precipitation for the TR was 2935 mm $year^{-1}$, with the estimated potential evapotranspiration (PET) of 1736 mm $year^{-1}$. The wet season starts from November to July with an average rainfall of 274 mm $month^{-1}$. The dry season starts from August to November, with an average rainfall of 155 mm month-1. In the TM region, the annual rainfall and PET were 2139 mm $year^{-1}$ and 1676 mm $year^{-1}$, respectively. The wet season starts from November to April (avg. 277 mm $month^{-1}$), and the dry season starts from May to October (avg. 40 mm $month^{-1}$). The annual precipitation for the TS region was only 32% of tropical rainforest (946 mm $year^{-1}$), but it has higher PET (1737 mm $year^{-1}$). The wet season started from January to March (avg. 180 mm $month^{-1}$), and April to December for the dry season (avg. 45 mm $month^{-1}$). Overall, our current calculated PET was slightly higher than the estimated PET by Zomer et al. (2022), which has a range of 1000 – 1500 mm $year^{-1}$ in these regions.

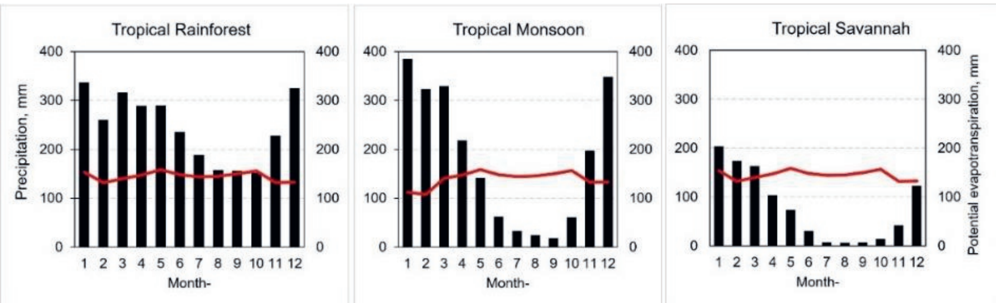

Figure 3.2. The annual rainfall and potential evapotranspiration pattern of three climate regions, including tropical rainforest, tropical monsoon, and tropical savannah

3.2.4 Scenario Analysis

3.2.4.1 Land productivity and environmental performance indicators

We simulated those scenarios for 20 years and analyzed the best possible management option in cacao-based LUS across different climate regions, using the LER as a metric (Khasanah et al. 2020). LER indicates the relative area under monocropping needed to achieve the same functionality as an area intercropped. We grouped functionality considerations under-provisioning (or land productivity) services (LER_P) and regulating services (e.g., litter production, water use efficiency (WUE), carbon stocks, N leaching) (LER_R). We calculated the two components of LER_P and LER_R for a multifunctionality service (LER_M). LER_M has been proven effective for exploration studies on synergy and complementarity of an alternative LUS (Khasanah et al. 2020; van Noordwijk et al. 2018). We adopted the equation from Khasanah et al. (2020) to calculate the productivity of LER_P and LER_R components:

$$\mathbf{LER_P = P_{M,1}/P_{S,1} + P_{M,2}/P_{S,2}} \quad (1)$$

With $P_{M,1}$ and $P_{M,2}$ was the time-averaged yield of two components in mixed systems (intercropping), and $P_{S,1}$ and $P_{S,2}$ were those in sole crops (monocultures), respectively. Cacao and intercropped yield were equally weighted for the LER_P calculations.

$$\mathbf{LER_R = \Sigma_j w_j \left(R_{j,M}/R_{j,F}\right)^{sj} / \Sigma_j w_j} \quad (2)$$

With $R_{j,M}$ and $R_{j,F,}$ the function $_j$ (per unit area) in a mixed (or similarly for monoculture) system, and forest conditions, respectively. While wj is a weighting factor and sj a sign (+1 for positive functions and -1 for dysfunctions).

We used results for both two functions and dysfunctions: (1) time-averaged aboveground C stock, (2) litter production, (3) WUE, (4) groundwater recharge (GWC), (5) surface runoff and (6) N leaching. However, for the sandy loam scenario (scenarios 2 and 4), the surface runoff parameter was excluded from the LER_M calculation as it became irrelevant (surface runoff <1% of total annual rainfall). Four versions of the weighting factor between functions and dysfunctions were applied during LER_R calculation, including equal weight (LER_{Req}), carbon centric (LER_{Rcs}), water quality centric (LER_{Rwqt}), and water quantity centric (LER_{Rwql}). The detailed weight distribution of each version is presented in **SI 3.3.**

Multifunctional LER_M was then calculated by combining the LER_P and LER_R as follows:

$$\mathbf{LER_M = LER_P + LER_R} \quad (3)$$

With LER_M as the LER for system multifunctionality, LER_P and LER_R were the LER for systems' provisioning and regulating services, respectively. We used an equal weighting factor between LER_P and LER_R for LER_M calculations.

3.2.4.2 Economic Performance Indicators

Net Present Value (NPV), Return to Labour (RtL), and Benefit Cost Ratio (BCR) were employed for further economic performance indicators and to determine the profitability of the mixed system relative to monoculture. The mixed system is profitable when NPV > 0, BCR >1, and RtL is higher than the daily wage rate. RtL is defined as the labour cost at which the NPV is zero. The NPV is calculated as follows:

$$\boldsymbol{NPV} = \sum_{t=0}^{t=n} \frac{R_t - C_t}{(1+i)^t} \quad (4)$$

Where: R_t is revenue at year *t*, C_t is the cost at year *t*, and *i* is the discount rate (Khasanah et al. 2020).

We developed a farm-level assessment for each system to assess its economic performance. We collected data on farm-level inputs consisting of labour hours and costs, amounts and prices of fertilizer and other chemical inputs, planting materials and tools required for cacao cultivation. Inputs and labour wage rates were estimated based on the local market prices and rates. For detailed information on farm-level input and labour wage rates, market prices of cash crops product for cacao, *P. cablin*, *D. zibethinus*, *F. mollucana*, and *T. grandis*) please see **SI. 4a and b**. An interest rate of 3%, a labour rate of 4US$, and a currency exchange of 15.000 rupiahs per 1 US$ were used during this analysis.

3.3 Results

3.3.1 Model performance evaluation

The model performance evaluation and comparison between simulated and measured/referenced cacao and companion shade trees are presented in **Figure 3.3** and **Table 3.5**. Model evaluation for cacao indicated a good to moderately good fit for biomass, litterfall, and yield, with coefficient determination (CD - optimal 1) values of 1.0, 0.6 and 0.4, respectively. The simulated result and referenced cacao yield have similar annual average dry weight cacao beans of 1.1 Mg ha^{-1} year^{-1} during the 20 years simulation duration, even though a noticeable discrepancy appeared during the third quarter of simulation time. Model simulation consistently produced slightly higher cacao aboveground tree biomass than measured data. The average cacao litterfall production from the model simulation was 5.3 Mg ha^{-1} year^{-1}, or 4% higher than the average field measurements. Meanwhile, overall evaluation for *F. mollucana* and *T. grandis* showed a good fit, indicated by CD values of 0.8 and 0.6 for tree height and 1.0 and 1.3 for tree diameter, respectively. The simulation results of *F. mollucana* and *T. grandis* fit our reference figure. Simulation results for *D. zibethinus* showed an acceptable fit for tree diameter (CD value of 0.4) and for the annual yield with fresh fruit weight 10.1 Mg ha^{-1} year^{-1} for the simulation result, compared to 10.7 Mg ha^{-1} year^{-1} from the references during the peak production within simulation period.

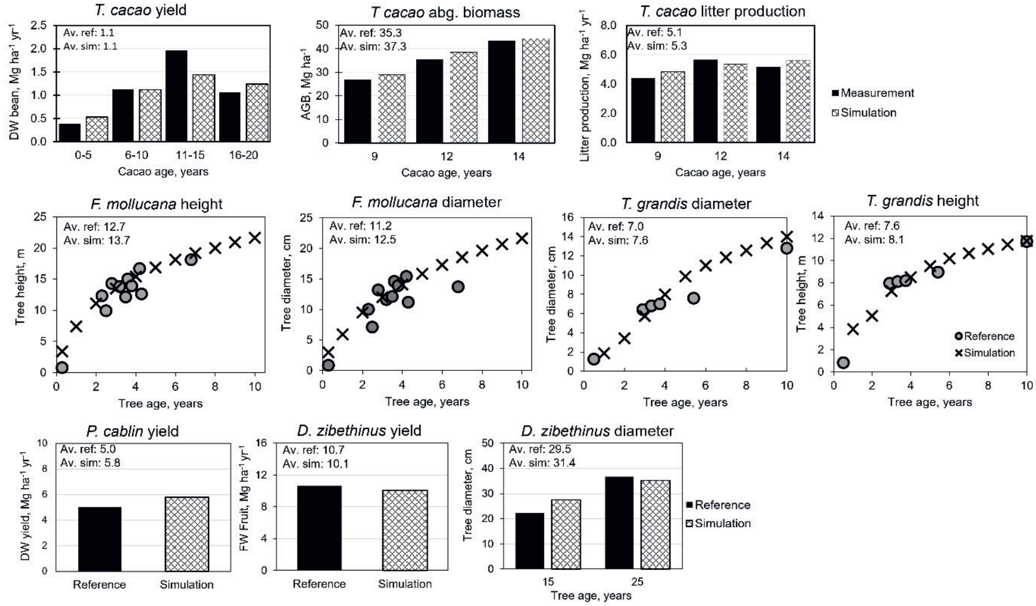

Figure 3.3. Comparison of simulated and measured/referenced of various tree parameters on *T. cacao*, *F. mollucana*, *T. grandis*, *P. cablin*, and *D. zibethinus.* Reference list: *T. cacao* yield (Khasanah 2021); *F. mollucana* (Hadiyan 2010; Varis 2011); *T. grandis* (Adinugraha and Fauzi 2015; Khasanah et al. 2015; Pudjiono et al. 2020); *P. cablin* (Dinas Perkebunan, 2013), *D. zibethinus* (Anisar 2018; BPS 2021; Djuhari et al. 2021; Watson 1983)

Table 3.5. Result of model performance evaluation according to Loague and Green (1991)

Criteria	*T. cacao*			*F. mollucana*		*T. grandis*		*D. zibethinus*	
	Biomass	Litterfall	Yield	Height	Diameter	Height	Diameter	Diameter	Yield
ME	3.2	0.5	0.5	3.4	4.8	2.7	2.9	5.2	1.8
RMSE	2.3	0.4	0.3	1.8	2.4	1.2	1.4	3.8	1.7
CD	1.0	0.6	0.4	0.8	1.0	0.6	1.3	0.4	0.2
EF	0.0	0.4	0.0	0.2	0.1	0.4	-0.4	0.6	0.8
CRM	-0.1	0.0	0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.1

Note: ME lower limit 0, optimum 0; RMSE lower limit 0, optimum 0; CD lower limit 0, optimum 1; EF maximum 1, optimum 1; CRM maximum 1, optimum 0

3.3.2 Cacao production in various limited water conditions under monoculture and agroforestry systems

The integration of cacao with shade trees intensifies water competition, as indicated by an increase in the number of days (in fractions) of cacao growth under water-limited conditions, but to varying degrees among different LUS (**Table 3.6**). This unfavourable water-related situation was pronounced in areas with lower annual rainfall (TS>TM>TR). The number of water-limited days for cacao was found to be more sensitive to different cacao root densities than soil textures, with high root density cacao trees showing less time under water-limited conditions. When integrated with the fast-growing timber tree of *F. mollucana*, cacao was estimated to experience the longest total water-limited period, which was 4.5 times longer than cacao monoculture across all scenarios and climate regions. In contrast, the combination with annual crops slightly reduced the number of days of cacao growth under water-limited conditions when compared to cacao monoculture.

Table 3.6. Number of days (represented in time fraction) of cacao growth under water-limited conditions in all scenarios

LUS	Scenario 1			Scenario 2			Scenario 3			Scenario 4		
	TR	TM	TS	TR	TM	TS	TR	TM	TS	TR	TM	TS
Cacao	0.00	0.07	0.27	0.00	0.02	0.17	0.00	0.04	0.24	0.00	0.01	0.15
Cacao + annual crops	0.00	0.02	0.25	0.00	0.00	0.09	0.00	0.03	0.24	0.00	0.00	0.16
Cacao + fruit tree	0.06	0.15	0.35	0.00	0.03	0.35	0.39	0.39	0.44	0.42	0.41	0.45
Cacao + fast-growing tree	0.08	0.42	0.51	0.07	0.20	0.51	0.48	0.51	0.55	0.34	0.38	0.45
Cacao + slow-growing tree	0.00	0.04	0.19	0.00	0.03	0.18	0.00	0.17	0.30	0.26	0.25	0.31

Note: Scenario 1: Silty loam - high cacao root density; scenario 2: Sandy loam - high cacao root density; Scenario 3: Silty loam - low cacao root density; scenario 4: Sandy loam - low cacao root density; TR: tropical rainforest; TM: tropical monsoon; TS: tropical savannah

The integration of trees or crops with cacao in all scenarios and climate regions reduced averaged total cacao production per area by half compared to the monoculture system (**Figure 3.4a**). However, this adverse effect was not necessarily occurred at the individual tree level of production (**Figure 3.4b**). For instance, combining cacao with fruit trees showed a 20% improvement in individual tree production, while combining cacao with a fast-growing timber tree reduced it by 26%. Apparently, the reduction of cacao productivity (per tree and area) was partly affected by the number of days of cacao growth under water-limited conditions.

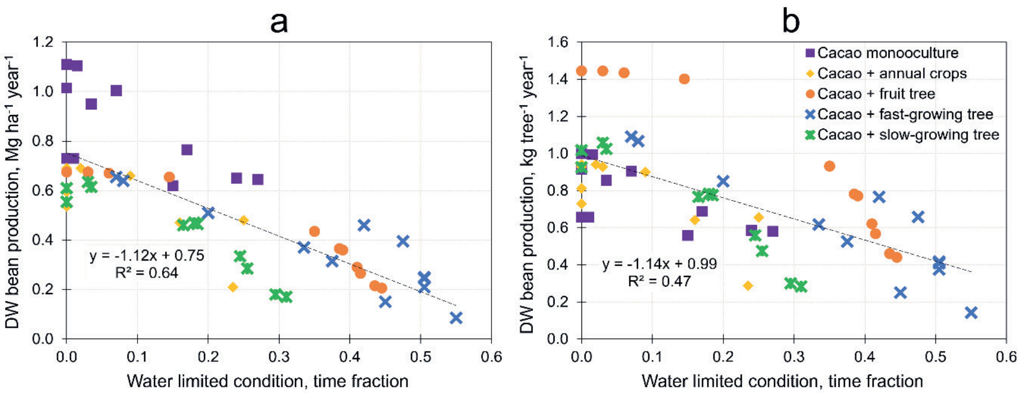

Figure 3.4. The relationship between water-limited conditions (in time fraction) for cacao and the production of cacao **(a)** per area and **(b)** per tree under different LUS

3.3.3 Land productivity and environmental performance indicators

LER_P represents the relative area required for monocropping to achieve the same level of productivity as intercropping (land sparing). Cacao agroforestry was projected to have a positive impact on provisioning services, as indicated by LER_P values >1 (**Table 3.7**), except for the combination of cacao + fruit tree (LER_P 0.98). Intercropping cacao with annual crops was predicted to have the best productivity (LER_P of 1.13), followed by cacao + slow-growing tree, and cacao + fast-growing tree with LER_P of 1.09 and 1.04, respectively.

The provisioning function of cacao-based LUS generally tends to be greater in areas with higher annual rainfall. The difference in root density on provisioning function was noticeable under tropical savannah climate regions, with higher root density positively correlated to higher productivity. Furthermore, the effect of different cacao root densities was more obvious in silt loam soil texture than in sandy loam. LER_P of agroforestry systems for each simulation scenario is presented in **SI 3.5.**

Table 3.7. The main effects summary results of the LUS, climate regions, soil textures, cacao root densities, and its interactions from LER_P (**SI 3.5**) and each regulating service (**SI 3.6**)

Main effects	LER_P	LER_R					
		Time avg ABG. C stock	Litter production	WUE	GWR	Surface runoff*	N Leaching*
LUS							
Cacao	1.00	0.44	1.17	0.58	1.43	2.72	1.38
Cacao + annual crops	1.13	0.31	0.72	0.41	1.28	3.85	1.11
Cacao + fruit tree	0.98	0.67	0.71	0.40	1.40	4.04	1.71
Cacao + fast-growing tree	1.04	0.51	0.74	0.59	1.26	3.62	2.84
Cacao + slow-growing tree	1.09	0.53	0.86	0.44	1.50	3.08	1.54
Climate region							
Tropical rainforest	1.08	0.38	0.80	0.37	1.47	2.90	1.87
Tropical monsoon	1.05	0.52	0.89	0.51	1.27	2.49	1.66
Tropical savannah	1.01	0.55	0.86	0.56	1.43	5.61	1.58
Soil texture							
Silt loam	1.05	0.44	0.74	0.46	1.16	3.46	1.61
Sandy loam	1.05	0.54	0.94	0.51	1.59	NA	1.82
Cacao root density							
High density	1.15	0.54	0.94	0.51	1.36	3.40	1.73
Low density	0.95	0.44	0.74	0.46	1.39	3.52	1.70
Interactions							
Root difference in TR	0.16	0.08	0.20	0.05	-0.04	-0.04	0.03
Root difference in TM	0.15	0.13	0.29	0.08	-0.04	-0.30	0.03
Root difference in TS	0.27	0.08	0.16	0.03	-0.01	-0.02	0.00
Root difference in silt loam	0.22	0.07	0.09	0.03	-0.01	-0.12	0.03
Root difference in sandy loam	0.18	0.11	0.30	0.06	-0.05	NA	0.03

Note: LUS = land use system LER_P = land equivalent ratio for productivity; WUE = water use efficiency; GWR = groundwater recharge; LER_R = land equivalent ratio for regulating services, relative to the natural forest; * = value above 1 means negative impact; NA = not applicable, surface runoff became irrelevant as the value is <1% of total annual rainfall

We used sixth environmental services component to calculate the LER for regulating services (LER_R), including time-averaged aboveground carbon stocks, litter production, WUE, GWR, surface runoff, and N leaching (**SI 3.6**).

Regarding the time-averaged aboveground carbon stocks, cacao-based LUS reduced around half of the carbon stocks expected from the forest, with the effect pronounced in the TR region (**Table 3.7**). However, the reduction as such can be minimized by planting cacao with high root density. We can expect a lower litter production in cacao-based LUS compared to the forest by 16%. Among cacao-based LUS, cacao monoculture was projected to produce more litter than agroforestry systems by around 30-46%. The higher litter production was partly correlated with higher WUE and carbon stocks (biomass production) of the systems (**SI. 3.7**). On average, cacao-based LUS have a considerably lower WUE than the forests. This condition leads to higher GWR, but with an unfavourable consequence of higher N leaching. Planting cacao with high root density, particularly in sandy soil, is beneficial to improve litter production substantially, but not for WUE and N leaching. The calculated LER_R under four different weighing factors based on those environmental components is presented in **SI. 3.8**.

3.3.4 Land equivalent ratio for multifunctionality (LER_M)

LER for multifunctionality (LER_M) was calculated from the combination of LER_P and LER_R using four different weighing factors, including LER_{Meq} (equal), LER_{Mcs} (carbon), LER_{Mwql} (water quality), and LER_{Mwqt} (water quantity). Within cacao-based LUS, cacao + slow-growing tree integration showed the highest averaged multifunctionality performance, specifically for carbon and water quantity functions (**Table 3.8**). In contrast, the combination of cacao + fast-growing tree was projected to have the lowest multifunctionality performance. Cacao monoculture and cacao + annual crops showed comparable overall multifunctionality performance, with the latter offering better water quality functions.

Cacao-based LUS showed consistent multifunctionality performance across climate regions. A significant difference was found between soil textures and cacao root densities. Cacao-based LUS showed better multifunctionality in sandy loam than silt loam. Meanwhile, cacao with high root density provided higher multifunctionality than its counterparts. The difference in root density effect on cacao-based LUS' multifunctionality was pronounced in lower annual rainfall regions. The calculated LER_M under four different weighing is presented in **SI. 3.9**.

Table 3.8. The main effects summary of LUS, climate regions, soil textures, cacao root densities, and their interactions from each LER_M version

Main effects	LER_{Meq}	LER_{Mcs}	LER_{Mwql}	LER_{Mwqt}
LUS				
Cacao	0.92	0.84	0.92	1.01
Cacao + annual crops	0.91	0.84	0.95	1.00
Cacao + fruit tree	0.85	0.84	0.83	0.94
Cacao + fast-growing tree	0.86	0.83	0.82	0.94
Cacao + slow-growing tree	0.93	0.88	0.91	1.03
Climate region				
Tropical rainforest	0.89	0.83	0.89	1.00
Tropical monsoon	0.90	0.85	0.89	0.97
Tropical savannah	0.89	0.85	0.88	0.98
Soil texture				
Silt loam	0.84	0.80	0.85	0.93
Sandy loam	0.94	0.89	0.92	1.05
Cacao root density				
High density	0.96	0.91	0.95	1.05
Low density	0.83	0.78	0.83	0.93
Interactions				
Root difference in TR	0.10	0.11	0.10	0.10
Root difference in TM	0.12	0.13	0.11	0.11
Root difference in TS	0.16	0.16	0.15	0.15
Root difference in silt loam	0.12	0.13	0.12	0.12
Root difference in sandy loam	0.13	0.13	0.12	0.12

Note: LUS = land use systems, LER_{Meq} = Equal LER_M, LER_{Mcs} = carbon centric LER_M, LER_{Mwql} = water quality centric LER_M, LER_{Mwqt} = water quantity centric LER_M.

3.3.5 Economic performance indicators

The economic performance of cacao-based LUS was assessed through three indicators: NPV, BCR, and RtL. On average, cacao agroforestry systems provide higher NPV than monoculture. The combination of cacao + fruit tree showed the highest NPV, followed by cacao + annual crops, cacao + slow-growing tree, and cacao + fast-growing tree with 3, 2.9, 1.2, 1.2 times higher than cacao monoculture, respectively (**Table 3.9**). Meanwhile, for the BC ratio, only the cacao + fast-growing tree combination showed a lower value than the cacao monoculture.

The integration of cacao + fruit tree, and cacao + slow-growing tree showed the highest RtL, indicating this system's compatibility with cacao smallholder context, where labour is the limiting factor for production input. Despite its high NPV and BCR, the combination of cacao + annual crops required more labour than cacao monoculture, indicated by its lower RtL (**Figure 3.5**).

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Table 3.9. The main effects summary of LUS, climate regions, soil textures, cacao root densities, and their interactions from each economic performance indicators

Main effects	NPV, USD ha^{-1}	BCR, ratio	RtL, USD person day^{-1}
LUS			
Cacao	10,422	1.9	24
Cacao + annual crops	30,545	2.6	20
Cacao + fruit tree	31,521	3.8	39
Cacao + fast-growing tree	12,193	1.9	24
Cacao + slow-growing tree	12,280	2.3	33
Climate region			
Tropical rainforest	27,406	3.0	35
Tropical monsoon	19,986	2.5	29
Tropical savannah	9,963	1.9	19
Soil texture			
Silt loam	19,925	2.5	29
Sandy loam	18,859	2.4	27
Cacao root density			
High density	23,653	2.8	35
Low density	15,131	2.1	21
Interactions			
Root difference in TR	11,189	0.9	18
Root difference in TM	6,738	0.6	11
Root difference in TS	6,029	0.5	10
Root difference in silt loam	8,022	0.7	13
Root difference in sandy loam	9,022	0.7	14

Note: LUS = land use system NPV = net present value, BCR= benefit cost ratio, RtL = return to labour

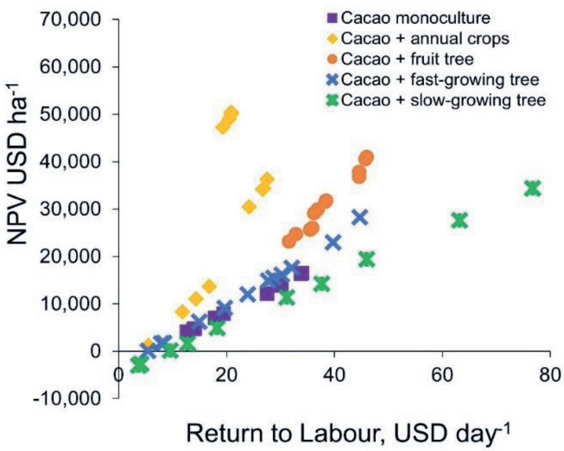

Figure 3.5. The relationship between return to labour (RtL) and net present value (NPV) of each cacao-based LUS

Developing cacao-based LUS in high annual rainfall regions offered better economic performances, as shown by all three economic performance indicators. Cacao-based LUS in TR provided 30 and 60% higher NPV, 20 and 40% higher BCR, and 10 and 40% higher RtL compared to TM and TS, respectively. While no considerable difference was found in growing cacao in silt loam and sandy loam soil textures, planting cacao with high root density has better economic performance, shown by 40% higher NPV and RtL, and 20% higher BCR than its counterparts. The benefit of planting cacao with high root density was more pronounced in TR than in other climate regions. The economic performance of all cacao-based LUS of each simulation scenario is presented in **SI 3.10.**

3.4 Discussion

The study explored the trade-off between the provisioning and regulating functions and the economic performance of cacao-based LUS in different scenarios, including soil textures, cacao root densities and climate regions. We used multiple metrics, including LER_P, LER_R, and LER_M for provisioning and regulating services, and NPV, BCR, and RtL for economic performance, to identify the best performance of cacao-based systems within those scenarios.

3.4.1 Cacao agroforestry increased water competition but did not necessarily reduce cacao production per tree

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It has been suggested that combining cacao with shade trees can serve as an adaptation strategy under severe adverse climate events such as drought (Tscharntke et al. 2011; Vaast and Somarriba 2014). However, our model simulation indicates that integrating shade trees or annual crops with cacao may increase water competition. Agroforestry systems increased the number of days of cacao growth under water-limited conditions, particularly in areas with lower annual rainfall, and used trees as companion plants to cacao (**Table 3.6**).

The sensitivity of cacao to water-limited conditions depends on its root density and the type of companion trees/crops. Quinkenstein et al. (2009) reported a similar conclusion, which found that the intensity of water competition depends on tree and crop species and, thus, on the relative root distribution of the trees and crops. Our results showed that the impact of different cacao root densities on production was more obvious than the effect of distinct soil texture (**Table 3.7**), with high root density cacao trees (scenarios 1 and 2) showing lesser time under water-limited conditions, and thus provided higher cacao production. A simulation study by Zuidema et al. (2005) using the SUCROS-cacao model, which is based on aboveground growth and physiology of cacao, found that the variation in simulated bean yield across 30 locations in 10 cacao-producing countries could be explained by a combination of annual radiation and rainfall during the two driest months. This result suggests a limited buffering capacity of the soil and root system of cacao in the dataset on which the model was calibrated (Ghana and Malaysia).

The competitive power of trees for water is proportional to their root density. Higher root density increases water uptake from the soil due to a more extensive water exploration area than low root density, enabling cacao trees to withstand water-limited conditions better. This statement is supported by our simulation results that found the average WUE of cacao-based LUS with high root density is nearly 10% higher than its counterparts (**Table 3.7**). Previous studies on crops and trees have shown that different root densities influence plant productivity and survival under water scarcity (Comas et al. 2013; Lobet et al. 2014; Solari et al. 2006a; Solari et al. 2006b). Plant with higher fine root density has a larger surface root area, resulting in higher WUE per soil area and greater ability to access water from the deep soil profile, particularly for plants with vertically distributed root density (Zhang et al. 2020). In contrast, plants with low root density may even have lower root exploration area and water acquisition during extreme drought conditions as root length density decreases (Zhou et al. 2018). Ongoing selection efforts for drought-resistant cacao in Venezuela and Brazil have identified promising clones with the potential for integration into breeding programs (Silva et al. 2023; Tezara et al. 2020). However, the specific investigations did not explicitly report on the rooting traits of these identified clones.

In the water-limited environment, the 'ideotype' of the root system would have roots evenly distributed along the depth axis, allowing for the exploration of resources on a larger soil volume (Lahive et al. 2018; Lynch 2013) and redistributing water from subsoil into the upper soil layers through hydraulic lift (Bayala and Prieto 2020). Additionally, a lower density of roots in the topsoil would allow the plant to extract water from deeper soil layers (Wasson et al. 2012), thus reducing water resource competition. However, it is essential also to consider the effect of lower root density in topsoil on nutrient acquisitions, which warrants further investigation. Under nutrient-limited conditions, reduced topsoil cacao root density may limit their competitiveness in nutrient foraging compared to companion plants, particularly for immobile and shallow-depth concentrated phosphorus. The carbon efficiency for nutrient acquisition or 'rhizoeconomic' of having a root system as such also needs further exploration (Wang et al. 2022).

The common hypothesis that states the net effect of integrating trees with high root density could lead to higher resource-related competition, thus reducing productivity, was not necessarily confirmed by this modelling study. Apparently, under a rather 'conservative' planting configuration of alley cropping used in this simulation, the strategic placement and optimal tree density provided adequate space for the cacao to explore water and nutrients. Hence, cacao productivity in agroforestry systems was not significantly limited by interspecific competition, or the positive effects (complementarity) of the intercropped trees outweighed any competition effects (Jaimes-Suárez et al. 2022; Niether et al. 2019; Rajab et al. 2018) under certain agroforestry combinations.

The sensitivity of agroforestry systems to water scarcity differs based on their specific companion tree species combination. For instance, despite having comparable tree populations, cacao integrated with a slow-growing *T. grandis* system has a higher yield than cacao + fast-growing leguminous tree species *F. mollucana*, particularly under lower annual rainfall. Fast-growing leguminous trees, which have access to additional nitrogen, are known to use a large amount of water, even in water-limited environments (Adams et al. 2016). The increased water usage beyond the system's buffering capacity resulted in higher water competition, leading to lower growth, production, and even cacao mortality, especially under extended severe drought conditions, as reported by Abdulai et al. (2018b) in Ghana. However, under the high annual rainfall of tropical agroforestry in Costa Rica, Nygren et al. (2013) reported that combining cacao + leguminous tree of *Inga edulis* could provide positive interaction for the N nutrition of cacao, but with envisioned competition for other nutrients. This nutrient competition can be minimized by fertilization and pruning management, as suggested by Muñoz and Beer (2001).

3.4.2 Agroforestry outperforms monoculture in terms of multifunctionality when the primary goal is aboveground carbon stocks

We found that agroforestry systems generally have the potential to increase provisioning (LER_P) and time-averaged aboveground carbon stocks functions. Many studies have reported total aboveground biomass and carbon stock improvement after practising agroforestry (Mortimer et al. 2018; Niether et al. 2019; Sari et al. 2020). The positive effects of agroforestry were especially pronounced under water-limited regions when cacao was intercropped with slow-growing timber trees and annual crops. Under the TS climate region, slow-growing timber trees provide less water competition to cacao than other tree-based agroforestry systems. However, our current simulations also suggested that agroforestry practices may be followed by unfavourable effects, such as lower litter production, WUE, and GWR, and higher surface runoff and nitrogen leaching, compared to cacao monoculture (**SI 3.6**). The adverse effects of cacao-based agroforestry, such as lower WUE and higher N leaching, were more pronounced in areas with higher annual rainfall.

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Different cacao root density significantly influences the productivity and environmental performance of cacao-based production systems (**Table 3.7**). Cacao with high root density was projected to have higher WUE but lower litter production and GWR than its counterparts. High WUE indicates that the plants can use a high fraction of rainfall, thus lowering litter production induced by water-limited conditions. However, this condition leads to a lower amount of water that can be permeated into the deep soil layer as a source of groundwater recharge, as a significant fraction of rainfall ends up as surface runoff, which is intensified by the lack of soil surface protection and water retention time in the soil surface, and lower soil infiltration, as a consequence of lower litter production (Saputra et al. 2020).

The multifunctionality perspective considers provisioning (LER_P) and regulating services (LER_R). This perspective is subject to stakeholder preferences regarding the relative importance of a function over others. We considered an equal and three other versions of the weighing factor for LER_R to calculate the LER_M. Our results indicated that when the target function was carbon stocks (LER_{Mcs}), agroforestry systems had higher average multifunctionality value than monoculture. However, when the target functions were water-related (LER_{Mwql} and LER_{Mwqt}), only the integration of cacao + annual crops and cacao + slow-growing trees, respectively, were found to be better than monoculture. It is worth noting that the specific tree/crop intercropped with cacao and the difference in cacao root density and soil texture led to distinct multifunctionality values (**Table 3.8**). This complexity, aligned with a review by Mortimer et al.

(2018), reported that cacao agroforestry could provide a wide range of support for provisioning and regulating services but is highly complex and context-dependent.

However, our multifunctionality assessment did not account for the beneficial effects of agroforestry on preserving biodiversity, improving pests and disease protection, and pollination (Mortimer et al. 2018; Udawatta et al. 2019). Tree diversity and shade cover management in agroforestry systems can enhance cacao pollinator habitat, which is critical for cacao production (Toledo-Hernández et al. 2017). Tree diversity is also advantageous in reducing fruit abortion (Bos et al. 2007). Therefore, to fully comprehend the effect of agroforestry on cacao-based LUS, the regulating services as such are also crucial to be considered.

3.4.3 Agroforestry systems not necessarily provided better economic performance than monoculture

The economic performance of agroforestry systems was assessed using three indicators: net present value (NPV), benefit-cost ratio (BCR), and return to labour (RtL). These indicators provide insight into agroforestry practices' profitability and financial sustainability compared to monoculture cacao. The overall results showed that agroforestry systems not necessarily provided better economic performance than monoculture. For instance, integrating low root density cacao + slow-growing trees in all climate regions must be carefully considered, as our simulation result indicated that this system provides lower NPV, BCR and RtL than monoculture. Similarly, integrating cacao (high and low root density) + fast-growing trees under water-limited conditions also resulted in lower economic performance than cacao monoculture.

On the other hand, integrating cacao + fruit tree offered the highest profit in terms of NPV, BCR, and RtL. A high RtL is essential, as cacao-based production systems are mainly smallholder farmers with limited labour availability. This result is consistent with the findings of Jaimes-Suárez et al. (2022), who reported that agroforestry's long-term benefit is reducing the required labour force. Product diversification in cacao-based agroforestry also can provide income stability and lower financial risk than cacao monoculture, especially when the cacao price fluctuates (Ramírez et al. 2001).

However, the agroforestry systems we tested in this study adopted the alley cropping configuration, which aimed to minimize resource-related competition between trees. The common traditional agroforestry practices of simply substituting cacao stand with shade tree species (simple and complex agroforestry) while maintaining the same plant density as the monoculture system may yield different results than our current simulation scheme. Another plausible option to have more than one type of system configuration (combination of cacao + different crops/trees) at a time, to gain more diversity and potentially improved economic benefits and reduced crop-tree interaction at the farm scale, is also beyond our current simulation study and merits further investigation. Moreover, our current economic performance analysis assumed stable prices, market demand, and production input prices, with no limitations on labour availability. Therefore, changes in assumptions as such could return in different outcomes and conclusions.

3.5 Conclusions

Cacao-based agroforestry systems, as investigated using the WaNuLCAS model, offer a range of economic and environmental trade-offs. Our simulation showed that practicing agroforestry could reduce cacao production per area, but not necessarily cacao production per tree. Furthermore, our findings demonstrated that agroforestry systems had overall better multifunctionality than monoculture when the primary target function was for higher time-averaged aboveground carbon stocks. Meanwhile, the variance of the agroforestry system performance compared to monoculture for the other target functions was determined by the specific intercropped tree/crop species. Cacao with high root density provides higher productivity and multifunctionality than its counterparts, particularly when cultivated in a water-limited region. Finally, integrating cacao with annual crops and cacao with fruit trees was found to be the best approach to achieving the highest economic performance, with the latter combination providing better RtL, which is highly relevant to the Indonesian context, as the cacao-based production systems are primarily smallholder farmers with limited labour availability. Choices made in the past in cacao germplasm development, especially breeding and selection for high yield in monoculture systems has limited the opportunities for cacao integration in mixed, climate-resilient LUS, renewed attention for belowground allocation of cacao is warranted.

