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Ahmad Ali Yuddin Fitra[1], Simon Oakley[2], Cahyo Prayogo[3], Rika Ratna Sari[3], Danny Dwi Saputra[3], Rizki Maulana Ishaq[3], Kurniawan Sigit Wicaksono[3], Didik Suprayogo[3*]

[1] Postgraduate student, Soil and Water Management Study Program, Faculty of Agriculture, Brawijaya University, Indonesia
[2] UKCenter of Ecology and Hydrology (UKCEH), Lancaster Environment Centre, Lancaster, United Kingdom
[3] Lecturer of Soil Science Department, and researcher of Tropical Agroforestry Research Centre, Faculty of Agriculture, Brawijaya University, Indonesia

* Email: suprayogo@ub.ac.id

Abstract. Coffee-pine agroforestry is a common land use system in Indonesia, that provides several benefits, including increased soil fertility, biodiversity, and economic returns. However, the management of coffee-pine agroforestry systems can significantly impact on soil water dynamics, affecting coffee bean yields. This study investigated the effects of different management systems on soil water dynamics and coffee bean yields in a coffee-pine agroforestry system in UB Forest, Malang East Java, Indonesia. Five different management systems were evaluated: (i) no management, (ii) pruned coffee with no fertilizer, (iii) pruned coffee with added organic fertilizer, (iv) pruned coffee with added organic-inorganic mix fertilizer, with a planting distance of pine trees of 3 x 2 m, and (v) pruned coffee with added organic-inorganic mix fertilizer under pine trees with a planting distance of 6 x 2 m. The soil water dynamics were measured at depths of 0-0.2 m with a soil moisture sensor and connected with a data logger measured within a year, started in April 2022. Coffee bean yield was measured with 100 coffee plants, then converted to production on ton ha^{-1}. The results showed that the different management systems significantly impacted soil water dynamics and coffee bean yields. The combination of pruning and fertilization is a promising management strategy for increasing coffee bean yields in coffee-pine agroforestry systems. The consequent better growth of coffee plants impacts increasing soil water extraction. This study provides valuable insights for farmers and forest managers who are interested in improving the productivity of coffee-pine agroforestry systems and conserving soil water or sometimes needing water addition through irrigation.

Keywords: Agroforestry, forest management, coffee cultivation, water dynamics, coffee yields

1. Introduction

The coffee production sector in Indonesia is declining, with an average decline rate of 1.4% per year and is expected to increase to 1.52% in 2022-2026 [1]. This decline is due to the not yet optimal management of coffee cultivation in Indonesia, because most coffee cultivation in Indonesia is carried out in a unique way, which is carried out in a forest area agroforestry system, either in simple or complex systems (multi-strata system) [2]. One of the most widely practiced coffee cultivation in Indonesia is coffee cultivation in a coffee-pine-based agroforestry system, this is because coffee cultivation in a coffee-pine-based agroforestry system has economic and ecological benefits [3], In addition to producing coffee beans, coffee cultivation in agroforestry systems also has the potential to maintain or even improve ecological processes, such as nutrient and water cycling, energy flow, and carbon storage. [4]. Based on this uniqueness, coffee cultivation in the agroforestry system also has challenges, one of which is related to water distribution in the agroforestry system, because cultivation in the agroforestry system is carried out without an irrigation system and fully relies on rainwater, so it needs proper management so that coffee production in the coffee-pine agroforestry system can achieve optimal results. [5].

Differences in agroforestry management impact the level of groundwater dynamics over a long period of time, and will affect the level of coffee bean yield. Water dynamics conditions that tend to be more stable will have an impact on increasing coffee bean yields, while extreme groundwater dynamics will reduce coffee bean yields, because it will result in excess water during the rainy season, and drought during the dry season [6], [7].

The growth and production of coffee plants is largely determined by the availability of water in the soil in optimal conditions, because the availability of water in the soil greatly affects the growth of shoots, shoot growth will have an impact on the quality of growth and production of coffee plants [5], [8]. Shoot growth is influenced by the availability of water in the soil, which can be absorbed by coffee plants optimally, if coffee plants experience water stress (deficit conditions) it will reduce the existence of shoots, and the number of nodes, and photosynthesis conditions are not optimal, thus affecting coffee production [9]. The level of coffee production is largely determined by the fulfilment of water needs for plants, because water deficit conditions in coffee plants will have an impact on reducing fruit nodes per tree, the number of fruits per node, and the size of coffee fruit. [5], [8], [10].