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3.6 Supplementary information

SI 3.1. Fertilizer quantity and application schedule

Schedule (year)	*T. cacao*			*P. cablin*			*D. zibethinus*			*F. mollucana*			*T. grandis*		
	N	P	Manure	N	P	Manure	N	P	Manure	N	P	Manure	N	P	Manure
	kg ha^{-1}														
1	25	20	5500	25	20	5500	25	20	5500	39	55	8000	25	5	8000
2	25	20	5500	25	20	5500	25	20	5500	39	55	8000	25	5	8000
3	41	32	5500	25	20	5500	41	32	5500	39	55	8000	48	10	8000
>3	129	162	5500	25	20	5500	129	162	5500	39	55	8000	72	14	8000

SI 3.2. The main aboveground and belowground characteristics used for trees and crop parameterisation in the WaNuLCAS model

Tree parameter	Units	*T. cacao*	*F. mollucana*	*D. zibethinus*	*T. grandis*	*P. cablin*
Max canopy radius	m	3.5	4.8	8.0	5.0	-
Max leaf Area Index (LAI)	[]	2.7	2.5	3.0	5.0	5.0
Max. root length density layer 1 (0-22 cm)	cm cm^{-3}	2.1	1.0	2.0	1.3	2.1
Max. root length density layer 2 (23-53 cm)	cm cm^{-3}	0.4	0.7	1.7	0.3	0.5
Max. root length density layer 3 (54-79 cm)	cm cm^{-3}	0.4	0.3	1.3	0.1	0.2
Max. root length density layer 4 (80-100 cm)	cm cm^{-3}	0.6	0.1	1.1	0.1	0.0

SI 3.3. Weighing factor distribution used to calculate LER_R based on its preferred regulating functions

LER_R	Weighing factor, fraction					
	Time avg ABG. C stock	**Litter production**	**WUE**	**GWR**	**Surface runoff**	**N Leaching**
LER_{Req}	0.20	0.20	0.20	0.20	0.00	0.20
LER_{Rcs}	0.50	0.13	0.13	0.13	0.00	0.13
LER_{Rwql}	0.13	0.20	0.13	0.13	0.00	0.40
LER_{Rwqt}	0.13	0.20	0.13	0.40	0.00	0.13

Note: LER_{Req} = Equal LER_R, LER_{Rcs} = carbon centric LER_R, LER_{Rwql} = water quality centric LER_R, LER_{Rwqt} = water quantity centric LER_R, WUE = water use efficiency, GWR = groundwater recharge

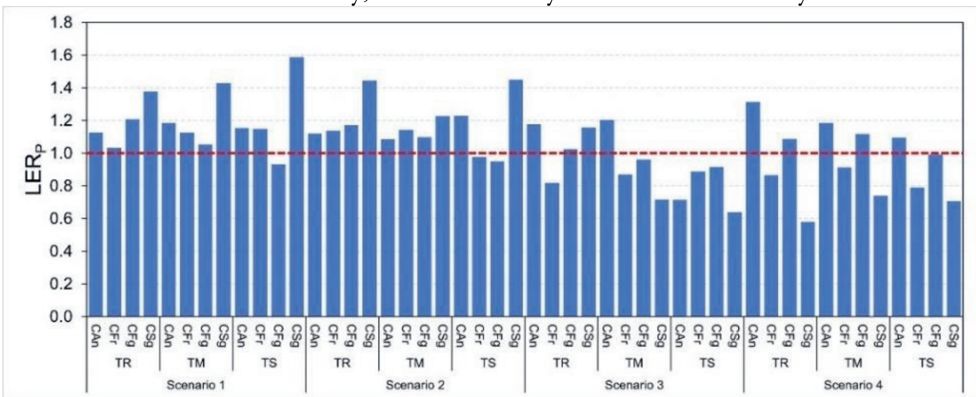
SI 3.4.a. Market prices of each commodity used in the simulations

Commodity	Product	Unit	Price, US$
T. cacao	Dry beans	kg	1.83
P. cablin	Dry weight	kg	0.83
F. mollucana	Wood log	m^3	50
T. grandis	Wood log	m^3	453.3
D. zibethinus	Fresh fruit	kg	0.67

SI 3.4. b. Production input prices and labour wage rates used to assess the economic performance

Variable	Unit	Price, US$
Fertilizer		
SP-36	kg	0.5
Urea	kg	0.6
Manure	Mg	83.3
Chemical		
Herbicide	litre	8.7
Pesticide	litre	10.7
Planting material		
T. cacao	indiv	0.7
T. grandis	indiv	1.0
P. cablin	indiv	0.1
D. zibethinus	indiv	2.3
F. mollucana	indiv	0.9
Equipment		
Spraying tank	unit	33.3
Hoe	unit	2.3
Machete	unit	2.3
Wheelbarrow	unit	23.3
Labour		
Planting preparations	working day	5.3
Others	working day	4.0

SI 3.5. Land equivalent ratio for productivity (LER_P) of agroforestry systems for each simulation scenario. Red dash line: reference value from cacao monoculture. CAn: cacao + annual crops, CFr: cacao + fruit tree, CFg: cacao + fast-growing tree, CSg: cacao + slow-growing tree. TR: tropical rainforest, TM: tropical monsoon, TS: tropical savannah. Scenario 1: silt loam - high cacao root density, Scenario 2: sandy loam - high cacao root density, Scenario 3: silt loam - low root density, Scenario 4: sandy loam - low root density



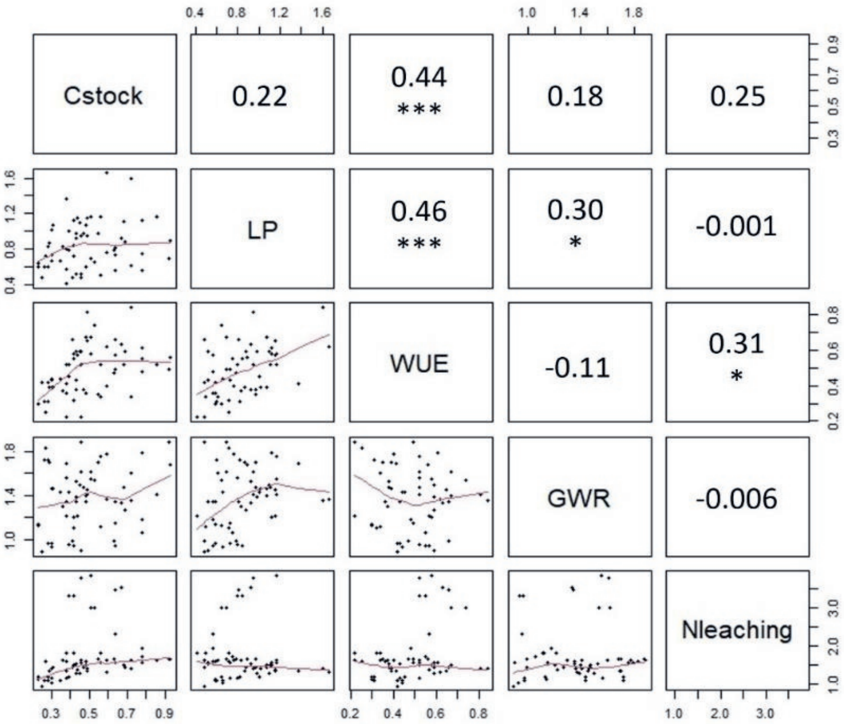
SI 3.6. Land sharing as indicated by six regulating services (LER_R) for each simulated scenario

Scenario	Climate region	LUS	LER_R Time avg ABG. C stock	Litter production	WUE	GWR	Surface runoff*	N Leaching*
Silt loam - high cacao root density (scenario 1)	Tropical rainforest	Cacao	0.31	1.07	0.39	1.46	2.34	1.43
		Cacao + annual crops	0.23	0.64	0.30	1.13	3.04	1.16
		Cacao + fruit tree	0.42	0.72	0.32	1.11	3.37	1.80
		Cacao + fast growing tree	0.42	0.84	0.55	0.94	2.99	3.31
		Cacao + slow growing tree	0.48	0.59	0.36	1.35	2.68	1.59
	Tropical monsoon	Cacao	0.44	1.15	0.57	1.22	1.82	1.36
		Cacao + annual crops	0.30	0.73	0.43	0.97	2.31	1.15
		Cacao + fruit tree	0.63	0.78	0.47	0.99	2.46	1.66
		Cacao + fast growing tree	0.64	0.56	0.57	0.95	2.27	2.32
		Cacao + slow growing tree	0.64	0.73	0.49	1.15	2.08	1.54
	Tropical savannah	Cacao	0.49	1.15	0.65	1.45	3.25	1.34
		Cacao + annual crop	0.30	0.66	0.44	0.93	6.04	1.03
		Cacao + fruit tree	0.78	0.75	0.55	1.06	6.20	1.71
		Cacao + fast growing tree	0.43	0.52	0.43	1.35	5.59	1.53
		Cacao + slow growing tree	0.69	0.88	0.59	1.27	4.55	1.44
Sandy loam - high cacao root density (scenario 2)	Tropical rainforest	Cacao	0.38	1.37	0.41	1.69		1.34
		Cacao + annual crops	0.28	0.82	0.31	1.72		1.17
		Cacao + fruit tree	0.55	0.97	0.35	1.70		1.66
		Cacao + fast growing tree	0.51	1.17	0.58	1.55		3.84
		Cacao + slow growing tree	0.59	0.76	0.40	1.78		1.60
	Tropical monsoon	Cacao	0.59	1.66	0.62	1.37		1.30
		Cacao + annual crops	0.39	1.00	0.45	1.43		1.16
		Cacao + fruit tree	0.86	1.16	0.52	1.41	NA	1.62
		Cacao + fast growing tree	0.67	0.92	0.63	1.33		3.52
		Cacao + slow growing tree	0.68	1.11	0.52	1.47		1.50
	Tropical savannah	Cacao	0.72	1.60	0.84	1.36		1.40
		Cacao + annual crops	0.45	1.10	0.59	1.50		1.28
		Cacao + fruit tree	0.93	0.89	0.56	1.68		1.66
		Cacao + fast growing tree	0.51	0.69	0.67	1.62		3.00
		Cacao + slow growing tree	0.78	1.12	0.61	1.79		1.55
Silt loam - low cacao root density (scenario 3)	Tropical rainforest	Cacao	0.30	1.02	0.39	1.46	2.36	1.40
		Cacao + annual crops	0.23	0.59	0.30	1.14	3.07	1.10
		Cacao + fruit tree	0.38	0.41	0.22	1.21	3.44	1.79
		Cacao + fast growing tree	0.39	0.79	0.52	0.96	3.06	3.32
		Cacao + slow growing tree	0.38	0.57	0.36	1.35	2.68	1.59
	Tropical monsoon	Cacao	0.42	1.12	0.58	1.20	3.26	1.50
		Cacao + annual crops	0.28	0.59	0.42	0.97	2.33	1.09
		Cacao + fruit tree	0.56	0.50	0.34	1.12	2.50	1.81
		Cacao + fast growing tree	0.46	0.52	0.59	0.90	2.32	1.54
		Cacao + slow growing tree	0.36	0.83	0.37	1.30	2.07	1.62
	Tropical savannah	Cacao	0.48	1.07	0.67	1.40	3.26	1.50
		Cacao + annual crops	0.25	0.48	0.42	0.89	6.28	0.93
		Cacao + fruit tree	0.78	0.56	0.48	1.18	6.30	1.93
		Cacao + fast growing tree	0.41	0.48	0.66	0.99	5.47	1.42
		Cacao + slow growing tree	0.47	0.97	0.38	1.47	4.43	1.42
Sandy loam - low cacao root density (scenario 4)	Tropical rainforest	Cacao	0.29	0.87	0.39	1.70		1.34
		Cacao + annual crops	0.26	0.60	0.31	1.72		1.08
		Cacao + fruit tree	0.46	0.48	0.22	1.89		1.62
		Cacao + fast growing tree	0.46	0.95	0.52	1.61		3.78
		Cacao + slow growing tree	0.27	0.72	0.25	1.83		1.57
		Cacao	0.43	0.98	0.59	1.39		1.28

	Cacao + annual crops	0.35	0.66	0.44	1.43		1.08
Tropical monsoon	Cacao + fruit tree	0.72	0.61	0.34	1.60	NA	1.60
	Cacao + fast growing tree	0.64	0.81	0.66	1.34		3.48
	Cacao + slow growing tree	0.43	0.92	0.38	1.53		1.53
Tropical savannah	Cacao	0.49	0.95	0.81	1.41		1.38
	Cacao + annual crops	0.38	0.80	0.52	1.56		1.15
	Cacao + fruit tree	0.92	0.69	0.49	1.88		1.65
	Cacao + fast growing tree	0.53	0.65	0.74	1.54		2.99
	Cacao + slow growing tree	0.56	1.16	0.52	1.76		1.54

Note: LUS = land use system WUE = water use efficiency, GWR = groundwater recharge, LER_R = land equivalent ratio for regulating services, relative to the natural forest. * = value above 1 means negative impact. NA = not applicable, surface runoff became irrelevant as the value is <1% of total annual rainfall

SI 3.7. The correlation between environmental indicators including time-averaged aboveground C-stocks (Cstock), litter production (LP), water use efficiency (WUE), groundwater recharge (GWR), and N leaching. Surface runoff was excluded from the analysis as the values were insignificant in sandy loam (scenario 2 and 4).

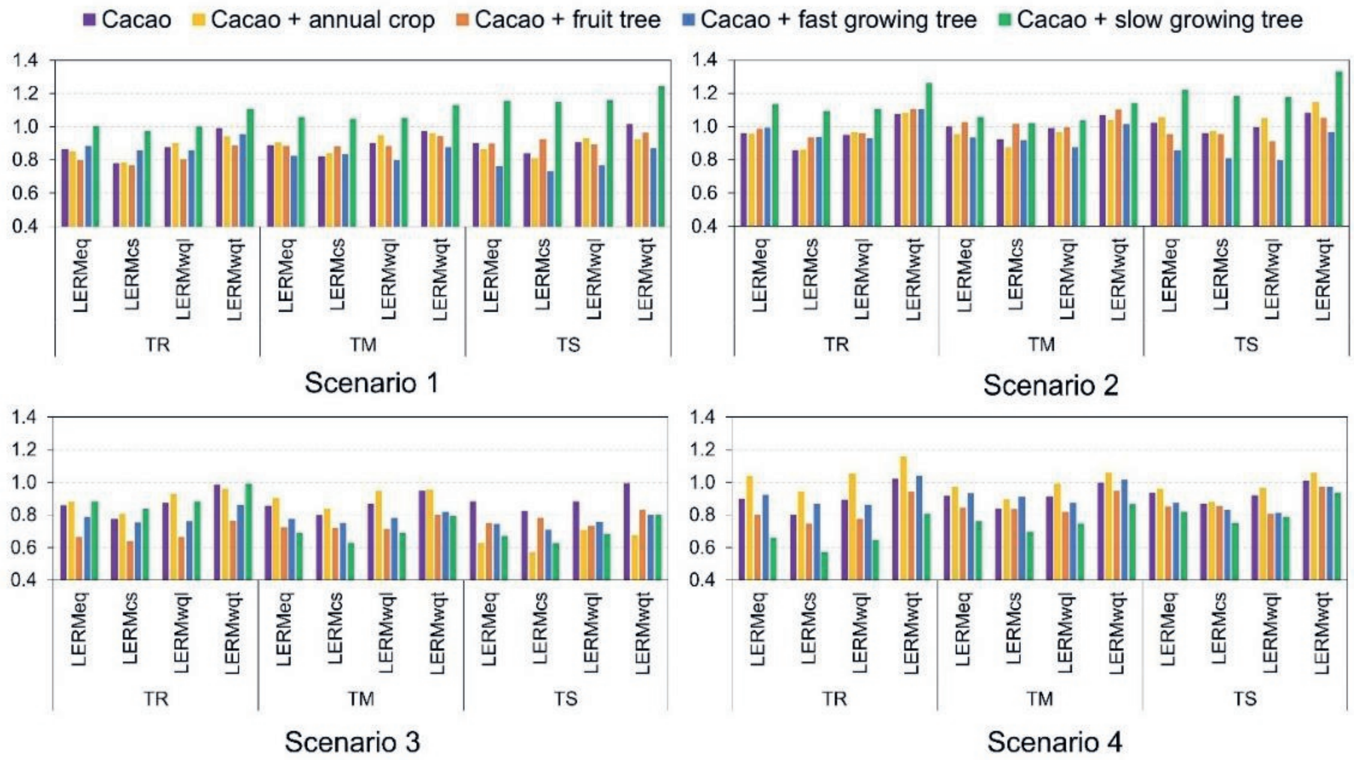


SI 3.8. Land equivalent ratio for regulating services (LER_R) under four different weighing factors based on its functions (aboveground carbon stocks, water quality and water quantity)

Scenario	LUS	LER_{Req}			LER_{Rcs}			LER_{Rwql}			LER_{Rwqt}		
		TR	TM	TS	TR	TM	TS	TR	TM	TS	TR	TM	TS
Silty loam - high root density (scenario 1)	Cacao	0.73	0.78	0.80	0.56	0.64	0.68	0.75	0.80	0.82	0.98	0.95	1.03
	Cacao + annual crop	0.58	0.62	0.58	0.44	0.49	0.47	0.67	0.71	0.71	0.75	0.74	0.69
	Cacao + fruit tree	0.57	0.64	0.65	0.51	0.64	0.70	0.58	0.65	0.64	0.74	0.76	0.78
	Cacao + fast growing tree	0.57	0.60	0.59	0.51	0.61	0.53	0.51	0.54	0.60	0.71	0.70	0.81
	Cacao + slow growing tree	0.63	0.69	0.72	0.57	0.67	0.71	0.63	0.68	0.73	0.84	0.83	0.90
Sandy loam - high root density (scenario 2)	Cacao	0.92	1.00	1.05	0.71	0.84	0.92	0.90	0.98	0.99	1.15	1.14	1.17
	Cacao + annual crop	0.80	0.83	0.88	0.60	0.66	0.72	0.81	0.85	0.87	1.04	1.00	1.06
	Cacao + fruit tree	0.84	0.91	0.93	0.73	0.89	0.93	0.78	0.85	0.84	1.08	1.06	1.13
	Cacao + fast growing tree	0.81	0.77	0.76	0.70	0.73	0.67	0.69	0.65	0.64	1.03	0.93	0.99
	Cacao + slow growing tree	0.83	0.89	0.99	0.74	0.81	0.91	0.77	0.84	0.91	1.08	1.06	1.21
Silty loam - low root density (scenario 3)	Cacao	0.72	0.71	0.77	0.55	0.60	0.65	0.75	0.74	0.77	0.97	0.90	0.99
	Cacao + annual crop	0.58	0.60	0.55	0.44	0.47	0.43	0.68	0.69	0.70	0.75	0.71	0.64
	Cacao + fruit tree	0.51	0.58	0.61	0.46	0.57	0.68	0.52	0.56	0.58	0.71	0.73	0.78
	Cacao + fast growing tree	0.55	0.59	0.57	0.48	0.54	0.51	0.50	0.60	0.60	0.70	0.68	0.69
	Cacao + slow growing tree	0.61	0.66	0.70	0.52	0.54	0.61	0.61	0.67	0.73	0.83	0.87	0.96
Sandy loam - low root density (scenario 4)	Cacao	0.80	0.83	0.88	0.61	0.68	0.73	0.79	0.83	0.84	1.04	0.99	1.02
	Cacao + annual crop	0.76	0.76	0.83	0.57	0.61	0.66	0.79	0.80	0.84	1.01	0.93	1.02
	Cacao + fruit tree	0.73	0.78	0.92	0.63	0.76	0.92	0.68	0.73	0.82	1.02	0.99	1.16
	Cacao + fast growing tree	0.76	0.75	0.76	0.65	0.71	0.67	0.64	0.63	0.64	1.00	0.91	0.96
	Cacao + slow growing tree	0.74	0.78	0.93	0.57	0.65	0.79	0.71	0.76	0.87	1.03	0.99	1.17

Note: LUS = land use system, LER_{Req} = Equal LER_R, LER_{Rcs} = carbon centric LER_R, LER_{Rwql} = water quality centric LER_R, LER_{Rwqt} = water quantity centric LER_R.

SI 3.9. Multifunctional land equivalent ratio (LER_M) based on the land sparing indicator for provisioning function (LER_P) and land sharing indicator for regulating services indicator (LER_R) for each simulation scenario. LER_{Meq} = Equal LER_M, LER_{Mcs} = carbon centric LER_M, LER_{Mwql} = water quality centric LER_M, LER_{Mwqt} = water quantity centric LER_M. TR = tropical rainforest, TM = tropical monsoon, TS = tropical savannah. Scenario 1: silt loam-high cacao root density, Scenario 2: sandy loam- high cacao root density, Scenario 3: silt loam-low root density, Scenario 4: sandy loam-low root density



SI 3.10. Economic performance indicators represented as Net Present Value (NPV), Benefit Cost Ratio (BCR), and Return to Labour (RtL) for each simulation scenario

Scenario	Climate region	LUS	NPV, USD ha^{-1}	BCR, ratio	RtL, USD person day^{-1}
Silt loam - high cacao root density (scenario 1)	Tropical rainforest	Cacao	16,498	2.4	34
		Cacao + annual crop	50,113	3.6	21
		Cacao + fruit tree	36,824	4.2	45
		Cacao + fast-growing tree	28,278	2.9	45
		Cacao + slow-growing tree	34,363	4.3	77
	Tropical monsoon	Cacao	13,951	2.2	30
		Cacao + annual crop	36,307	3.0	28
		Cacao + fruit tree	37,825	4.3	45
		Cacao + fast-growing tree	14,925	2.1	28
		Cacao + slow-growing tree	27,607	3.6	63
	Tropical savannah	Cacao	4,678	1.4	14
		Cacao + annual crop	11,104	1.7	14
		Cacao + fruit tree	26,085	3.3	36
		Cacao + fast-growing tree	6,239	1.5	15
		Cacao + slow-growing tree	14,245	2.4	38
Sandy loam - high cacao root density (scenario 2)	Tropical rainforest	Cacao	16,498	2.4	34
		Cacao + annual crop	49,078	3.5	20
		Cacao + fruit tree	41,003	4.5	46
		Cacao + fast-growing tree	22,992	2.7	40
		Cacao + slow-growing tree	34,363	4.3	77
	Tropical monsoon	Cacao	16,367	2.4	34
		Cacao + annual crop	34,408	2.9	27
		Cacao + fruit tree	40,512	4.5	46
		Cacao + fast-growing tree	15,508	2.1	29
		Cacao + slow-growing tree	19,430	2.8	46
	Tropical savannah	Cacao	7,966	1.7	19
		Cacao + annual crop	13,665	1.8	17
		Cacao + fruit tree	25,653	3.3	35
		Cacao + fast-growing tree	1,769	1.2	8
		Cacao + slow-growing tree	11,338	2.2	31
Silt loam - low cacao root density (scenario 3)	Tropical rainforest	Cacao	13,848	2.2	30
		Cacao + annual crop	50,431	3.6	21
		Cacao + fruit tree	31,566	3.8	38
		Cacao + fast-growing tree	17,592	2.3	32
		Cacao + slow-growing tree	4,919	1.6	18
	Tropical monsoon	Cacao	12,177	2.1	27
		Cacao + annual crop	34,151	2.9	27
		Cacao + fruit tree	31,809	3.8	38
		Cacao + fast-growing tree	9,118	1.7	20
		Cacao + slow-growing tree	4,919	1.6	18
	Tropical savannah	Cacao	4,828	1.4	14
		Cacao + annual crop	1,213	1.1	5
		Cacao + fruit tree	24,742	3.2	33
		Cacao + fast-growing tree	71	1.1	5
		Cacao + slow-growing tree	-2,670	1.0	4
Sandy loam - low cacao root density (scenario 4)	Tropical rainforest	Cacao	7,064	1.6	18
		Cacao + annual crop	47,250	3.4	19
		Cacao + fruit tree	29,139	3.6	36
		Cacao + fast-growing tree	16,152	2.2	30
		Cacao + slow-growing tree	158	1.2	10
	Tropical monsoon	Cacao	7,064	1.6	18
		Cacao + annual crop	30,511	2.6	24
		Cacao + fruit tree	29,937	3.6	37
		Cacao + fast-growing tree	12,006	1.9	24

	Cacao + slow-growing tree	1,663	1.4	13
Tropical savannah	Cacao	4,128	1.4	13
	Cacao + annual crop	8,303	1.5	12
	Cacao + fruit tree	23,153	3.1	32
	Cacao + fast-growing tree	1,660	1.2	8
	Cacao + slow-growing tree	-2,969	1.0	4

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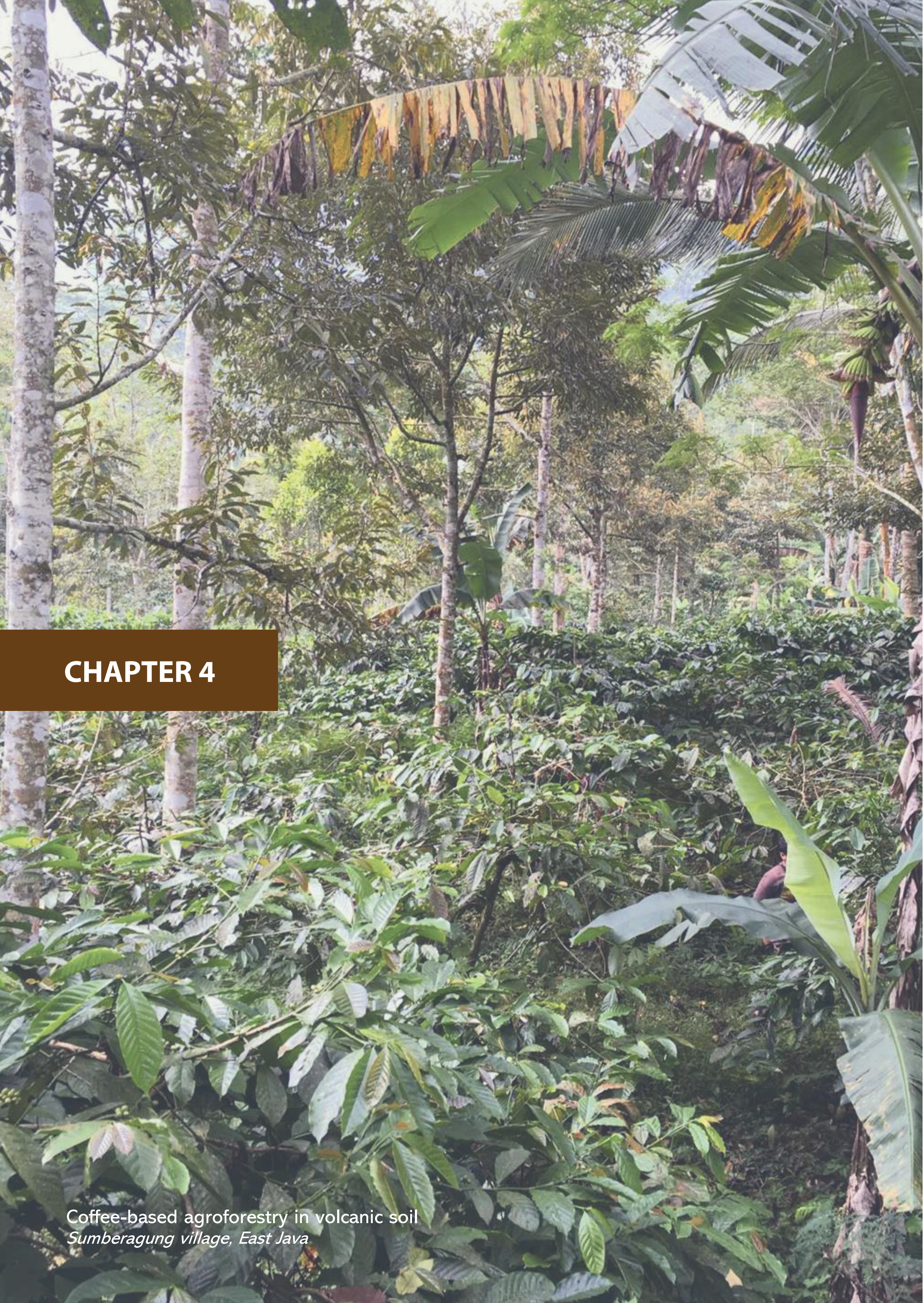

CHAPTER 4

Coffee-based agroforestry in volcanic soil
Sumberagung village, East Java

Recovery after volcanic ash deposition: vegetation effects on soil organic carbon, soil structure and infiltration rates

This chapter is based on published article:

Saputra DD, Sari RR, Hairiah K, Widianto, Suprayogo D, van Noordwijk M (2022). Recovery after volcanic ash deposition: vegetation effects on soil organic carbon, soil structure and infiltration rates.

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Abstract

Volcanic eruptions of pyroclastic tephra, including the ash-sized fraction (<2 mm; referred to as volcanic ash), have negative direct impacts on soil quality. The intensity (deposit thickness, particle-size distribution) and frequency (return period) of tephra deposition influence soil formation. Vulnerability and subsequent recovery (resilience) of the plant-soil system depend on land uses (vegetation and management). Few previous studies covered the whole deposition-recovery cycle. We investigated the volcanic ash deposition effects on soil properties and their recovery across land-uses on a densely populated volcanic slope.

We measured the canopy cover and volcanic ash thickness six years after the 2014 Mt. Kelud eruption in four land use systems: remnant forests, complex agroforestry, simple agroforestry, and annual crops. Each system was monitored in three landscape replicates (total 12 plots). For the soil recovery study, we measured litter thickness, soil texture, SOC, soil C stocks, aggregate stability, porosity, and soil infiltration in three different observation periods (pre-eruption, three, and six years after eruption).

Post-eruption volcanic ash thickness varied between land use systems and was influenced by the plots slope position rather than canopy cover. The average soil texture and porosity did not vary significantly between the periods. Surface volcanic ash and soil layers initially had low aggregate stability and limited soil infiltration, demonstrating hydrophobicity. While SOC slowly increased from low levels in the fresh volcanic ash, surface litter layer, aggregate stability, and soil infiltration quickly recovered.

Different land-use management resulted in different recovery trajectories of soil physical properties and function over the medium to long term after volcanic ash deposition.

Keywords: volcanic eruption, resilience, agroforestry, hydrophobicity, soil quality, soil degradation, soil restoration, tephra

4.1 Introduction

Volcanic soils have extraordinarily high soil fertility once ash deposited on the surface has become soil with Andic properties (Sanchez 2019). However, farming on volcanic slopes and adjacent valleys also involves exposure to extreme circumstances during volcanic eruptions. This includes pyroclastic materials deposition of <2 mm tephra fractions (it includes sand, silt and clay particles in conventional texture analysis) which is often directly referred to as 'volcanic ash' (Arnalds 2013; Fuentes et al. 2020; Müller et al. 2019; Rossi et al. 2021; Suh et al. 2019), and subsequent volcanic ash (VA) movement in the landscape (Anda et al. 2016; Ayris and Delmelle 2012; Zobel and Antos 2017). Parts of the literature on volcanic soils describes long-term soil genesis (Babiera and Takahashi 1997; Dahlgren and Ugolini 1989; Fiantis et al. 2021; Fiantis et al. 2017; James et al. 2016; Ontiveros et al. 2016; Schlesinger et al. 1998). Other authors have a focus on the short-to-medium term consequences for vegetation dynamics (del Moral and Lacher 2005; Magnin et al. 2017; Swanson et al. 2016; Zobel and Antos 2017), the hydrological characteristics and sedimentation in the drainage basin (Hendrayanto et al. 1995; Leavesley et al. 1989; Major et al. 2009; Manville et al. 2009; Pierson and Major 2014), or soil development and biological communities (Fernández et al. 2018; Ferreiro et al. 2018; Fiantis et al. 2019; Fiantis et al. 2016; Tateno et al. 2019; Yamanaka and Okabe 2006). However, few studies have described the extensive short-medium-long term changes and recovery of soil physical characteristics and functions.

Indonesia has the largest number of active volcanoes on earth, and nearly all are densely populated. Six out of ten of the most populous active volcanoes in the world are located in Indonesia (Small and Naumann 2001). Among them is Mt. Kelud (also known as Kelut) in East Java, which had a human population density of more than 800 km^{-2} in 2020. Mt. Kelud has erupted more than 30 times since 1000 AD (Nihayatul et al. 2019), including the most recent significant eruptions in 1990 and 2014 (Goode et al. 2019; Maeno et al. 2019; Nakada et al. 2016).

The severity and variety impacts of volcanic materials depositions depend on the intensity metrics (tephra characteristics, such as layer thickness and grain size) and vulnerability of the exposed land-use system(s) (Arnalds 2013; Craig et al. 2016). Differences in vegetation structure (stem and leaf architecture, height and density) may influence the amount of VA captured, but will certainly affect the VA layer thickness retained on the soil profile (Cutler et al. 2016). A tree canopy or a shrub is expected to locally modify air turbulence, and capture and retain a portion of the air-borne VA (Ayris and Delmelle 2012). This VA is subsequently transferred to the ground as leaves drop or wind and rain mobilize the ash out of the canopy (Swanson et al. 2013). Dugmore et al. (2018) found that tephra layers developed underneath tall shrubs were 36% thicker than the original fallout when evenly distributed. This implies that tree-based systems may be more vulnerable to change its soil properties due to thicker tephra deposits compared to monoculture crop systems.

Tephra interception by tree canopies may lead to leaf abrasion and/or induce litterfall (Ayris and Delmelle 2012; Korup et al. 2019; Swanson et al. 2013). Changes in soil characteristics following volcanic events may have a substantial effect on plant establishment and development (Fernández et al. 2018). Tephra deposits on soil surface may change soil structure (Blong et al. 2017) and impede water infiltration, a characteristic sometimes described as hydrophobicity (Anda et al. 2016; Hairiah et al. 2016; Pierson and Major 2014). However, plant growth will eventually recover with time, and new soil will develop simultaneously. A conceptual diagram of VA deposition and its aftermath (**Figure 4.1**) describes a typical sequence of processes as:

1. Volcanic eruption ejects tephra (including VA) into the atmosphere, deposited on forests and agricultural land, depending on the height of the eruption plume, wind direction, wind speed. The deposition pattern is potentially modified by the surface roughness of the vegetation and its turbulence effects.
2. VA causes direct and indirect damage to trees - some trees survive, others die due to the loss of canopy and/or leaf abrasion from the heavy ash load.
3. VA and fresh litter partially or fully cover the original soil. After interacting with rainwater, ash may be redistributed downhill and/or quickly become compacted due to the lower aggregate stability and porosity. This compacted layer (crust) can temporarily disconnect the underlying soil from the atmosphere.
4. The disconnection may disrupt the water and nutrient balance in the soil due to lower soil infiltration and aeration, including inhibition of soil organic matter (SOM) decomposition and mineralisation.
5. Severely damaged leaves combined with low soil nutrient and water availability reduce tree photosynthesis, and lead to low production during the early years post volcanic event, as trees may skip flowering and fruiting.
6. To improve the soil condition after the eruption, some farmers mixed the VA and fresh litter with the original soil and added inorganic fertilizer and organic matter (from manure).
7. Mixing fresh VA, litter and manure with original soil increases SOM content and triggers higher soil organism activities (bioturbation). This process may improve the soil structure as indicated by a higher soil aggregate stability and macroporosity, thus improving the water and nutrient balances.
8. Weathered VA starts to provide nutrients for plants.
9. A better nutrient and water balance in the soil accelerates the recovery of the trees that survived immediate impacts and/or the growth of the newly established or planted trees.
10. Trees that are recovered and/or newly planted consistently begin to produce litter and contribute to the further accumulation of SOM. Higher SOM contents may increase the presence and activity of soil biota, thus improving soil structure and increasing the availability of water and nutrients. This favourable condition may further accelerate soil development and recovery of the land use system (LUS) – until the next disturbance restarts the cycle.

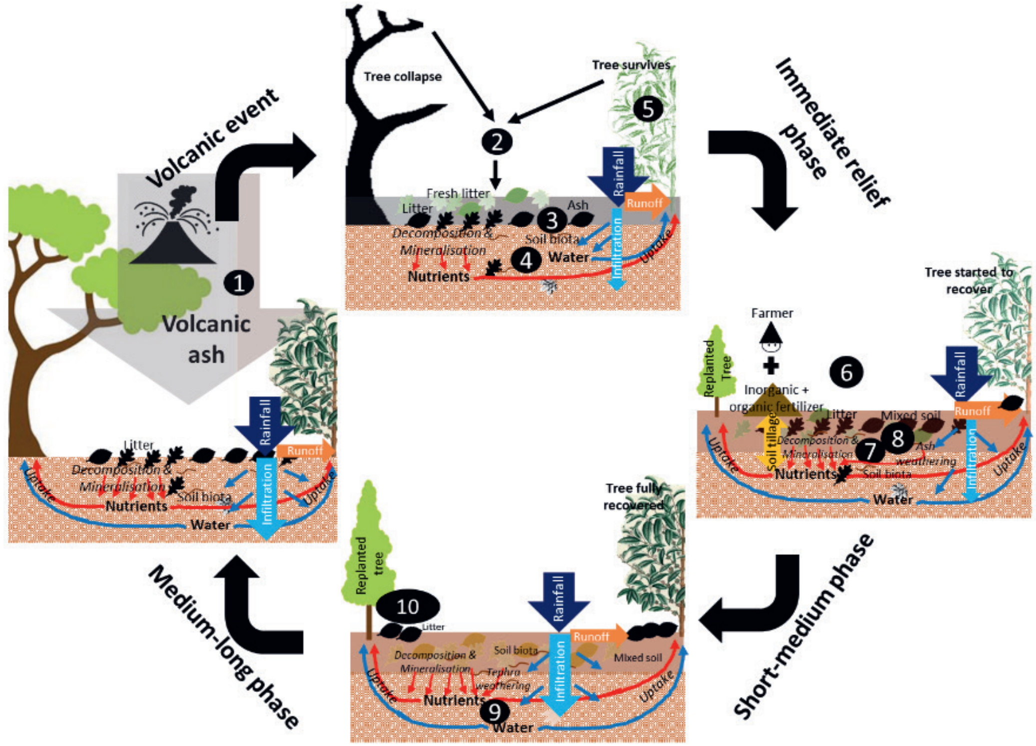

Figure 4.1. The conceptual diagram on volcanic ash deposition impacts on plant and soil development in the tree-based system; processes 1–10 is described in the text

The rate of ecosystem recovery post-eruption depends on the interrelation between VA characteristics and environmental factors, including climate, the resilience of the ecosystem and farmer management. Ferreiro et al. (2018) showed that two years post-eruption, the forests tephra accumulated more biomass and litter than bare tephra, accelerating the invertebrate and microbial development. The development of biological activity in fresh VA layers may enhance the soil organic carbon (SOC) and nitrogen availability, positively affecting plant growth (Fiantis et al. 2019). On the other hand, human intervention after volcanic events in agricultural systems such as replanting trees, adding organic matter (OM), and incorporating VA with original soil may contribute to ecosystem recovery (Craig et al. 2016; Ishaq et al. 2020b; Sword-Daniels et al. 2011; Wilson et al. 2011).

The timeframe for ecosystem recovery depends on VA thickness: decades necessary for thin, centuries for moderate, and millennia for very thick layers (Arnalds 2013). However, the knowledge on change in soil characteristics and soil functions in natural and agricultural ecosystems has not been well developed, as most studies only cover limited phases of the eruption-recovery cycle. In addition, the next disturbance may come earlier before recovery of the system is achieved, particularly for the locations with frequent VA deposition.

The general aims of this study were (1) to provide an assessment of the VA thickness in natural and agricultural LUS and (2) to explore the resilience of natural and agricultural systems after VA deposition by investigating the litter thickness, and soil physical characteristics and function in relation to vegetation development and system recovery. Our research opportunity arose when Mt. Kelud erupted in February 2014 and precipitated up to 20 cm of VA in the Ngantang sub regency, East Java (Nakada et al. 2016). This eruption affected existing long-term research plots established in 2007 in a landscape mosaic with remnant forests, coffee and fruit tree agroforestry, and open field vegetable production. We resampled these plots after the immediate relief phase of three and six years after the 2014 eruption, allowing us to monitor the changes in vegetation and soil characteristics, and to explore the local ecological knowledge and farmer decisions in response to the event. We will focus on the soil physical properties and soil function changes post VA deposition as consideration for farmer decisions to modify their LUS. In this study, we have three research questions:

1. Are there indications of any causal relation between canopy cover and VA thickness six years after the volcanic eruption?
2. Do the present LUS and farmer practices affect the recovery of litter thickness, SOC, soil structure, and soil infiltration after VA deposition?
3. How does litter thickness in various LUS relate to SOC and recovery of infiltration rates?

We hypothesized that: (1) Canopy cover increases the VA thickness; (2) Tree-based LUS (forests and agroforestry) had a thicker litter layer, a higher SOC, a better soil structure, and higher water infiltration rates compared to annual crops; (3) Infiltration rates in tree-based systems were recovering faster than the annual crops. We expected that a more detailed understanding of soil changes in response to farmer management could contribute to the successful planning and implementation of restoration activities in the aftermath of future volcanic eruptions, based on the tree and soil management optimization.

4.2 Methods

4.2.1 Study area and research approach

This study took place in the Kalikonto Watershed (7°45'57"- 7°56'53"S and 112°19'18"- 112°29'57" E, with elevation ranging from 600-2800 m above-sea-level (m a.s.l.), located in Ngantang Sub-district, Malang Regency, Indonesia. The study area is 13-15 km north of Mt. Kelud (7°55′48″S - 112°18′29″E) (Supplementary information 4.1 **(SI.4.1)**). The Kalikonto watershed is characterized by a tropical monsoon climate, with a dry season from June to October and a rainy season from November to March. The annual rainfall varies from 2995 to 4422 mm year^{-1}, with the annual average temperature between 20°–22°C, without much seasonality (BMKG 2018).
A 'chronosequence' of plots in four LUS with different degrees of change from the original natural forest cover was established in 2007/08 and resampled in 2016/17 and 2019/2020. Relative to the

2014 Mt. Kelud eruption, we labelled the 2007/08 data as ‘pre-eruption (PRE)’ condition. Meanwhile, the 2016/17 and 2019/20 datasets were labelled as ‘3 and 6 years after eruption (YAE)’ respectively. Given the 24-years between the last major events (1990 – 2014), datasets also represent the short-medium (3 to 6 years) and long term (17 years) impacts of ash deposition.

4.2.2 Land use systems

To test the hypotheses, we measured the soil physical properties of soil and VA (particles size <2mm) layer in four LUS: remnant (degraded) forests (RF), coffee-based complex agroforestry system (CAF), coffee-based simple agroforestry system (SAF), and monoculture annual crops (CR). Each LUS included 3 plots on different locations, which can be considered landscape-level replications (total of 12 plots). A relative similar distance between the study site and the volcano implied that they probably received similar amounts of tephra with identical composition during the recent eruption (Cutler et al. 2016). All soils of these plots were classified as Inceptisols according to the USDA classification and Cambisols according to the FAO classification (Driessen et al. 2001).

Remnant (degraded) forests (RF)

The term remnant (degraded) forests as used in this article is based on the FAO definition: “changes within the forests which negatively affect the structure or function of the stand or site, and thereby lower capacity to supply products and/or services” (Schoene et al. 2007). Relatively open forests (but still having more than 10% of canopy cover that met the forest definition used by FAO) mainly resulted from human activities such as overexploitation of forest trees for timber or fuelwood. In the local context, degradation implies a reduction of woody biomass, and changes in tree species composition, structure and productivity compared to natural forests expected for such climate and soil conditions. All RF plots were located at altitudes ranging from 900-1133 m a.s.l. with an average gradient of 40% at the lower slopes of local relief.