In addition to drought conditions, excess water conditions also have a negative impact on coffee growth and production, excess water conditions will have an impact on low oxygen levels in the soil, thus inhibiting growth, and causing death in coffee plants [11], [12]. The condition of the roots and leaves will be disrupted if the coffee plant experiences excess water conditions, one of the initial responses that occurs when the coffee plant experiences excess water stress is the closing of stomata which is accompanied by a decrease in the photosynthetic rate of the plant [13], [14], [15]. Excess water also results in the failure of optimal flower formation for coffee plants, as well as fruit rot in the early phase [12].

The growth and production of coffee plants in the agroforestry system is very diverse, this diversity is thought to be one of the factors due to the non-optimal water needs in the agroforestry system caused by fluctuations in soil water levels (water is easily lost or soil conditions are too much water). [16], [17]. The difference in soil water dynamics at the same time is due to differences in soil texture, bulk density, and soil organic matter content [18]. Soil moisture content has a positive relationship with increasing clay content in the soil, and a negative relationship with sand content in the soil [18], [19]. Soil bulk density and organic matter are among the components of soil physical properties that play an indirect role in the water storage capacity of the soil [20]. The denser soil, it means high soil bulk density and low organic carbon. [21], and water availability in the soil have a positive relationship with soil organic matter content, structure, and constant mineralogy. A 1% increase in soil C-organic will increase water content by 2-5% [20], [22].

Coffee cultivation in agroforestry systems is highly dependent on the management patterns carried out to maintain optimal conditions for coffee plants, some management patterns have been carried out by local communities, including a.) regulation of plant populations, b.) fertilization, c.) tree pruning, and d.) addition of organic materials [23]. However, it has not been proven to maintain optimal soil water dynamics for plant growth, i.e. avoiding water deficiency or excess. Here, we will examine to improve the management potential of coffee cultivation in the pine-coffee agroforestry system by focusing on how to maintain soil water dynamics in optimal conditions for growth and impact on coffee plant production.

2. Materials and Methods

2.1. Study area

This research was conducted on Andisol in April-September 2022, located in the "*Special Purpose Forest Area* (KHDTK)" or UB Forest, Sumbersari, Tawangargo Village, Karangploso District, Malang Regency (Figure1). The elevation of the research site ranges from 700-1100 meters above sea level. Laboratory analysis was conducted at the Soil Physics Laboratory, Soil Science Department, Faculty of Agriculture of Brawijaya University.

2.2. Research and data collection

The experiment was arranged in a nested design with one research factor, namely coffee management interventions, with three replications (Table 1). The five research plots are traditionally managed by farmers in the UB Forest area with a plot size of 20 x 20 m. This study compared soil water content and production rates across five different kind of agroforestry management interventions. The soil water contents were measured at depths of 0-0.2 m with soil moisture sensor and connected with data logger measured within six months, started at April 2022. Coffee bean yield was measured with 100 coffee plants, then converted to production on ton ha^{-1}.

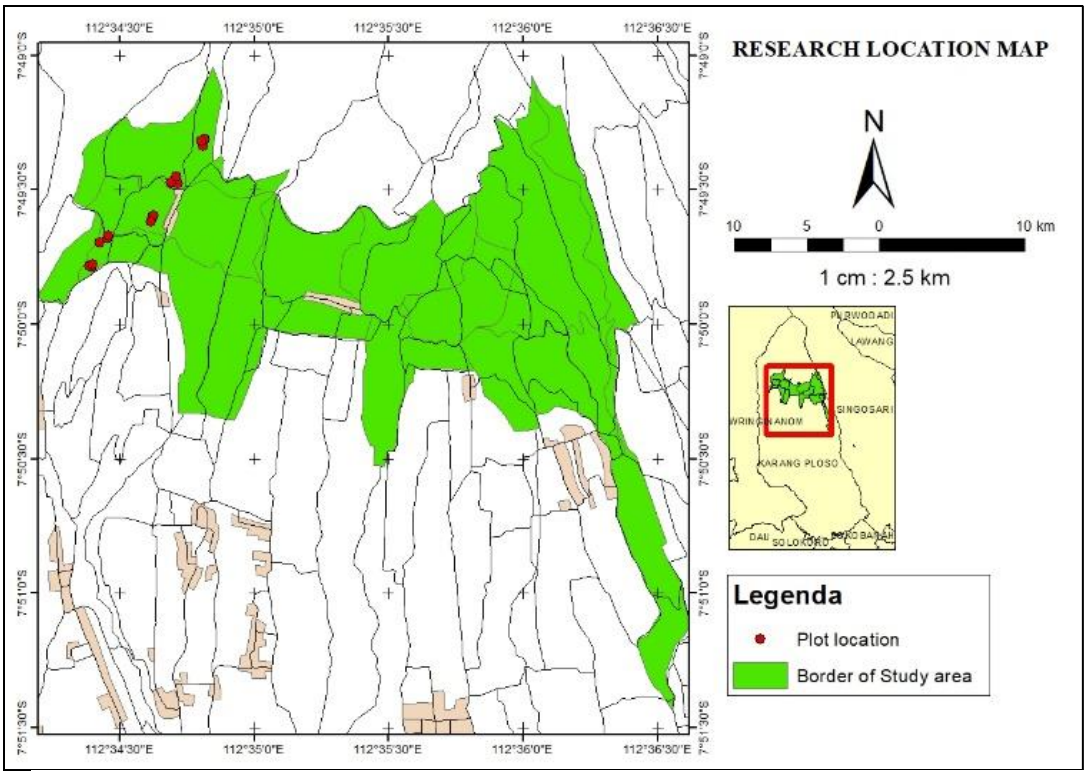

Figure 1. Research Location

Table 1. Description of management intervention (treatment) on research location

Plot	Management Intervention
Without Management (WM)	Pine forest aged 32 years with a tree planting distance of 3 m x 2 m with coffee plants aged 8 years, no management efforts were made,
Management Without Fertilizer (WF)	Pine forest aged 32 years with a tree spacing of 3 m x 2 m with coffee plants aged 8 years, with the intervention of coffee stems being pruned, not fertilized.
Organic Fertilizer Management (OF)	Pine forest aged 32 years with a tree spacing of 3 m x 2 m with coffee plants aged 8 years, with the intervention of coffee stems being pruned, fertilized organic matter at doses around 10 Mg ha^{-1} $year^{-1}$.
Mixed Fertilizer Management (MF)	Pine forest aged 32 years with a tree spacing of 3 m x 2 m with coffee plants aged 8 years, with the intervention of coffee stems being pruned, fertilized organic matter at doses around 10 Mg ha^{-1} $year^{-1}$ and NPK inorganic fertilizers at doses of 100 gram $trees^{-1}$ $year^{-1}$.
Recommended Management (RM)	Pine forest aged 32 years with a tree spacing of 3 m x 2 m with coffee plants aged 8 years, with the intervention of coffee stems being pruned, fertilized organic matter at doses around 10 Mg ha^{-1} $year^{-1}$ NPK inorganic fertilizers at doses of 100 gram $trees^{-1}$ $year^{-1}$ and thinning at 10 years old, so pine trees spacing becomes 6 m x 2 m.

2.2.1 Coffee bean yield production
Calculation of coffee yield production samples used of 20 x 20 m harvest area. The coffee beans were harvested from each tree inside the plot. Then the wet coffee beans were weighed and 100 samples of coffee plants were taken from each research plot to determine the weight of oven-dried beans. The equations used to calculate coffee bean production are as follows [3]:

$$Bean\ water\ content = \frac{wt\ of\ wet\ beans\ (g) - wt\ of\ dry\ bean\ (g)}{wt\ of\ dry\ beans\ (g)}$$

$$Beans\ yield = wt\ of\ wet\ beans - wt\ of\ water\ content$$

2.2.2 Soil water content
Soil samples were measured in the topsoil at a depth of 0-0.2 m. Furthermore, the water content was measured by soil moisture sensor, connected with a data logger within a year. Dynamic soil water content was measured in a six month, from April-September 2022. Data from the sensor has been calibrated using actual data in the field, namely by comparing sensor data with data from direct measurements by using gravimetric method at the same time.

2.3. Data Analysis
The data obtained from the observations was analysed using ANOVA, if the results of variance are significantly different, then proceed with the Fisher's LSD 5% level test. Furthermore, each research variable was be tested for regression and correlation to determine the influence and relationship between variables.