Coffee-based complex agroforestry (CAF) and simple agroforestry (SAF)

We used the relative basal area of the dominant tree crop and the number of companion tree species to differentiate between complex and simple agroforestry (Sari et al. 2020). Agroforestry systems combine cash crops and shade trees with a relative basal area of the main crop (coffee) of less than 80%; otherwise, they are described as ‘monocultures’. Agroforestry systems with at least 5 tree species in a 20 m by 20 m plot were defined as complex agroforestry and those with 2-4 tree species as simple agroforestry (Hairiah et al. 2020). Relative coffee basal area was calculated for a standard 20 m by 20 m observation plot (Hairiah et al. 2006; Sari et al. 2020). CAF plots were mainly located on slopes with an altitude ranging from 750-950 m a.s.l., and an average gradient of 11%. SAF plots were found at similar elevations but further from the settlement on steeper terrain with an average gradient of 23%. Both CAF and SAF were situated in the middle part of the local relief. After the eruption, CAF and SAF farmers reportedly removed the VA near the tree trunk manually and applied an organic (2.5-3.5 Mg ha^{-1} manure $year^{-1}$) and inorganic fertilisers (120 kg N, 30-60 kg P,

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and 30-60 kg K ha^{-1} $year^{-1}$). Important trees in farmer-managed agroforestry system include *Durio zibethinus ('durian')* as an indigenous fruit and timber tree, *Swietenia mahagony ('mahogani'),* an introduced timber tree, and *Toona sureni* (*'suren'*), an indigenous timber tree.

Annual crops (CR)

CR plots were situated at a lower altitude than other LUS (673-761 m a.s.l.) with an average gradient of 2%. The main crops were napier grass (*Cenchrus purpureus*), maize (*Zea mays*), groundnut (*Arachis hypogea*), cabbage (*Brassica oleracea*), chilli pepper (*Capsicum annuum*), and upland rice (*Oryza sativa*). Land management mainly was intensive, with 2-3 planting cycles in a year. Soil tillage, fertilizer (organic and inorganic) application, weeding and pest control were associated with the planting cycles. After the eruption, some farmers mixed the soil and VA using a small hand tractor and applied organic (5.6 Mg ha^{-1} manure $year^{-1}$) and inorganic fertilisers (200 kg N, 120 kg P, 120 kg K ha^{-1} $year^{-1}$).

4.2.3 Data collection and statistical analysis

4.2.3.1 Canopy cover and VA thickness

We measured the canopy cover and 'preserved' VA thickness in the plots on October 2020 or six years after 2014's Mt. Kelud eruption (6 YAE). Three sampling points were placed on the diagonal of the plots for canopy cover and VA thickness measurements (**SI 4.2**). We split each sampling point into four sampling directions (based on the slope direction), with the coffee tree as a centre point in CAF and SAF. Each direction was then divided into 30 cm length grids. Canopy cover was measured with an upward-facing photograph and the 'CanopyApp' in each grid, 30 cm above the soil level surface. This method was reported to show a strong and linear relationship (R^2 = 0.87) to canopy cover measurement using a spherical densitometer (Davis et al. 2019).

We exposed a cross-section of the VA and soil layers for the preserved ash thickness measurements by creating a shallow trench with a sharp spade (Dugmore et al. 2018). The trench was dug up underneath the canopy cover measurement points. We directly measured the VA thickness with a ruler perpendicular to the soil surface. The preserved VA layer was easily differentiated as it laid very close to the surface and showed a different colour and texture from the original soil underneath (**Figure 4.4c**). For further statistical analysis, the canopy cover and VA thickness were averaged per plot.

The Mt. Kelud 2014 eruption is sufficiently recent that vegetation cover in tree-based systems has not changed dramatically. Therefore, we only included the data points from tree-based systems and excluded the CR data for the correlation analysis between canopy cover and VA thickness. However, we included data from all LUS for the correlation analysis between slope position and VA thickness.

4.2.3.2 Litter thickness and soil parameters

We used the litter thickness to assess litter layer development (Marín-Castro et al. 2017). Standing litter thickness was measured using a ruler inside a 0.5m x 0.5m frame (Hairiah et al. 2006), placed on the same three diagonal points as the VA thickness measurement. Soil samples were collected from the upper 30 cm of the soil layer at three different periods (PRE, 3 YAE, and 6 YAE). This layer includes VA deposits and some parts of original soil material, that were mixed in naturally and/or anthropogenic ways.

The disturbed and undisturbed soil samples were collected from 2 sampling points near the litter measurement. We mixed the disturbed soil sample from two sampling points to create a composite sample. Composited soil samples were air-dried for 48 hours and stored at room temperature (28°C) before further analysis.

Soil and VA texture (% of sand, silt, and clay) was determined using the pipette method, while SOC was determined using Walkley and Black method (Anderson and Ingram 1993). The top 30 cm of soil C stocks was calculated based on the IPCC guideline for national greenhouse gas inventories standard by multiplying soil SOC with the bulk density (Hairiah et al. 2011). Soil aggregate stability was measured through wet sieving methods and was represented as mean weight diameter (MWD, mm) (Carrizo et al. 2015). Soil porosity was calculated as Nimmo (2004): porosity (%) = 100 * (1 – bulk density/particle density). All soil samples were prepared and analysed in the Soil Science Laboratory of Brawijaya University.

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Soil infiltration was measured using a single ring infiltrometer (Sahin et al. 2016). The infiltration rate was determined from two measurement points for each plot. The infiltration rate was expressed in water volume per ground surface and per unit of time (cm h^{-1}). Steady-state infiltrability was afterwards estimated by mean of curve fitting to Horton's equation (Toebes 1962) using SigmaPlot 14.5 edition.

4.2.4 Statistical analysis

To assess the likely effect of LUS, we used a space-for-time substitution or chronosequence approach, checking for indications of a priori soil differences due to landscape position. We analysed data on canopy cover, VA thickness, litter thickness, and soil variables with a standard analysis of variance (ANOVA, α=0.05). *Post-hoc* multiple comparisons between LUS and observation periods were performed using Tukey's HSD (honestly significantly difference) test. Statistical differences were considered significant when $p \leq 0.05$. A Pearson correlation and stepwise linear regression were performed to investigate the relationships between variables. All statistical analysis was performed in R 4.0 (R Core Team, 2020).

4.3 Results

4.3.1 Canopy cover and preserved volcanic ash thickness 6 years after the volcanic eruption

Canopy cover differed significantly between LUS (**Figure. 4.2a**). The lowest canopy cover was found in CR (12.7%). No significant differences were found in canopy cover between CAF and SAF (an average of 75%). Finally, the highest canopy cover was observed in DF (88.2%). The canopy cover variability under tree-based systems was lower compared to CR.

Preserved VA thickness across all different sampling points ranged from 2 – 14 cm, with an average of 8.5 cm (**Figure. 4.2b**). RF had the highest VA thickness (9.9 cm) followed by CAF (7 cm), with no significant difference between SAF and CR. VA thickness in SAF and CR was 23% thicker than CAF, with an average of 8.6 cm. The VA thickness variability under CR was higher compared to DF and agroforestry systems.

We found no relationship between canopy cover and preserved VA thickness six year post volcanic eruption (R^2 = 0.03, p = 0.3). However, we identified a more consistent pattern and significant relationship between VA thickness and plot position in each local relief (R^2 = 0.28, p <0.001). Plot situated in lower slope position (valley) had 25 and 85% thicker of VA layer than in the middle and upper part, suggesting that LUS and slope position were confounded on VA preservation.

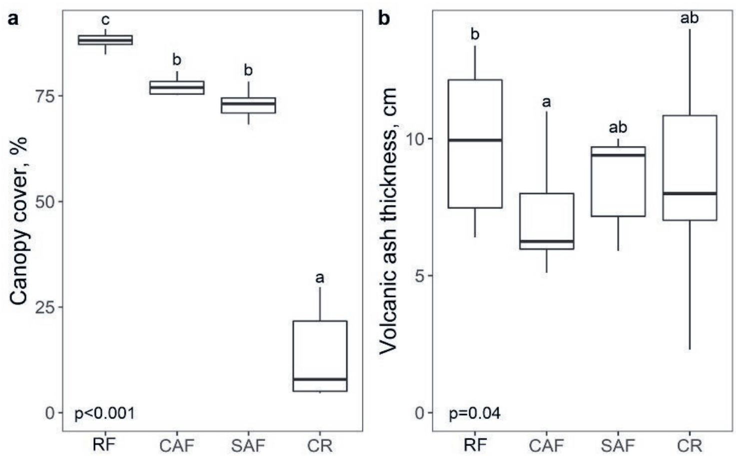

Figure 4.2. (**a**) Canopy cover and (**b**) VA thickness in various LUS (RF=remnant forest, CAF=coffee-based complex agroforestry, SAF=coffee-based simple agroforestry, CR=annual crop) and three different periods (PRE=pre eruption, 3 YAE=3 years after eruption, and 6 YAE=6 years after eruption). Different letters indicate significant differences between LUS ($p \leq 0.05$).

4.3.2 Litter thickness recovery across LUS post volcanic eruption

Litter thickness differed significantly across LUS and between observation periods (p <0.001). The highest average of litter thickness was found in RF (1.17 cm), followed by SAF, CAF, and CR

(0.88, 0.68, and 0.05 cm, respectively). Overall, litter thickness in 3 YAE (on average 0.38 cm) was noticeably lower than in PRE and 6 YAE (0.75 and 0.82 cm, respectively).

Litter thickness of tree-based LUS was increased significantly within 3 to 6 YAE (**Figure 4.3**). Litter thickness in CAF in 6 YAE was higher than the PRE condition, indicating complete recovery. Assuming that the original litter layer was entirely covered with VA deposition, the highest litter accumulation rate during the first three years was in DF (0.22 cm year^{-1}), followed by CAF, SAF, and CR (0.16, 0.12, and 0.007 cm year^{-1}, respectively). The accumulation rate in DF and CAF was reduced to 0.15 and 0.10 cm year^{-1} within 3 to 6 YAE. In contrast, the litter accumulation rate in SAF remained high with 0.13 cm year^{-1}. Based on the 6 YAE datasets, we found that litter thickness increased with the denser canopy cover (R^2 = 0.78, p < 0.001). The increase of 10% canopy cover estimated could add 0.25 cm of litter layer.

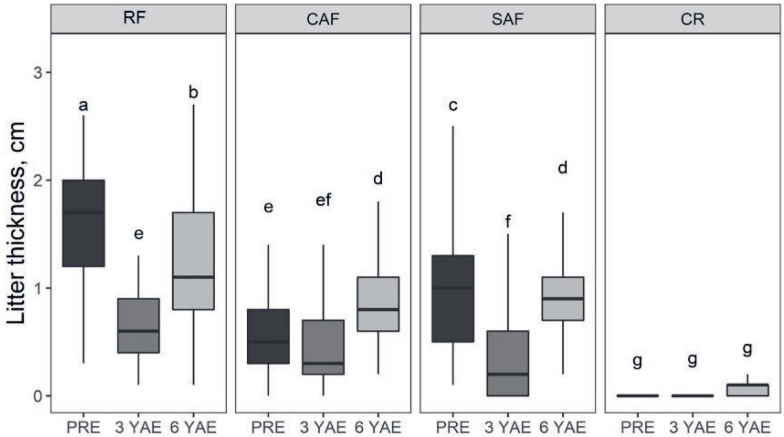

Figure 4.3. Litter thickness in various LUS (RF=remnant forest, CAF=coffee-based complex agroforestry, SAF=coffee-based simple agroforestry, CR=annual crop) and three different periods (PRE=pre eruption, 3 YAE=3 years after eruption, and 6 YAE=6 years after eruption). Different letters indicate significant differences between LUS and periods ($p \leq 0.05$)

4.3.3 Soil properties recovery across land-use systems post volcanic eruption

4.3.3.1 Soil organic carbon (SOC) and soil carbon stocks (soil C stocks)

We found that SOC and soil C stocks differed significantly across LUS (p <0.001). The average SOC and soil C stocks were substantially higher in RF (2.15% and 54.36 Mg ha^{-1}), followed by CAF (1.24% and 37.48 Mg ha^{-1}) and SAF (0.97% and 28.1 Mg ha^{-1}), while CR was the lowest (0.7% and 22.05 Mg ha^{-1}). We found no significant difference in average SOC and soil C stocks between observation periods (1.26% and 35.5 Mg ha^{-1}). However, SOC and soil C stocks of RF and CAF in 6 YAE were marginally higher than in the PRE conditions, indicating soil rejuvenation (**Table 1**).

If we assume that SOC of fresh VA is zero, the SOC accumulation rate during the first three years was significantly higher in RF (0.67% year^{-1}), followed by SAF, CAF, and CR (0.34, 0.32, and 0.32% year^{-1}, respectively). SOC of RF and CAF continuously increased within 3-6 years post-eruption (0.17 and 0.07% year^{-1}, respectively), conversely to SAF and CR, which were reduced at a rate of 0.01 and 0.13% year^{-1}, respectively.

4.3.3.2 Mean weight diameter (MWD) and soil porosity

Soil aggregate stability as represented by MWD differed significantly across LUS and observation periods (p <0.001). The weakest soil aggregate stability was found at 3 YAE (1.55 mm). There was no significant difference in MWD between PRE and 6 YAE (average 2.67 mm), indicating complete soil aggregate recovery (**Table 4.1**). Within LUS, the lowest MWD was found in SAF and CR (average 1.8 mm), while RF had almost two times higher MWD than SAF and CR (3.47 mm).

We found no significant difference in soil porosity within observation periods (average of 55%). However, soil porosity differed across LUS. The highest average soil porosity was found in RF (61%), followed by CR (56%). The lowest soil porosity was found in CAF and SAF (average 53%). There was no significant difference in soil porosity found between PRE and 6 YAE across LUS (**Table 4.1**), which may correlate to negligible soil texture changes during observation periods. The composition of VA deposition (81% sand, 14% silt, and 5% clay) slightly changed the soil texture in the early years after a volcanic eruption. The texture of mixed soil and VA layer in 3 YAE was sandy loam (54% sand, 34% silt, and 13% clay), while in PRE and 6 YAE were loam (50% sand, 36% silt, and 14% clay).

Table 4.1. Soil organic carbon (SOC), soil carbon stocks (Soil C stocks), mean weight diameter (MWD), and porosity in each LUS (RF=remnant (degraded) forest; CAF=coffee-based complex agroforestry; SAF=coffee-based simple agroforestry; CR=annual crops; LUS=land use system). Each value indicates means ± standard error (SE). Different letters indicate significant differences between LUS and periods ($p \leq 0.05$)

LUS	Period	SOC, %	Soil C stocks, Mg ha^{-1}	MWD, mm	Porosity, %
RF	PRE	1.93±0.15^{ab}	50.93±3.84^{ab}	4.65±0.08^{a}	58.57±0.86^{ab}
RF	3 YAE	2.00±0.35^{ab}	45.43±8.48^{ab}	1.59±0.20^{cd}	64.53±0.91^{a}
RF	6 YAE	2.50±0.26^{a}	66.70±5.98^{a}	4.18±0.40^{ab}	58.53±0.96^{ab}
CAF	PRE	1.60±0.35^{abc}	48.60±9.49^{ab}	3.05±0.27^{bc}	51.63±1.20^{cde}
CAF	3 YAE	0.97±0.09^{bc}	28.40±2.25^{bc}	1.59±0.19^{cd}	53.90±2.06^{bcd}
CAF	6 YAE	1.17±0.20^{bc}	35.40±6.70^{bc}	1.73±0.52^{cd}	54.00±0.17^{bcd}
SAF	PRE	0.83±0.12^{c}	27.57±2.99^{bc}	1.76±0.15^{cd}	47.87±2.50^{de}
SAF	3 YAE	1.03±0.19^{bc}	26.90±4.66^{bc}	1.52±0.28^{d}	55.87±1.27^{bc}
SAF	6 YAE	1.00±0.06^{bc}	29.87±1.30^{bc}	2.87±0.13^{bcd}	53.23±0.39^{bcde}
CR	PRE	0.57±0.19^{c}	16.00±5.26^{c}	1.69±0.36^{cd}	59.77±1.13^{ab}
CR	3 YAE	0.97±0.19^{bc}	34.17±6.38^{bc}	1.51±0.30^{d}	47.33±1.37^{e}
CR	6 YAE	0.57±0.07^{c}	15.97±1.82^{c}	1.46±0.28^{d}	59.57±0.57^{ab}

4.3.3.3 Soil infiltration recovery across land-use systems post volcanic eruption

Steady-state infiltration rate markedly differed after VA deposition, from an average of 28.9 cm h^{-1} in PRE plummeting to 3.7 cm h^{-1} in 3 YAE (**Figure 4.4**). However, the soil infiltration was quickly recovered to its PRE condition after six years. The fastest average soil infiltration was found in RF (38 cm h^{-1}), while the slowest was in CR (4 cm h^{-1}). There was no significant difference between CAF and SAF (average 20.5 cm h^{-1}).

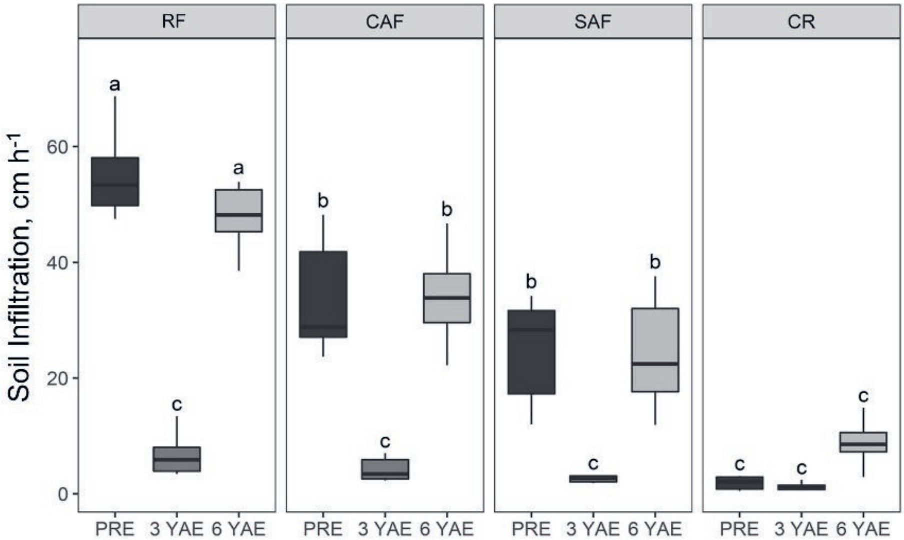

Figure 4.4. Soil infiltration in various LUS and three different periods (RF=remnant forest, CAF=coffee-based complex agroforestry, SAF=coffee-based simple agroforestry, CR=annual crops; PRE=pre eruption, 3 YAE=3 years after eruption, and 6 YAE=6 years after eruption). Different letters indicate significant differences between LUS and periods ($p \leq 0.05$)

4.3.3.4 Relationships between litter thickness, soil properties and infiltration

We expected that the litter thickness has a definite correlation to SOC. However, we found an insignificant positive association between SOC and litter thickness during the early years after volcanic eruption (**Figure 4.5**). The relationship between litter thickness and SOC became substantial with time (**Figure 4.6**), suggesting that a LUS with a thick litter layer is more likely to have higher SOC content.

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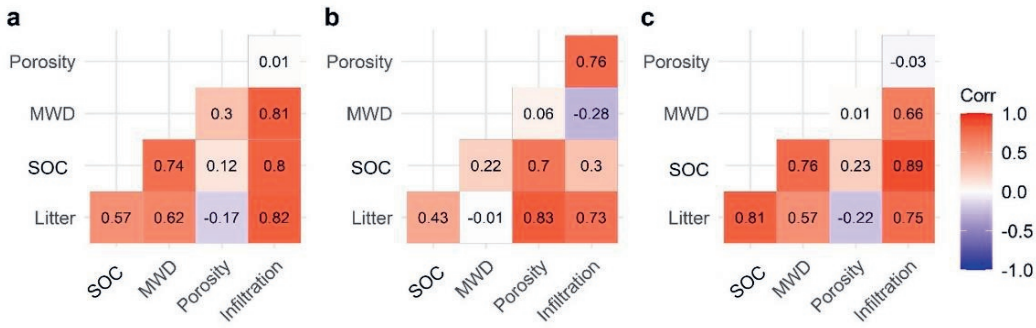


Figure 4.5. Coefficient correlation of litter thickness (Litter), soil organic carbon content (SOC), mean weight diameter (MWD), soil porosity (Porosity), and soil infiltration (Infiltration) in **(a)** PRE eruption, **(b)** 3 YAE, and **(c)** 6 YAE. (YAE=year after the eruption). The colour and number inside the boxes indicate the correlation value

The soil surface protection from the litter layer contributed to the higher soil infiltration, as shown by the solid and consistent relationships between variables throughout observation periods. Additionally, the differences in vegetation and soil management practices of each LUS potentially influenced soil infiltration through soil properties modification. Litter thickness and SOC were strongly correlated to porosity in the early years after the volcanic eruption. Higher soil porosity indeed had a positive impact on soil infiltration. However, a substantial difference in infiltration rate between 3 YAE and 6 YAE showed that higher soil porosity was insufficient to deliver faster infiltration without better soil aggregate stability. We found a significant correlation between litter thickness, SOC, and MWD with soil infiltration in 6 YAE, supporting our previous finding.

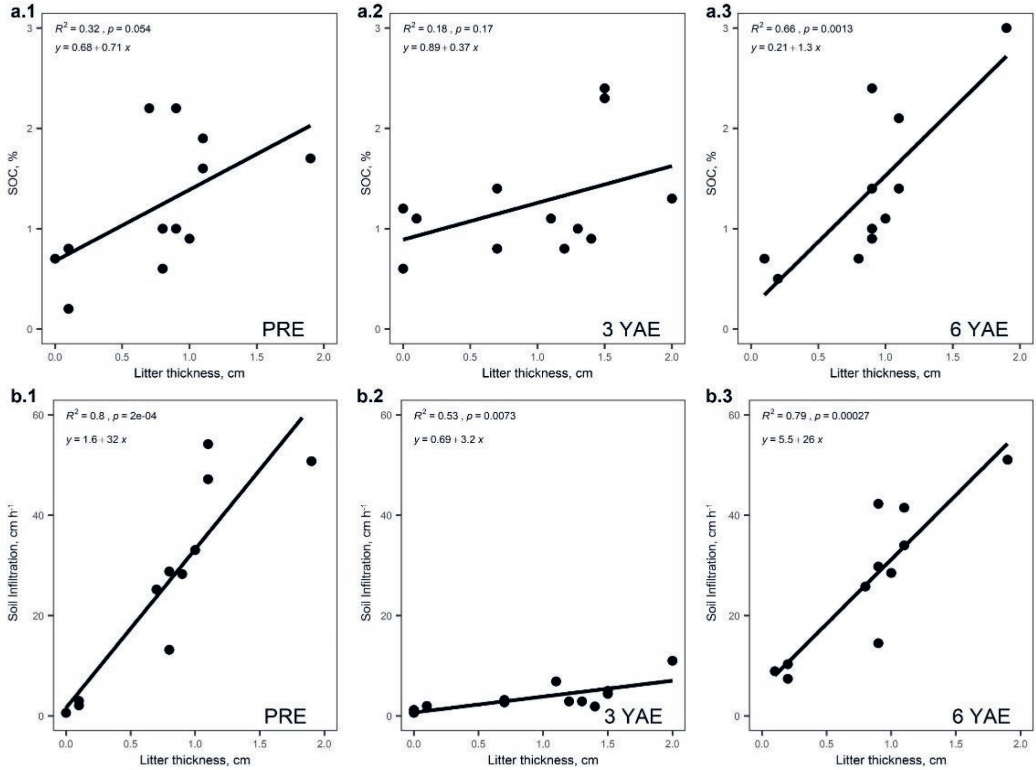


Figure 4.6. Relationships between litter thickness and **(a)** SOC content, and **(b)** soil infiltration in three different periods of (**1**) PRE eruption, (**2**) 3 YAE, and (**3**) 6 YAE. YAE=year after the eruption

4.4 Discussion

4.4.1 The relation between canopy cover and volcanic ash thickness

We observed that the average VA thickness 6 YAE of each LUS was within 7 - 9.9 cm. However, the initial VA layer may be thicker than the 'preserved' VA we measured. Blong et al. (2017) discovered that the average VA thickness in various vegetation types and slopes was 40% less than its original fallout after two years of VA redistribution and compaction process. Based on that, we estimated that the initial VA fallout deposited in our study area was approximately 9.8 – 13.9 cm. These estimates were within the range (10-20 cm) of the initial/original VA fallout measured near the research area in an open field a month after the 2014 Mt. Kelud eruption reported by Nakada et al. (2016).

We expected that VA thickness had a positive association with the canopy density. However, VA thickness correlated more to the plots' slope position in the local relief rather than canopy cover. The lateral mobilization and stabilization of VA by water and air erosion occurred after the volcanic eruption resulting in a downslope thickening of the VA layer. Additionally, we found that the VA thickness in monoculture crops had higher variability than in the forests and agroforestry systems (**Figure 4.2b**). Our results agreed with Dugmore et al. (2018), which found that sloping sites with a consistent canopy cover such as forested areas might produce more reliable and uniform stratigraphic records of fallout than the flat sites with varied vegetation. The exposed condition in the open, scatter, and short vegetation resulted in sharp local air and water erosion variation, leading to VA thickening under the vegetation patches and marked small-scale variability in VA thickness (Cutler et al. 2016).

4.4.2 Soil properties and function recovery after volcanic ash deposition across land-use systems

Soil recovery is essential in ecosystem succession after significant disturbance from VA deposition following a volcanic eruption. The recovery starts with the interactions between remaining or surviving organisms and new colonists that could modify the site conditions such as nutrient input and water availability (Antos and Zobel 2005). As an energy source, OM availability drives these interactions. For the context of the volcanic soil, the increase of OM inputs from organic fertilizer and/or above- and belowground plants biomass, alongside the exceptional capability of VA to sequester and store a large quantity of carbon, could accelerate the SOC and soil C stocks accumulation (Fiantis et al. 2016).

However, the lower litter thickness in CR was not directly reflected in smaller SOC content. The correlations between litter thickness (representing aboveground biomass production and decomposition balance) and SOC were insignificant, particularly in 3 YAE (**Figure 4.6**). This result indicates that the manure application (5.4 Mg ha^{-1} $year^{-1}$) in CR during the early year post eruption could accumulate SOC comparable to agroforestry systems with its thick litter layer. However, CR roughly needs two times higher OM input to maintain its SOC at the level of agroforestry systems in the long term. A study by Ferreiro et al. (2020) in Argentina confirmed that the application of OM (compost) could promote short-term rehabilitation of open bare-soil affected by VA deposition.

Three years after the eruption, RF had a higher SOC accumulation rate (average of 0.68% $year^{-1}$) than the other LUS (0.32 – 0.35% $year^{-1}$). These early years SOC accumulation rate of VA was similar to the study conducted by Fiantis et al. (2019) in Mt. Talang with a sequestration rate of 0.2 – 0.5% $year^{-1}$ but relatively lower than Mt. Sinabung (0.53 – 1.4% $year^{-1}$). However, it was relatively high compared to those found in temperate regions (Ferreiro et al. 2018; Halvorson and Smith 2009; Halvorson et al. 2005). Nevertheless, it appears that the high soil carbon sequestration rate in soil material derived from VA is not reflected in the existing IPCC national accounting standard that is based on the 0-30 soil layer, without acknowledging the addition of 'new' soil. Adjustments in the accounting systems may be needed (Hairiah et al. 2020; Minasny et al. 2021) before these volcanic soils are recognized for exceeding the targets of the '4 per mille Soil for Food Security and Climate' initiative (Minasny et al. 2017).

The most dramatic change following the volcanic eruption was the substantial shift in infiltration rate (**Figure 4.4**). The average infiltration rate of 29 cm h^{-1} in the PRE condition dropped to only 3.7 cm h^{-1} within three years after VA deposition. The latter can be exceeded during rainstorms, leading to overland flow. Our finding agrees with earlier studies that showed a double-digit soil infiltration change after VA deposition (Arnalds 2013; Major and Yamakoshi 2005; Pierson and Major 2014). The VA deposition on top of the soil surface creates encrusted surface strata with low hydraulic conductivity and infiltration (Anda et al. 2016; Pierson and Major 2014; Tarasenko et al. 2019). However, we found no substantial difference in soil porosity between PRE and 6 YAE. This result indicates that beyond total porosity as such, the distribution and orientation of soil particles, the diameter, tortuosity, and connectivity of macropores can influence soil infiltration. Faster soil infiltration has been linked to a higher proportion of surface-connected soil macropores and more stable soil aggregate in volcanic (Müller et al. 2018; Tejedor et al. 2013) and non-volcanic soils (Bryk and Kołodziej 2021; Saputra et al. 2020). These two determining factors were the manifestation of higher OM availability combined with highly active soil ecosystem engineers through the bioturbation process. On the other hand, the rapid loss and recovery of infiltration capacity on volcanic soils may have additional causes. The lower soil infiltration may be related to the emergence of soil water repellency (SWR) caused by the combination of the hydrophobic characteristic of VA (Berenstecher et al. 2017) and hydrophobic substances derived from SOM decomposition (Jimenez-Morillo et al. 2017; Kawamoto et al. 2007; Neris et al. 2013; Poulenard et al. 2004).

Nevertheless, the soil regained its infiltration rate equal to the PRE condition after six years, except for CR. At this point, the predominant surface hydrological functions in this watershed had returned to pre-eruption states under normal precipitation conditions. Our result agrees with the study performed by Major and Yamakoshi (2005), which showed the rapid change in infiltration capacity after VA deposition.

Tree-based systems could provide better soil infiltration rate compared to monoculture crops during medium-long time frames because: (1) the systems have a sufficient supply of SOM used by soil ecosystem engineers to create a better soil macropore and aggregate stability; (2) dense canopy cover could regulate microclimate that favourable for more active soil organisms during the bioturbation process; (3) together with closed canopy cover, thick litter layer produces by trees could provide direct soil surface protection, and guarantee surface-connected macroporosity for a faster infiltration and lower soil erosion, thus improves water balance on the systems (Chen et al. 2017; Hairiah et al. 2006; Saputra et al. 2020; van Noordwijk et al. 2019a).

Overall, our study provides new insights into the short-medium-long term impact and recovery of soil properties and functions after VA deposition across different LUS. The severe but temporary shifts of some soil properties, such as aggregate stability and soil infiltration, were unavoidable in natural and agricultural systems during the early years after VA deposition. The recovery phase of a particular LUS depends on its plants and soil management.

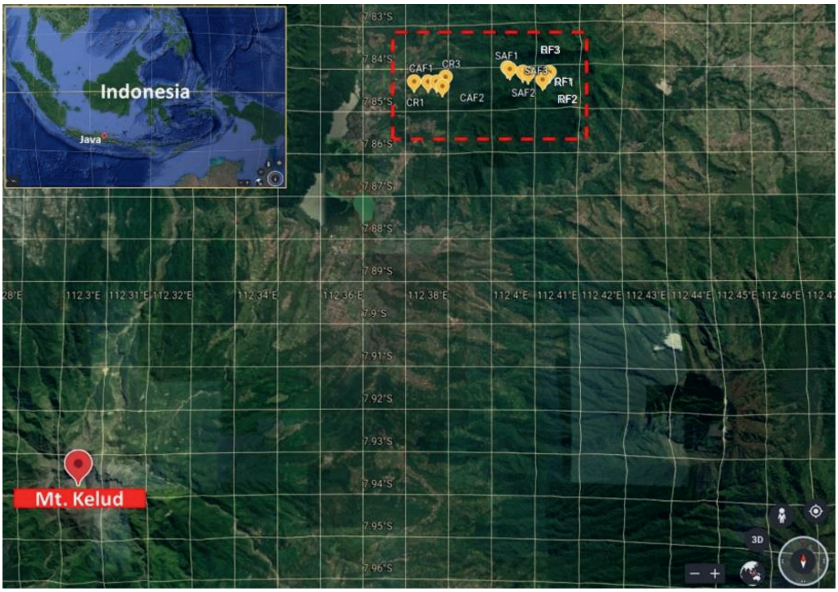
However, not all soil attributes changes can be described as recovery. Some attributes might diverge farther from the pre-disturbance condition due to the continuing change of the system internally (soil and plant management) as well as climate change. As stated by Antos and Zobel (2005), “the fundamental difficulty assessing post disturbance succession and rates or convergence on the previous condition is that even old forests are constantly changing”. Nevertheless, a comprehensive study using a proper simulation model that can minimize those uncertainties might improve our understanding of the complete cycle of soil functions recovery process after the volcanic eruption.

4.5 Conclusions

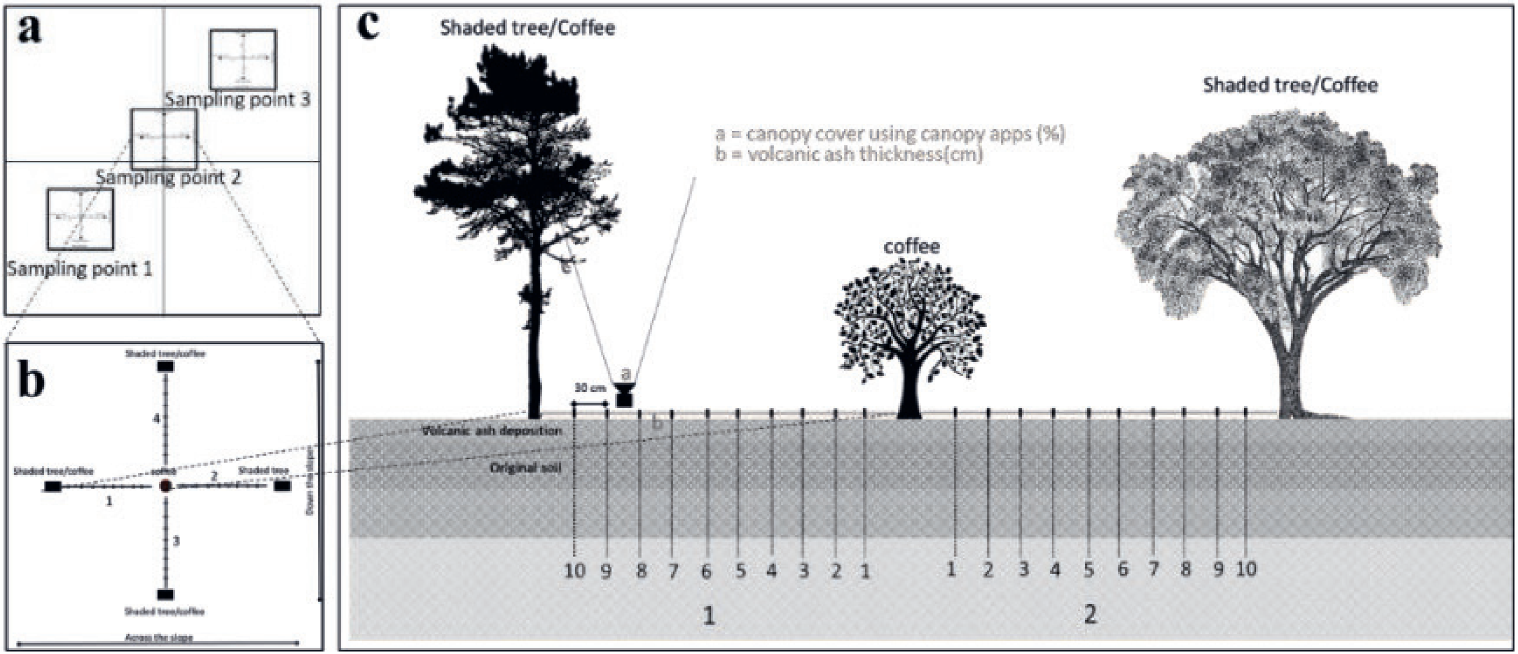
We found that preserved VA thickness was related to the plot position on the local relief rather than by canopy cover. The VA mobilization and stabilization process resulted in a downslope thickening of the VA layer. The relatively closed canopy cover of tree-based systems generated more homogenous VA layers than the exposed and scattered short-vegetation in CR. Relatively thick VA deposition onto the soil surface affected soil physical properties positively and negatively. VA deposition homogenized soil properties and function across different LUS during the short term. Litter thickness, MWD, and soil infiltration changed rapidly after VA deposition but quickly recovered. In contrast, SOC, soil C stocks, and porosity were unchanged. Different LUS management results in different recovery trajectories of soil physical properties and function over the medium-long term.

4.6 Supplementary information

SI 4.1. The map of research area (red dash) which located near Mt. Kelud, East Java, Indonesia. RF=remnant forest; CAF=coffee-based complex agroforestry; SAF=coffee-based simple agroforestry; CR=annual crop. Map derived from Google Earth.



SI 4.2. (a) Three sampling points were systematically placed within the standard 20m x 20m plots for canopy cover and VA thickness measurement. Each sampling point was split into four sampling directions based on the slope direction (across and down the slope), with the coffee tree as the centre point. Each direction was then divided into 30 cm length grids; (b) Canopy cover images were captured with an upward-facing photograph in each grid, 30 cm above the soil surface. Canopy cover percentages were estimated using the 'CanopyApp' (https://apktada.com/app/edu.unh.mobile. canopyapp) ; (c) A pit underneath canopy cover measurements points were created to expose the VA layer. The 'preserved' VA layer was easily differentiated and measured from the original soil, as it showed a different colour and texture.



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CHAPTER 5

Volcanic ash and surface litter layer underlying the original topsoil
Sumberagung village, East Java

Water repellency by volcanic ash interacting with organic matter: incubation response and effect on infiltration

This chapter is based on published article:

Saputra DD, Sari RR, Sari IN, Suprayogo D, van Noordwijk M (2023). Water repellency by volcanic ash interacting with organic matter: Incubation response and effect on infiltration.

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Abstracts

Volcanic ash deposition disrupts soil surface hydrology. Our previous study showed that soil infiltration was reduced eightfold after a volcanic eruption in various land-use systems adjacent to Mount Kelud (Indonesia). Yet, soil macroporosity was relatively unchanged, indicating soil hydrophobicity. We tested the hypothesis that hydrophobicity or water repellency (WR) can be induced by volcanic ash interacting with organic matter and quantified its effect on surface water infiltration.

We combined volcanic ash with leaf litter from coffee, durian, pine and mixed sources and tested for WR as a function of incubation time (0-16 weeks) and soil water content (θ, %), with Water Drop Penetration Time (WDPT, s) and Contact Angle (CA, °) as WR metrics. Lipids content (%) and pH were also analysed during incubation. Water droplets were placed onto a material tested for WR in a slope-adjustable stage to determine the critical angle for droplet runoff before penetration. Finally, to quantify the effect of WR on water flow, we layered 5 and 10 cm of ash with organic matter additions on top of a control soil column and performed infiltration (hydraulic conductivity) measurements.

Among litter sources, pine litter induced the highest WR. There were significant relationships between WR, lipid, and pH. However, these relationships became weaker with material water contents >7%. A significant relationship was also found between CA and critical slope of both small and large drops. A higher CA lowered the minimum critical slope for droplet runoff to 7° and 10° for the diameters of large and small water droplets, respectively. The mixture of volcanic ash and organic matter layered into the soil surface resulted in a five-times lower average hydraulic conductivity, with indications of air entrapment limiting water infiltration in a thicker ash layer. A higher CA was strongly associated with a lower hydraulic conductivity ratio, particularly under the 5 cm organic matter treatment. The WR effects on hydraulic conductivity were equivalent to at least a ten-fold reduction in effective soil porosity. By reducing infiltration, WR may contribute to ash movement in the volcanic landscape.