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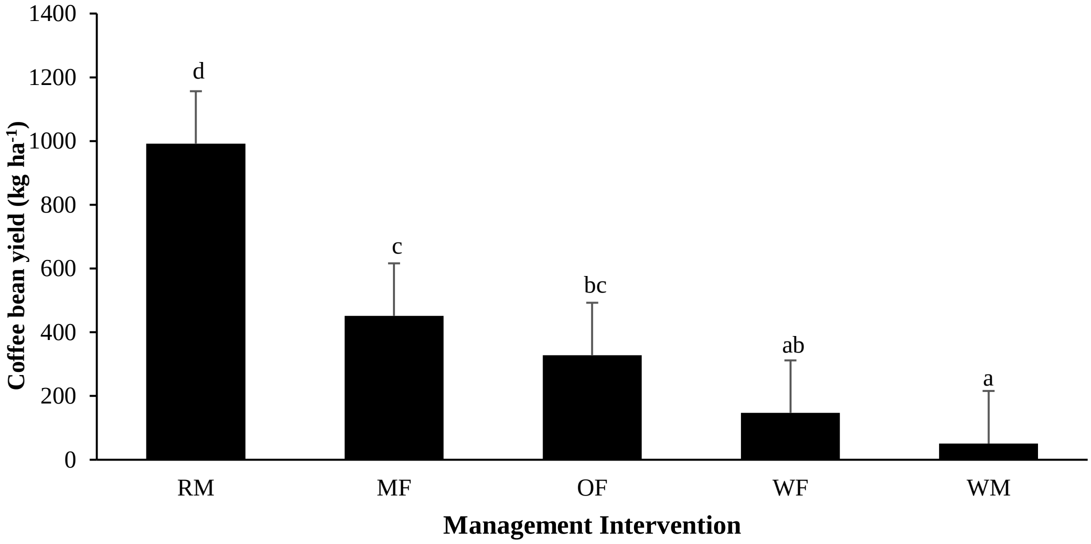

Figure 2. The comparison of coffee bean yield in five coffee-pine agroforestry treatments: recommended management (RM), mixed fertilizer management (MF), organic fertilizer management (OF), without fertilizer (WF), and without management (WM).

3. Result

3.1. Coffee bean yield

The results showed that yield increased significantly ($p<0.05$) in the organic fertilizer (OF), mixed fertilizer (MF), and recommended management (RM) treatments, when compared to the no management (WM) treatment (Figures 2). The highest production yields were obtained in the recommended management treatment (RM), which carried out pruning, organic and inorganic fertilization, and thinning of pine trees with an increase of almost 20 times more than the no management treatment (WM).

3.2. Soil dynamics water

The results showed that there was a significant difference in soil water content ($p<0.05$) in the recommended treatment (RM), when compared to the others management treatment at a depth of 0-0.2 m from April until September (Figure 3). The recommended management treatment tended to have lower water content when compared to all management treatment.

The results also showed that there was a significant negative correlation between soil water content and coffee yield in April (r=0,92); May (r=0,90), June (r=0,66), July (r=0.77), August (r=0.70) and September (r=0,80) (Figure 4).

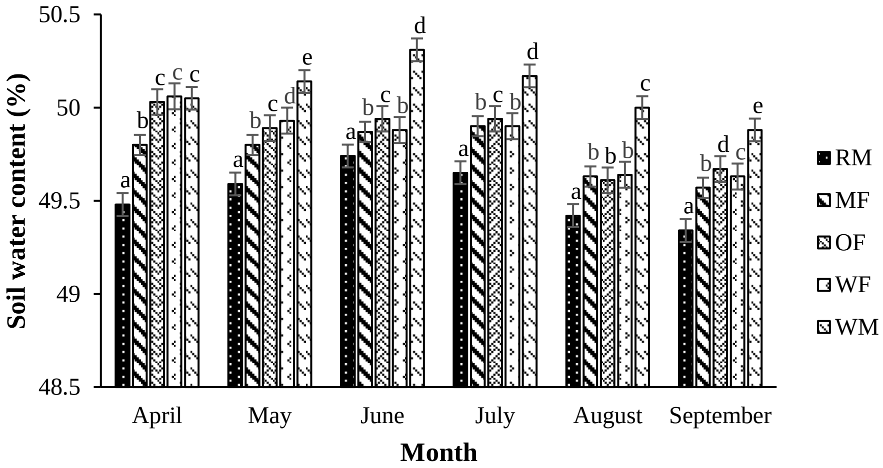

Figure 3. The comparison of soil water content in five different coffee management over six months.