Keywords: Litter quality; tephra; hydrophobicity; lipids; water drop penetration time; contact angle

5.1 Introduction

Mature volcanic soils, Andosols, generally have high porosity, rapid infiltration of rainfall, and highly stable soil aggregates, leading to strong resistance to water-based erosion (Neris et al. 2012; Zehetner and Miller 2006). By contrast, fresh volcanic ash (VA) is prone to soil erosion (Korup et al. 2019). Many studies documented that the deposition of volcanic materials, including tephra (lapilli and VA), hampered water infiltration and exacerbated erosion and sediment transport (Arnalds 2013; Lavigne 2004; Pierson and Major 2014). VA could form encrusted strata with low hydraulic conductivity and infiltration rates on top of an older, more developed soil surface (Anda et al. 2016; Wilson et al. 2011). A lower hydraulic conductivity of fresh VA (Tarasenko et al. 2019) was commonly linked to the orientation of soil particles and its consequences for macropore continuity. However, the way water interacts with the surface of soil particles might also contribute to this lower hydraulic conductivity.

Soil pores provide pathways for water to infiltrate into soils. Soil infiltration could be based on soil pores that were not yet water-saturated or on typically saturated pores that passed the water onto deeper layers. Soil porosity would be high where soil texture was coarse, bulk density was low, and the soil structural development led to stable, continuous pores (Baker 1979; Tejedor et al. 2013). Even in such conditions, however, infiltration could be slow if the soil surfaces exhibit water repellency (WR) due to hydrophobic compounds (Doerr et al. 2000). Without WR phenomena, initial infiltration rates tended to be high, as soil pores absorbed water, and then gradually approach a 'saturated hydraulic conductivity' dominated by the largest pore sizes, where the rate of outflow from a soil column determined the inflow rate. The presence of non-polar (hydrophobic) molecules at the soil particle surfaces, coupled with the cohesive nature of water, results in water droplets remaining intact and unable to penetrate the available pores. Additionally, air entrapment could restrict infiltration into dry soils (Hammecker et al. 2003; Sakaguchi et al. 2005; Wang et al. 1998).

VA deposition from the 2014 eruption of Mt. Kelud in East Java, Indonesia, led to soil hydrophobicity and severely inhibited infiltration (up to 8 times slower than the pre-eruption condition), despite relatively unchanged soil porosity (Saputra et al. 2022). The deposition of VA up to 20 cm in Ngantang District (Nakada et al. 2016) led to subsequent erosion and sediment transport that substantially reduced the water storage capacity of two important reservoirs in this region, Wlingi and Ledoyo, by half (Hidayat et al. 2017). This case provides an opportunity to analyse the relative roles of VA as such and VA plus organic debris as the cause of the recorded soil water repellency (SWR) in the field.

The underlying processes of WR, caused by the interactions between VA and organic matter (OM), and its consequences on soil hydraulic conductivity (infiltration), have rarely been studied compared to research conducted on other soil types or under different management practices (such as vegetation type, soil management) or fire history (Jordán et al. 2011; Jordán et al. 2009; Lucas-

Borja et al. 2022). To understand the development of WR following a VA deposition, we may need to consider a sequence of events as illustrated in **Figure 5.1**.

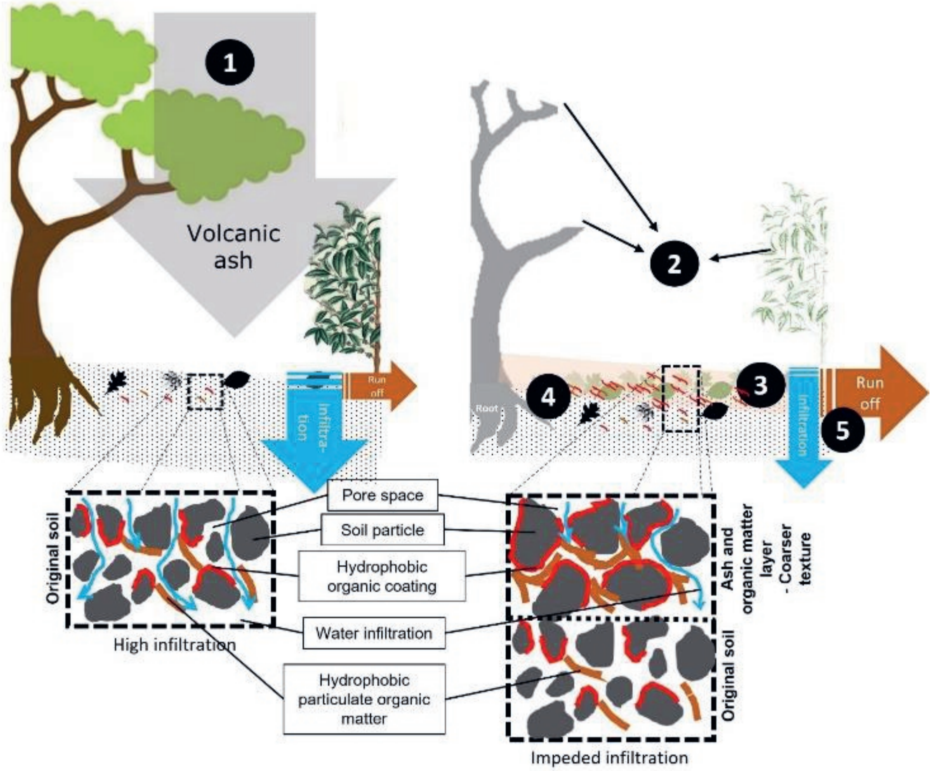

Figure 5.1. Schematic process of VA deposition on an agriculture system. In the short-medium term, VA deposition may dramatically change the soil water balance through a sequence of processes: (1) volcanic eruption ejects ash materials to the atmosphere that gets deposited on agricultural land, (2) all plants may drop leaves or severely experience leaves surface abrasion (some trees survive, some die) and add a substantial amount of fresh organic matter (OM) into the soil, (3) original soil and standing litter layer may be buried under fresh VA and OM, (4) VA and OM from leaves litter and root may interact and create a water repellent surface layer, (5) soil infiltration may decrease, and on slopes, runoff and erosion occur

In the short-medium term, VA deposition may dramatically change the soil water balance through a sequence of processes (**Figure 5.1**). Regarding steps 1, 2 and 3, the heavy load of VA deposits during a volcanic eruption may directly damage the natural and agricultural ecosystems and cause many crops and trees to partly die (Anda et al. 2016; Korup et al. 2019). The soil may suddenly be loaded with a high amount of VA and plant litter, resulting in a new layer overlaying the original topsoil. This layer could lead to the development of hydrophobic material from the interaction of OM and VA. Hydrophobic substances could form a water repellent coat on VA particle surfaces

(Franco et al. 2000) and a water repellent particulate OM. The type of water repellent substances produced may vary depending on the molecular composition and properties of the OM (Dao et al. 2022; Ellerbrock et al. 2005; Jimenez-Morillo et al. 2017). Lozano et al. (2013) found that lipids were one of the molecular substances strongly linked to SWR in a semi-arid Mediterranean forest. In addition, soil pH also could affect SWR by influencing soil microbial and fungi activity, which released hydrophobic substances (Doerr et al. 2006; Lozano et al. 2013). Other factors like soil-pH dependent chemical interaction may also play role in the formation of SWR (Smettem et al. 2021). In soil, pH could be influenced by the soil water content directly through the dilution of ions in the soil solution or the decrease of the solution volume due to intense evaporation. Additionally, pH could be indirectly influenced by soil water content through soil microbial activity as they released or consumed acidic or basic compounds (Husson 2013).

Regarding step 4 (**Figure 5.1**), the inhibited soil infiltration post volcanic eruption may be attributed to the establishment of a water repellent layer on the soil surface. The WR of this layer may be induced by the hydrophobic characteristics of VA (Berenstecher et al. 2017), and/or through hydrophobic substances derived from organic debris interacting with the VA (Jimenez-Morillo et al. 2017; Kawamoto et al. 2007; Poulenard et al. 2004). However, the relative importance of these effects remains unclear (Bachmann et al. 2000; Neris et al. 2013; Poulenard et al. 2004) and may depend on (as yet unidentified) contextual factors.

Regarding step 5 (**Figure 5.1**), 'WR' and 'saturated hydraulic conductivity' were mutually exclusive concepts. The dependency of SWR on soil water content suggested that it was a transient phenomenon. However, while it persisted, it could reduce infiltration rates and result in overland flow and erosion. Beyond the first rewetting phase, the negative impact of SWR on soil infiltration could return when the soil surface dries. In relatively dry initial soil conditions, soil pores were filled with air. Water reaching this dry soil surface could not continue to enter soil pores if those air bubbles become trapped, especially during high-intensity rainfall (or irrigation). The combined effect of the WR layer and entrapped air bubbles within the soil matrix could have a significant impact on soil hydraulic conductivity and infiltration (Wang et al. 2000). However, the impact may still be underestimated due to the limited number of studies investigating this specific combination of factors. The topic of WR and entrapped air bubbles have been discussed separately.

This research aimed to investigate whether the establishment of WR in a mixture of VA and OM layers was correlated with the types of organic materials and quantify the effect of WR on infiltration (hydraulic conductivity). This controlled laboratory setting experiment could help to provide evidence that the WR phenomenon generated in the lab could be related to the reduction of infiltration rate in the field. Our research questions were:

Q1A. Do the types of OM that are mixed with VA influence WR? **B.** Is this effect associated with lipid content and pH changes?

Q2. How does water content influence the severity and persistence of WR?

Q3. Do WR and water drop sizes influence the critical slope at which surface runoff starts? and,

Q4. How does surface-level WR relate to column-level and field measurements of infiltration rates?

5.2 Materials and Methods

5.2.1 Water repellency (WR) metrics

We used two methods to evaluate WR, including (1) the Water Drop Penetration Time (WDPT) (Doerr et al. 2005), (2) the contact angle (CA) of water droplets with a Sessile Drop Method (SDM) (Leelamanie et al. 2008).

The WDPT test involves placing drops of distilled water onto the sample surface and recording the time for complete drop penetration. We put 15 grams of VA sample or a mix of VA and various litter sources (see section 2.4.1) on a 90 mm diameter petri dish and levelled it with a spatula. Three water droplets were placed on the sample surface, and the actual time required for complete infiltration was recorded (de Blas et al. 2013). We took the average infiltration time values of three droplets to represent the sample.

We also measured the CA of water droplets. The sample particles were sprinkled on a double-sided tape (1.5 cm x 1.5 cm) pasted onto a smooth surface of a 90 mm diameter of petri dish. The particles adhering to the tape were pressed using a 100-gram load for 10 seconds to get a thin one-grain sample layer with a similar diameter. The sample layer was then gently tapped to remove surplus soil particles from the sample. The procedure was repeated twice. After preparation, the samples were placed on a stage in front of a digital camera, as illustrated in Supplementary information 5.1 (**SI. 5.1**). Three droplets of 10 μL distilled water were sequentially placed onto an unaffected (from the previous drop) part of the sample surface using a pipette. A digital photograph of the horizontal view of each water droplet was taken within one second (Leelamanie et al. 2008). The CA of both sides of each water droplet was determined by analysing the photograph images using ImageJ apps with drop-analysis plug-ins (Stadler and Sage 2020). The mean CA value from both sides of the water droplets was used for further analysis. A sample was classified as hydrophobic if CA was greater than 90° (Simpson et al. 2015).

5.2.2 The effect of WR on the relationship between critical slope and runoff

As a novel, additional method, a simple procedure was designed to test the relationships between the slope and runoff of droplets before infiltration. To generate the slope dataset, we placed samples of different WR levels (CA >90°) inside a petri dish on an adjustable stage (sturdy handphone holder) to set the slope (**SI. 5.2**). We placed a droplet of distilled water into the sample, quickly took a photograph for CA measurement, and adjusted the gradient to a point where the droplet started to slide down (representing the soil runoff occurrence). This procedure took approximately 5 seconds. Slope adjustments immediately made after the water droplets were applied to the WR surface may allow for movements and energy changes that may impact the infiltration process. Nevertheless, such effects may only marginally change the runoff initiation with the increasing slope. The diameter of drop sizes was crucial for this experiment. Here, we used two different water drop diameters of small (2.8 mm) and large (8.5 mm), as it represented the range of raindrop diameter sizes in tropical regions, as reported by Yakubu et al. (2016).

5.2.3 Volcanic ash (VA) collection and preparation

We used VA materials from the 2014 Mt. Kelud eruption deposited in Sumberagung Village, Ngantang District, East Java, Indonesia. VA term referred to the pyroclastic materials deposition of <2 mm tephra fractions (Arnalds 2013; Rossi et al. 2021). Farmers collected the VA approximately two months after the eruption. VA was stored in a dry condition and has not been modified by the interaction with the existing vegetation in the landscape. Saputra et al. (2022) reported that the VA has material distribution sizes of 81%, 14%, and 5% sand-, silt-, and clay-size particles, respectively. VA also had a very low soil organic carbon content (SOC) of <0.01%.

VA was sieved using a 2 mm mesh sieve. To dry the VA, we heated the sample to a temperature of 200°C for 60 minutes using a muffle furnace. In the preliminary experiment (**SI. 5.3**), VA exhibited a hydrophobic state (CA >90°) after the heating process. However, it was observed that the VA returned to a hydrophilic state in less than 48 hours. This particular high-temperature treatment was within the estimated temperature range of VA flow from the Merapi eruption in Indonesia (<300°C) inside the radial distance of 9-16 km from the vent (Jenkins et al. 2013). Similarly, Pensa et al. (2019) estimated VA temperature in an unconfined distal area up to 8-10.5 km from the crater as in 170°-220°C range during the Volcan de Colima eruption (Mexico). The dried VA was stored at laboratory conditions (temperature between 23-25°C with an average relative air humidity of 65%) for two days before further being used for laboratory analyses and experimental materials.

5

5.2.4 Experiments setup

5.2.4.1 First experiment: The effect of different organic matter (OM) sources on WR indicators

To answer **Q1,** we designed an experiment with three different plant litter sources and one mixture litter to represent the range of OM expected in the agroforestry landscapes affected by Mt. Kelud ash. The OM sources include litter from *Coffea canephora* (Robusta coffee), *Durio zibethinus* (Durian), *Pinus merkusii (*Pine) and mixed litter *of C. canephora, D. zibethinus* and *P. merkusii*. The experiment included five treatments: (1) volcanic ash (VA), (2) VA + *C. canephora*, (3) VA + *D. zibethinus*, (4) VA + *P. merkusii*, and (5) VA + mixed.

Litter from *C. canephora, D. zibethinus* and *P. merkusii* were classified as high, medium, and low litter quality, respectively (Chae et al. 2019; Ishaq et al. 2020b; Purwanto et al. 2007). High litter quality had a low C:N ratio and lignin plus polyphenol to N ratio, (L+Pp)/N, and decomposed rapidly (Sari et al. 2022). We gathered freshly abscised leaf litter from agroforestry plots, at the same place where we collected the ash materials. The litter was air-dried for 48 hours and ground. The ground litter was then sieved using a 2 mm mesh sieve and stored under laboratory conditions before further chemical analysis. We used ≤2 mm of particle size as it induced the highest CA compared to larger OM particle size treatments (**SI. 5.4**), representing the maximum-potential level of WR that OM could produce. Furthermore, ≤2 mm also represented the size of decomposed organic materials when they turned into soil organic matter (SOM).

VA and litter were mixed to achieve a 16% OM proportion. This OM proportion was based on the third preliminary experiment (**SI. 5.5**) that tested a wider range of VA to OM ratios for the degree of WR induced. This high OM proportion was realistic for the top few cm of mixed VA + OM layer formed after the volcanic eruption. During the volcanic eruption, VA precipitation induced significant defoliation and abrasion of leaves and other tree components (biomass) and buries all the standing litter (necromass).

The mixing of VA and litter of each treatment was performed manually in large quantities. For each replication, around 30 grams of material were incubated in small aliquots, with one for each time step. To maintain a constant water content, each aliquot was placed in a sealed plastic bag. Before measuring WR, the material in each aliquot was homogenized. The WDPT and CA were measured initially and after five-time steps (0, 1, 2, 4, 8, 16 weeks) to understand the longevity/persistence of WR for each treatment and its correlation with extractable lipids content and soil pH (for further explanation on lipids and pH analysis, please see section 5.2.5). Each treatment was replicated four times for a total of 120 samples. However, for CA and WDPT, a total of 360 data points were recorded, as we measured each sample three times (please see section 5.2.1).

5.2.4.2 Second experiment: The effect of soil water content on WR

We designed the second experiment to determine the WR sample's critical water content (CWC) and transition zone (**Q2**). The VA + *P. merkusii* material from the first experiment was used, as this treatment induced the highest WR. CWC referred to the water content at which the effect of WR on the material was no longer present. Various amounts of water were added to the sample to create different water contents (θ, %). Samples were carefully mixed, put inside a sealed plastic bag, and left for a day to equilibrate before the first measurement. The actual water content was determined gravimetrically before measuring CA and WDPT. Five different water content treatments, including <4%, 4-7%, 7-10%, and >10%, were used in this experiment. The persistence of WR was studied by conducting measurements at five different times after the start of the experiment (0, 1, 2, 4, 8, 16 weeks). All treatments were replicated four times, for a total of 96 samples.

5.2.4.3 Third experiment: The critical slope–runoff relationship affected by WR

The third experiment was designed to study the relationships between WR (represented by CA) and the critical (minimum) slope at which water droplets started to run off (**Q3**). VA + *P. merkusii* material with varying water content to create a range of CA. To achieve different CA, we conditioned the samples by adding 0.25 ml, 0.5 ml, and 1 ml of water into each sample unit. After homogenizing and incubating the samples for one day, we measured the actual water content gravimetrically. The actual water content ranged from 1-1.6%, 2-2.6%, 4.1-5.2% for the 0.25, 0.5-, and 1-ml water additions, respectively. This procedure produced CA values ranging from 95° to 153°. We replicated all treatments five times. For detailed WR measurement procedures please see section **SI. 5.2**.

5.2.4.4 Fourth experiment: The effect of WR as a surface layer property on soil infiltration and hydraulic conductivity

The fourth experiment aimed to assess the impact of VA and OM layer on infiltration (hydraulic conductivity) (**Q4**). For this purpose, six treatments were applied, including (1) original soil 'as a control', (2) original soil + VA, (3) original soil + VA + *C. canephora*, (4) original soil + VA + *D. zibethinus*, (5) original soil + VA + *P. merkusii*, and (6) original soil + VA + mixed litter. The 'original' soil column used in the experiment was obtained from the topsoil of coffee-based agroforestry systems and had the following characteristics: loam texture with 16% clay, 37% silt, and 50.8% sand, a bulk density of 0.99 g cm^{-3} and SOC content of 1.1%. Two different treatments of 5 and 10 cm depth of water repellent material layer were added to the original soil column before conducting the infiltration (hydraulic conductivity) measurement. These values represented the range of deposited VA thickness measured near Mt. Kelud after the 2014 eruption (Saputra et al. 2022). We tried to re-create the field condition post volcanic eruption where our field-measured steady state infiltration rate was dramatically drop compared the pre-eruption. The treatments were replicated four times. All experiments (1 to 4) were performed under a climate-controlled laboratory setting at an air temperature ranging from 23 - 25°C and an average relative air humidity of 65%.

Soil hydraulic conductivity was assessed using a 'falling' head method in a laboratory setting (Novák et al. 2009). The undisturbed soil column samples were collected using a plastic cylinder with a volume of 238 cm^3 (diameter 5.5 cm) at the same location where the VA and litter were taken. The field-collected soil column samples were saturated using tap water from the sample bottom to allow the air to escape for 48 hours. We applied a 5 or 10 cm layer of dry water repellent material on top of the original soil column and then added water to the soil column until the water level reached 23 cm above the sample surface. We measured the difference between the first and second water level reading at 1-minute interval. If the water level reduced to around 15 cm above the sample surface, we readjusted it back by adding additional water. This process was repeated for a total observation time of 2 hours. This procedure was applied for all measurements.

5

We expected to observe the common infiltration pattern in water repellent material, where the initial low infiltration rate would increase over time as the material became more wettable. However, our data did not show this pattern. Within two hours of observation time, the infiltration rate declined from the initially high to a lower rate. Therefore, to estimate the initial infiltration rate as well as the steady state infiltration rate, which was equal to hydraulic conductivity, we used the standard Horton equation (Horton 1941; Mahapatra et al. 2020). The estimation was done by curve fitting of Horton's equation using SigmaPlot 10 software (Saputra et al. 2020) as follows:

$$f_p = f_{min} + (f_{max} - f_{min})e^{-k_d t} \quad (1)$$

Where:

f_p : infiltration rate at time t, cm h^{-1}

f_{max} : initial infiltration capacity or maximum infiltration rate, cm h^{-1}
f_{min} : (quasi)-steady state infiltration rate representing hydraulic conductivity, cm h^{-1}
k_d : exponential decay constant specific to soil, $time^{-1}$

The equation predicted a smooth decline from the initially high infiltration rate, when water could fill air-filled pore spaces, to the rate at which it could be passed, supposedly indefinitely, through the whole column once this was saturated and the largest pore sizes dominate the result. As an alternative to analysis of the temporal change in f_p, the rates were also compared to the RelCumInf parameter that divides the cumulative infiltration by the total pore space in the soil column (whether air-filled or water-filled at the start of the measurements).

In standard theory the f_{min} parameter in equation (1) represented K_{sat} or saturated hydraulic conductivity. In our case, there were doubts that the soil was completely water-saturated towards the end of the measurement periods. Faybishenko (1995) refered to this term as quasi-saturated hydraulic conductivity to describe the state in which air was trapped in soil but not connected to the atmosphere. We refered to the f_{min} or quasi-saturated hydraulic conductivity parameter simply as K_{obs}, the observed hydraulic conductivity.

We compared this K_{obs}, derived as the f_{min} parameter in equation (1), to what the van Genuchten (Hodnett and Tomasella 2002) pedotransfer function (hydraulic conductivity = f(texture, macroporosity)) predicted for a soil with the same texture and bulk density (K_{ref}). However, as the predicted hydraulic conductivity values from the van Genuchten pedotransfer function were higher than our lab measurements for the original soil, we used the ratio between the two values rather than directly used the predicted values.

Furthermore, a 'relative equivalent porosity' term was defined as the relative macroporosity for which the reference soil (in the van Genuchten pedotransfer function) would yield the observed K_{sat}. We used a log10 transform to interpolate between the tabulated points generated from the van Genuchten pedotransfer function. Hydraulic conductivity ratio (K ratio) in equation 2 and relative equivalent porosity in equation 3 were used to test the consequence of WR (represented by CA) as a surface property on soil column hydraulic conductivity (**Q4**).

$$K\ ratio = K_{obs} / K_{ref} \quad (2)$$

where:

K_{obs} : observed hydraulic conductivity.
K_{ref} : reference hydraulic conductivity.

$$Relative\ equivalent\ porosity = \Phi_{ref} / \Phi_{obs} \quad (3)$$

where:

Φ_{ref} : reference macroporosity.
Φ_{obs} : observed macroporosity.

5.2.5 Physico-chemical analysis

Physico-chemical analysis of VA was performed at the Soil Science and Forestry Department laboratory of Brawijaya University. The soil organic carbon (SOC) content was measured using the wet oxidation of Walkley and Black method (Anderson and Ingram 1994). This method involves the oxidation of OM by potassium dichromate ($K_2Cr_2O_7$) with sulfuric acid (H_2SO_4) to heat the dilution, followed by colorimetric titration. Soil texture was determined using the pipette method (Bieganowski and Ryżak 2011). The pH of the soil-water mixture (1:5 ratio) was measured using an electrodes-connected pH meter.

The extractable lipids content of 120 samples was analysed with the Soxhlet method (Perera and Brown 1996) in the Food Technology Laboratory of Universitas Muhammadiyah Malang. Lipids content from a 2 g freeze-dried sample was extracted with 20 ml of petroleum ether solvent using Soxhlet apparatus for six hours. Extracts were filtered and dried (evaporated) at 40°C for about 30 minutes until no solvent was seen and were kept in a desiccator at room temperature before weighing. Total lipids content was gravimetrically determined and expressed as percentages of the dry sample weight (Helrich 1990).

5.2.6 Statistical analysis

The main and interactive effects of treatments of WR (expressed by CA and log WDPT), pH, lipids content, and K_{obs} were analysed using two-way ANOVA after evaluating the data normality by checking the skewness and kurtosis metrics. The WDPT data (experiments 1 and 2) were log-transformed, while the CA (experiment 1) and lipids (experiment 2) were square root-transformed prior to analysis to meet the normality assumption. The non-transformed data were used for data presentation in figures and tables, except for WDPT. Statistical differences were considered significant at $p \leq 0.05$ level. Pairwise differences were tested using Tukey's HSD *post-hoc* test. We fitted a logarithmic regression model to address the relationships between CA and log WDPT with lipids, and a linear regression model between CA and log WDPT with pH (**Q1** and **Q2**). The relationships between CA with the critical slope for runoff (**Q3**), and CA with K_{sat} ratio and relative equivalent porosity (**Q4**) were fitted using a simple linear regression model. We performed all statistical analyses using R 4.1.2 (R Core Team 2021).

5.3 Results

5.3.1 The effect of different organic matter types on lipids, pH, and WR indicators

The incubation time had a strong effect on the CA and log WDPT of the water-repellent material, with the concentration of lipids as a potential causal factor. Additionally, the pH difference between samples with and without litter gradually increased over time (**Figure 5.2**). Exponential decay functions were used to model the difference between VA and VA + litter, and they provided a good fit for the data. The effect on CA, log WDPT and lipids decreased 1.5, 0.8 and 4.6% per week, respectively.

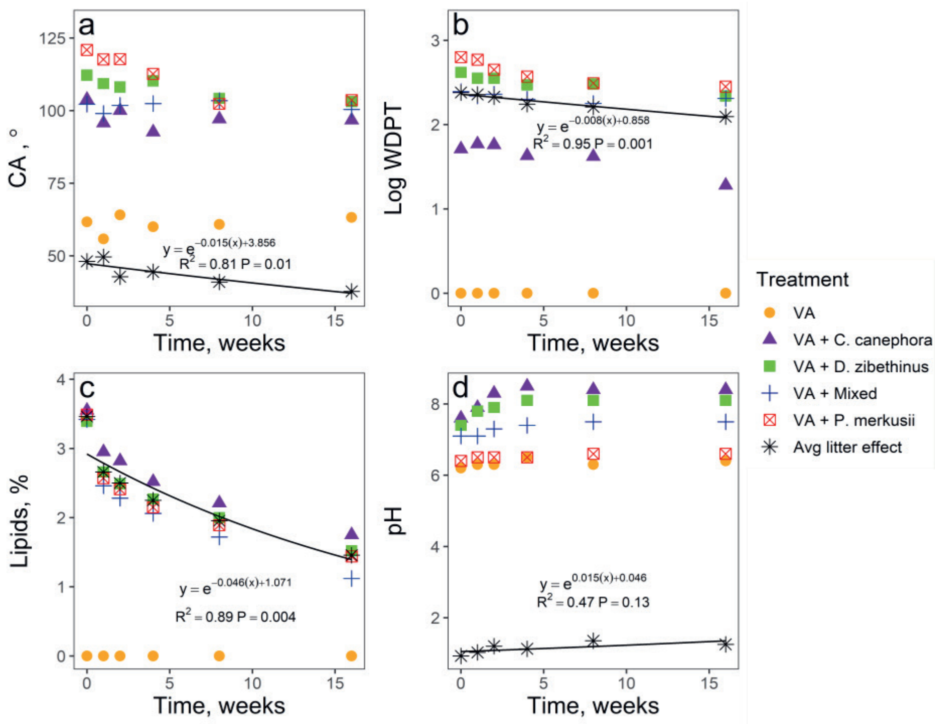

Figure 5.2. The measured (a) CA, (b) log WDPT, (c) lipids content and (d) pH of water repellent materials during a 16-week incubation in experiment 1. The average litter effect (Avg. litter effect) was calculated by subtracting the control treatment (VA) from the average value of all litter treatments. The average litter effect was fitted using an exponential regression model. CA: Contact Angle, WPDT: Water Drop Penetration Time, WR: Water Repellency, VA: Volcanic Ash

Lipids content was zero for the VA samples and 2.4% on average for the VA + litter samples, without statistically significant difference between the litter sources, but a substantial decline over time (**SI. 5.6**). A substantial decrease in lipids was found during the first week of incubation time, with an average reduction of 23% relative to the initial value. The most significant reduction was found in VA + mixed OM treatment (28%) during this first week, followed by VA + *P. merkusii*, VA + *D. zibethinus,* and VA + *C. canephora* with 26%, 22%, and 17%, respectively. Whereas, between weeks 2 to 16, we identified a slow and steady lipids reduction in all VA + OM treatments with an average relative decline of 2.2% per week.

The pH differed significantly among the treatments. In general, OM addition to VA increased pH. The VA + *C. canephora* treatment increased pH by nearly two units compared to only VA. Whereas, the VA + *P. merkusii* elevated the pH by 0.2, the lowest among other treatments. There was a tendency for pH to increase with observation periods. However, significant increases were only found for VA + *C. canephora*, VA + *D. zibethinus*, and VA + mixed OM treatments.

The mix of VA and various OM sources induced WR showed by its CA and log WDPT values (**SI. 5.6**). VA + OM treatments increased CA to >90° (indicating hydrophobicity). VA + *P. merkusii* treatment had the highest average of CA (112°), followed by VA + *D. zibethinus*, VA + *C. canephora*, and VA + mixed OM (108°, 99.6° and 97.6°, respectively). The increases of CA values followed by a more extended time needed for the water droplets to infiltrate into the sample, as shown by a higher log WDPT (**SI. 5.7**). The time range required for a water droplet to penetrate the VA and OM samples was between 17 to 755 s, corresponding to slight to severe WR based on the classification of Bisdom et al. (1993). The highest average of log WDPT was found in VA + *P. merkusii*, VA + *D. zibethinus*, VA + mixed (strong WR level), followed by VA + *C. canephora* (slight WR level). In contrast, the water droplets were instantly infiltrated into the sample for the VA treatment, with an average CA of 61°.

During the 16-weeks observation period, all treatments involving a combination of VA and OM showed WR (CA>90°). The persistence of CA varied significantly among treatments. The treatment of VA + mixed litter exhibited the slowest decline in CA (-0.4 % per week), while VA + *P. merkusii* showed the fastest decline (-2.6 % per week). The other two litter sources showed a decline similar to the overall average (-1.5 % per week). In contrast, VA and VA + mixed litter showed constant CA throughout the 16-weeks period.

5.3.2 The effect of different water contents on lipids, pH, and WR (CA and log WDPT)

We used the VA + *P. merkusii* treatment sample (which had the highest WR), to analyse the effect of soil water content on lipids, pH and WR indicators, and their temporal change (second experiment). The decline of lipids within the observation period was slowest for the driest soil treatment (**Table 5.1**). The average lipids content across the observation times at <4% water content treatment was 1.4, 2.0, and 2.4 times higher than that found in the 4-7, 7-10, and >10% treatments, respectively.

The decay of lipids was 3.8, 10, 17 and 22% per week, while pH increased by 2.33, 1.94, 2.36, and 6.62% per week for soils kept at a water content of <4%, 4-7%, 7-10% and >10%, respectively. The CA difference between the average control treatment (VA) in experiment 1 and the average of OM addition treatments in experiment 2 (ΔCA) decreased by 2.2, 2.5, and 3.5% per week for water content < 4%, 4-7%, and >10%, respectively. However, we found a slight increase (0.43% per week) of 7-10% water content. It should be noted that at soil water contents >7%, the initial ΔCA was already small. The log WDPT decreased by 2.4, 0.9% per week for water content <4% and 4-7%, but slightly increased by 0.69 and 0.01% per week for water content 7-10% and >10%, respectively, again with a small initial effect size at soil water contents >7%.

The critical water content (CWC) for WR to be noticeable in the VA + *P. merkusii* treatment was 10% (v/v). The samples with CA <90° in the >10% water content treatment exhibited a short WDPT. However, the average log WDPT of 0.17 was classified as wettable based on the Bisdom et al. (1993) WR rating.

Interaction between water content and observation periods on CA among the treatments was only significant for water content <7%, with a decreased tendency along with the time observations (Table 1). Meanwhile, for the log WDPT, that interaction was substantial for water content <4%. The CA difference between hydrophobic samples (<4%, 4-7%, and 7-10% treatments) became marginal at the end of the observation time. The consistently significant differences in log WDPT along the observation periods were found between samples with <7% water content. The Bisdom et al. (1993) WR ratings were wettable (>10%), slight (7-10%), and strong (4-7 and <4%) with the average log WDPT of 0.17,1.5, and 2.65, respectively.

Table 5.1. The observed lipids, pH, contact angle, and log water drop penetration time (Log WDPT) of the mixed VA + *P merkusii* material from four different water content treatments of <4%, 4-7%, 7-10%, and >10%

Treatments	Weeks	Lipids, %	pH	Contact angle, °	Log WDPT, s
< 4%	0	3.49 ± 0.08^{n}	6.40 ± 0.04^{a}	126.6 ± 2.9^{hi}	2.9 ± 0.01^{e}
< 4%	1	2.53 ± 0.02^{m}	6.35 ± 0.05^{a}	120.3 ± 1.3^{ghi}	2.7 ± 0.02^{cde}
< 4%	2	2.24 ± 0.07^{lm}	6.65 ± 0.03^{bcd}	115.4 ± 2.7^{fgh}	2.6 ± 0.04^{cd}
< 4%	4	2.02 ± 0.06^{klm}	6.68 ± 0.03^{bcde}	108.4 ± 2.3^{defg}	2.6 ± 0.04^{cd}
< 4%	8	1.83 ± 0.07^{jkl}	6.68 ± 0.06^{bcde}	107.3 ± 0.5^{cdef}	2.5 ± 0.05^{c}
< 4%	16	1.58 ± 0.06^{ijk}	6.80 ± 0.00^{defghi}	104.4 ± 0.9^{bcdef}	2.4 ± 0.02^{c}
Av. < 4%		$\mathbf{2.28 \pm 0.13^{C}}$	$\mathbf{6.59 \pm 0.04^{A}}$	$\mathbf{113.7 \pm 1.8^{C}}$	$\mathbf{2.61 \pm 0.03^{C}}$
4-7%	0	3.49 ± 0.08^{n}	6.59 ± 0.01^{bc}	128.7 ± 4.0^{i}	$2.8 \pm 0.07d^{e}$
4-7%	1	2.24 ± 0.10^{lm}	6.71 ± 0.03^{cdef}	112.2 ± 2.3^{efg}	2.7 ± 0.06^{cde}
4-7%	2	1.25 ± 0.12^{hij}	6.83 ± 0.03^{defghi}	109.8 ± 1.9^{efg}	2.7 ± 0.07^{cde}
4-7%	4	1.10 ± 0.12^{ghi}	6.89 ± 0.02^{fghij}	107.4 ± 1.7^{cdef}	2.6 ± 0.06^{cd}
4-7%	8	0.88 ± 0.13^{fgh}	6.91 ± 0.03^{ghi}	100.6 ± 1.4^{bcde}	2.6 ± 0.04^{cd}
4-7%	16	0.48 ± 0.15^{cde}	6.98 ± 0.05^{hi}	100.7 ± 1.2^{bcde}	2.6 ± 0.05^{cd}
Av. 4-7%		$\mathbf{1.57 \pm 0.21^{BC}}$	$\mathbf{6.8 \pm 0.03^{B}}$	$\mathbf{109.9 \pm 2.1^{C}}$	$\mathbf{2.7 \pm 0.03^{C}}$
7-10%	0	3.49 ± 0.08^{n}	6.51 ± 0.02^{ab}	94.5 ± 4.3^{b}	1.5 ± 0.23^{b}
7-10%	1	1.76 ± 0.04^{jkl}	6.75 ± 0.02^{cdefgh}	92.4 ± 4.3^{b}	1.5 ± 0.21^{b}
7-10%	2	0.74 ± 0.05^{efg}	6.91 ± 0.04^{ghi}	95.2 ± 1.3^{bc}	1.5 ± 0.15^{b}
7-10%	4	0.57 ± 0.06^{def}	6.85 ± 0.02^{efghi}	95.5 ± 0.9^{bc}	1.6 ± 0.12^{b}
7-10%	8	0.29 ± 0.07^{bcd}	6.93 ± 0.01^{ghi}	94.7 ± 2.5^{b}	1.6 ± 0.11^{b}
7-10%	16	0.14 ± 0.04^{ab}	7.04 ± 0.02^{i}	96.4 ± 0.8^{bcd}	1.6 ± 0.13^{b}
Av. 7-10%		$\mathbf{1.16 \pm 0.24^{AB}}$	$\mathbf{6.8 \pm 0.04^{B}}$	$\mathbf{94.8 \pm 1.0^{B}}$	$\mathbf{1.5 \pm 0.06^{B}}$
>10%	0	3.49 ± 0.08^{n}	6.50 ± 0.04^{ab}	70.1 ± 3.8^{a}	0.2 ± 0.02^{a}
>10%	1	1.32 ± 0.14^{hij}	6.83 ± 0.02^{defghi}	68.8 ± 2.5^{a}	0.2 ± 0.03^{a}
>10%	2	0.55 ± 0.07^{def}	6.72 ± 0.07^{cdefg}	68.0 ± 1.1^{a}	0.1 ± 0.03^{a}
>10%	4	0.19 ± 0.03^{abc}	6.89 ± 0.02^{fghi}	72.4 ± 1.3^{a}	0.2 ± 0.03^{a}
>10%	8	0.09 ± 0.02^{ab}	7.49 ± 0.01^{j}	65.9 ± 1.3^{a}	0.1 ± 0.02^{a}
>10%	16	0.06 ± 0.01^{a}	7.58 ± 0.03^{j}	66.2 ± 0.8^{a}	0.2 ± 0.02^{a}
Av. >10%		$\mathbf{0.95 \pm 0.25^{A}}$	$\mathbf{7.0 \pm 0.08^{B}}$	$\mathbf{68.6 \pm 0.9^{A}}$	$\mathbf{0.17 \pm 0.01^{A}}$

Note: Av. = average value of each treatment; the values displayed were means ± standard error (SE); the interaction between treatments with incubation time was represented by the lowercase letter following the values in each treatment; the difference between treatments was represented by the uppercase letter following the average value in each treatment (in bold); different letters within a variable were significantly different at P < 0.05

5.3.3 The relationships between lipids content, pH and WR indicators from the different OM treatments

Although the various parameters exhibited different patterns of change with incubation time, significant relationships were found across different observation times between CA and log WDPT with lipids (**Figure 5.3**). Within litter treatments, the most significant relationship between WR (CA and log WDPT) and lipids was found in VA + P. *merkusii* (**SI. 5.8**). An increase in lipids content beyond 1% associated with a marginal increase in WR. Interestingly, although similar lipids content was found between VA + *C. canephora* and other OM treatments, the log WDPT in this treatment was noticeably lower, indicating that other factors beyond those measured may also contribute to WR development. Additionally, a reduced WR was noted with increased pH, as shown in **Figure 5.3.**

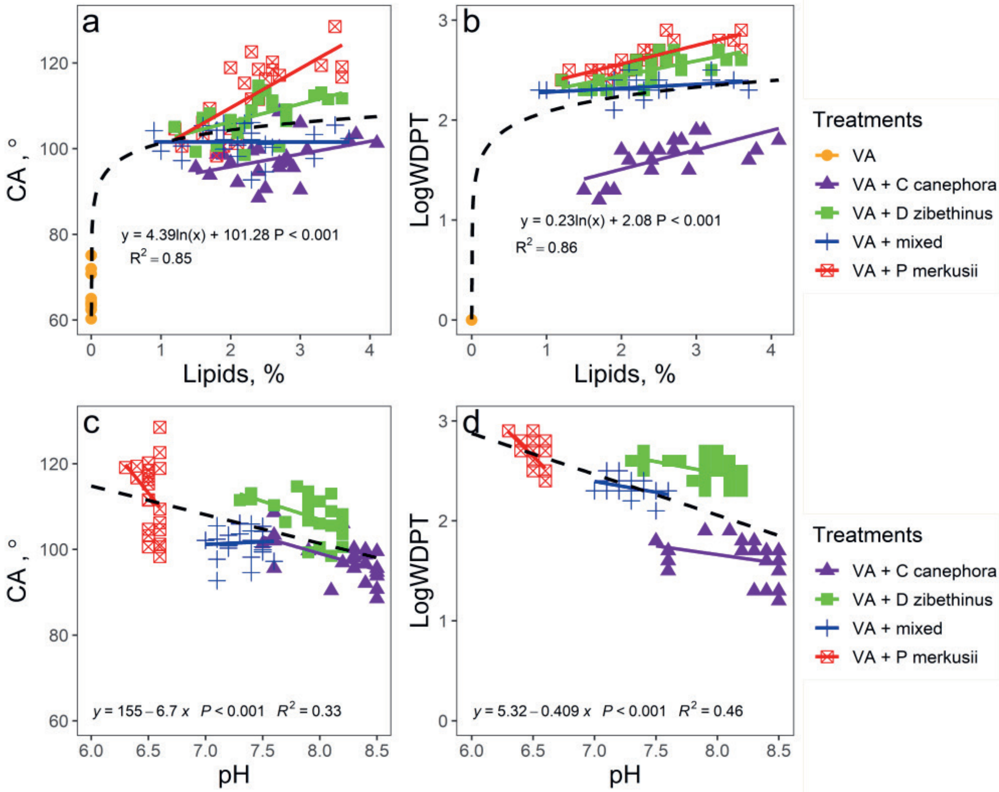

Figure 5.3. The relationships between lipids content and (**a**) CA, (**b**) log WDPT; and between pH and (**c**) CA and (**d**) log WDPT under VA and different organic matter sources treatments. We excluded VA dataset for the pH and WR indicators (CA and log WDPT) regression analyses. CA: Contact Angle, WDPT: Water Drop Penetration Time, VA: Volcanic Ash

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5.3.4 The relationships between lipids, pH, and WR indicators from the different water content treatments

We found that lipids content was positively associated with WR, while pH was otherwise (**Figure 5.4**). WR represented by CA was more closely correlated to lipids and pH changes than log WDPT. However, our data demonstrate that WR changes were substantially controlled by water content treatments rather than lipids and pH. This tendency was indicated by the development of data clusters that refers to the water content treatments, particularly noticed in the >7% water content treatments. However, lipids and pH in drier materials were highly related to CA and Log WDPT (**SI. 5.8**).