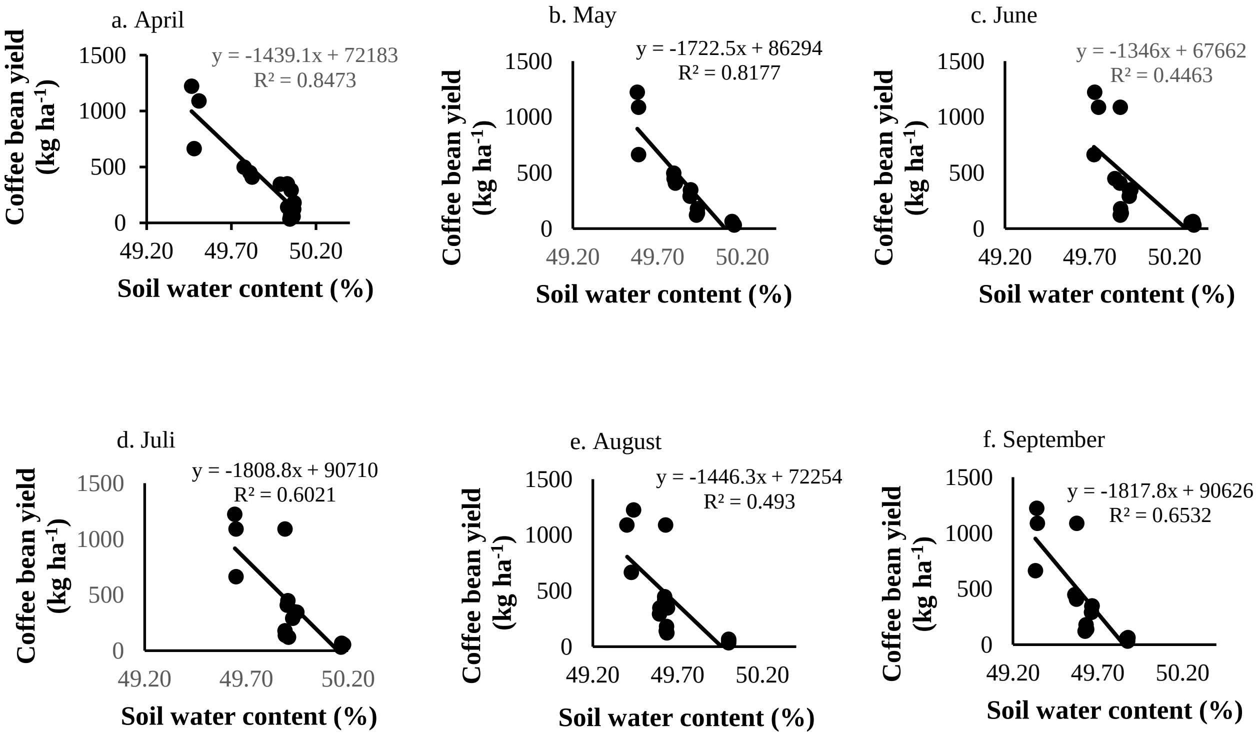

Figure 4. The correlation between soil water content and coffee bean yield for six months a) April; b) May; c) June; d) July; e) August; and f) September

4. Discussion

Differences in agroforestry system management impact on growth rate, coffee production, and soil water content in the system. The results of coffee plant production show that the highest production is in the recommended management (RM), this is due to the management of coffee branch pruning and thinning of pine shade plants which causes optimal light and water entering the agroforestry system. Water content is clearly visible between the treatments. So a soil water dynamic that has been measured in April, May, June, July, August, and September 2022. The recommended management treatment has a lower level of water content when compared to the treatment without management. This is due to differences in the density of shade plants because of tree spacing, where the recommended management has less shade cover, with a planting distance of 6 x 2 m. Less shade cover will result in higher light intensity received by the plants, thus increasing the evapotranspiration rate. The high rate of evapotranspiration that occurs both on the plant and the soil surface will reduce the level of water content and moisture in the soil.

There is a negative correlation between soil moisture content and coffee bean production, Further details are discussed below.

4.1. Soil water dynamic

Cultivating coffee with a shading or agroforestry system will protect coffee plants from extreme microclimatic dynamics. This aims to create optimal growing environmental conditions for coffee plants in the long term [23]. So it is necessary to have the proper agroforestry system management so that microclimate conditions (temperature, soil water content, humidity) can support coffee production optimally [24]. In this study we focused on the dynamics of soil water that occurred in five different managements, of all the existing management conditions, the soil water content was adequate for the needs of coffee plant growth and production, that not less than 30% [15], [25]. The more water content available in the soil, the better the performance of the coffee plant in growing and producing coffee beans [26], [27].