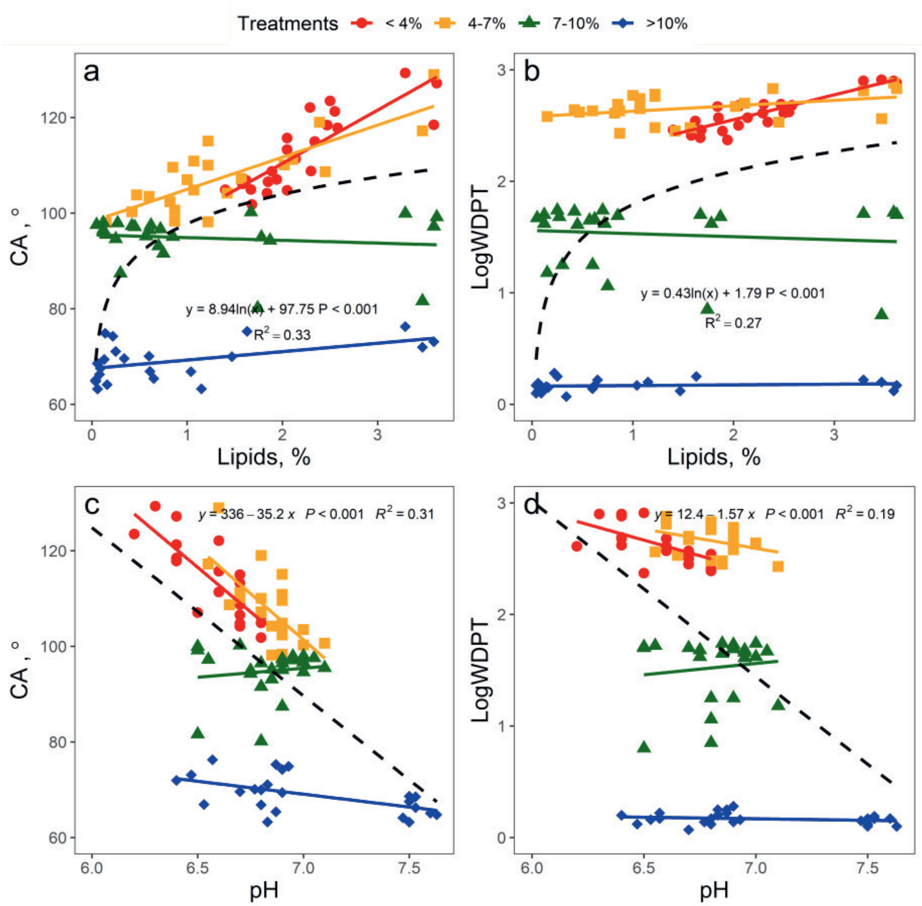

Figure 5.4. The relationships between lipids content and (**a**) CA, (**b**) log WDPT; and between pH and (**c**) CA and (**d**) log WDPT under different water content treatments. CA: Contact Angle, WDPT: Water Drop Penetration Time

5.3.5 The relationship between CA and critical slope for runoff

CA was negatively related to the critical slope when runoff starts. However, the relationships differed with droplet size (**Figure 5.5 and SI. 5.8**). A lower critical slope was required for immediate runoff in a large raindrop diameter (range of 7-16° critical slope) than the small diameter (range of 10-45° critical slope) within the WR treatments.

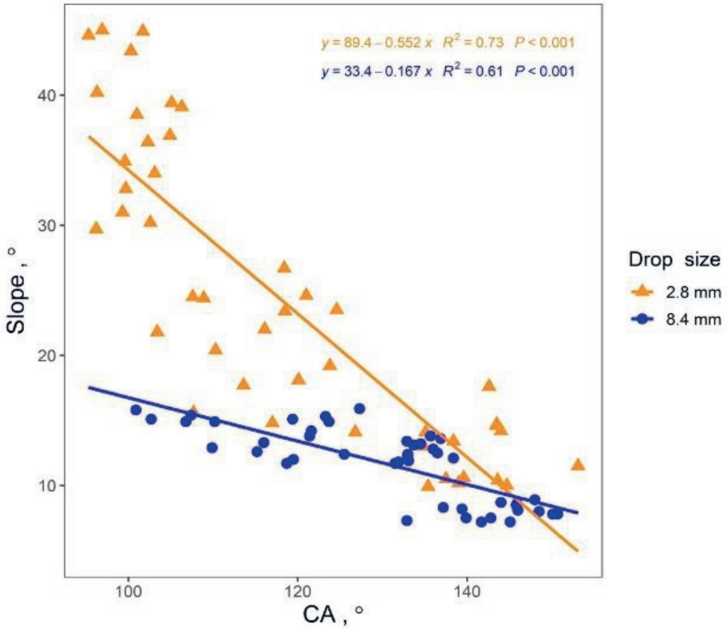

Figure 5.5. The relationship between contact angle (CA) and critical slope for runoff to start for two different water droplet diameters

5.3.6 The effect of WR surface layer on infiltration and observed hydraulic conductivity (K_{obs})

The initial infiltration rates were well correlated with the quasi-steady state infiltration (**Figure 5.6**), with an intercept that reflects more than proportional reductions of f_{min} relative to f_{max} in soils with low overall infiltration rates. Although the Horton equation used to estimate the K_{obs} values produced acceptable fits (**Figure 5.7**), the change with time in the observed infiltration rate in the VA soils differed from the gradual approach to a K_{obs} that can be sustained for as long as measurements would be continued. Instead, the VA + organic sources showed a continuously declining infiltration rate, with the most substantial effect seen in the 10 cm layer of VA + *P. merkusii*. When the infiltration rate was related to the RelCumInf parameter, results indicated that K_{obs} was obtained after the total soil pore volume had been many times (10 – 100 times) replaced, indicating a strong preferential flow (as opposed to 'piston flow').

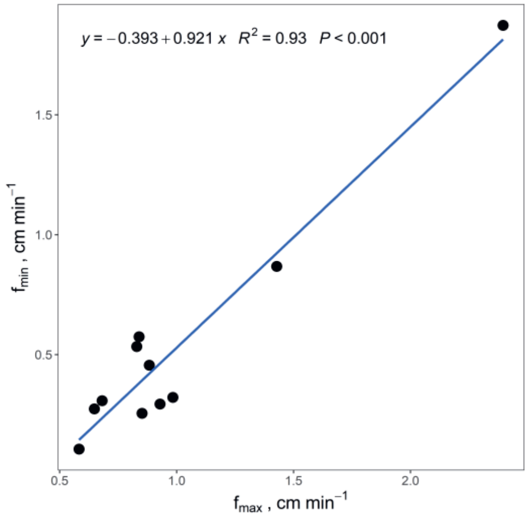

Figure 5.6. The initial (f_{max}) and quasi-steady state infiltration rates (f_{min}) estimated from the Horton equation

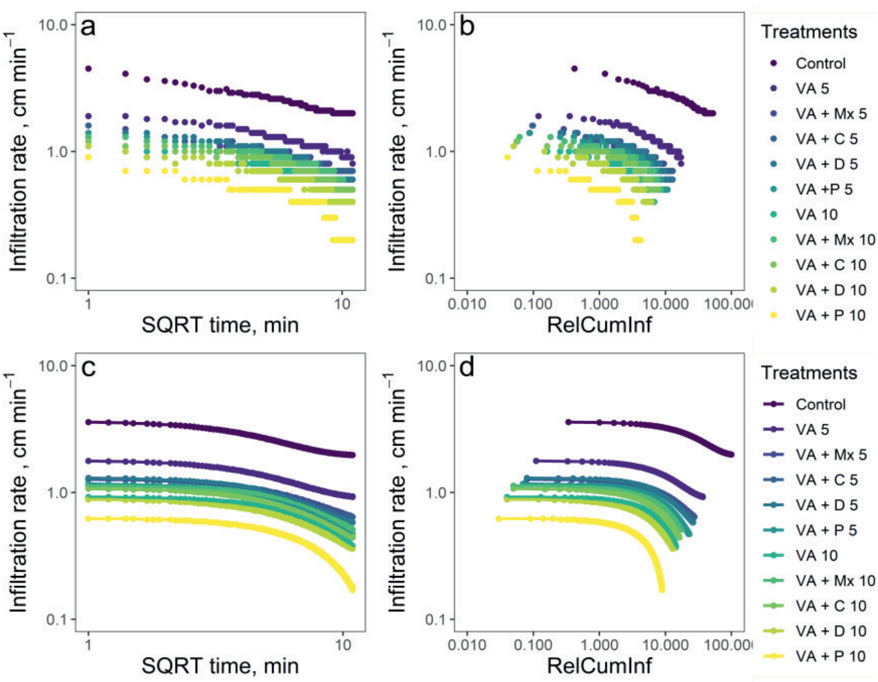

Figure 5.7. The infiltration rate as a function of the square root of (SQRT) time (**a** and **c**) and cumulative infiltration relative (RelCumInf) to total porosity (**b** and **d**). Two upper figures (a and b) were observed data, while two lower figures (c and d) were fitted data using Horton equations. Columns of control soil had 0, 5 or 10 cm of volcanic ash (VA) mixed with different OM sources on top. Volcanic ash (VA), VA + OM (Mx = mixed quality, C = *C. canephora*, D = *D. zibethinus*, P = *P. merkusii*)

The K_{obs} values generated from the Horton equation were log-normally distributed, with the value range of 6 - 131 cm h^{-1}. Overall, the added layer treatments significantly reduced K_{obs} by an average of 79% (24 cm h^{-1}), or five times lower than the reference soil (112 cm h^{-1}) (**Figure 5.8**). Relative to control soil, VA and OM treatments reduced the averages of K_{obs} by 71 and 87% for 5 and 10 cm layer thickness, respectively. The addition of various OM as hydrophobic materials further hampered K_{obs} by an average of 45% (5 cm layer) and 25% (10 cm layer) relative to VA treatments. The highest K_{obs} reduction was observed for the combination of VA + *P. merkusii*, almost 19 times lower than the reference soil. Similar to K_{obs}, we found that the initial infiltration (initial rate of water flows into the WR layer + soil column) was significantly different between the control and treated soil columns. Adding VA and various OM sources to the original soil column surface reduced the averaged initial infiltration rate from 143 cm h^{-1} to 52 cm h^{-1}. Even though we found no significant difference in the infiltration rate decay constant or *-k* among treatments (**SI. 5.9a and b**), we identified that WR metrics (CA and log WDPT) have a negative relation to *-k* (**SI. 5.10a and b**).

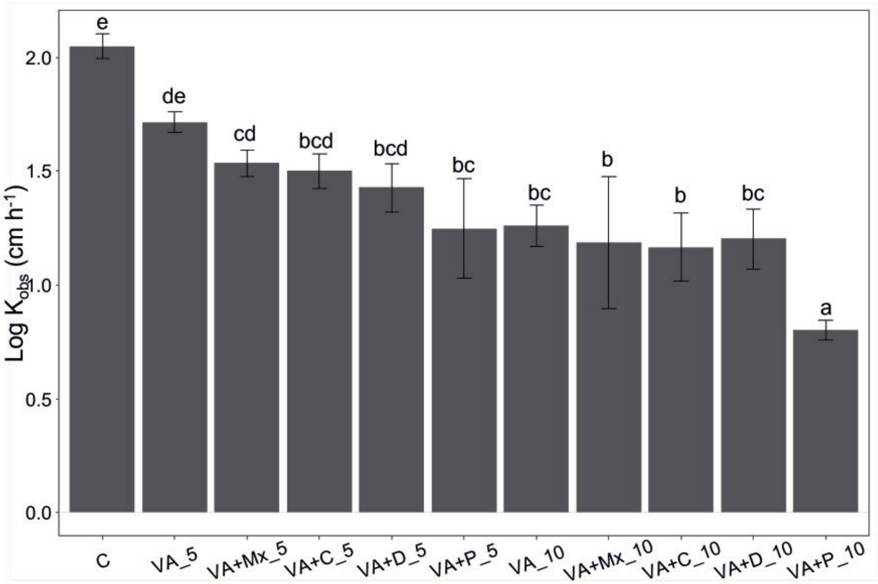

Figure 5.8. The observed hydraulic conductivity presented as log K_{obs} (mean ± SE) of two water repellence layers thickness (5 and 10 cm), and six treatments of control/untreated soil (Control), volcanic ash (VA), VA + OM (C = *C. canephora*, D = *D. zibethinus*, P = *P. merkusii*, Mx = mixed quality). The different letters indicate statistical differences between treatments ($p \leq 0.05$)

We found strong negative relationships between K ratio and relative equivalent porosity with CA in 5 and 10 cm layers of VA and VA + OM treatments (**Figure 5.9**). However, the lower regression line gradient of 10 cm layer thickness compared to 5 cm treatment indicates that the influence of

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WR on K ratio and relative equivalent porosity reduction became less substantial with thicker VA and OM layer added.

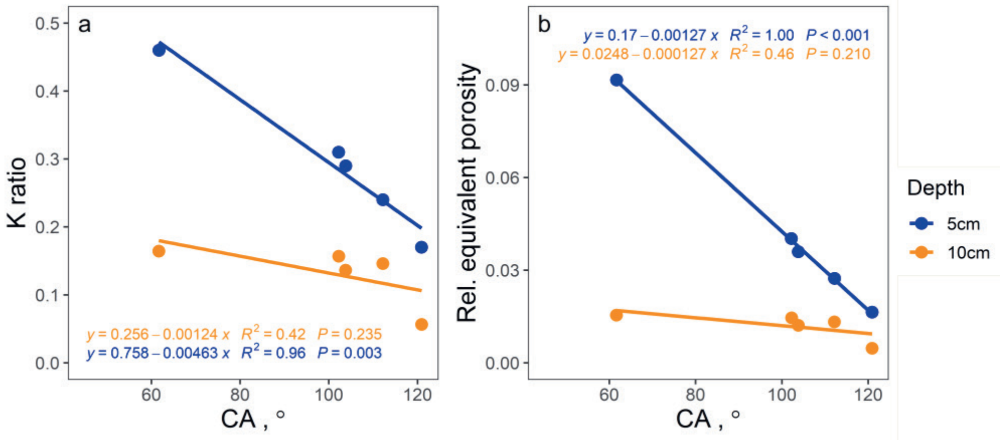

Figure 5.9. The relationships between contact angle (CA) and (a) K ratio and (b) relative equivalent porosity on two different water repellence layer thicknesses (5 and 10 cm)

5.4 Discussion

The experiments showed that the types of OM mixed with VA influence WR (**Q1A**). However, a direct attribution to lipids content and pH changes could not be made, as the temporal dynamics differed between parameters (**Q1B**). We also found that soil water content influences the severity and persistency of WR, with a critical soil water content of 10% above which WR effects were negligible (**Q2**). WR and droplet diameter size influenced the critical slope at which drops of water would runoff before they infiltrate (**Q3**). Finally, we found that the column-level soil infiltration and hydraulic conductivity was affected by surface-level WR (**Q4**).

In matching our process-level laboratory results to the field conditions, a number of steps in the experimental procedure need to be taken into account, such as the homogenization of litter material. We used ground fresh litter material, as this type of OM was probably predominant in the newly deposited VA, but we did not explore the effects of litter particle sizes, and litter to ash ratios beyond the preliminary experiment (**SI. 5.4 and 5.5**).

***Q1**: Difference litter sources induced a different level of WR through their lipids content and pH modification*

The addition of litter to VA induced WR. However, the severity of WR depended on the litter source. We found that the litter from *P. merkusii* induced the highest severity of WR compared to other litter treatments, with a CA of 112° and log WDPT of 2.62. Our results were similar to those of Neris et al. (2013), who found that the pine forest floor in Tenerife (Canary Islands, Spain) exhibited extreme SWR, with log WDPT ranging from 1.8 to 3.6. SWR has been broadly associated with tree species such as pine due to their hydrophobic substance content (Mataix-Solera et al. 2007).

Lipids, as a hydrophobic substance in plants, were related to CA and log WDPT (**Figure 5.3**). Our result here was similar to the study by Lozano et al. (2013), who found that the increases in lipids content from pine litter induced longer WDPT. In contrast, even though the VA + C. *canephora* mixture had comparable lipids content to other litter sources, it resulted in lower log WDPT. This result might suggest that lipids content alone was insufficient to explain the different WR. Research done by Dao et al. (2022) by physically mixing leaf powder from different plant species with acid-washed sand revealed that WR related to the differences in the concentration and diversity of *n*-alcohols, *n*-fatty acids, and high *n*-alkanes in the leaves. A wider range of plant characteristics may give further insights into which components were primarily responsible for the observed WR.

Our result demonstrated that pH was negatively related to WR, as also shown by some studies (Bonanomi et al. 2016; Mataix-Solera et al. 2007). pH could affect WR by influencing soil microbial and fungi activity. Fungi and other soil microbial activity could induce WR by releasing hydrophobic substances (Doerr et al. 2006; Lozano et al. 2013). Within the pH range of 6 – 9, fungi biomass decreased with higher pH (Rousk et al. 2009). Therefore, it reduced the hydrophobic substances produced by fungi, thus lowering WR. However, we have no empirical data on fungi activity in this experiment. Hence further work is needed. An alternative explanation was linked to soil pH-dependent chemical interaction, such as condensation or hydrolysis as proposed by Smettem et al. (2021). These interactions could lead to the formation or breaking of chemical bonds between organic molecules and soil particles, thus increasing or reducing WR. Furthermore, pH-dependent protonation or deprotonation of phenolic and carboxylic groups, which changes the polarity, have also been found to be correlated with WR (Terashima et al. 2004).

***Q2**: The critical water content (CWC) and transition zone of water repellent material*

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The CWC value of the materials in our experiment (10%) was within the range reported by Chau et al. (2014), who found values varying from 0 to >19% (depending on the specific sample locations), but below the value reported by Doerr and Thomas (2000) with 28%. Meanwhile, the water repellent materials' transition zone in this study was between 0 to 10% water content, corresponding to a 0 to 0.1 m^3 m^{-3}. This range was consistent with the results of several studies, such as Dekker et al. (2001) with a range of 0.02 up to 0.05 m^3 m^{-3}; Leighton-Boyce et al. (2005) with 0.14 to 0.27 m^3 m^{-3}; and Stoof et al. (2011) with 0.18 to 0.41 m^3 m^{-3}.

Knowledge of the CWC and the transition range where soils turn from a hydrophobic to a completely wettable state was valuable, as it provided essential information for remediating or overcoming water-repellent soils. Soil with less persistent WR and lower CWC implied that a large rainfall event may rapidly eliminate the WR. Soil with a high CWC would be prone to preferential flow and runoff due to its lower infiltrability as the soil was persistently hydrophobic at higher water contents. This condition could reduce water storage in the topsoil (Chau et al. 2014). However, once water moves to a greater depth, it may have a longer residence time, as the soil has a slower water movement due to tortuosity of the soil capillary system (Gupta et al. 2015). A hydrophobic soil surface later could also trap the moisture in underlying subsoil layers and provided a barrier to evaporation, which was beneficial during periods of high moisture stress during the dry season (Rye and Smettem 2017; Smettem et al. 2021).

The emergence of WR in a 'fresh volcanic soil' could be dissimilar to heat exposure-induced WR during a forest fire. In high temperatures during heat exposure, the volatilization and condensation of hydrophobic substances produced from burned OM subsequently coated soil particles up to 5 cm below the soil surface, creating a water-repellency layer (DeBano 1991). The extreme hydrophobic materials could also originate from the fine ash produced after the fire (Bodí et al. 2011; Stoof et al. 2011). Whereas hydrophobicity in volcanic soils did not always involve heat exposure to OM to create WR substances. Coarse-textured VA deposited in agricultural land experiences a cool-down period while drifting in the atmosphere and was not heating the soil when deposited. However, in a particular area close to the eruption epicentre or along the pyroclastic materials flow paths, there was a possibility that OM could be exposed to high temperatures and produce hydrophobic substances comparable to forest fire process. In this research, we emphasized the WR formation related to the presence of relatively fine hydrophobic particulate OM in pore space which was directly correlated to the abundance of OM in the soil. This specific condition was more or less similar to the non-fire-induced hydrophobic phenomena in sandy soils (Franco et al. 2000; Pierson et al. 2008; Siteur et al. 2016).

***Q3**: Strong WR properties minimize the critical slope for runoff to start*

Dissimilar to the non-water repellent soils, the existence of severe and persistent hydrophobic substances in relatively dry soils and sloping terrain could reduce infiltration and cause fast ponding, thus reducing runoff/erosion generation time. The relationship between WR and the critical slope for the runoff process was essential to predict the runoff/erosion scenarios in different intensities and frequencies of rainfall events.

The minimum critical slope for runoff to start for a large raindrop diameter was 7° (16%). Within our local context, the high rainfall intensity that often occurs in this mountainous area could create a greater risk of runoff and erosion, as the landscape of this region had a slope range from 2 – 40% (Saputra et al. 2022). The temporal variability of runoff generation between non- and water-repellent plots has been found to be highly variable in the short term (early time after the rainfall/irrigation or when the soil water content was still below the CWC). However, as the water content increased beyond CWC and the WR diminished with time, the runoff generation time could become comparable (Pierson et al. 2008). However, at the catchment scale, the overall impact of SWR on runoff, erosion and sedimentation was influenced by the spatial connectivity of the overland flow (runoff) sources areas, as well as the temporary and spatial variability of SWR. This complexity makes it challenging to establish direct links between SWR and erosion (Shakesby et al. 2000). Therefore, a better understanding of the temporal and spatial dynamics of SWR and its interactions with catchment-scale hydrological process is needed to better predict the impacts of SWR on runoff, erosion, and sedimentation.

***Q4**: Strong water-repellent surface layer reduced infiltration and hydraulic conductivity*

Our observed hydraulic conductivity (K_{obs}) values (6 - 131 cm h^{-1}) were within the range of sandy soils observed by García-Gutiérrez et al. (2018). Related to WR, our results showed that adding a 5-10 cm layer of hydrophobic material on the soil surface decreased K_{obs} from 69 to 94% (K ratio of 0.31 – 0.06) compared to the K_{ref}. Hydrophobic materials reduce the relative equivalent porosity for the water transmission process in the soil profile (**Figure 5.9b**).

We expected that the effect of WR on K_{obs} reduction would be limited to the early phase of the measurement when the water-repellent surface layer was relatively dry. Once the water content of the layer exceeded the CWC, we anticipated that the WR effect would disappear. However, we found that the WR effect on K_{obs} persisted throughout the measurement, rather than being a transient phenomenon in early wetting, as suggested by the effects of soil water content on WDPT.

To interpret these patterns, we proposed that air entrapment in soil pores (Faybishenko 1995) played a role in hindering the passage of water. It should be noted that the hydraulic conductivity measurements started with the water repellent materials in oven-dried conditions and apparently only partially saturated throughout the measurement. Entrapped air reduces the pore effectiveness to transmit water as it blocked the already limited water pathways (macropores) available in water-repellent material. This effect became more pronounced with time as the air bubbles that previously distributed in smaller pores then concentrate in larger pores where water movement mainly occurred, resulting in a sharp declined in infiltration rate in **Figure 5.7**, specifically on the tail section of the infiltration data, and therefore the estimated K_{obs}. At the end, the infiltration rate often slightly increased, but not at the level where it could significantly change K_{sat}, as the air bubbles release to the atmosphere (Concialdi et al. 2019). However, we doubted that we reached this state during this measurement, as we did not observe this pattern from the transient infiltration data (except for the control treatment) in **Figure 5.7**. It was likely because the measurement time was not sufficient for the air bubbles to be fully released.

To quantify the impact of air entrapment on soil infiltration and hydraulic conductivity, Dohnal et al. (2013) used x-ray computed tomography and magnetic resonance imaging combined with three dimensional numerical modelling. Their study indicated that the change of the water flow rate resulted by the air entrapment. Many authors reported that entrapped air could reduce the K_{obs} by 2-20 times compared to air-draining conditions (Faybishenko 1995; Marinas et al. 2013; Sakaguchi et al. 2005), but this fluctuates depending on the air outflow (Wang et al. 1998). This incomplete saturation of the water-repellent surface layer in the falling head experiments as a plausible reason for decreasing hydraulic conductivity with increasing WR was also previously reported by Shillito et al. (2020). Entrapped air affect the K_{obs} simultaneously with other factors such as soil particle rearrangement and blockage of soil porosity (self-filtration) as reported by Dikinya et al. (2008) that simultaneously. Self-filtration might occur as a consequence of vertical migration of the fine-size water repellent litter, as well as soil particles, during the measurement, and thus naturally lowered the water transmission and hydraulic conductivity. However, we did not find visual evidence of the ash and litter transported to the original soil column after we vertically sliced the soil sample after the measurement. Therefore, further investigation is necessary.

Daily rainfall intensity in East Java, Indonesia peaked at 105-164 mm day^{-1}, with a return period of 5-50 years (Faradiba 2021). Most rainfall occurs within 1-4 hours (Priambodo et al. 2019). Therefore, it was rather likely that water ponding could occur in the field, particularly for the soils which have >10 cm layer of mixed VA + OM originating from *P. merkusii*, *C. canephora*, and *D. zibethinus* (with an average K_{obs} of 63-, 153-, and 164-mm h^{-1}, respectively). With the rainfall intensity exceeding infiltration capacity, overland flow could occur in this sloping-mountainous area, despite the high soil macroporosity. However, on days with low rainfall intensity but long duration, entrapped air may easily escape to the soil surface, and WR may be overcome when the soil rewets. Nevertheless, WR would re-emerge when the soil water content was reduced to the transition zone.

WR dynamics on the volcanic landscape

In addition to soil water contents, the dynamics of WR may depend on two other processes: the mobilization of the hydrophobic substances due to soil erosion; and the input (supply) and decomposition rate of hydrophobic substances which was controlled by litter types, microbial activity, and microclimate. Surface runoff was likely to carry the soil materials (including the hydrophobic substances) within the steep slope area and might be deposited in the valley or a relatively flat area. However, the WR effect in the valley area may not be as apparent as in the upper part of the landscape, as the valley area usually has high water content (which was likely to exceed the CWC of this particular area).

Furthermore, it was commonly acknowledged that hydrophobic substances come from the non-polar aliphatic hydrocarbons and polar amphiphilic hydrocarbons groups derived from OM (Doerr et al. 2000). Therefore, further decomposition of OM and its hydrophobic substances contained therein, which was controlled by the soil organisms' (decomposer) activity, could lead to a decrease in WR. However, as an OM decomposer, the presence of fungi and other microorganisms may also induce WR (Doerr et al. 2006; Lozano et al. 2013). However, the long-term net effect depended on the standing OM content, determined by its input and decomposition rate balance. The dynamics of SOM were influenced by vegetation types (quality and quantity OM), microclimate conditions (temperature and water content), and the activity of soil microorganisms (decomposers) (Sari et al. 2022). Post-volcanic eruption soil management by farmers in the study area, such as adding a significant amount of external OM and mixing it with VA and the underlying original soil appeared to accelerate soil recovery (Ishaq et al. 2020b). However, this practice may also have an adverse effect by inducing WR of the soil surface.

WR implications on landscape modification and its ecological functions

At the plot and landscape scale, the development of WR contributed to VA distribution. VA was not only transported to the landscape directly during the volcanic eruption via the atmosphere, but also through further movement from the runoff and erosion process due to the low infiltration. The potential negative impact of WR on the landscape level could be costly, for example, when it was associated with river/water reservoir sedimentation and water quality. Heavy sedimentation of volcanic materials in the water reservoir could disrupt the electricity supply, generate eutrophication, and cause irrigation water shortages. On the other hand, WR established in volcanic soils could also have positive effect on soil moisture conservation against evaporative loss, facilitate groundwater recharge, and replenishment of deep moisture storage (Gupta et al. 2015; Lozano et al. 2013; Rye and Smettem 2017; Smettem et al. 2021).

5.5 Conclusions

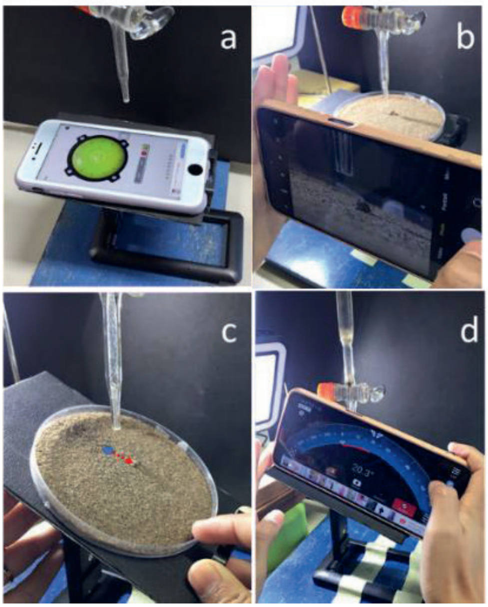
It was concluded that adding various litter sources to VA at a range of soil water contents affected the WR dynamics during a 16-weeks incubation period. Stronger WR was partially associated with higher lipids content and lower pH, indicating another possible influencing factor related to OM composition. The lower WR was directly controlled by the water content rather than changes in lipids and pH, particularly at water treatments >7%. Additionally, we found that the minimum critical slope for droplets to runoff (before infiltration) was 7° and 10° for large and small water droplet diameters, respectively. Finally, the addition of VA and litter on the surface of the control soil resulted in a five-times lower average hydraulic conductivity due to the combined effect of soil WR and entrapped air in the soil column. This combination effect led to the effective porosity reduction to transmit water, with 10 cm of layer addition showing the largest effect.

The WR phenomena in relatively young volcanic soils likely contributed to shaping volcanic landscapes. Despite the negative short-term consequences, VA might benefit soil moisture conservation, nutrient addition, and potential carbon sequestration in soils. Therefore, further research on optimising the benefit and reducing the adverse effects of VA through land use management is needed.

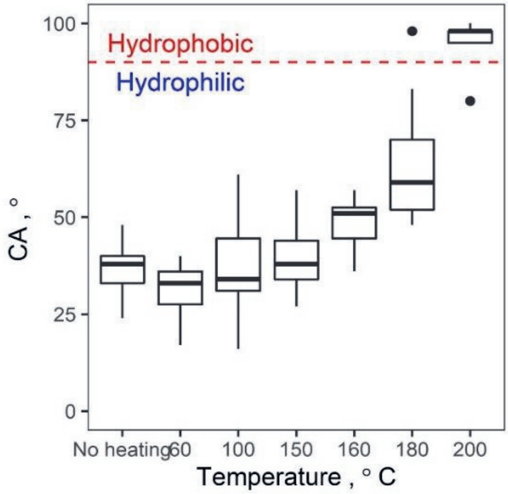
5.6 Supplementary information

SI 5.1. The experimental setup for the modified Sessile Drop Method (**a**); Photographs of samples with different contact angles (CA) (**b**); CA obtained using the ImageJ software and drop_analysis plug-in (http://bigwww.epfl.ch/demo/dropanalysis/), the samples showed CA 116° (hydrophobic) and 74.5° (hydrophilic) (**c**).

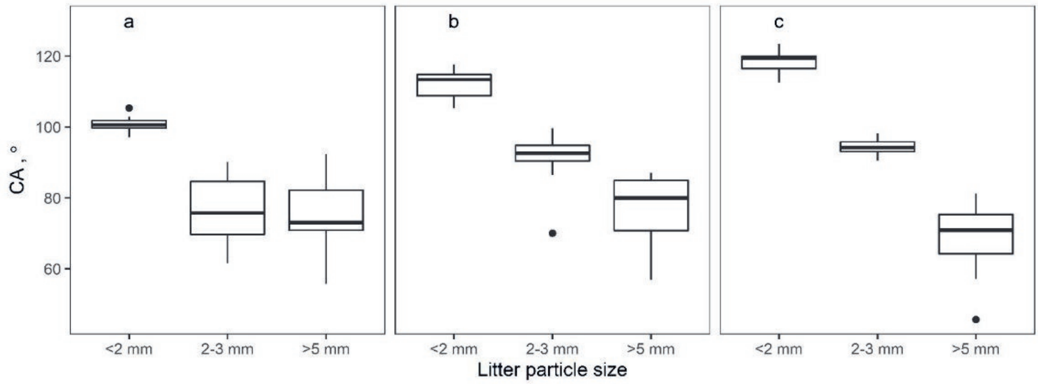
SI 5.2. A digital water pass app was used to control the initial platform slope (**a**); digital photograph was subsequently taken for a contact angle (CA) measurement (**b**); the stage slope was gradually adjusted to the point where the water droplet started to slide down (**c**); the final slope was measured using the digital clinometer (**d**).



SI 5.3. The contact angle (CA) of VA, without organic matter additions, after exposure for 60 minutes to different temperatures. VA reached a hydrophobic state after being exposed to heat up to 200°C. VA returned to a hydrophilic state after being stored at room temperature for 48 hours.



SI 5.4. The contact angle (CA) of different OM particle sizes (<2, 2-5, and >5 mm). The OM used was from (**a**) *C. canephora*, (**b**) *D. zibethinus* and (**c**) *P. merkusii* litter collected from a coffee-based agroforestry system.



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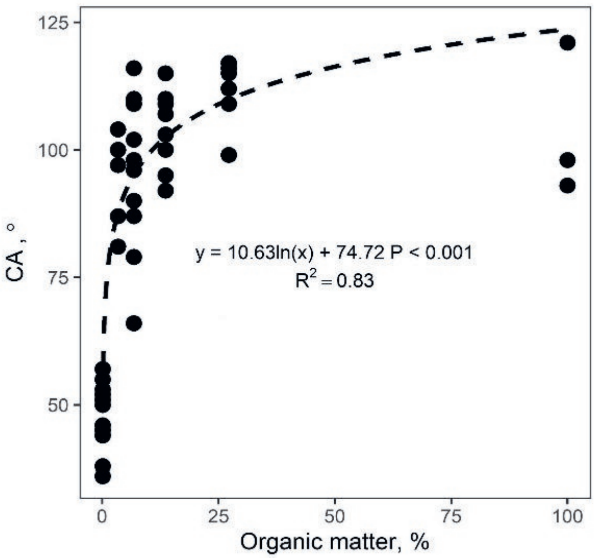
SI 5.5. The contact angle (CA) of mixed VA and different proportion of OM addition. Mixed VA and OM reached a hydrophobic state after 16% of OM addition. The OM was from coffee litter collected from a coffee-based agroforestry system.