However, it is interesting that, coffee plant production is best obtained from soil conditions with lower water content, despite on the rainy month and dry months. The main reason for this could be that coffee plants tend to be stunted in their growth and production when there is excess water and waterlogging, when the soil water content is more than 50% [15], [28].

In addition, if coffee plants get good management and can produce well, it will cause high demand for water, to help the formation of flowers and ripening of fruit, wich will cause soil moisture conditions to decrease [29], [30]. Fertilizer application and intensifying coffee production often result in higher coffee plant growth and more vigorous growth. This, in turn, increases the water demand of coffee plants. The additional nutrients from fertilizers stimulate plant growth and fruit production, requiring more water to support these processes. As a result, coffee plants draw more water from the soil to meet their increased water demand.

4.2. Coffee development and coffee bean yields

The results of this study indicate that the best management to produce high coffee bean production is recommended management treatment, with management of fertilization, pruning, and thinning of shade plants to 6 x 2 m. This is because the effect of thinning the shade is to provide optimal microclimate conditions [25]. The condition of an agroforestry system that is too dense with shade plants will reduce the intensity of sunlight obtained by cultivated plants, the impact is that coffee plants will experience photosynthetic inhibition [31]. The condition of an agroforestry system that is too dense with shade plants will slow down the process of soil evaporation, thus creating a humid and excess water environment [32]. Humid environmental conditions and excess water will disrupt the physiological processes of the coffee plant, with the loss of flowers when entering the generative phase and fruit rot in the early phase [33].

In addition, pruning on coffee plants will accelerate the generative phase. This is evidenced by when compared to agroforestry systems without management, the condition of stem diameter in agroforestry systems without management tends to be larger. This indicates that the focus of photosynthesis tends to be used for cambium formation rather than flower and fruit formation [33], [34].

5. Conclusion

Coffee bean yields were significantly affected by the different management systems. The combination of pruning and fertilization resulted in the highest coffee bean yields, while the no-management treatment had the lowest coffee bean yield, The combination of pruning and fertilization is a promising management strategy for increasing coffee bean yields in coffee-pine agroforestry systems. We also conclude that the different management systems significantly impacted on soil water dynamics. The no-management treatment had the highest soil water content, while the combination of pruning and fertilization treatment had the lowest soil water content. The consequent better growth of coffee plants has an impact on increasing the extraction of soil water. This study provides valuable insights for farmers and forest managers interested in improving the productivity of coffee-pine agroforestry systems and conserving soil water or sometimes need water addition through irrigation.

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References

[1] Pusat Data dan Informasi Pertanian, “Outlook Komoditas Perkebunan Kopi,” pp. 1–100, 2022.
[2] R. Evizal, “Etno-agronomi Pengelolaan Perkebunan Kopi di Sumberjaya Kabupaten Lampung Barat,” *Agrotrop: Journal on Agriculture Science*, vol. 3, no. 2, pp. 1–12, 2015.
[3] K. A. Sudharta *et al.*, “Soil organic matter and nitrogen in varying management types of coffee-pine agroforestry systems and their effect on coffee bean yield,” *Biodiversitas*, vol. 23, no. 11, pp. 5884–5891, 2022, doi: 10.13057/biodiv/d231142.
[4] J. R. Saragih, “Sistem Usahatani Kopi Arabika Berpelindung sebagai Strategi Konservasi Lahan di Sumatera Utara,” *sarasehan Peringatan Hari Penanggulangan Degradasi Lahan dan Kekeringan se - Dunia*, no. 1992, pp. 1–12, 2017.
[5] A. F. León-Burgos, C. Unigarro, and H. E. Balaguera-López, “Can prolonged conditions of water deficit alter photosynthetic performance and water relations of coffee plants in central-west Colombian?,” *South African Journal of Botany*, vol. 149, pp. 366–375, 2022, doi: 10.1016/j.sajb.2022.06.034.
[6] E. Rahn *et al.*, “Opportunities for sustainable intensification of coffee agro-ecosystems along an altitudinal gradient on Mt. Elgon, Uganda,” *Agric Ecosyst Environ*, vol. 263, no. February, pp. 31–40, 2018, doi: 10.1016/j.agee.2018.04.019.
[7] I. Merle, R. Villarreyna-Acuña, F. Ribeyre, O. Roupsard, C. Cilas, and J. Avelino, “Microclimate estimation under different coffee-based agroforestry systems using full-sun weather data and shade tree characteristics,” *European Journal of Agronomy*, vol. 132, no. August 2020, 2022, doi: 10.1016/j.eja.2021.126396.
[8] M. P. Padovan *et al.*, “Water loss by transpiration and soil evaporation in coffee shaded by Tabebuia rosea Bertol. and Simarouba glauca dc. compared to unshaded coffee in sub-optimal environmental conditions,” *Agricultural and Forest Meteorology*, vol. 248, no. August 2017, pp. 1–14, 2018, doi: 10.1016/j.agrformet.2017.08.036.