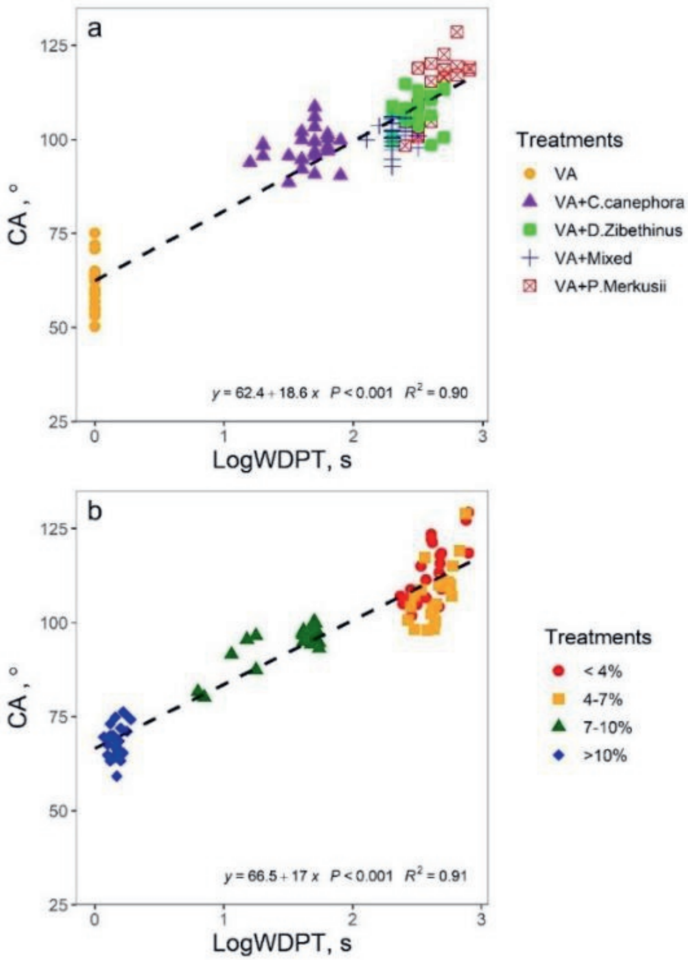


SI 5.6. The observed lipids, pH, contact angle, and log water drop penetration time (Log WDPT) of water repellence material from six different treatments of volcanic ash (VA), VA + *C. canephora*, VA + *D. zibethinus*, VA + *P. merkusii*, and VA + mixed (*C. canephora* + *D. zibethinus* + *P. merkusii*)

Treatments	Weeks	Lipids, %	pH	Contact angle, °	Log WDPT, s
VA	0	0.00 ± 0.00^{a}	6.2 ± 0.05^{a}	61.7 ± 2.2^{a}	0.00 ± 0.00^{a}
VA	1	0.00 ± 0.00^{a}	6.3 ± 0.09^{ab}	55.8 ± 1.6^{a}	0.00 ± 0.00^{a}
VA	2	0.00 ± 0.00^{a}	6.3 ± 0.04^{abc}	64.1 ± 3.8^{a}	0.00 ± 0.00^{a}
VA	4	0.00 ± 0.00^{a}	6.5 ± 0.03^{abc}	60.0 ± 2.5^{a}	0.00 ± 0.00^{a}
VA	8	0.00 ± 0.00^{a}	6.3 ± 0.08^{abc}	60.8 ± 4.6^{a}	0.00 ± 0.00^{a}
VA	16	0.00 ± 0.00^{a}	6.4 ± 0.03^{abc}	63.2 ± 2.8^{a}	0.00 ± 0.00^{a}
Av. VA		**0.00 ± 0.00^{A}**	**6.3 ± 0.03^{A}**	**60.9 ± 1.2^{A}**	**0.00 ± 0.00^{A}**
VA + *C. canephora*	0	3.55 ± 0.30^{m}	7.6 ± 0.03^{ef}	103.8 ± 1.7^{bcdef}	1.71 ± 0.04^{c}
VA + *C. canephora*	1	2.95 ± 0.06^{kl}	7.9 ± 0.13^{gh}	95.7 ± 2.0^{b}	1.77 ± 0.10^{c}
VA + *C. canephora*	2	2.82 ± 0.06^{jk}	8.3 ± 0.03^{ij}	100.0 ± 2.2^{bcde}	1.76 ± 0.01^{d}
VA + *C. canephora*	4	2.52 ± 0.07^{ghijk}	8.5 ± 0.03^{j}	92.6 ± 1.9^{b}	1.63 ± 0.05^{c}
VA + *C. canephora*	8	2.21 ± 0.09^{efghi}	8.4 ± 0.03^{j}	97.1 ± 1.8^{bcd}	1.62 ± 0.04^{c}
VA + *C. canephora*	16	1.75 ± 0.08^{cde}	8.4 ± 0.05^{j}	96.7 ± 1.2^{bc}	1.28 ± 0.03^{b}
Av. VA + *C. canephora*		**2.63 ± 0.13^{B}**	**8.2 ± 0.07^{E}**	**97.6 ± 1.0^{B}**	**1.63 ± 0.04^{B}**
VA + *D. zibethinus*	0	3.39 ± 0.08^{lm}	7.4 ± 0.03^{de}	112.2 ± 0.4^{fg}	2.62 ± 0.03^{hij}
VA + *D. zibethinus*	1	2.66 ± 0.11^{ijk}	7.8 ± 0.08^{fg}	109.3 ± 1.1^{defg}	2.55 ± 0.03^{fgh}
VA + *D. zibethinus*	2	2.49 ± 0.10^{ghijk}	7.9 ± 0.05^{gh}	108.1 ± 3.1^{cdefg}	2.55 ± 0.05^{ghi}
VA + *D. zibethinus*	4	2.27 ± 0.11^{fghi}	8.1 ± 0.05^{ghi}	110.2 ± 1.9^{efg}	2.47 ± 0.07^{efgh}
VA + *D. zibethinus*	8	2.00 ± 0.12^{defg}	8.1 ± 0.07^{hi}	104.2 ± 2.1^{bcdef}	2.48 ± 0.05^{efgh}
VA + *D. zibethinus*	16	1.52 ± 0.12^{bcd}	8.1 ± 0.08^{hi}	103.1 ± 1.9^{bcdef}	2.34 ± 0.02^{def}
Av. VA + *D. zibethinus*		**2.39 ± 0.13^{B}**	**7.9 ± 0.06^{D}**	**107.9 ± 1.0^{C}**	**2.50 ± 0.02^{D}**
VA + Mixed	0	3.42 ± 0.13^{lm}	7.1 ± 0.03^{d}	102.2 ± 1.7^{bcdef}	2.39 ± 0.03^{defg}
VA + Mixed	1	2.46 ± 0.08^{fghi}	7.1 ± 0.05^{d}	99.0 ± 2.1^{bcdef}	2.34 ± 0.03^{def}
VA + Mixed	2	2.28 ± 0.08^{efgh}	7.3 ± 0.04^{de}	101.8 ± 2.7^{bcdef}	2.36 ± 0.05^{defg}
VA + Mixed	4	2.06 ± 0.09^{efgh}	7.4 ± 0.03^{de}	102.4 ± 1.6^{bcdef}	2.30 ± 0.03^{de}
VA + Mixed	8	1.72 ± 0.07^{cde}	7.5 ± 0.03^{e}	103.4 ± 1.2^{bcdef}	2.25 ± 0.04^{de}
VA + Mixed	16	1.12 ± 0.09^{b}	7.5 ± 0.03^{ef}	100.4 ± 1.4^{bcde}	2.31 ± 0.01^{de}
Av. VA + Mixed		**2.18 ± 0.15^{B}**	**7.3 ± 0.03^{C}**	**101.6 ± 0.7^{B}**	**2.33 ± 0.02^{C}**
VA + *P. merkusii*	0	3.49 ± 0.08^{m}	6.4 ± 0.06^{abc}	120.9 ± 2.6^{h}	2.80 ± 0.03^{j}
VA + *P. merkusii*	1	2.57 ± 0.06^{hijk}	6.5 ± 0.00^{abc}	117.6 ± 0.5^{gh}	2.77 ± 0.03^{ij}
VA + *P. merkusii*	2	2.41 ± 0.07^{ghij}	6.5 ± 0.03^{bc}	117.7 ± 2.4^{gh}	2.65 ± 0.04^{hij}
VA + *P. merkusii*	4	2.15 ± 0.09^{efghi}	6.5 ± 0.03^{bc}	112.6 ± 3.0^{fg}	2.57 ± 0.03^{ghi}
VA + *P. merkusii*	8	1.89 ± 0.07^{cdef}	6.6 ± 0.03^{c}	102.4 ± 2.4^{bcdef}	2.49 ± 0.02^{efgh}
VA + *P. merkusii*	16	1.44 ± 0.09^{bc}	6.6 ± 0.03^{c}	103.6 ± 1.2^{bcdef}	2.45 ± 0.04^{defgh}
Av. VA + *P. merkusii*		**2.32 ± 0.14^{B}**	**6.5 ± 0.02^{B}**	**112.5 ± 1.7^{D}**	**2.62 ± 0.03^{E}**

Note: Av. = average value of each treatment; the values displayed were means ± standard error (SE); the interaction between treatments with incubation time is represented by the lowercase letter following the values in each treatment; the difference between treatments is represented by the uppercase letter following the average value in each treatment (in bold); different letters within a variable were significantly different at $P < 0.05$.

SI 5.7. The relationship between contact angle (CA) and log water drops penetration time (Log WDPT) for various treatments in (**a**) Experiment 1 and (**b**) Experiment 2.



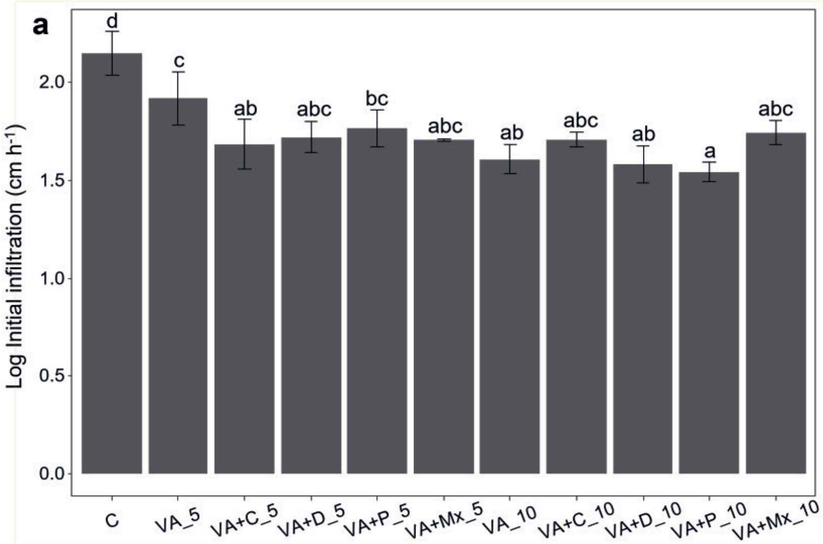
SI 5.8. Model describing the relationship between lipid contents and soil pH with CA and Log WDPT on various litter sources (**Figure 5.3**) and water content treatments (**Figure 5.4**).

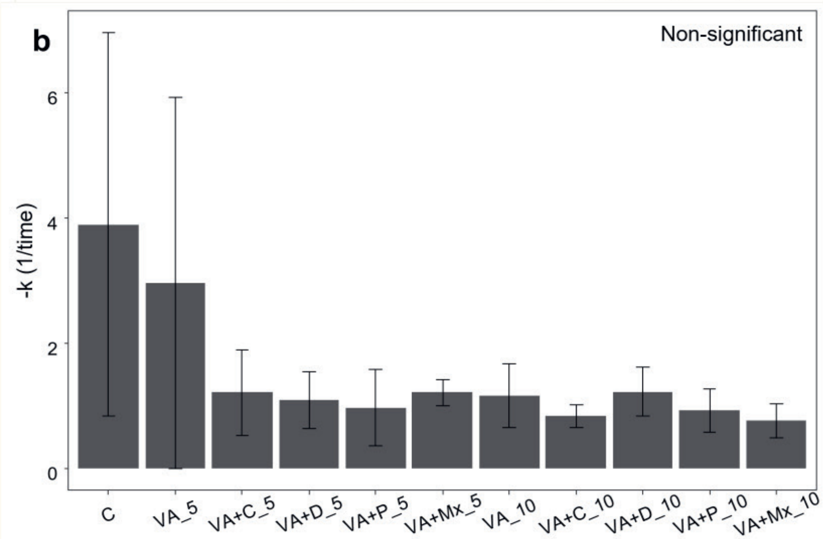
Figure	Treatments		Reg. Equation	R^2	p-value	SE - slope	SE - intercept
2	a.	Time VS CA	$y = e^{-0.015x + 3.856}$	0.81	0.01	0.004	0.028
	b.	Time VS Log WDPT	$y = e^{-0.008x + 0.858}$	0.95	0.001	0.001	0.007
	c.	Time VS Lipids	$y = e^{-0.046x + 1.071}$	0.89	0.004	0.008	0.059
	d.	Time VS pH	$y = e^{0.015x + 0.046}$	0.47	0.13	0.008	0.062
3a	VA + *C. canephora*		y = 2.95x + 89.85	0.15	0.058	1.482	4.012
	VA + *D. zibethinus*		y = 4.18x + 97.87	0.29	0.006	1.372	3.379
	VA + *P. merkusii*		y = 9.26x + 90.93	0.56	<0.001	1.766	4.264
	VA + Mixed		y = 0.038x + 101.64	<0.1	0.970	1.044	2.395
	Overall		*y = 4.39ln(x) + 101.2*	*0.85*	*<0.001*	*0.169*	*0.711*

3b	VA + *C. canephora*	y = 0.20x + 1.09	0.45	<0.001	0.048	0.130
	VA + *D. zibethinus*	y =0.14x + 2.17	0.51	<0.001	0.028	0.070
	VA + *P. merkusii*	y = 0.19x + 2.19	0.74	<0.001	0.023	0.057
	VA + Mixed	y = 0.04x + 2.24	0.14	0.070	0.020	0.046
	Overall	*y = 0.23ln(x) + 2.08*	*0.86*	*<0.001*	*0.008*	*0.035*
3c	VA + *C. canephora*	y = -7.62x + 160	0.31	0.005	2.438	19.98
	VA + *D. zibethinus*	y = 8.55x + 175	0.27	0.009	3.034	23.97
	VA + *P. merkusii*	y = -33.2x + 329	<0.1	0.130	21.47	140.0
	VA + Mixed	y = 1.18x + 92.9	<0.1	0.790	4.545	33.28
	Overall (without VA)	*y = -6.69x + 154.96*	*0.33*	*<0.001*	*0.986*	*7.408*
3d	VA + *C. canephora*	y =-0.18x + 3.12	0.11	0.110	0.111	0.913
	VA + *D. zibethinus*	y = -0.23x + 4.32	0.31	0.005	0.073	0.583
	VA + *P. merkusii*	y = -1.19x + 10.32	0.41	<0.001	0.304	1.985
	VA + Mixed	y = -0.23x + 3.99	0.26	0.010	0.081	0.594
	Overall (without VA)	*y = - 0.41x + 5.32*	*0.46*	*<0.001*	*0.045*	*0.342*
4a	<4%	y = 11.76x + 86.89	0.75	<0.001	1.462	3.461
	4-7%	y = 8.65x + 96.35	0.75	<0.001	1.063	2.000
	7-10%	y = -0.58x + 95.5	<0.1	0.530	0.900	1.485
	>10%	y = 0.66x + 67.94	<0.1	0.370	0.727	1.127
	Overall	*y = 8.94ln(x) + 97.75*	*0.33*	*<0.001*	*1.312*	*1.633*
4b	<4%	y = 0.22x + 2.10	0.78	<0.001	0.025	0.060
	4-7%	y = 0.048x + 2.58	0.16	0.050	0.023	0.044
	7-10%	y = -0.028x + 1.56	<0.1	0.590	0.051	0.084
	>10%	y = 0.006x + 0.163	<0.1	0.470	0.008	0.013
	Overall	*y = 0.43ln(x) + 1.79*	*0.27*	*<0.001*	*0.073*	*0.091*
4c	<4%	y = -39.095x + 371.43	0.64	<0.001	6.201	40.88
	4-7%	y = -54.68x + 482.65	0.56	<0.001	10.34	70.47
	7-10%	y = 3.80x + 68.82	<0.1	0.540	6.118	41.81
	>10%	y = -4.015x + 96.67	0.14	0.060	2.087	14.63
	Overall	*y = -35.2x + 336*	*0.31*	*<0.001*	*5.862*	*38.95*
4d	<4%	y = 0.56x + 6.33	0.39	0.001	0.152	1.002
	4-7%	y = -0.35x + 5.02	0.15	0.058	0.174	1.187
	7-10%	y = 0.206x + 0.121	<0.1	0.560	0.348	2.384
	>10%	y = -0.028x + 0.36	<0.1	0.300	0.026	0.184
	Overall	*y = -1.57x + 12.41*	*0.19*	*<0.001*	*0.335*	*2.287*
5	Small drop	y = 89.4 - 0.552x	0.73	<0.001	0.052	6.177
	Large drop	y = 33.4 - 0.167x	0.61	<0.001	0.020	2.646
6	f_{min} VS f_{max}	y = - 0.39 + 0.921x	0.93	<0.001	0.092	0.000
9a	5 cm layer	y = 0.758 - 0.0046x	0.96	0.003	0.000	0.054
	10 cm layer	y = 0.256 - 0.0012x	0.42	0.234	0.000	0.086
9b	5 cm layer	y = 0.17 - 0.0013x	0.99	<0.001	0.000	0.000
	10 cm layer	y = 0.0248 - 0.0001x	0.46	0.210	0.000	0.000

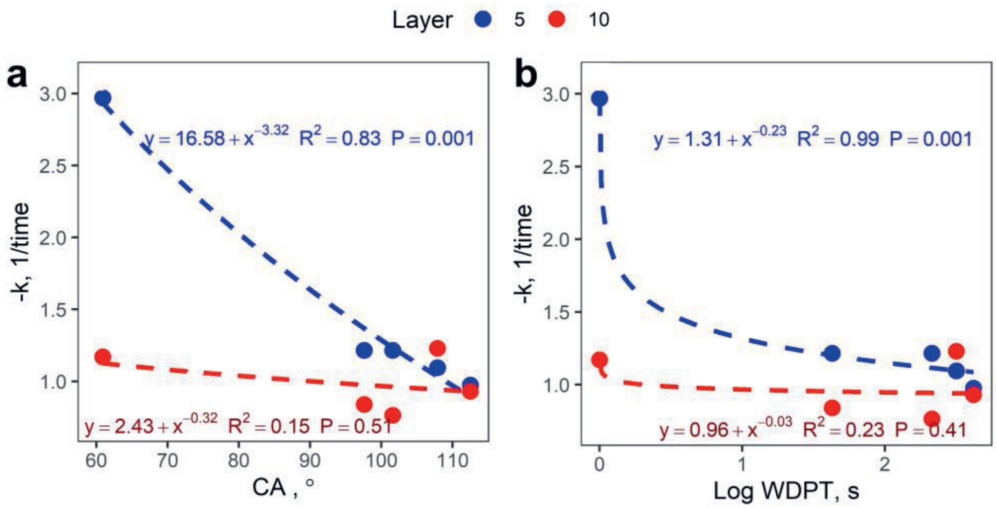
Note: CA: contact angle, Log WDPT: Log water drop penetration time, VA: volcanic ash, R^2 = the coefficients of determination, SE: standard error

SI 5.9. The estimated initial infiltration rate (f_{max}) was represented as (a) log initial infiltration and (b) infiltration rate decay as -k (mean ± standard error) under two water repellence layers thickness (5 and 10 cm) and six treatments (control/untreated soil (C), volcanic ash (VA), VA + organic matter (C = *C. canephora*, D = *D. zibethinus*, P = *P. merkusii*, Mx = mixed quality)). The different letters indicate statistical differences between treatments ($p \leq 0.05$).





SI 5.10. The relationship between (**a**) contact angle (CA), and (**b**) log water drop penetration time (Log WDPT) with the infiltration rate decay constant or -k under 5 cm (blue) and 10 cm (red) of mixed VA and OM layer thickness.



5

CHAPTER 6

Farmer mixing volcanic ash with the original topsoil
Sumberagung village, East Java

Steps towards a process-based soil structure – function model for agroforestry on volcanic slopes

Abstract

Application of the process-based WaNuLCAS (Water, Nutrient and Light Capture in Agroforestry Systems) model to a scenario that involves the impacts of and recovery from volcanic ash deposition events, requires additional modules, beyond (re)parametrization of the existing model. These modules represent three key factors that need to be adequately represented in the WaNuLCAS model: topsoil structure and configuration changes, soil organic carbon (SOC) dynamics, and water cycle dynamics related to soil hydrophobicity. In this chapter, we developed an improved framework for soil structure-function dynamics that can enhance the WaNuLCAS 4.4 model's capability to capture and simulate the complex interactions and dynamics of agroforestry systems with dynamic soil properties on volcanic slopes. While progress has been made in implementing these ideas, a fully functioning model has yet to be available.

Keywords: Volcanic ash, SOC, Century model, Millennial model, WaNuLCAS model

6.1 Introduction

The Water, Nutrient and Light Capture in Agroforestry System (WaNuLCAS) model is a representation of above and belowground interactions in agroforestry systems, incorporating tree-soil-crop interactions (van Noordwijk and Lusiana 1998; van Noordwijk et al. 2011). The model offers flexibility in representing various tree-soil-crop management options and directly estimating economic and environmental impacts (Khasanah et al. 2015; Khasanah et al. 2020), which is crucial for analysing trade-offs (Paul et al. 2017). WaNuLCAS model has been widely utilized in numerous agroforestry studies involving different tree-crop combinations (Coulibaly et al. 2014; Hussain et al. 2016; Khasanah et al. 2015; Khasanah et al. 2020; Magcale-Macandog 2014; Noulèkoun et al. 2018; Paul et al. 2017), including in our study on Chapter 3.

In Chapter 3, the WaNuLCAS 4.4 model was used to explore the dependence on climate, soil properties and details of root development of the productivity and economic performance of a range of cacao agroforestry systems. The model evaluation for cacao in Chapter 3 (**Table 3.5**) indicates a good to moderately good fit for several parameters we assessed. Building on this solid performance, we further used this model to assess the trade-off between provisioning and regulating functions, as well as the economic performance of different cacao-based LUS scenarios.

However, applying the same model to simulate the impacts of- and recovery from-volcanic ash disturbance on various LUS, as studied in Chapters 4 and 5, requires additional modules beyond the existing model's parametrization. This chapter will consider what changes are needed and discuss the work-in-progress to implement these ideas.

In order to simulate scenarios involving soil disturbance caused by volcanic ash (VA) deposition and its subsequent recovery, there are some key factors that the current WaNuLCAS model does not adequately represent:

1) Depending on the properties of the current vegetation, the heavy load of VA deposited in the vegetation canopy induces litterfall. Then, a relatively homogeneous, newly-formed layer of deposited VA and litter was established. This layer modified the C, N, P, and soil water content, as well as the functional properties of the soil profile as a whole, affecting C, N and P cycling and transport (**Figure 6.1**).
2) The VA + OM layer further becomes new topsoil. This new topsoil has an initial rapid increase in the various SOC pools, depending on soil management practices such as the addition of external OM sources, induced root turnover when plants die and incorporation of litter during (light) tillage operations.
3) The new topsoil initially inhibits soil infiltration during rainfall events and the hydraulic conductivity (K_{sat}) of the soil due to the interactions between VA and OM, as indicated in Chapter 5; the relationship between soil structure pore space and function (water transport) is modified, reversibly. The pedotransfer functions currently used by WaNuLCAS 4.4 model for describing infiltration and K_{sat} require adjustment to account for the temporary and reversible appearance of hydrophobicity (water repellency).

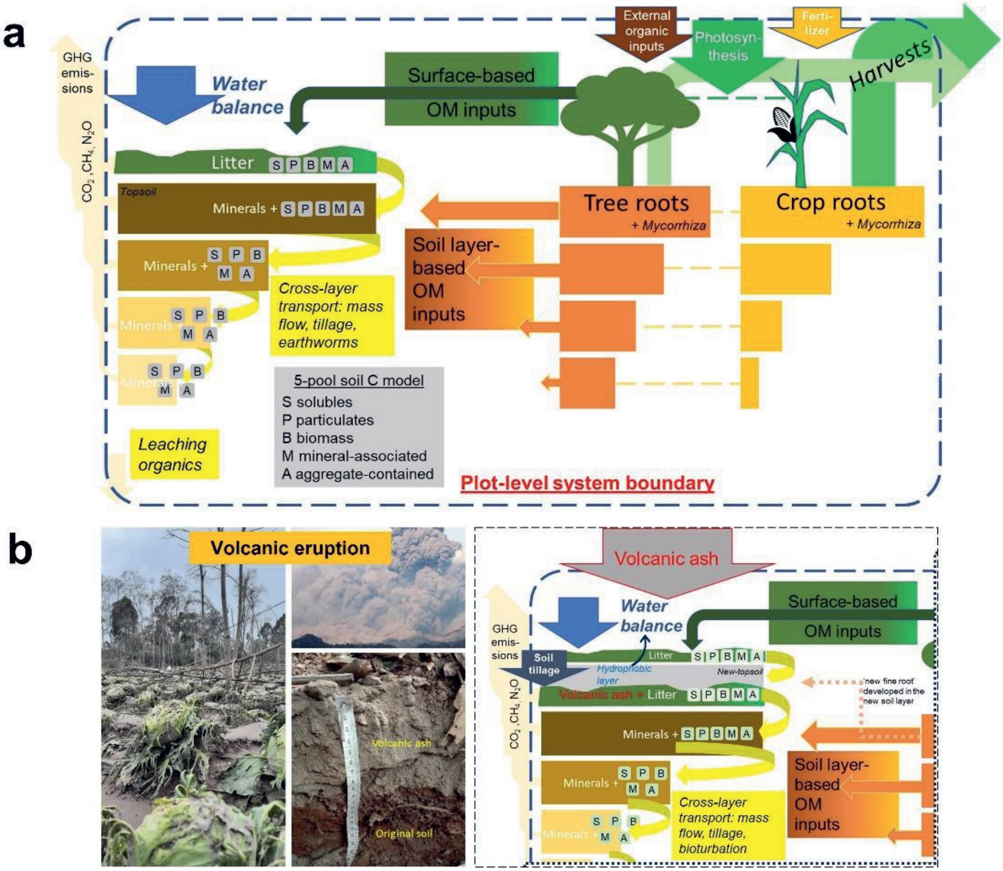


Figure 6.1. **(a)** Schematic illustration of the dynamic of above- and belowground OM-derived SOC in the litter layer and soil profile (adapted from van Noordwijk et al. (2023)), **(b)** the SOC dynamics and its associated functions altered due to volcanic ash deposition

Hence, the objective of this chapter was to develop an improved soil structure-function dynamics framework that effectively incorporates these three processes of change into the existing WaNuLCAS model. This enhancement will improve the model's ability to capture and simulate the complex interactions of agroforestry with dynamic soil properties on volcanic slopes. Progress was made in implementing these ideas, but no fully functioning model is available as yet.

6.2 Bookkeeping of soil changes during and shortly after VA deposition

Ash deposition event, at time = T_{ash}

Volcanic eruption ejects VA into the atmosphere and further deposited on land. The VA deposition process may cause direct and indirect damage to the plants. Depending on their sensitivity, some crops and trees may die, and others survive due to the heavy load of ash that caused (partial) canopy loss and/or leaf abrasion. The canopy loss that occurred to trees and crops may also induce fine root turnover similar to the canopy pruning effect. This event leads to the transfer of carbon from aboveground biomass to surface necromass and root turnover in all applicable soil layers.

Ash deposition event, at time = $T_{ash} + 1$

VA deposition may further change the soil layer configuration, with VA mixed with surface litter covering the original topsoil. This process could transform the previous surface litter into a 'new topsoil layer'. Despite VA entering the soil system with very low carbon content, its inherently high capacity to sequester carbon (Fiantis et al. 2016; Minasny et al. 2021) can turn this new topsoil layer into a significant C sink, as long as there is a sufficient and continuous OM input to this layer. Farmer practices on mixing VA with the original topsoil through light tillage (Ishaq et al. 2020b), mass flow of soluble components ('leaching') (van Noordwijk et al. 2023), and 'bioturbation' by soil ecosystem engineers (Hairiah et al. 2006; Jouquet et al. 2006; Rodríguez et al. 2021), facilitate further transfer of OM into the soil layers. Overall, the deposition of VA and OM on the soil surface (overlaying the surface litter and original topsoil), followed by changes in root dynamics, could create changes in soil layers configurations and further modify the SOM, nutrient (N and P) and the water cycle. The schematic representation of these events is illustrated in **Figure 6.2**.

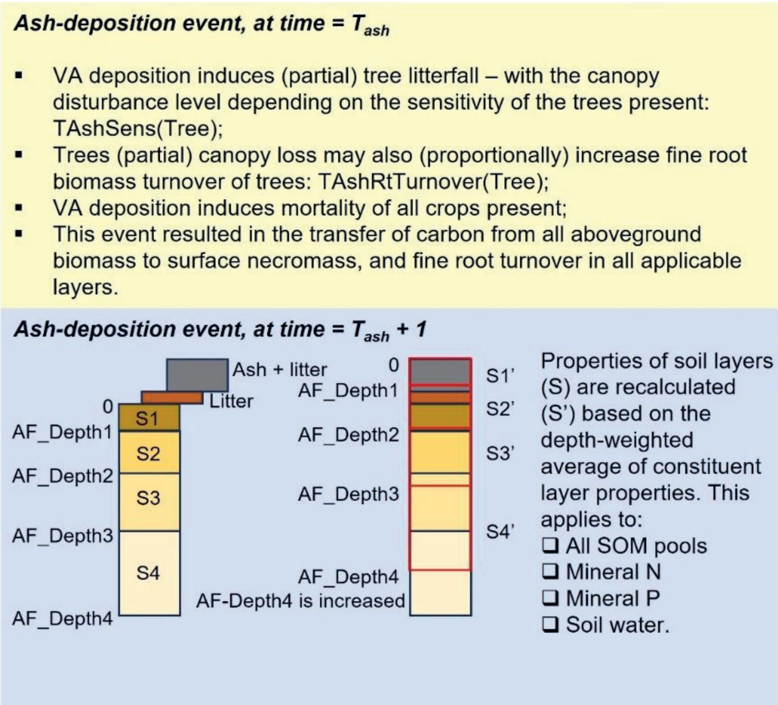


Figure 6.2. The schematic representation of changes in soil layers configuration and its associated impact during and shortly after volcanic ash and organic materials deposition

6.3 The adjustment of process-based soil C and structure dynamics submodel in WaNuLCAS 4.4

The SOC dynamics sub-model adopted by the current WaNuLCAS model from its start is based on the widely-used SOC dynamics Century model (van Noordwijk and Lusiana 1998). The Century model framework was constructed based on conceptual rather than physically defined polls, making it challenging to verify using measurable constituents pools (Abramoff et al. 2018). In this model, carbon pools were operationally defined based on presumed chemical composition and turnover times. Yet, with an improved understanding of the chemical and physical characteristics of SOC, it has become evident that the physical structure of soil and chemical associations with soil minerals also play a role in SOC pool turnover times. This model's lack of mechanistic processes for predicting SOC may limit its capability to effectively simulate current global change scenarios, particularly those related to land use intensification and climate changes.

In the current WaNuLCAS model, the C dynamic Century submodel allows the root-based carbon input, but its 'layered' version depends on cross-layer transfers for which the empirical basis is weak. The model also has some macropore representation, but with no explicit aggregation. Based on these limitations, the process-based soil C dynamic submodel in the WaNuLCAS needs to be adjusted to the framework of the recently developed "Millennial" (Abramoff et al. 2018) and "MEMS" (Zhang et al. 2021) models.

The Millennial and MEMS models have five SOC pools and fluxes that are measurable, including the mineral-associated organic carbon (MAOM), entrapped carbon in the aggregate, dissolved (soluble) carbon, particulate organic matter (POM), and microbial biomass carbon. These measurable SOC pools allow for model parameterization, calibration, and verification/validation attempts, which is lacking using the Century models. Under these current models, SOC dynamics across litter surface and soil layer (cross-layer transport) under particular LUS are better predicted. This model calculates the SOC distribution within the soil profile based on all three possible processes: mass flow/leaching (water balance), soil tillage, and bioturbation processes (involving soil ecosystem engineers, particularly earthworms). **Figure 6.3** illustrates the conceptual structure differences between Century and Millennial models.

This adjustment is essential to facilitate a better simulation process involving organic input changes and associated SOC and soil structure dynamics. SOC content (which depends on the OM derived from surface litter and external OM application), coupled with mycorrhiza, can directly and indirectly influence soil structure development through 'binding and bonding' mechanisms (Hoffland et al. 2020). Bioturbation processes involving soil ecosystem engineers (such as roots, earthworms, ants, and termites) also contribute to the establishment of macropores and strong aggregate stability, which can lead to SOC stabilization. However, soil ecosystem engineers, particularly roots and earthworms, may also destabilize SOC through the destruction of soil macro-aggregates during bioturbation processes (Bailey et al. 2019). Additionally, the increased activity of microorganisms in the soil provides C stabilization through physical protection and reduced activation energy due to chemical composition, known as the 'entombing effect,' resulting in greater SOC accumulation (Liang et al. 2017).

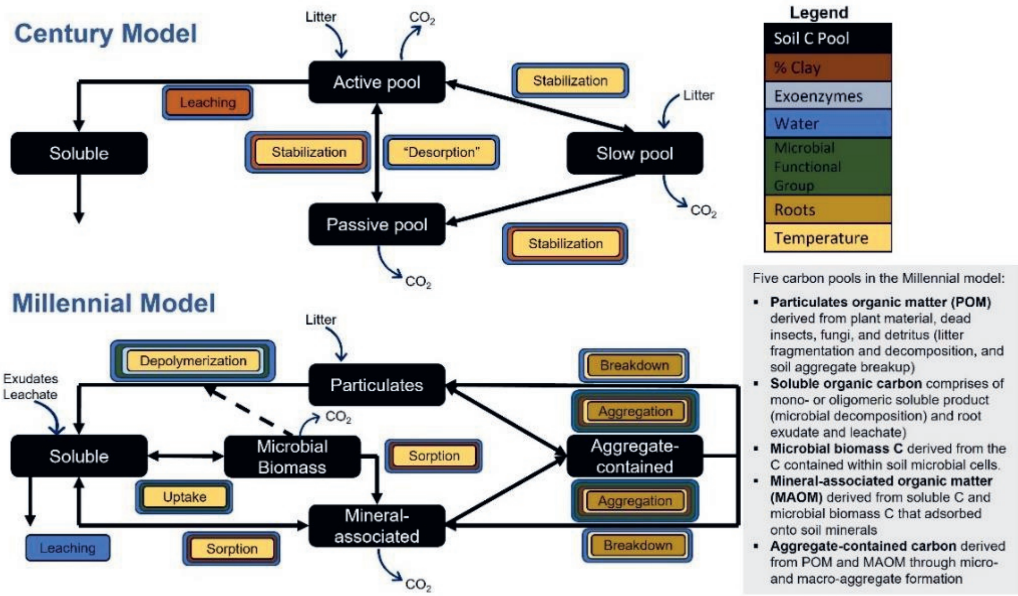


Figure 6.3. The conceptual diagram of the Century and Millennial SOC dynamics models (adapted from Abramoff et al. (2018). The diagram represents carbon pools as black boxes and fluxes as coloured boxes; solid arrows indicate the direction of each flux; dash lines represent the controls (i.e., microbial biomass regulates the depolymerization rate)

The Century model handled all soil organic matter (SOM) within a soil profile as a spatially mixed and freely interacting set of C pools. The potential improvement of precision of a soil-layer based representation comes with a requirement of specifying the possible transfers between pools of the same type in different layers, interacting with that between different pools in a single layer. For the soluble fraction, a leaching routine can be used, with the mass flow of water carrying solutes – with the possible correction for 'preferential flow' in macropores with a lower solute concentration. For microbial biomass, some water-based transport is also possible, but other pools depend on 'bioturbation' (depending on soil fauna) and (in the case of agricultural soils) tillage operations. In a layered soil C model, root-based inputs (exudation, rhizodeposits, mycorrhizal hyphae and structural root turnover) dominate soil C formation below the topsoil where leachates from the litter layer or fauna-based bioturbation will focus.

6.4 A dynamic water repellency representation

The interaction between VA and OM in the 'newly-formed topsoil' may induce SWR that can modify the soil water balance, as indicated in Chapters 4 and 5. SWR reduces the soil's effective porosity, resulting in slower soil infiltration. Conversely, the establishment of SWR might also reduce water loss through evaporation (Gupta et al. 2015; Rye and Smettem 2017; Smettem et al.

2021). As hydrophobic compounds disappear from the soil surface (decomposed or transported elsewhere) or when soil moisture exceeds its critical water content (CWC) to induce SWR, the hydrophobic effect diminishes. However, it may reappear when new OM with a high concentration of hydrophobic compounds enters the system and/or when soil moisture decreases below CWC. The presence of SWR results in the deviation of hydraulic conductivity value (derived from the textured-based pedotransfer (PTF) formula) used in the model compared to the actual rate. Hence, further adjustments on soil hydrophobicity affected-soil hydraulic conductivity need to be made. Furthermore, depending on the LUS, slope and rainfall intensity and duration, soil infiltration (hydraulic conductivity) influences soil water availability, surface runoff, and erosion. The latter controls whether VA remains on-site or is transported to lowland valleys.

There are three options can be considered to adjust the existing van Genuchten-based treatment of hydraulic conductivity in the WaNuLCAS model through a set of texture-based pedotransfer functions (PTF) (Hodnett and Tomasella 2002), including:

1. An empirical reduction of the 'effective porosity' that reduces K_{sat} (primarily based on microporosity); this would be relatively easy to implement, but may not match the physical reality,
2. A reduction of 'effective porosity' that mostly affects micro- (and meso-) pores, as water repellency starts to disappear once soil water contents exceed 7% (v/v),
3. A representation of air entrapment in meso-pores if higher macropores have become waterfilled.

Among those three options (illustrated in **Figure 6.4**), our empirical evidence suggested that a mechanism similar to number 3 prevails. However, the model's representation of this infiltration-related dynamics process needs further refinement and definition.

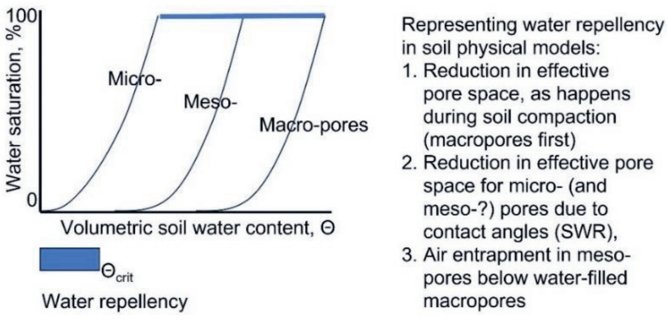


Figure 6.4. Schematic illustration of changes in soil layer configuration following volcanic ash and organic materials deposition.

For a period to be decided, the rules for water infiltration during rainfall events are modified, likely leading to increased surface runoff and soil erosion (if the Rose equation currently used in the WaNuLCAS model is used to calculate erosion deposition). The entrainability parameter for soil particles (the likelihood they join in overland flow) may have to be adjusted. The gradual return to 'normal' conditions is to be specified.

6.5 Recovery after volcanic ash deposition event

Soil tillage, bioturbation, and mass flow of OM soluble components facilitate the further transfer of SOM into the soil layers. Root development and turnover of the new and/or resprout plants also contributed to the OM supply to the soil layers (following the new layers definitions). The increases in SOM content, together with soil ecosystem engineers and mycorrhiza activities, further support the soil structure developments (as a form of pore space establishment and strong aggregate stability) directly and indirectly through 'bonding and binding' mechanisms. Depending on its specific processes, the soil structure dynamics (aggregation and breakdown) may stabilize or destabilize SOC (**Figure 6.2**). These processes led to the re-balance of SOM pools and marked the subsequent recovery processes of the soil after VA deposition. In the model, the subsequent recovery processes follow the 'normal' process rules under the SOM modules (submodels). To obtain the measured C accumulation rates in the ash-derived layers requires both litter- and root-based C inputs. The adjustment of root distribution to the new soil profile is a key process, in this respect, for which no direct empirical data exist.

CHAPTER 7

"Cacao litter keeps the soil moist" – Pak Susi – cacao smallholder farmer
Wonuahoa village, Southeast Sulawesi

General Discussion

7.1 Overview

This thesis explored the recovery of soil structure and functions in cacao and coffee agroforestry systems following soil disturbance and degradation. It aimed to understand the linked effects of aboveground litter and root turnover on soil organic carbon (SOC) dynamics, soil structure development, and surface hydrological functions. Here, soil recovery was focused on the R.I Ecological restoration within land use systems (LUS) and R.II. Recovery/regeneration within a local social-ecological system, following the land restoration intensities level proposed by van Noordwijk et al. (2020). While this thesis emphasized the recovery of soil physical properties and its associated water-related environmental services aspects, the aboveground ecological recovery (tree species and their properties) and its relation with social aspects (such as farmer preferences) were discussed in a separate thesis by Sari (2023).

In the first half of the thesis, the soil physical properties recovery of various LUS from the gradual soil degradation following deforestation stated in Research Question 1 (RQ 1) was studied. RQ1 was addressed through a case study of cacao-based LUS in Southeast Sulawesi, Indonesia, with the hypothesis that soil structure and its functions could be restored in near-forest conditions by the inclusion of suitable trees in a complex agroforestry system. To further investigate the best management options for cacao-based LUS, the process-based WaNuLCAS 4.4 model was utilized. The multifunctionality and economic performances of LUS under different climate, soil, and cacao root scenarios (RQ2) were explored, with the hypothesis that agroforestry systems provided stronger multifunctionality and economic performance than monoculture systems.

In the second half of the thesis, the focus shifted to the soil recovery in various LUS following the disturbance caused by volcanic ash (VA) deposition in the neighbourhood of an erupting volcano (RQ 3). The recovery of soil structure and infiltration after disturbance was hypothesized to be accelerated by increasing litter and SOC by including suitable trees in complex agroforestry systems. the interactions between different types of surface litter and VA concerning the development of water repellency (WR), as well as their impact on soil infiltration and hydraulic conductivity, were further explored (RQ 4). WR was hypothesized to inhibit soil infiltration and hydraulic conductivity, and its establishment is associated with the type of litter.

Building upon the findings from Chapters 4 and 5, Chapter 6 proposed a conceptual framework for understanding the dynamics of SOC with the complications studied in the preceding chapters. This framework can be used to modify the existing tree-soil-crop interaction WaNuLCAS 4.4 model, so that it may (in the future) be used to effectively explore the LUS recovery for the specific challenges following the soil disturbance caused by a volcanic eruption.

Two main approaches were employed to address the pattern and process aspects of the RQs. It included spatial pattern analysis by comparing field-measurement data across different LUS (Chapters 2 and 4), dynamic process analysis using laboratory experiments (Chapter 5), and process-based modelling (Chapters 3 and 6). While the spatial pattern approach provided 'snapshots' of real-world settings, it had limitations in drawing a clear conclusion due to potential confounding factors (e.g., non-random selection of LUS) and its limited regional applicability beyond the interpolation range. On the other hand, the dynamic process approach allowed for the exploration of numerous possible scenarios, limited only by the capabilities of the model or experiment, while having control over other (unintended) factors. This approach facilitated the examination of temporal changes and the underlying mechanisms behind spatial patterns. However, its real-world applicability is constrained by the simplifications made to represent the real-world complexities in the model or experiment. Combining these two approaches allows for an expansion beyond describing patterns or processes in isolation. The focus was the interconnectedness and interdependencies between spatial patterns and dynamic processes (Nelson et al. 2017).

7.2 Summary of key findings

The main findings of the four RQs defined in Chapter 1.8 were as follows:

RQ 1. To what extent can cacao-based agroforestry systems recover soil aggregate stability, porosity, and infiltration by increasing litter, SOC, and root density to the local forest reference, compared with cacao monoculture and cropped fields?

In Chapter 2, it was observed that integrating diverse tree species in complex cacao-based agroforestry systems showed a higher root density in the upper soil layer than in other agricultural systems, albeit only half of that was found in the remnant forests (RF). There was an indication that increasing fine root distribution, following higher tree diversity, positively correlated with SOC. Furthermore, complex agroforestry (CAF) had a slightly higher mean weight diameter (MWD) of aggregates and higher macroporosity than other agricultural systems, particularly in the upper soil layer. These favourable properties led to higher measured soil infiltration than other agricultural systems. However, a considerable gap remained between CAF and RF conditions.

This result partly supported the hypothesis that soil structure and its functions can be maintained in near-forest conditions by the inclusion of suitable trees in CAF. The considerable gap between reference RF and CAF in this research might be related to the relatively low maturity level of the cacao plots measured (9-14 years; where gardens can be maintained for decades when internal rejuvenation techniques are used). Thus, the recovery process probably was still in its early phase, as also reported by Wartenberg et al. (2017). A similar result was also reported by Gusli et al. (2020), stating that soil properties (such as SOC, bulk density, macroporosity, K_{sat}, and available water capacity) had decreased after forest conversion to cacao-based agroforestry systems in Southeast Sulawesi. The young cacao agroforestry (4-5 years old) had the lowest soil quality, but soil properties approached the reference values for the local forest as the LUS matured in 17- to 34-year-old cacao agroforestry, and in multistrata agroforest (45-68 years after forest conversion). In cacao-based agroforestry in Ghana, Dawoe et al. (2014) reported that the deteriorated topsoil (0-20 cm) quality of 3 years old gardens started to improve after 15 and 30 years of cacao agroforestry. This report indicated that the SOC loss rate during initial soil degradation processes in cacao-based LUS was faster than its increment (asymmetric response), leading to a relatively slow SOC recovery rate (Jensen et al. 2020).

In a study conducted by De Vries et al. (2022), it was observed that the conversion of rainforests in Central Sulawesi to facilitate annual cultivation of maize and cacao-based agroforestry practices resulted in a decrease in K_{sat}, particularly in near-surface K_{sat}. Extensive management practices in cacao agroforestry systems maintained infiltration capacities comparable to moderately disturbed forests. However, significantly lower K_{sat} values were observed in more intensively managed LUS, including cacao, annual crop fields, and grassland. The findings further highlighted that these lower K_{sat} values, which reflected degraded soil conditions, were primarily associated with management intensities rather than the direct specific LUS and cultivation duration.

RQ 2. To what extent can cacao-based agroforestry systems provide stronger multifunctionality and economic performances than monoculture systems under various scenarios?

Chapter 3 suggested that cacao-based agroforestry systems (involve different companion trees and crops, including a fast-growing tree of *Falcataria mollucana*, slow-growing tree of *Tectona grandis*, fruit tree of *Durio zibethinus*, and annual crops of *Pogostemon cablin*) provide stronger multifunctionality and economic performance than cacao monocultures under particular scenarios. This result partially supported the third hypothesis. Cacao-based agroforestry systems exhibited more robust multifunctionality performance than cacao monoculture when the primary objective was to increase the C stocks, but they had modest impacts on water-related functions.

The model simulation demonstrated that cultivating cacao with a high root density provides stronger multifunctionality than its low-root density counterparts, particularly in water-limited regions. This result highlights the importance of root structure and distribution on cacao resiliency towards lower water availability. Several authors have reported the importance of roots for tree/crop resilience against water scarcity (Comas et al. 2013; Lobet et al. 2014; Solari et al. 2006b). However, there is surprisingly little data on root length densities comparing 'wildtype' and 'preferred cultivars' for cacao or coffee for a relevant range of soil and climate conditions. The noted contrast, within the sparse data available, between seed-based improved cultivars (reduced root densities) and clones grafted on local (close-to-wildtype) rootstocks (good root development) is suggestive. Breeding-based strategies dominate in Latin America and Africa, while grafted clones are prevalent in Indonesia (Bekele and Phillips-Mora 2019; Lopes et al. 2011; Rodriguez-Medina et al. 2019; Zakariyya and Yuliasmara 2015), but no direct comparisons appear to have been made.

The relative performances of each cacao-based agroforestry system compared to cacao monoculture vary, depending on the specific tree or crop species intercropped. Integrating cacao with annual crops or fruit trees is projected to be the most effective approach to achieve the highest economic performance among the other systems. The latter combination offered lower labour requirements, which is highly relevant for cacao smallholder farmers in Indonesia. The benefits of having lower labour requirements from long-term agroforestry practices were also reported by Jaimes-Suárez et al. (2022).

On the other hand, intercropping cacao with fast-growing trees in a water-limited region harmed the cacao and led to lower productivity and economic performance. The negative impact of having a fast-growing leguminous shade tree of *Albizia ferruginea* intercropped with cacao during an extreme drought in Ghana was reported by Abdulai et al. (2018b), for a combination that did not access soil water below a depth of 50 cm (according to data in the same study, but not highlighted in its conclusions).

RQ 3. After soil disturbance caused by volcanic ash deposition, to what extent can coffee-based agroforestry systems recover soil aggregate stability, porosity, and infiltration by increasing litter and SOC compared with local remnant forests and cropped fields?

Chapter 4 explored the impact of VA deposition on topsoil characteristic changes and their recovery from various LUS. To analyse the changes, the topsoil properties of each LUS were compared between three different measurement points, including before eruption (PRE), three years after eruption (3 YAE), and six years after eruption (6 YAE). The result showed that VA deposition changed soil physical properties and surface hydrological functions that previously differed among LUS into a more homogenous soil during the first three years after the volcanic eruption, indicating that the disturbance intensity was probably beyond all LUS buffering capacity.

The averages of standing litter thickness, aggregate stability, and soil infiltration from all LUS were dropped within 3 YAE compared to the PRE condition, but quickly recovered within 6 YAE. Soil infiltration in 3 YAE was eight times slower than in PRE condition, even though no significant changes were found in soil porosity, indicating soil hydrophobicity that may be induced by VA and surface litter interactions.

On the other hand, no significant differences in the average SOC from all LUS were found during all measurement periods. However, it does not imply that there were no changes in SOC within those measurement periods, particularly during the early period after VA deposition. Instead, it can be an indication that the SOC rapidly recovered, probably in less than three years (quicker than the first measurement after the eruption). The newly deposited fresh VA is widely known for its low (or even zero) organic C content (Fiantis et al. 2019; Utami et al. 2019). However, VA has an inherent high capacity to accumulate C due to its poorly non-crystalline minerals with large surface areas, enabling complexation for C storage and physical protection for C stabilization (Crow et al. 2015; Fiantis et al. 2019).

When comparing LUS, significant differences in SOC were found before and after the volcanic eruption. This result indicates that the specific tree and soil management practices (embedded in different LUS) were associated with SOC dynamics. Here, a clear indication emerged that the increases in litter thickness, following the inclusion of various trees under a complex agroforestry system, contributed to higher SOC, aggregate stability, and soil infiltration compared to the annual crops system over the medium-long term, albeit the gap with the local remnant forests reference remained.

RQ 4. Do the types of organic matter mixed with volcanic ash influence water repellency, and how does this surface-level water repellency relate to column-level soil infiltration and hydraulic conductivity?

Chapter 5 confirmed the hypothesis that water repellency (WR) inhibits water infiltration and hydraulic conductivity, and its establishment is correlated to the type of organic matter (OM). The study found that various OM types (with their different lipids content) mixed with VA induced different levels of WR during the 16-weeks incubation period, as indicated by the significant difference in the substance's contact angle (CA) and water drop penetration time (WDPT) values. The strongest WR was produced by the mix of VA with *Pinus merkusii* (pine) litter, followed by

Durio zibethinus (Durian), mixed OM, and *Coffea canephora* (Robusta coffee), respectively. Stronger WR was only partially associated with higher lipids content of OM, suggesting that the broader plant characteristics such as *n*-alcohols, *n*-fatty acids, and *n*-alkanes may give further insight into which components are primarily responsible for WR, as reported by Dao et al. (2022). This study also highlighted that once soil water contents exceeded 7%, the lipids content was no longer correlated with WR.

Layering a WR substance on the soil surface reduced soil hydraulic conductivity up to five times, with a more significant effect observed at 10 cm than at 5 cm layer addition. Given the naturally-transient characteristic of WR, the significant drop in hydraulic conductivity throughout the measurement event may not be solely due to the impact of the WR substance but might also be related to the entrapped air bubbles, which could reduce hydraulic conductivity by 2-20 times (Marinas et al. 2013; Sakaguchi et al. 2005), and soil particle rearrangement and blockage of soil porosity (self filtration) in the soil column (Dikinya et al. 2008), which reduces the effective soil porosity for water transmission, which merits further exploration. The idea that post-fire ash clogs soil pores was challenged by Stoof et al. (2016) and did not appear to be prominent in these experiments. Entrapment of air during infiltration in the field or lab experiments appears to play a more prominent role than so far recognized (see 7.4).

7.3 The contribution of surface litter and roots on SOC, soil structure, and infiltration recovery

The management intensities of trees and soil in different LUS significantly influence soil C. These management intensities affect the quality and quantity of both above- and below-ground OM and the local microclimate modification. Tree-based systems, characterized by increases in root biomass and mycorrhiza (belowground OM source) and abundance of surface litter (aboveground OM source), contribute to the accumulation of SOC. Multiple studies and review articles have highlighted the importance of roots in driving soil C investment, emphasizing their substantial contribution compared to surface litter (Austin et al. 2017; Hairiah et al. 2020; Quigley and Kravchenko 2022; Rasse et al. 2005; van Noordwijk et al. 2023).

In the context of an active volcanic landscape, the narrative regarding the contribution of surface litter and roots to SOC dynamics may slightly differ. In a C poor-newly deposited VA layer, surface litter may gain importance in improving SOC levels, as it directly and rapidly interacts with the deposited VA, especially during the early stage of soil recovery (**Figure 7.1**). During volcanic eruptions, the heavy load of VA deposits can directly damage the vegetation and cause many crops and trees to (partly) die due to canopy loss and/or leaf abrasion (Anda et al. 2016; Korup et al. 2019; Sari et al. 2023). This process resulted in significant OM input to the newly-formed VA and litter layer and increased SOC accumulation in the soil profile. While at the same time, fine root decomposition in topsoil became slower, as indicated by the mean resident time that extended by an average of two weeks after VA addition to the soil (Purnamasari et al. 2021).

The study also highlighted the potential use of an ash-adapted native tree species, *Parasponia rigida*, for SOC recovery. The decomposition of the roots of *Parasponia* was faster than that of other commonly used tree species in the study area. This non-leguminous N-fixing tree species exhibited faster recovery after volcanic eruptions and was reported to be highly effective for soil recovery and restoration, particularly in the most extreme and nitrogen-deficient parts of the volcanic landscape. However, the domestication process of this particular species in agricultural land in order to assist soil recovery post volcanic eruption is challenging (Ishaq et al. 2020a; Ishaq et al. 2020b).

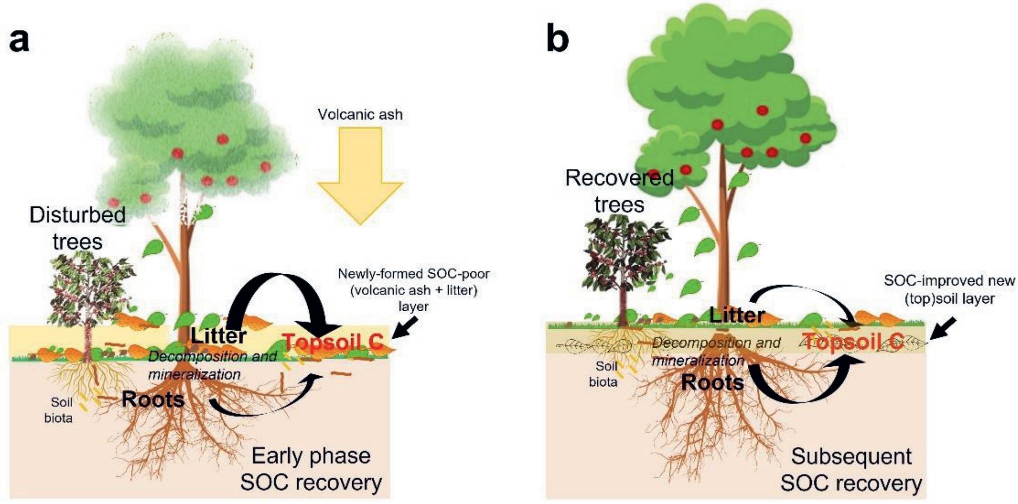


Figure 7.1. During the early stages after volcanic ash deposition (**a**), surface litter can contribute significantly to the topsoil C recovery and restoration (as indicated by a thicker black arrow) than roots. However, roots may start to gain relative importance as time progresses and the ecosystem undergoes subsequent phases of SOC recovery and restoration (**b**)

The significant disturbance to the tree canopy caused by the heavy load of VA during the volcanic eruption can have a subsequent impact on fine root development, similar to the effects observed with canopy pruning. The influence of canopy pruning on root development has shown varied results in different plant species (Saifuddin et al. 2010; Tomasi et al. 2020). Peter and Lehmann (2000) conducted a study on the *Acacia saligna* hedgerow agroforestry system and observed that canopy pruning reduced tree root development. However, they also noted that pruned trees exhibited a higher proportion of dead roots compared to unpruned trees during the dry season. The accelerated fine root turnover can contribute to higher SOC accumulation, which further improves the soil structure by facilitating the 'bonding' of soil minerals into micro-aggregates, and (in collaboration with mycorrhiza) 'binding' of micro-aggregates into macro-aggregates (Hoffland et al. 2020).

The presence of shade trees in agroforestry systems could also facilitate soil structure development through the C-fuelled bioturbation process. Agroforestry systems exhibited higher above- and belowground biomass production than monoculture systems (Rajab et al. 2018), and they created relatively more stable microclimate conditions that promoted a more active bioturbation process

(Hairiah et al. 2006). The developed soil structure and increased SOC in agroforestry systems have positive implications for soil water availability, as they could accelerate soil infiltration and enhance water holding capacity (Gusli et al. 2020). Furthermore, a feedback process exists between SOC and aggregate development. The formation of soil micro-aggregates provides physical protection to SOC, thereby inhibiting its further decomposition (Quigley and Kravchenko 2022). Additionally, micro-aggregate development creates diverse micro-environments that regulate SOC dynamics (Six et al. 2004).

The faster decomposition and mineralisation of OM, facilitated by favourable soil conditions, can increase nutrient availability in the newly deposited VA layer. This improved water and nutrient availability can attract roots to grow in this layer, enabling them to explore available resources. As a result, roots can increase their contribution to the SOC accumulation in this inherently C-poor layer through their biomass, root exudates, or rhizodeposits (Rasse et al. 2005), marking the subsequent phase of soil recovery and restoration following a volcanic eruption.

During the subsequent phase of recovery, as the VA and surface litter layer begin to form a more developed soil layer, roots, which have already established a direct interaction with the deposited ash layer, may increase their importance in the increment of topsoil SOC. A study by Purnamasari et al. (2021) in a coffee-based agroforestry system in East Java (Indonesia) found that roots decomposed three times faster than surface litter. Under a non-volcanic soil context, Sari et al. (2022), who conducted an aboveground litter study in cacao agroforestry in Southeast Sulawesi (Indonesia), reported that the soil C content below the litterbags at the end of the 16-week experiment was higher than it should be, further indicating the important contribution of belowground litter input from roots to the higher SOC content.

Finally, the abundance of soil macropores, which directly formed from decayed roots and through micro- and macro-aggregate formation, along with the soil surface protection provided by the surface litter layer, facilitated faster soil infiltration, as reported in Chapter 2 and Chapter 4 of this thesis.

Regarding the research methodology, this dynamic process highlighted the importance of considering the timing of measurements during these phases to comprehensively understand the effect of surface litter and roots on SOC increments. In this case, relying only on ‘snapshots’ through spatial pattern analysis might not be sufficient, and a dynamic pattern approach using a process-based model can be helpful in providing a more comprehensive understanding.

7.4 Organic matter, water repellency and soil hydrological functions

In Chapter 5, the study findings revealed that a high proportion of OM (16%) in the soil negatively impacts water dynamics by altering soil infiltration and hydraulic conductivity. The interaction between surface litter OM with VA induced WR and modified water dynamics, with the magnitude of effects dependent on the OM quality and soil water content. The mixed litter quality from various trees reduced WR severity compared to the single type of OM that was rich in lipids and other hydrophobic compounds, highlighting the potential benefits of practicing agroforestry. However, the dense fine root distribution combined with rapid root turnover in agroforestry systems could also contribute to WR development, as root-derived litter was reported to produce an even stronger WR substance (suberin) than leaf litter (Mao et al. 2014). However, it remains uncertain whether diverse root qualities (following higher tree diversity) could also minimize the WR severity, as in the case of surface litter-derived WR. This aspect extends beyond the scope of the present study and warrants further investigation.

The impact of WR on soil infiltration and hydraulic conductivity was expected to be transient, indicating that the increases in soil water content during the measurement would eliminate WR. However, the impact of WR persisted longer than initially anticipated, likely due to an entrapped air bubble within the soil matrix. Wang et al. (2000) reported that the combined effect of the WR layer and entrapped air bubbles can significantly affect soil hydraulic conductivity and infiltration. Although more advanced and detailed methods exist to quantify the impact of entrapped air bubbles on water transmission (Dohnal et al. 2013), such analyses were beyond the scope of this research.

Previous studies on soil water repellency (SWR) have predominantly focused on a specific condition, such as post forest fire (Caltabellotta et al. 2022; DeBano 1991; Lucas-Borja et al. 2022; Stoof et al. 2011), sandy soils (Doerr et al. 2005; Siteur et al. 2016; Wong et al. 2022; Wong et al. 2021), under certain tree species known to contain hydrophobic compounds like pine and eucalyptus (Leighton-Boyce et al. 2005; Lozano et al. 2013; Mataix-Solera et al. 2007; Neris et al. 2013) or volcanic ash-derived soils (Jordán et al. 2011; Jordán et al. 2009; Kawamoto et al. 2007; Saputra et al. 2023). However, SWR under a cacao-based system, with the non-specific conditions mentioned before, has not been well characterized until recently reported by Farrick and Gittens (2022) in Trinidad and Tobago. Their study investigated SWR in cacao agroforestry of different ages (5-, 12-, and >30-year-old) during the wet and dry seasons. Results revealed that the soil in 5- and 12-year-old stands exhibited extreme repellency (twice as severe as in > 30-year-old stands) during the dry season. The author hypothesized that the higher repellency in younger cacao stands was influenced by a highly repellent compound produced by shallow roots from grass/sedge soil cover that is widely grown in this relatively open canopy young agroforestry system, contrasting with the predominant leaf-derived hydrophobic compound in older cacao stands. Additionally, soil temperature showed a significant correlation with SWR, as the elevated temperatures in young cacao stands could alter the composition and orientation of the hydrophobic compounds in OM, leading to increased SWR. However, unexpectedly, the soil infiltration rate was found to be faster in younger cacao stands compared to older stands, attributed to the presence of large soil cracks (0.5-3 cm wide and up to 16 cm deep) that facilitated rapid infiltration and counteracted the impact of severe SWR in these plots.

Despite its adversity, SWR could also have positive impacts on ecosystems. SWR has been associated with the improvement of soil aggregate stability and soil carbon sequestration, indicating its potential positive influence on ecosystem functioning (Goebel et al. 2011; Mataix-

Solera and Doerr 2004). SWR developed from a particular tree species OM may serve as a competitive strategy for tree survival (vegetation feedback) during water-limited periods by suppressing competitor vegetation germination and improving water availability in the deeper soil layers (Mataix-Solera et al. 2007). Trees can induce SWR patches in their vicinity through the hydrophobic compounds present in their litter and roots, as well as through the activities of fungi and microbes in the tree rhizosphere (Doerr and Thomas 2000). Additionally, the OM produced by trees can influence SWR by altering soil properties, such as pH. For instance, Lozano et al. (2013) found that OM produced by Pine and Quercus lowers soil pH, leading to increased SWR. During a rainfall or irrigation event, areas with SWR patches can facilitate water transmission into the deeper soil layers through preferential flow pathways and retain it, enabling absorption by trees with deep roots (Smettem et al. 2021). Moreover, the presence of SWR in the topsoil can reduce water evaporation (Rye and Smettem 2017) due to the diffusion of water vapour and the tortuosity of soil capillaries (Gupta et al. 2015), offering potential strategies for water conservation (Doerr et al. 2000). However, this adaptation strategy of out-competing other individual plants for water acquisition may lead to reduced plant diversity, as demonstrated by modelling work in WR-coastal dune ecosystems (Siteur et al. 2016). Furthermore, long-term changes in vegetation structure on WR soils can further enhance SWR severity through the dominance of drought-resistant vegetation and fungi, which are rich in hydrophobic compounds (Goebel et al. 2011).

Consequently, any options on management strategies aimed at eradicating or inducing SWR in specific areas must carefully evaluate the overall potential impacts on ecosystem water dynamics. SWR can have positive and negative effects on the ecosystem, such as influencing soil water availability, infiltration, and evaporation. Therefore, implementing such management strategies should consider the overall potential consequences for ecosystem functions. Further research is crucial in developing effective management approaches that mitigate negative impacts while harnessing the potential benefits of SWR in specific contexts.

7.5 Trees with high root length density performed better under sub-optimal soil and climate conditions

As highlighted in the general introduction, the specific forms of Genotype (G) x Environment (E) x Management (M) cause soil degradation, yet they also form the basis of restoration when appropriately managed. In Chapter 3, the investigation revolved around the performance of different cacao root genotypes in agroforestry and monoculture systems, focusing on their multifunctionality using the process-based WaNuLCAS model. Two distinct root densities were examined: a relatively dense and evenly distributed fine root density based on measurements conducted in Sulawesi (Chapter 2) and a low fine root density commonly observed in Ghana (Borden et al. 2019) and Brazil (Kummerow et al. 1981).

The findings indicated that cacao with a high root density exhibited stronger multifunctionality than its low root density counterpart. The performance difference was particularly pronounced in regions with low annual rainfall, encompassing various target functions related to carbon and water-related environmental services. The superior performance of cacao with high root density can be attributed to its ability to better withstand water scarcity due to a more extensive water exploration area, resulting in more robust tree development. Previous studies have also highlighted the significance of root density in relation to survival under water-limited conditions for both trees and crops (Comas et al. 2013; Lobet et al. 2014; Solari et al. 2006a; Solari et al. 2006b).

However, higher water use efficiency (WUE) associated with dense root systems may have unintended consequences, such as reduced litter production and diminished groundwater recharge (Saputra et al. *Under review*). These adverse effects were particularly unfavourable in areas with high annual rainfall regimes and served as water catchment areas. The reduction of surface litter, which provides soil surface protection and facilitates soil infiltration (adding water retention time to the soil surface), can lead to increased surface runoff and erosion, while the reduced groundwater replenishment further exacerbates the issue.

The choice of specific companion trees or crops intercropped with cacao in agroforestry systems plays a crucial role in determining the trade-offs involved. In the case of water-limited regimes, incorporating the fast-growing tree *Falcataria mollucana* as a companion tree resulted in reduced cacao production and its associated environmental services, primarily due to intensified water competition. This finding aligns with field measurements conducted by Abdulai et al. (2018b), who observed increased water competition between cacao and fast-growing leguminous shade trees, leading to reduced cacao production and increased cacao mortality during prolonged severe drought conditions in Ghana. Conversely, integrating cacao with the slow-growing tree species *Tectona grandis* positively impacted the performance of agroforestry systems.

In volcanic landscape contexts, the primary ecosystem disturbance following VA deposition is often associated with reduced soil water availability. In regions with low annual rainfall, limited soil water availability arises from a combination of naturally lower water input (rainfall) and higher evapotranspiration rates. Meanwhile, in post volcanic events, soil water availability can be low, even in high annual rainfall regions, due to factors such as soil compaction, the formation of surface crust, and the establishment of SWR, which hinder soil infiltration (Pierson and Major 2014).

Under these circumstances, selecting trees with a high and evenly distributed root density to increase the resiliency of the system to water limitations is crucial. Trees with well-developed vertical and horizontal root systems have superior water and nutrient exploration capabilities within the soil profile. Therefore, promoting optimal growth of the plants and aiding soil recovery through improvements in SOC through the decomposition of above- and belowground litter, the development of soil structure, and enhanced soil infiltration rates. However, when choosing companion trees or crops for agroforestry systems, careful consideration must also be given to their litter quality, as in certain circumstances, it can potentially induce SWR, as discussed in Section 7.4.

The findings of this study highlighted that the performance of agroforestry systems can vary depending on the specific companion tree used, environmental factors (including rainfall and temperature), and farmer management. Optimal performance is achieved when appropriate tree selection (G) is cultivated in a suitable environment (E), ensuring a harmonious match between GxE. Conversely, mismatching these factors can lead to unfavourable outcomes. Moreover, the overall performance of agroforestry systems can be further enhanced through the implementation of Good Agricultural Practices (GAP) by the farmers (M), including better shade management, integrated pest and disease management, and proper fertilization (van Vliet and Giller 2017). It is worth noting that these GAP aspects, particularly pest and disease management and fertilization, extend beyond the scope of this thesis and warrant further investigation.

7.6 The economic performance of agroforestry systems

The WaNuLCAS 4.4 model output in Chapter 3 was used to conduct an economic performance analysis of cacao-based LUS using Net Present Value (NPV), Benefit Cost Ratio (BCR), and Return to Labour (RtL) metrics. The combination of cacao and the fast-growing timber tree *F. mollucana*, under high annual rainfall conditions, demonstrated better economic performance compared to monoculture systems. However, in a water-limited regime with coarse-textured soils (low buffering capacity), the economic performance was negative for the same practices. On the other hand, integrating cacao with different tree and crop species, such as *Durio zibethinus*, *Tectona grandis*, or *Pogostemon cablin,* positively influenced the economic performance, although the specific outcome varied. Agroforestry systems incorporating timber and fruit trees exhibited higher labour efficiency in the long term than monoculture systems, which is particularly beneficial for smallholder cacao farmers facing labour availability constraints in Indonesia. It is important to note that the choice of companion trees in this study represents the regional preferences of cacao smallholder farmers in Southeast Sulawesi. Thus, their relevancy may differ in other regions, as farmer decisions are influenced not only by market product availability, but also by cultural and gender preferences (Mulyoutami et al. 2015; Mulyoutami et al. 2023; Sari et al. 2020), land tenure, and knowledge, technology, and skills (Rahman et al. 2016). Furthermore, agroforestry systems can provide income stability through product diversity and versatility, mitigating the effects of price fluctuations (Ramírez et al. 2001). Combining cacao with annual crops is predicted to yield the highest NPV and BCR, but such systems tend to be more labour-intensive, making them less preferable.

Agroforestry farmers also have another opportunity to gain economic benefits from the environmental services they provide through initiatives like the Rewarding Upland Poor for Environmental Services (RUPES) project in Indonesia and Asia (van Noordwijk et al. 2016). These initiatives offer performance-based reward payments or co-investment in environmental stewardship, recognizing and incentivizing farmers for their contributions to biodiversity protection, soil and water conservation, and carbon sequestration. By providing financial incentives, these programs promote the adoption and maintenance of sustainable agroforestry practices, ensuring the long-term sustainability of both farmers and the environment.

7.7 Study limitations and potential follow-up research

This thesis focuses on assessing the performance of cacao- and coffee-based agroforestry systems in mitigating soil quality degradation and disturbance. Here, cacao and coffee were used as substitutes, as these two commodities have a wide range of similarities, including their perennial nature and natural occurrence in the forest understorey. In traditional coffee and cacao agroforestry, they are cultivated under the canopy of diverse shade tree species. The tree canopy and root architecture also exhibit comparability. Additionally, the study specifically targets cacao and coffee smallholder farmers who employ typical management practices such as pruning and fertilization. However, it is essential to recognize that despite these similarities, there are underlying differences between cacao and coffee, such as litter quality variations and turnover rates. These differences present challenges when generalizing the effects of agroforestry practices on soil and ecosystem recovery and restoration. Consequently, it is crucial to consider these nuances to gain a comprehensive understanding of the impact of agroforestry systems on soil and ecosystem dynamics.

This thesis did not specifically investigate the impact of different coffee-based agroforestry practices on multifunctionality and economic performance under the VA disturbance scenario due to the model limitations, as outlined in Chapter 6. However, it was observed that certain trees within the agroforestry systems recovered faster than others (Sari et al. 2023). The hypothesis posits that careful selection of appropriate tree species to be integrated into agroforestry can support soil recovery and accelerate farmers' economic recovery after the volcanic eruption, enhancing the resiliency of social-ecological systems (Sari, 2023).

Additionally, it should be noted that this thesis did not encompass the comprehensive examination of other significant benefits associated with agroforestry practices, including the preservation of biodiversity, facilitation of pollination, and protection against pests and diseases (Cerda et al. 2020; Durand-Bessart et al. 2020; Jaimes-Suárez et al. 2022; Jezeer et al. 2019; Mokondoko et al. 2022; Mortimer et al. 2018). These aspects contribute to the overall multifunctionality of agroforestry systems but were not within the scope of this particular thesis. Notably, the role of agroforestry in supporting the pollination process is particularly relevant for cacao and coffee, which rely on specific pollinator agents (midge for cacao and bees for coffee) who can thrive under well-managed agroforestry systems (De Beenhouwer et al. 2013; Toledo-Hernández et al. 2017). Hence, an effective design of agroforestry practices should consider these aspects by adopting a multidisciplinary approach.

7.8 Concluding thoughts

In conclusion, this thesis has contributed to the understanding of the intricate dynamics of soil recovery and restoration within different LUS following the gradual soil degradation and disturbance. By investigating the links between surface litter, roots, SOC dynamics, soil structure development, and surface hydrological functions has yielded insights into the multifaceted processes that drive soil recovery and restoration.

Complementing the spatial analysis, dynamic process analysis using process-based modelling and laboratory experiments has been employed to examine temporal changes in soil properties and uncover underlying mechanisms. By manipulating variables to develop a wide range of scenarios for model simulation, a broader perspective on the factors influencing the performance of agroforestry system has been gained, and potential land use strategies for enhancing ecosystem multifunctionality have been identified.

The findings further highlight the significance of incorporating suitable tree species in suitable environments within cacao- and coffee-based agroforestry systems to improve system multifunctionality. The relatively "unknown" complementary role of surface litter and roots in facilitating soil recovery after soil disturbances, as well as their interactions with VA on inducing soil hydrophobicity that affects soil water dynamics, has also been explained Additionally, the development of a conceptual framework for SOC and soil structure dynamics opens avenues for modifying the existing tree-soil-crop process-based WaNuLCAS 4.4 models to better explore LUS recovery following specific soil disturbances after volcanic eruptions.

Finally, the implications of this research can extend beyond academic discourse. The insights gained from this thesis can inform land managers, policymakers, and practitioners in making informed decisions regarding land use and soil management. Recognizing the critical role of suitable tree species and their associated surface litter and roots in promoting soil quality and its functions' recovery enables the development of tailored approaches for restoring degraded soils, enhancing ecosystem resilience, and improving farmers' livelihoods to make contributions to all 17 SDGs (Katila et al. 2019; van Noordwijk et al. 2020). Just as 'Farmer Managed Natural Regeneration' is a working-with-nature, but slower alternative to tree planting, tree-based soil function recovery is another working-with-nature, but slower alternative to direct input-based interventions. Agroforestry supports recovery when degradation is stopped early enough.

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Summary

One-third of the Earth's land, including the soil therein, is degraded, which means it lost some of the functions soil under undisturbed native vegetation performs. Naturally and/or anthropogenically, soils are disturbed and lose their quality and functionality. This means that they are unable to support the increasing human population and their well-being. Land use systems (LUS) serve as an interface between 'actors' and 'land cover' can be characterized by GxExM interplay, representing the Genotype (G) by Environment (E) interactions, subject to Management (M). GxExM is a major cause of soil degradation, which is usually starts with soil organic carbon (SOC) depletion. However, GxExM interactions can also serve as the basis for soil restoration, such as through agroforestry practices that involve retaining, planting and well-managing (M) the right trees (G) in the right places on farms (E). Rather than attributing degradation to 'agriculture' at large, a more process-based understanding is needed to guide recovery.

Indonesia is significant for the global supply stability of two high-value commodities: cacao (*Theobroma cacao*) and coffee (especially *Coffea canephora*). The majority of Indonesia's cacao and coffee production comes from smallholder gardens or plantations, which are primarily located at the interface between forests and agricultural areas in mountainous landscapes. The expansion of coffee and cacao cultivation, following periods of national decline in productivity, have often been linked with deforestation and environmental degradation. This unfortunate situation puts the smallholder farmers at the centre of a long-standing stakeholder debate on appropriate land use management that can effectively support productivity and environmental services. While "intensive" monocultures have indeed succeeded in boosting agricultural productivity, they often do so at the expense of environmental degradation, posing significant sustainability challenges. On the other hand, agroforestry has emerged as a promising strategy to improve soil quality and its associated functions. Comparisons between monocultures and mixed systems, as the fundamental differentiators between these systems, need to be carried out and tested under various challenging conditions to assess their performance consistency. This knowledge serves as a focal point for determining the most effective strategies to develop multifunctional and sustainable LUS.

Retaining diverse shade trees for smallholder agroforestry farmers is fundamental to halt soil degradation and support its recovery, as the external sources for direct input interventions are often limited. The interactions between aboveground tree/crop growth and belowground properties of roots, litter, SOC, soil structure, and their functions can be understood as a structure-function-services chain. Together with its capability to regulate micro-climate, the presence of shade trees in agroforestry guarantees sustainable organic matter (OM) input from aboveground (leaf and woody parts litter) and belowground (roots litter) to improve SOC. In various ways, SOC contributes to soil structure development indicated by abundant and continuous soil surface macropores, and stable soil aggregate. Combined with soil surface protection from surface litter, well-developed soil structure facilitates faster soil infiltration and reduces runoff and soil erosion,

creating favourable water cycle to support plant productivity and LUS multifunctionality, as well as developing a more resilient system against climate uncertainty.

In this thesis I explore to what extent cacao- and coffee-based agroforestry systems can support soil recovery from natural- and human-induced soil disturbance and degradation while simultaneously maintaining their multifunctionality and economic performance. Three main approaches to the pattern-process interactions were employed in this study: starting from (spatial) patterns by comparing field-measurement data across LUS (in Chapters 2 and 4), starting from dynamic process aspects by lab experiments (in Chapter 5), integrating process-based, spatially explicit modelling (in Chapters 3 and 6). Combining these approaches enables a contribution to better understanding of the interconnectedness and interdependencies between spatial patterns and dynamic processes.

Chapter 2 studies the soil recovery of various LUS from the gradual soil degradation following deforestation based on the case study of cacao LUS in SE Sulawesi, Indonesia. Here, we compared the fine roots density and soil properties of various LUS, including remnant forest (RF), cacao-based simple and complex agroforestry system (SAF and CAF), cacao monoculture (CM), and annual food crops (CR). We hypothesized that soil structure and its functions could be restored/recovered in near-forest conditions by the inclusion of suitable trees in a CAF. Our results partly supported the hypothesis. We found that integrating diverse tree species in CAF showed a higher root density, particularly in the upper soil layer, than other agricultural systems, albeit only half of what was found in reference RF. The higher root density was found to be positively correlated to SOC. Higher fine root density and SOC on the upper soil layer of CAF were highly associated with higher macroporosity, but modest with aggregate stability and soil infiltration. A considerable gap between the RF and CAF we found might be related to the relatively low maturity level of the cacao plot we measured (9-14 years, where gardens can be maintained for decades when internal rejuvenation is used). Thus, the recovery process was still in the early phase, as also reported by several studies.

The GxExM interactions within agroforestry components are, unfortunately, often complex, context-dependent, and occasionally inconsistent. **Chapter 3** explored the multifunctionality and economic performance consistency of cacao-based agroforestry systems using the process-based WaNuLCAS model. The model has G representation of functional tree and crop properties, E representation of soil and climate as abiotic and plant-plant interactions as biotic conditions, and M representation of spacing, planting schedules, pruning, harvesting and fertilization. We evaluated various cacao-based agroforestry systems involving different companion trees and crops, including a fast-growing tree *Falcataria mollucana*, slow-growing tree *Tectona grandis*, fruit tree *Durio zibethinus*, and annual crops *Pogostemon cablin* to be compared with monoculture system. The system's performance was tested against various scenarios, including cacao root densities, soil textures, and climate regimes. Our model simulation suggested that cacao-based agroforestry systems provide stronger multifunctionality and economic performance than cacao monoculture under particular scenarios. Cacao agroforestry exhibited a more robust multifunctionality performance than cacao monoculture when the primary objective was to increase the C stocks, but it had modest impacts on water-related functions. Our simulation also demonstrated that in water-limited regions, cacao with high root density showed superior performances than its low-root density counterparts, highlighting the importance of root structure and distribution in the resiliency of cacao towards water scarcity. Among agroforestry systems, the integration of cacao with annual crops or fruit trees is projected to achieve the highest economic performance, with the latter combination offering better labour efficiency. In contrast, intercropping cacao with fast-growing trees in water-limited regions harmed the cacao growth and led to lower multifunctionality and economic performance than cacao monoculture.

Unlike the soil degradation caused by LUS mismanagement, as explored in Chapter 2, which decreased soil quality and its function gradually, soil disturbance due to volcanic events affect almost instantly. **Chapter 4** studies the impact of volcanic ash (VA) deposition on topsoil properties changes and its recovery from various LUS surrounding the highly-active volcano of Mt. Kelud in East Java, Indonesia, including RF, coffee-based SAF and CAF, and annual food crops (CR). To study the soil changes, we compared the topsoil (0-30 cm) properties of each LUS between three different measurement periods, including before eruption (PRE), 3, and 6 years after eruption (3 YAE, and 6 YAE). Within 3 years, we found that VA deposition homogenized soil properties and functions in all LUS, indicating that the disturbance intensity was beyond the LUS buffering capacity. Some properties, such as litter thickness, aggregate stability, and soil infiltration, were significantly dropped within 3 YAE but quickly recovered after 6 YAE. Soil infiltration in 3 YAE was 8 times slower than in PRE condition, even though no significant changes were found in soil porosity, indicating soil hydrophobicity that may be induced by VA and surface litter interactions. Given the very low (or even zero) organic C content of fresh VA, the SOC was rapidly recovered, showed by insignificant changes between before and after VA deposition. Meanwhile, when comparing between systems, we found a clear indication that the increases in litter thickness, following the inclusion of various trees under CAF, contributed to higher SOC, aggregate stability, and soil infiltration compared to CR, despite the gap with RF remained.