[9] B. Yang *et al.*, "Coffee performs better than amomum as a candidate in the rubber agroforestry system: Insights from water relations," *Agricultural Water Management*, vol. 244, no. July 2020, p. 106593, 2021, doi: 10.1016/j.agwat.2020.106593.

[10] V. De Leijster *et al.*, "Ecosystem services trajectories in coffee agroforestry in Colombia over 40 years," *Ecosystem Services*, vol. 48, no. August 2020, p. 101246, 2021, doi: 10.1016/j.ecoser.2021.101246.

[11] J. Kreuzwieser and H. Rennenberg, "Molecular and physiological responses of trees to waterlogging stress," *Plant Cell and Environment*, vol. 37, no. 10, pp. 2245–2259, 2014, doi: 10.1111/pce.12310.

[12] E. Loreti, H. van Veen, and P. Perata, "Plant responses to flooding stress," *Current Opinion in Plant Biology*, vol. 33, pp. 64–71, 2016, doi: 10.1016/j.pbi.2016.06.005.

[13] M. A. Else, J. M. Taylor, and C. J. Atkinson, "Anti-transpirant activity in xylem sap from flooded tomato (Lycopersicon esculentum Mill.) plants is not due to pH-mediated redistributions of root- or shoot-sourced ABA," *Journal of Experimental Botany*, vol. 57, no. 12, pp. 3349–3357, 2006, doi: 10.1093/jxb/erl099.

[14] J. Rodríguez-Gamir, G. Ancillo, M. C. González-Mas, E. Primo-Millo, D. J. Iglesias, and M. A. Forner-Giner, "Root signalling and modulation of stomatal closure in flooded citrus seedlings," *Plant Physiology and Biochemistry*, vol. 49, no. 6, pp. 636–645, 2011, doi: 10.1016/j.plaphy.2011.03.003.

[15] M. A. Toral-Juárez *et al.*, "Drought-tolerant coffee plants display increased tolerance to waterlogging and post-waterlogging reoxygenation," *Environmental and Experimental Botany*, vol. 182, no. October 2020, 2021, doi: 10.1016/j.envexpbot.2020.104311.

[16] P. E. M. Silva, P. C. Cavatte, L. E. Morais, E. F. Medina, and F. M. DaMatta, "The functional divergence of biomass partitioning, carbon gain and water use in Coffea canephora in response to the water supply: Implications for breeding aimed at improving drought tolerance," *Environmental and Experimental Botany*, vol. 87, pp. 49–57, 2013, doi: 10.1016/j.envexpbot.2012.09.005.

[17] D. F. López-Bravo, E. de M. Virginio-Filho, and J. Avelino, "Shade is conducive to coffee rust as compared to full sun exposure under standardized fruit load conditions," *Crop Protection*, vol. 38, pp. 21–29, 2012, doi: 10.1016/j.cropro.2012.03.011.

[18] T. N. Nath, "Soil texture and total organic matter content and its influences on soil water holding capacity of some selected tea growing soils in Sivasagar district of Assam, India," *International Journal of Chemical Sciences*, vol. 12, no. 4, pp. 1419–1429, 2014.

[19] A.Vengadaramna and P. T. J. Jashothan, "Effect of organic fertilizers on the water holding capacity of soil in different terrains of Jaffna peninsula in Sri Lanka," *Journal of Natural Product and Plant Resources*, vol. 2, no. 4, pp. 500–503, 2011.

[20] B. De Vos, M. Van Meirvenne, P. Quataert, J. Deckers, and B. Muys, "Predictive Quality of Pedotransfer Functions for Estimating Bulk Density of Forest Soils," *Soil Science Society of America Journal*, vol. 69, no. 2, pp. 500–510, 2005, doi: 10.2136/sssaj2005.0500.