Chapter 5 explored the impact of the interaction between VA and various type of OM on inducing water repellency (WR) and quantified its impact on soil infiltration and hydraulic conductivity. We found that the interaction of VA and various OM types induced different levels of WR during 16-week incubation periods, as indicated by the significant difference in contact angle (CA) and water drop penetration time (WDPT) of the substances. The strongest WR was produced by the mix of VA with *Pinus merkusii* (pine) litter, followed by *Durio zibethinus* (Durian), mixed OM, and *Coffea canephora* (Robusta coffee), respectively. Stronger WR was only partially associated with higher lipids content of OM, suggesting that the broader plant characteristics such as n-alcohols, n-fatty acids, and n-alkanes may give further insight into which components are primarily responsible for WR. Furthermore, our study also highlights that when soil water content exceeded 7%, lipids content was no longer correlated with WR. Furthermore, layering WR substance on the soil surface reduced soil hydraulic conductivity up to five times, with an indication of entrapped air bubbles that made the WR effect persist instead of transient.

Building from the results of Chapters 4 and 5, we proposed a conceptual framework of SOC dynamic models that can be used to modify the existing WaNuLCAS model in **Chapter 6**, so it could facilitate the simulation scenario that involves specific challenges of post eruption disturbance and recovery under agroforestry practices.

Synthesizing the results from all core chapters, the general discussion of **Chapter 7** elucidated the relatively "unknown" complementary role of surface litter and roots in facilitating the recovery of SOC and its associated functions following soil disturbances and degradation. Additionally, it highlighted the interactions between different types of OM with VA, which can induce soil hydrophobicity and influence soil water dynamics. Furthermore, we emphasized the significance of incorporating suitable tree species in suitable environments within cacao- and coffee-based agroforestry systems to improve their multifunctionality and economic performance. Tree-based soil restoration through agroforestry practices is a working-with-nature, a slower alternative to direct input intervention, but can effectively halt ongoing- and reverse past-degradation when both above- and belowground components work in harmony.

Samenvatting

Een derde van het land op aarde, inclusief de bodem daarin, is gedegradeerd, wat betekent dat het een deel van de functies heeft verloren die de bodem onder ongestoorde vegetatie vervult. Op natuurlijke en/of antropogene wijze worden de bodems verstoord en verliezen ze hun kwaliteit en functionaliteit. Dit betekent dat ze niet in staat zijn de groeiende menselijke bevolking en haar welzijn te ondersteunen. Landgebruiksystemen (LUS) dienen als interface tussen 'actoren' en 'landbedekking' en kunnen worden gekarakteriseerd door GxOxM-interactie, die de interacties tussen genotype (G) en omgeving (O) vertegenwoordigt, onderhevig aan management (M). GxOxM interacties zijn een belangrijke oorzaak van bodemdegradatie, die meestal begint met de uitputting van organische koolstof (SOC) in de bodem. GxOxM-interacties kunnen echter ook dienen als basis voor bodemherstel, bijvoorbeeld door agroforestry-praktijken waarbij de juiste bomen (G) op de juiste plaatsen op boerderijen worden behouden, geplant en goed beheerd (M). In plaats van degradatie toe te schrijven aan de 'landbouw' in het algemeen, is een meer procesgebaseerd begrip nodig om het herstel te sturen.

Indonesië speelt een rol in de mondiale aanbodstabiliteit van twee hoogwaardige grondstoffen: cacao (*Theobroma cacao*) en koffie (vooral *Coffea canephora*). Het grootste deel van de Indonesische cacao- en koffieproductie is afkomstig van kleine tuinen of plantages, die voornamelijk gelegen zijn op het grensvlak tussen bossen en landbouwgebieden in bergachtige landschappen. De uitbreiding van de koffie- en cacaoteelt, na perioden van nationale productiviteitsdaling, wordt vaak in verband gebracht met ontbossing en aantasting van het milieu. Deze ongelukkige situatie plaatst de kleine boeren in het middelpunt van een al lang bestaand debat tussen belanghebbenden over passend beheer van landgebruik dat de productiviteit en milieudiensten effectief kan ondersteunen. Hoewel 'intensieve' monoculturen er inderdaad in zijn geslaagd de landbouwproductiviteit te vergroten, doen ze dit vaak ten koste van de aantasting van het milieu, wat aanzienlijke duurzaamheidsproblemen met zich meebrengt. Aan de andere kant is agroforestry naar voren gekomen als een veelbelovende strategie om de bodemkwaliteit en de daarmee samenhangende functies te verbeteren. Vergelijkingen tussen monoculturen en gemengde systemen, als fundamentele onderscheidende factoren tussen deze systemen, moeten onder verschillende uitdagende omstandigheden worden uitgevoerd en getest om de consistentie van hun prestaties te beoordelen. Deze kennis dient als centraal punt voor het bepalen van de meest effectieve strategieën om multifunctionele en duurzame LUS te ontwikkelen.

Het behouden van diversiteit in schaduwbomen voor kleine agroforestry-boeren is van fundamenteel belang om de bodemdegradatie een halt toe te roepen en het herstel ervan te ondersteunen, aangezien de externe bronnen voor directe input-interventies vaak beperkt zijn. De interacties tussen bovengrondse boom-/gewasgroei en ondergrondse eigenschappen van wortels, strooisel, SOC, bodemstructuur en hun functies kunnen worden begrepen als een keten van structuur-functie-diensten. Samen met het vermogen om het microklimaat te reguleren, zorgt de aanwezigheid van schaduwbomen in agroforestry voor een duurzame input van organisch

materiaal (OM) van bovengronds (strooisel van blad- en houtachtige delen) en ondergronds (wortel afbraak) om de SOC te verbeteren. Op verschillende manieren draagt SOC bij aan de ontwikkeling van de bodemstructuur, wat blijkt uit overvloedige en continue macroporiën in het bodemoppervlak en stabiele bodemaggregaten. Gecombineerd met bescherming van het bodemoppervlak door een strooisellaag, vergemakkelijkt een goed ontwikkelde bodemstructuur snellere bodeminfiltratie en vermindert het afvloeiing en bodemerosie. Dit creëert een gunstige watercyclus en ondersteunt de productiviteit van planten en multifunctionaliteit van het landgebruik. Het maakt het systeem ook veerkrachtiger en bestand tegen klimaat veranderingen.

In dit proefschrift onderzoek ik in hoeverre op cacao en koffie gebaseerde agroforestry-systemen het bodemherstel kunnen ondersteunen na natuurlijke en door de mens veroorzaakte bodemverstoring en -degradatie, terwijl tegelijkertijd hun multifunctionaliteit en economische prestaties behouden blijven. In deze studie zijn drie hoofdbenaderingen van de patroon-procesinteracties gebruikt: beginnend bij (ruimtelijke) patronen door veldmetingsgegevens over landgebruik te vergelijken (in de Hoofdstukken 2 en 4), beginnend bij dynamische procesaspecten door laboratoriumexperimenten (in Hoofdstuk 5), het integreren van procesgebaseerde, ruimtelijk expliciete modellering (in Hoofdstukken 3 en 6). Door deze benaderingen te combineren, kan een bijdrage worden geleverd aan een beter begrip van de onderlinge verbondenheid en afhankelijkheden tussen ruimtelijke patronen en dynamische processen.

Hoofdstuk 2 bestudeert het bodemherstel door verschillende vormen van landgebruik volgend op de geleidelijke bodemdegradatie na ontbossing. Het is gebaseerd op een studie van cacao landgebruik in Zuidoost-Sulawesi, Indonesië. Hier hebben we de fijne worteldichtheid en bodemeigenschappen van verschillende LUS vergeleken, waaronder resterend bos (RF), op cacao gebaseerd eenvoudig en complex agroforestry-systeem (SAF en CAF), cacaomonocultuur (CM) en jaarlijkse voedselgewassen (CR). Onze hypothese was dat de bodemstructuur en zijn functies kunnen worden hersteld/hersteld in omstandigheden die dicht bij het bos liggen, door het opnemen van geschikte bomen in een CAF. Onze resultaten ondersteunden de hypothese ten dele. We ontdekten dat de integratie van diverse boomsoorten in CAF tot een hogere worteldichtheid leide, vooral in de bovenste bodemlaag, dan bij andere landbouwsystemen, zij het slechts de helft van wat werd gevonden in referentie-RF. De hogere worteldichtheid bleek positief gecorreleerd te zijn met SOC. Hogere fijne worteldichtheid en SOC op de bovenste bodemlaag van CAF waren sterk geassocieerd met hogere macroporositeit, maar zwakker met aggregaatstabiliteit en bodeminfiltratie. Een aanzienlijke kloof tussen de RF en de CAF die we hebben gevonden, kan verband houden met de relatief lage leeftijd van het cacaoperceel dat we hebben gemeten (9-14 jaar, waarbij tuinen tientallen jaren kunnen worden onderhouden als interne verjonging wordt gebruikt). Het herstelproces bevond zich dus nog in de beginfase, zoals ook uit verschillende onderzoeken blijkt.

De GxOxM-interacties binnen agroforestry-componenten zijn helaas vaak complex, contextafhankelijk en soms inconsistent. **Hoofdstuk 3** onderzocht de multifunctionaliteit en economische prestatieconsistentie van op cacao gebaseerde agroforestry-systemen met behulp van het procesgebaseerde WaNuLCAS-model. Het model heeft een G-weergave van functionele boom- en gewaseigenschappen, O-weergave van bodem en klimaat als abiotische en plant-plant-interacties als biotische omstandigheden, en M-weergave van de plant afstand, plantschema's, snoeien, oogsten en bemesting. We evalueerden verschillende op cacao gebaseerde agroforestry-systemen waarbij verschillende begeleidende bomen en gewassen betrokken waren, waaronder een snelgroeiende boom *Falcataria mollucana*, langzaam groeiende boom *Tectona grandis*, fruitboom *Durio zibethinus* en eenjarige gewassen *Pogostemon cablin* om te vergelijken met het monocultuursysteem. De prestaties van het systeem zijn getest aan de hand van verschillende scenario's, waaronder de wortellengte-dichtheid van cacaowortels, bodemtexturen en klimaatregimes. Onze modelsimulatie suggereerde dat op cacao gebaseerde agroforestry-systemen onder bepaalde scenario's sterkere multifunctionaliteit en economische prestaties bieden dan cacao-monocultuur. Cacao-agroforestry vertoonde robuustere multifunctionaliteitsprestaties dan cacao-monocultuur als het primaire doel het vergroten van de koolstof opslag was, maar het had een bescheiden impact op watergerelateerde functies. Onze simulatie toonde ook aan dat onder water-beperkende omstandigheden cacao met een hogere wortellengtedichtheid beter presteert dan tegenhangers met een lage worteldichtheid. Dit benadrukt het belang van de wortelstructuur en distributie in de veerkracht van cacao ten aanzien van waterschaarste. Onder de agroforestry-systemen zal de integratie van cacao met eenjarige gewassen of fruitbomen naar verwachting de hoogste economische prestaties opleveren, waarbij de laatste combinatie een betere arbeidsefficiëntie oplevert. Het mengen van cacao met snelgroeiende bomen in gebieden met weinig water schaadde daarentegen de cacaogroei en leidde tot lagere multifunctionaliteit en economische prestaties dan de monocultuur van cacao.

In tegenstelling tot de bodemdegradatie veroorzaakt door suboptimaal landgebruik, zoals onderzocht in Hoofdstuk 2, waardoor de bodemkwaliteit en de functie ervan geleidelijk afnam, heeft bodemverstoring als gevolg van vulkanische gebeurtenissen vrijwel onmiddellijk effect. **Hoofdstuk 4** bestudeert de effecten van de afzetting van vulkanische as (VA) op veranderingen in de eigenschappen van de bovengrond en het herstel ervan uit verschillende vormen van landgebruik rond de zeer actieve vulkaan van de berg Kelud in Oost-Java, Indonesië. Het betreft RF, op koffie gebaseerde SAF en CAF, en eenjarige voedselgewassen (CR). Om de bodemveranderingen te bestuderen, vergeleken we de eigenschappen van de bovengrond (0-30 cm) van elke landgebruik tussen drie verschillende meetperioden, inclusief vóór uitbarsting (PRE), 3 en 6 jaar na uitbarsting (3 YAE en 6 YAE). Binnen drie jaar ontdekten we dat VA-afzetting de bodemeigenschappen en -functies in alle vormen van landgebruik homogeniseerde, wat aangeeft dat de verstoringsintensiteit de buffercapaciteit te boven ging. Sommige eigenschappen, zoals de dikte van het strooisel, de stabiliteit van het aggregaat en de bodeminfiltratie, daalden aanzienlijk binnen 3 YAE, maar herstelden zich snel na 6 YAE. De bodeminfiltratie in 3 YAE was 8 keer langzamer dan in PRE-conditie, ook al werden er geen significante veranderingen gevonden in de porositeit van de bodem, wat wijst op hydrofobiciteit van de bodem die kan worden veroorzaakt door VA en interacties met oppervlaktestrooisel. Gegeven het zeer lage (of zelfs afwezige) organische C-gehalte van verse VA, werd de SOC snel hersteld, wat bleek uit onbeduidende veranderingen tussen vóór en na VA-afzetting. Ondertussen vonden we bij het vergelijken tussen systemen een duidelijke indicatie dat de toename in de dikte van het strooisel, na de opname van verschillende bomen onder CAF, bijdroeg aan een hogere SOC, aggregaatstabiliteit en bodeminfiltratie vergeleken met CR, ondanks dat de kloof met RF bleef bestaan.

Hoofdstuk 5 onderzocht de impact van de interactie tussen VA en verschillende soorten OM op het induceren van waterafstotendheid (WR) en kwantificeerde de impact ervan op bodeminfiltratie en hydraulische geleidbaarheid. We ontdekten dat de interactie van VA en verschillende OM-typen verschillende niveaus van WR induceerde tijdens incubatieperioden van 16 weken, zoals aangegeven door het significante verschil in contacthoek (CA) en waterdruppel-penetratietijd (WDPT) van de stoffen. De sterkste WR werd geproduceerd door de mix van VA met *Pinus merkusii* (dennen) strooisel, gevolgd door respectievelijk *Durio zibethinus* (Durian), gemengde OM en *Coffea canephora* (Robusta koffie). Sterkere WR werd slechts gedeeltelijk geassocieerd met een hoger lipidengehalte van OM, wat suggereert dat de bredere plantkenmerken zoals n-alcoholen, n-vetzuren en n-alkanen verder inzicht kunnen geven in welke componenten primair verantwoordelijk zijn voor WR. Bovendien benadrukt ons onderzoek ook dat wanneer het bodemwatergehalte hoger was dan 7%, het lipidengehalte niet langer gecorreleerd was met WR. Bovendien verminderde het aanbrengen van lagen WR-substantie op het bodemoppervlak de hydraulische geleidbaarheid van de bodem tot vijf keer, met een indicatie van ingesloten waterbellen waardoor het WR-effect aanhield in plaats van van voorbijgaande aard.

Voortbouwend op de resultaten van de hoofdstukken 4 en 5 hebben we een conceptueel raamwerk van dynamische SOC-modellen voorgesteld dat kan worden gebruikt om het bestaande WaNuLCAS-model in **Hoofdstuk 6** aan te passen, zodat het het simulatiescenario zou kunnen vergemakkelijken dat specifieke uitdagingen van verstoring en herstel na de uitbarsting met zich meebrengt bij gebruik van agroforestry.

De resultaten uit alle eerdere hoofdstukken samenvattend, heeft de algemene discussie van **Hoofdstuk 7** de relatief onbekende complementaire rol van oppervlaktestrooisel en wortels bij het faciliteren van het herstel van SOC en de bijbehorende functies na bodemverstoringen en -degradatie opgehelderd. Bovendien benadrukte het de interacties tussen verschillende soorten OM met VA, die hydrofobiciteit van de bodem kunnen veroorzaken en de grondwaterdynamiek kunnen beïnvloeden. Het ondersoek toonde ook het belang aan van het integreren van geschikte boomsoorten in geschikte omgevingen binnen op cacao en koffie gebaseerde agroforestry-systemen om hun multifunctionaliteit en economische prestaties te verbeteren. Op bomen gebaseerd bodemherstel door middel van agroforestry-praktijken is een samenwerking met de natuur, een langzamer alternatief voor directe input-interventie, maar kan op effectieve wijze de aanhoudende degradatie een halt toeroepen en terugdraaien wanneer zowel boven- als ondergrondse componenten in harmonie samenwerken.

Ringkasan

Sepertiga dari daratan bumi, termasuk tanah, mengalami degradasi, yang berarti tanah telah kehilangan beberapa fungsi seperti kondisi yang disediakan oleh vegetasi asli saat kondisi masih utuh. Secara alami dan/atau antropogenik, tanah dapat mengalami gangguan, kehilangan kualitas dan fungsinya. Artinya, tanah tidak mampu mendukung peningkatan populasi manusia dan kesejahteraan mereka. Sistem Penggunaan Lahan (LUS) berfungsi sebagai media pertemuan antara 'aktor' dan 'tutupan lahan' yang dapat dicirikan oleh interaksi GxExM, yang merepresentasikan interaksi Genotipe (G) dengan Lingkungan (E), yang diatur melalui Manajemen (M). GxExM merupakan penyebab utama degradasi tanah, yang biasanya dimulai dengan penurunan kandungan karbon organik tanah (SOC). Namun, interaksi GxExM juga dapat berfungsi sebagai dasar restorasi tanah, contohnya melalui praktik agroforestri yang melibatkan perawatan, penanaman, dan pengelolaan (M) pohon yang tepat (G) di tempat yang tepat dari lahan pertanian (E). Pemahaman berbasis proses lebih diperlukan untuk memandu pemulihan, daripada hanya menghubungkan degradasi dengan 'pertanian' secara luas.

Indonesia berperan penting dalam menjaga stabilitas pasokan global untuk dua komoditas bernilai tinggi: kakao (*Theobroma cacao*) dan kopi (khususnya *Coffea canephora*). Mayoritas produksi kakao dan kopi di Indonesia berasal dari perkebunan rakyat, yang sebagian besar terletak di perbatasan antara hutan dan kawasan pertanian di lanskap pegunungan. Perluasan budidaya kopi dan kakao, setelah periode penurunan produktivitas nasional, sering kali dikaitkan dengan deforestasi dan degradasi lingkungan. Situasi yang tidak menguntungkan ini menempatkan petani kecil menjadi pusat perdebatan yang sudah berlangsung lama antara para pemangku kepentingan terkait dengan pengelolaan penggunaan lahan yang tepat yang dapat secara efektif mendukung produktivitas dan jasa lingkungan. Meskipun praktik pertanaman monokultur "intensif" memang berhasil meningkatkan produktivitas pertanian, namun praktik ini sering kali berdampak terhadap degradasi lingkungan, sehingga menimbulkan tantangan keberlanjutannya secara signifikan. Di sisi lain, agroforestri telah berkembang sebagai strategi potensial untuk meningkatkan kualitas tanah dan fungsi-fungsinya. Perbandingan antara sistem monokultur dan sistem campuran, sebagai pembeda mendasar antara sistem-sistem tersebut, perlu dilakukan dan untuk selanjutnya diuji dalam berbagai kondisi yang menantang untuk menilai konsistensi kinerja dari kedua sistem tersebut. Pengetahuan ini berfungsi sebagai fokus utama untuk menentukan strategi yang paling efektif untuk mengembangkan sistem penggunaan lahan yang memberikan banyak manfaat (multifungsi) dan berkelanjutan.

Mempertahankan keanekaragaman pohon penaung kopi/kakao bagi petani agroforestri merupakan hal yang penting untuk menghentikan degradasi tanah dan mendukung pemulihannya, karena sumber-sumber eksternal sebagai input untuk intervensi secara langsung seringkali terbatas. Interaksi pertumbuhan antara bagian diatas permukaan tanah (tajuk pohon, produksi seresah) dengan bagian dalam tanah tanah (akar, karbon organik tanah, struktur tanah) dan fungsinya dapat dipahami sebagai suatu rantai dari struktur-fungsi-jasa/manfaat. Selain kemampuannya dalam mengatur iklim mikro, keberadaan pohon penaung dalam agroforestri menjamin masukan bahan organik (OM) secara berkelanjutan dipermukaan tanah (serasah daun dan bagian kayu) dan bawah tanah (serasah akar) untuk meningkatkan karbon organik tanah (SOC). Dalam berbagai mekanisme, SOC berkontribusi dalam perkembangan struktur tanah yang ditunjukkan oleh jumlah dan konektivitas makropori di lapisan tanah atas, serta agregat tanah yang stabil. Dikombinasikan dengan perlindungan permukaan tanah oleh lapisan serasah, struktur tanah yang berkembang dengan baik mampu memfasilitasi infiltrasi air lebih cepat dan mengurangi limpasan permukaan serta erosi, menciptakan siklus air yang mendukung produktivitas tanaman dan sistem penggunaan lahan yang multifungsi, serta mengembangkan sistem yang lebih tahan terhadap ketidakpastian iklim.

Dalam tesis ini saya mengeksplorasi sejauh mana sistem agroforestri berbasis kakao dan kopi dapat mendukung pemulihan tanah dari gangguan dan degradasi tanah yang disebabkan oleh alam dan manusia, sekaligus menjaga multifungsi dan kinerja ekonominya. Penelitian ini mengacu pada tiga pendekatan utama interaksi pola-proses: dimulai dari eksplorasi pola (spasial) dengan membandingkan data pengukuran lapangan di berbagai LUS (di Bab 2 dan 4), proses dinamis melalui percobaan laboratorium (di Bab 5), kemudian mengintegrasikan pemodelan spasial eksplisit berbasis proses (dalam Bab 3 dan 6). Penggabungan pendekatan ini dapat berkontribusi terhadap pemahaman yang lebih baik mengenai keterhubungan dan ketergantungan antara pola spasial dan proses dinamis.

Bab 2 mempelajari pemulihan tanah yang terdegradasi secara bertahap setelah deforestasi berdasarkan studi kasus dari berbagai LUS berbasis kakao di Sulawesi Tenggara, Indonesia. Di sini, kami membandingkan kerapatan akar halus dan sifat tanah dari berbagai LUS, termasuk hutan tersisa (RF), sistem agroforestri sederhana dan kompleks berbasis kakao (SAF dan CAF), kakao monokultur (CM), dan tanaman pangan semusim (CR). Kami berhipotesis bahwa struktur dan fungsi tanah dapat dipulihkan hingga kondisinya menyerupai hutan dengan mengintegrasikan pohon-pohon yang tepat dalam wujud sistem agroforestri kompleks (CAF). Sebagian hasil penelitian kami mendukung hipotesis tersebut. Kami menemukan bahwa dengan mengintegrasikan beranekagam spesies pohon, CAF memiliki kerapatan akar yang lebih tinggi, khususnya di lapisan tanah bagian atas, dibandingkan sistem pertanian lainnya, namun kerapatan akar yang ditemukan hanya setengah dari yang ada di RF. Kerapatan akar yang tinggi berkorelasi positif dengan SOC. Kerapatan akar halus dan SOC yang tinggi di lapisan tanah atas dari CAF sangat terkait dengan tingginya makroporositas, namun tidak berpengaruh terhadap stabilitas agregat dan infiltrasi. Kesenjangan kualitas tanah yang cukup besar antara RF dan CAF yang kami temukan kemungkinan terkait dengan umur lahan kakao yang kami ukur masih muda (9-14 tahun, dimana sistem ini dapat dipertahankan selama beberapa dekade jika dilakukan peremajaan internal). Dengan demikian, proses pemulihan sistem agroforestri kakao masih dalam tahap awal, sebagaimana dilaporkan oleh beberapa penelitian lain.

Interaksi GxExM dalam komponen agroforestri, sayangnya seringkali rumit, tergantung pada konteks, dan terkadang tidak konsisten. **Bab 3** mengeksplorasi multifungsionalitas dan konsistensi performa ekonomi sistem agroforestri berbasis kakao dengan menggunakan model berbasis proses WaNuLCAS. Model tersebut memiliki representasi Genotipe (G) yang menunjukkan sifat fungsional pohon dan tanaman, E representasi dari tanah dan iklim sebagai faktor abiotik dan interaksi tanaman-tanaman sebagai faktor biotik, dan M representasi dari jarak tanam, jadwal tanam, pemangkasan, pemanenan dan pemupukan. Kami mengevaluasi berbagai sistem agroforestri berbasis kakao dengan melibatkan berbagai jenis pohon dan tanaman pendamping, termasuk pohon yang cepat tumbuh *Falcataria mollucana*, pohon yang lambat tumbuh *Tectona grandis*, pohon buah-buahan *Durio zibethinus*, dan tanaman semusim *Pogostemon cablin* untuk dibandingkan dengan sistem monokultur. Performa sistem ini diuji dengan berbagai skenario, termasuk perbedaan kerapatan akar kakao, tekstur tanah, dan rezim iklim. Simulasi model kami menunjukkan bahwa sistem agroforestri berbasis kakao memberikan multifungsionalitas dan performa ekonomi yang lebih kuat dibandingkan kakao monokultur dalam skenario tertentu. Agroforestri kakao menunjukkan performa multifungsionalitas yang lebih kuat dibandingkan kakao monokultur ketika tujuan utamanya adalah meningkatkan cadangan karbon, namun dampaknya tidak terlalu besar terhadap fungsi yang terkait dengan air. Simulasi kami juga menunjukkan bahwa di daerah dengan ketersediaan air terbatas, kakao dengan kerapatan akar tinggi menunjukkan performa yang lebih unggul dibandingkan kakao dengan kerapatan akar rendah, hal ini menegaskan pentingnya struktur dan distribusi akar dalam ketahanan kakao terhadap kondisi kelangkaan air. Di antara berbagai sistem agroforestri, integrasi kakao dengan tanaman tahunan atau pohon buah-buahan diperkirakan akan memberikan performa ekonomi tertinggi. Kombinasi kakao dan pohon buah-buahan menawarkan efisiensi tenaga kerja yang lebih baik. Sebaliknya, kombinasi kakao dengan pohon cepat tumbuh di daerah dengan ketersediaan air terbatas akan merugikan pertumbuhan kakao dan mengarah pada rendahnya multifungsionalitas dan performa ekonomi dibandingkan kakao monokultur.

Berbeda dengan degradasi tanah yang disebabkan oleh ketidaktepatan pengelolaan lahan seperti yang dibahas dalam Bab 2, yang menurunkan kualitas dan fungsi tanah secara bertahap, sedangkan gangguan tanah akibat aktivitas vulkanik berdampak hampir secara instan. **Bab 4** mempelajari dampak deposisi abu vulkanik terhadap perubahan sifat tanah lapisan atas dan proses pemulihannya dari berbagai sistem penggunaan lahan di sekitar G. Kelud yang sangat aktif di Jawa Timur, Indonesia, termasuk di hutan (RF), agroforestri sederhana (SAF) dan agroforestri kompleks (CAF) berbasis kopi, dan tanaman pangan semusim (CR). Untuk mempelajari dinamika tanah, kami membandingkan sifat-sifat tanah lapisan atas (0-30 cm) dari masing-masing sistem penggunaan lahan pada tiga periode pengukuran yang berbeda, termasuk sebelum letusan (PRE), 3, dan 6 tahun setelah letusan (3 YAE, dan 6 YAE). Dalam waktu 3 tahun, kami menemukan bahwa deposisi abu vulkanik menghomogenisasi sifat dan fungsi tanah di seluruh sistem penggunaan lahan, mengindikasikan bahwa intensitas gangguan berada di luar kapasitas penyangga lahan. Beberapa sifat seperti ketebalan serasah, stabilitas agregat, dan infiltrasi tanah, turun secara signifikan pada kisaran waktu 3 YAE namun pulih dengan cepat setelah 6 YAE. Infiltrasi tanah pada 3 YAE adalah 8 kali lebih lambat dibandingkan pada kondisi sebelum letusan

(PRE), meskipun tidak ditemukan adanya perubahan signifikan dari porositas tanah. Hal ini mengindikasikan munculnya sifat hidrofobisitas tanah yang mungkin disebabkan oleh adanya interaksi antara abu vulkanik dengan serasah permukaan. Mengingat kandungan C organik dari abu vulkanik segar yang sangat rendah (atau bahkan nol), karbon organik tanah (SOC) pulih dengan cepat, ditunjukkan oleh perubahan yang tidak signifikan antara sebelum dan sesudah deposisi abu vulkanik. Sementara itu, ketika membandingkan kondisi antar sistem penggunaan lahan, kami menemukan indikasi yang jelas bahwa peningkatan ketebalan serasah, mengikuti inklusi berbagai pohon di dalam sistem agroforestri komplek, berkontribusi terhadap kandungan SOC, stabilitas agregat, dan infiltrasi tanah yang lebih tinggi dibandingkan dengan CR, meskipun kesenjangan dengan RF tetap ada.

Bab 5 mengeksplorasi dampak interaksi antara abu vulkanik (VA) dengan berbagai jenis bahan organik (OM) dalam memunculkan sifat anti air atau hidrofobisitas (WR), dan mengukur dampaknya terhadap infiltrasi dan konduktivitas hidrolik tanah. Kami menemukan bahwa interaksi abu vulkanik dan berbagai tipe bahan organik memunculkan WR pada tingkatan yang berbeda selama 16 minggu masa inkubasi, seperti yang ditunjukkan oleh perbedaan signifikan dalam sudut kontak (CA) dan waktu penetrasi tetesan air (WDPT) dari berbagai campuran bahan yang diuji. WR terkuat dihasilkan oleh campuran abu vulkanik dengan serasah *Pinus merkusii* (pinus), diikuti oleh *Durio zibethinus* (Durian), campuran berbagai bahan organik, dan *Coffea canephora* (Kopi Robusta). WR yang lebih kuat hanya terkait sebagian dengan tingginya kandungan lipid dari bahan organik, mengindikasikan bahwa karakteristik tanaman lain seperti *n*-alkohol, *n*-asam lemak, dan *n*-alkana dapat memberikan informasi lebih lanjut mengenai komponen mana yang paling bertanggung jawab atas WR. Selain itu, penelitian kami juga menyoroti ketika kadar air tanah melebihi 7%, kandungan lipid tidak lagi berkorelasi dengan WR. Aplikasi substansi WR/hidrofobik di permukaan tanah mengurangi konduktivitas hidrolik tanah hingga lima kali lipat, dengan indikasi adanya gelembung udara yang terperangkap sehingga membuat efek WR bertahan lama dan tidak bersifat sementara.

Berdasarkan hasil Bab 4 dan 5, kami mengusulkan kerangka konseptual model dinamis karbon organik tanah (SOC) di **Bab 6**, yang dapat digunakan untuk memodifikasi model WaNuLCAS yang ada saat ini, sehingga dapat memfasilitasi skenario simulasi yang melibatkan tantangan spesifik gangguan dan pemulihan lahan pasca letusan gunung api dibawah berbagai praktek agroforestri.

Mensintesis hasil dari seluruh bab inti, pembahasan umum di **Bab 7** menjelaskan peran komplementer yang relatif “belum diketahui” dari serasah permukaan dan akar dalam memfasilitasi pemulihan karbon organik tanah dan fungsinya setelah adanya gangguan dan degradasi tanah. Selain itu, penelitian ini menyoroti interaksi antara berbagai jenis bahan organik dengan abu vulkanik, yang dapat menyebabkan munculnya sifat hidrofobisitas tanah dan mempengaruhi dinamika air tanah. Berikutnya, kami menekankan pentingnya penggabungan spesies pohon yang tepat di lingkungan yang sesuai dalam sistem agroforestri berbasis kakao dan kopi untuk meningkatkan multifungsionalitas dan performa ekonominya. Restorasi tanah berbasis pohon melalui praktik agroforestri merupakan upaya yang melibatkan alam, sebuah alternatif yang lebih lambat dibandingkan intervensi input secara langsung, namun dapat secara efektif menghentikan dan membalikkan degradasi di masa lalu ketika komponen di atas dan di bawah permukaan tanah bekerja secara harmonis.

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About the author

Danny Dwi Saputra was born on the 17th of March 1986 in Tuban, East Java, Indonesia. After high school, He moved to Malang to study Soil Science at Brawijaya University in 2004. He finished his BSc in 2008 with a thesis focusing on the role of agroforestry in maintaining ecosystem services, particularly on the impact of soil macropores and aggregate stability on infiltration.

After completing his BSc, Danny started to work as a research assistant at the Tropical Agroforestry Research Group for one year. He then started an MSc in Environmental Resources Management and Development at Brawijaya University, graduating in 2011. During his MSc, he studied land use changes and their impact on water balance at the landscape level. After obtaining his master's degree, Danny started working as a lecturer at the Department of Soil Science, the Faculty of Agriculture, Brawijaya University. Apart from giving lectures and community services, he was involved in some research, including the soil quality assessment and management of coffee-based agroforestry and oil palm plantations, the ecological recovery of Bromo Tengger Semeru National Park, and the management of volcanic soils in East Java.

He started his PhD in December 2019 at the Plant Production Systems Group at Wageningen University with full financial support from the Ministry of Finance, Republic of Indonesia, through the Indonesia Endowment Fund for Education (LPDP) scholarships award. During his early PhD, he went for data management training at the Centre of Ecology and Hydrology (CEH) in Lancaster, UK, through the collaboration between Brawijaya University and CEH of the SUNRISE research project. For his PhD, Danny studied the soil recovery in cacao and coffee agroforestry systems in Indonesia, particularly related to the litter, roots, carbon, and water. The results of his PhD research are presented in the current thesis.

After his PhD, he will return to Brawijaya University and continued as a lecturer at the Soil Physic Laboratory, Department of Soil Science and Forestry, and a researcher at Tropical Agroforestry Research Group. He can be reached through email at danny_saputra@ub.ac.id and dannydwisaputra@gmail.com.

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Saputra, D.D., 2022a. Pemulihan lahan pertanian terdampak letusan gunung berapi: pelajaran dari erupsi Gunung Kelud 2014. The Conversation Indonesia, January 5, 2022.

Saputra, D.D., 2022b. Pascaletusan Gunung Kelud, kualitas tanah di kawasan agroforestri lebih cepat membaik dibandingkan lahan pertanian. The Conversation Indonesia, June 2, 2022.

Saputra, D.D., Kusumawati, I.A., Mardiani, M.O., Sari, R.R. 2023. Agroforestry khas lereng Gunung Kawi *in* Suprayogo, D.; Hairiah, K.; Hafidzianor; Rahayu, S. (Eds) Agroforestri Khas Pegunungan Nusantara: Jendela Jawa Timur. INAFE and World Agroforestry (ICRAF), Bogor, Indonesia.

Hairiah, K., Ishaq, R.M., **Saputra, D.D.,** Purnamasari, E., Kurniawan, S. 2023. Agroforestry khas lereng Gunung Kelud *in* Suprayogo, D.; Hairiah, K.; Hafidzianor; Rahayu, S. (Eds) Agroforestri Khas Pegunungan Nusantara: Jendela Jawa Timur. INAFE and World Agroforestry (ICRAF), Bogor, Indonesia.

Sari, R.R., Kusumawati, I.A., Mardiani, M.O., **Saputra, D.D.,** Lusiana, B., Hairiah, K. 2023. Agroforestry khas lereng Gunung Anjasmoro *in* Suprayogo, D.; Hairiah, K.; Hafidzianor; Rahayu, S. (Eds) Agroforestri Khas Pegunungan Nusantara: Jendela Jawa Timur. INAFE and World Agroforestry (ICRAF), Bogor, Indonesia.

Saputra, D.D. 2023. 'Cuan' berlipat agroforestri kakao: pulihnya lingkungan dan tambahan pendapatan petani *in* Lubis, A.M; Maqoma, R. (Eds) *E-book:* Dari Ahli untuk Bumi: 15 Analisis Pilihan The Conversation Indonesia Seputar Pelestarian Lingkungan (pp. 8-11). The Conversation Indonesia, Jakarta, Indonesia.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review/project proposal (6 ECTS)

- Cacao and coffee agroforestry on hillslope in Indonesia: root, soil structure, infiltration and ecological restoration

Post-graduate courses (7 ECTS)

- Root ecology; PE&RC (2020)
- Companion modelling; PE&RC (2020)
- Structural equation modelling; PE&RC (2020)
- Resilience of living systems; PE&RC (2021)

Laboratory training and working visits (3 ECTS)

- Research database management and research field visit; Centre of Ecology and Hidrology, Lancaster, United Kingdom (2019)

Invited review of journal manuscripts (2 ECTS)

- Journal of Mountain Science: the influence of forest restoration on soil infiltrability: a case study from central Spain (2021)
- Journal of Agricultural and Forest Meteorology: tropical rubber-cocoa agroforestry systems intercepts soil nutrients (2021)

Competence, skills and career-oriented activities (3.65)

- Searching and organising literature; WGS (2019)
- Ethics in plant and environmental sciences; WGS (2019)
- Scientific writing; WGS (2020)
- Scientific publishing; PE&RC (2020)
- Reviewing a scientific manuscript; WGS (2021)
- Research database management; WGS (2021)
- Writing preposition; PE&RC (2023)

PE&RC Annual meetings, seminars and PE&RC weekend/retreat (1.45 ECTS)

- PE&RC Midterm weekend (2017)
- PE&RC Afternoon event (2020)
- PE&RC Day: biodiversity: reflecting on the past to transform the future (2021)
- PhD Workshop carousel; WGS (2022)
- Last stretch of PhD (2023)

Discussion groups/local seminars or scientific meetings (5.95 ECTS)

- International seminar and congress of Indonesian soil science society; Bandung, Indonesia (2019)

- The 3rd international conference in agroforestry: adopting modern agroforestry toward smart social forestry program; Yogyakarta, Indonesia (2019)
- PhD Workshops: how to present your research online and stress management during your PhD; The Royal Belgian Zoological Society; Belgium (2020)
- Workshop on data visualisation the information is beautiful way; WUR (2020)
- Strategi pembangunan perkebunan kakao untuk meningkatkan produktivitas dalam rangka recovery ekonomi pasca pandemi Covid-19 (2020)
- Soil biodiversity, a nature-based solution; Global Soil Partnership (2020)
- RECSOIL: recarbonization of global soil; Global Soil Partnership (2020)
- Global symposium on soil biodiversity keep soil alive, protect soil biodiversity; virtual (2021)
- Sustainable cacao and coffee discussion group (2021)
- Management of soil carbon in arable cropping systems (2022)
- Management of soil carbon in grassland/pasture systems (2022)
- Cacao workshop biodiversity-positive cocoa value chain (2022)
- Wageningen-Indonesia scientific exposure (2023)

International symposia, workshops and conferences (8.8 ECTS)

- 4th World congress on agroforestry; poster presentation; Montpellier, France (2019)
- 5th World congress agroforestry; oral presentation; Quebec, Canada (2022)
- 22nd World congress of soil science; poster presentation; Glasgow, Scotland (2022)
- 1st International conference on tropical agroforestry; oral presentation; Malang, Indonesia (2023)

Societally relevant exposure (1.2 ECTS)

- Popular science magazine article: Disasters in Batu: How does climate change and degraded upstream watershed area exacerbate flash flood risks? (2021)
- Popular science magazine article: The recovery of volcanic eruption-affected agricultural land: Lessons from the 2014 eruption of Mount Kelud (2022)
- Popular science magazine article: Multiple profits from cacao agroforestry: environmental recovery and additional income for farmers (2022)
- Popular science magazine article: Post Mt. Kelud eruption, the soil quality of agroforestry systems recovered more rapidly than monoculture crops (2022)

Lecturing/supervision of practicals/tutorials (2.1 ECTS)

- Forests hydrology (2021)
- Agroforestry: virtual field trip case study of Indonesia (2021-2023)

BSc/MSc thesis supervision (3 ECTS)

- The effect of litter on soil porosity and infiltration at different cacao-based land use system in Konawe, Southeast Sulawesi, Indonesia (2019)

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