[21] W. M. Cornelis, M. Khlosi, R. Hartmann, M. Van Meirvenne, and B. De Vos, "Comparison of Unimodal Analytical Expressions for the Soil-Water Retention Curve," *Soil Science Society of America Journal*, vol. 69, no. 6, pp. 1902–1911, 2005, doi: 10.2136/sssaj2004.0238.

[22] S. L. Herron, A. N. Sharpley, K. R. Brye, and D. M. Miller, "Optimizing Hydraulic and Chemical Properties of Iron and Aluminum Byproducts for Use in On-Farm Containment Structures for Phosphorus Removal," *Journal of Environmental Protection*, vol. 07, no. 12, pp. 1835–1849, 2016, doi: 10.4236/jep.2016.712146.

[23] A. Sarmiento-Soler *et al.*, "Effect of cropping system, shade cover and altitudinal gradient on coffee yield components at Mt. Elgon, Uganda," *Agriculture, Ecosystems and Environment*, vol. 295, no. March, p. 106887, 2020, doi: 10.1016/j.agee.2020.106887.

[24] D. Suprayogo *et al.*, "Tree and plant interactions in the agroforestry system : does the management of coffee intensification disrupt the soil hydrological system and pine growth ? Tree and plant interactions in the agroforestry system : does the management of coffee intensific," 2020, doi: 10.1088/1755-1315/449/1/012045.

[25] F. M. Damatta, R. T. Avila, A. A. Cardoso, S. C. V. Martins, and J. C. Ramalho, "Physiological and Agronomic Performance of the Coffee Crop in the Context of Climate Change and Global Warming: A Review," *Journal of Agricultural and Food Chemistry*, vol. 66, no. 21, pp. 5264–5274, 2018, doi: 10.1021/acs.jafc.7b04537.

[26] E. Rahn *et al.*, "Opportunities for sustainable intensification of coffee agro-ecosystems along an altitudinal gradient on Mt. Elgon, Uganda," *Agriculture, Ecosystems and Environment*, vol. 263, no. February, pp. 31–40, 2018, doi: 10.1016/j.agee.2018.04.019.

[27] F. Zhao *et al.*, "An increase in intercropped species richness improves plant water use but weakens the nutrient status of both intercropped plants and soil in rubber–tea agroforestry systems," *Agricultural Water Management*, vol. 284, no. May, p. 108353, 2023, doi: 10.1016/j.agwat.2023.108353.

[28] C. Rigal, J. Xu, G. Hu, M. Qiu, and P. Vaast, "Coffee production during the transition period from monoculture to agroforestry systems in near optimal growing conditions, in Yunnan Province," *Agricultural Systems*, vol. 177, no. August 2019, p. 102696, 2020, doi: 10.1016/j.agsy.2019.102696.

[29] M. Baca, P. Läderach, J. Haggar, G. Schroth, and O. Ovalle, "An integrated framework for assessing vulnerability to climate change and developing adaptation strategies for coffee growing families in mesoamerica," *PLoS ONE*, vol. 9, no. 2, 2014, doi: 10.1371/journal.pone.0088463.

[30] R. Horn, "Time Dependence of Soil Mechanical Properties and Pore Functions for Arable Soils," *Soil Science Society of America Journal*, vol. 68, no. 4, pp. 1131–1137, 2004, doi: 10.2136/sssaj2004.1131.

[31] M. Díaz-Zorita and J. H. Grove, "Duration of tillage management affects carbon and phosphorus stratification in phosphatic Paleudalfs," *Soil and Tillage Research*, vol. 66, no. 2, pp. 165–174, 2002, doi: 10.1016/S0167-1987(02)00024-7.

[32] H. Marrou, L. Guilioni, L. Dufour, C. Dupraz, and J. Wery, "Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels?," *Agricultural and Forest Meteorology*, vol. 177, pp. 117–132, 2013, doi: 10.1016/j.agrformet.2013.04.012.

[33] P. Vaast, J. Angrand, N. Franck, J. Dauzat, and M. Génard, "Fruit load and branch ring-barking affect carbon allocation and photosynthesis of leaf and fruit of Coffea arabica in the field," *Tree Physiology*, vol. 25, no. 6, pp. 753–760, 2005, doi: 10.1093/treephys/25.6.753.

[34] B. P. Dufour, I. W. Kerana, and F. Ribeyre, "Effect of coffee tree pruning on berry production and coffee berry borer infestation in the Toba Highlands (North Sumatra)," *Crop Protection*, vol. 122, no. May, pp. 151–158, 2019, doi: 10.1016/j.cropro.2019.05.003.