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Research Article

Optimizing coffee yields in agroforestry systems using WaNuLCAS model: A case study in Malang, Indonesia

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Abstract

Agroforestry systems have significant potential for development in increasing coffee production in Indonesia. Besides providing economic benefits, agroforestry can also have ecological impacts, such as improving soil structure, reducing erosion, and other environmental services. There is a complex interaction between trees, soil, and crops in agroforestry systems, making modeling a valuable approach to unraveling these processes. We utilized the spatial and temporal explicit model WaNuLCAS to (i) evaluate the model's performance in depicting actual events (through coffee production and soil water content), (ii) assess the dynamic processes influencing coffee production and the environmental impact of management patterns, (iii) formulate and simulate optimal scenarios for coffee production optimization. Data from a one-year period involving five agroforestry management patterns for coffee-pine in UB Forest were used as input for the model. The model validation results showed satisfactory and acceptable outcomes for coffee production and groundwater dynamics. WaNuLCAS simulation results indicated that pruning and thinning management are crucial factors in increasing coffee production and are related to creating optimal conditions for coffee plants (light, humidity, and inter-plant competition). Additionally, fertilization management can be combined as a supporting factor to meet the nutritional needs of coffee plants. WaNuLCAS simulation results also suggested that pruning and thinning can improve soil physical properties, but thinning increases surface runoff within the system. This research provides insights into how modeling can be used as a decision-making tool.

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Introduction

The Food and Agriculture Organization of the United Nations (FAO) stated that Indonesia was the fourth largest coffee producer in the world in 2018, with production of 700,000 t, and contributes to 8% of global coffee production (Putri et al., 2018; Septiani and Kawuryan, 2021). Of this amount, it is estimated that about 70% is produced under agroforestry systems in forest areas (FAO and UNEP, 2020). However, the coffee commodity production sector in Indonesia is experiencing a declining trend, with an average annual production decrease of 1.42%. Inappropriate land management practices are identified as one of the factors contributing to this decline. Coffee cultivation in Indonesia is mainly conducted within agroforestry systems in forest areas, employing either simple or multistrata (complex) patterns. Hence, there is a need for proper management to achieve optimal production results and environmental services (Evizal, 2015; Rijal et al., 2019). Coffee cultivation within agroforestry systems offers both economic and ecological benefits (Sudharta et al., 2022). Agroforestry systems based on coffee-pine not only yield coffee beans but also have the potential to enhance ecological processes, such as nutrient and water cycles and energy flow (Saragih, 2017; Sudharta et al., 2022). Additionally, the multistrata concept in coffee-pine agroforestry is considered an effective conservation system (Kraft et al., 2021). The economic and ecological advantages of agroforestry systems often clash with farmers' limited knowledge of coffee cultivation within agroforestry systems, resulting in empirical development (Suyadi et al., 2018; Rimbawan et al., 2021). These challenges lead to suboptimal agroforestry system management and a subsequent decline in coffee production levels.

Efforts to optimize coffee production within agroforestry systems have been reported successful in increasing coffee yields. Optimization management practices, such as plant population control, fertilization, tree pruning, and organic matter addition, have been applied in various research locations (Sakai et al., 2015; Sarmiento-Soler et al., 2020) stated that a spacing of 1.6 m x 1 m between coffee plants and 5 m x 3 m between shade trees optimized edaphoclimatic factors (i.e., sunlight reception and soil moisture conditions), resulting in a 15% increase in coffee production (Suyadi et al., 2018). Moreover, pruning and organic matter application impact coffee productivity, triggering the formation of productive branches while reducing the impact of pest and disease attacks. Pruning also aids in providing additional organic matter above the soil surface, serving as organic mulch to suppress weeds conventionally, maintain soil temperature, and preserve soil moisture conditions (Sileshi et al., 2014; Staver et al., 2020; Kawabata et al., 2021).

Modeling is an alternative for optimizing the overall operational management potential of agriculture for better decision-making (Kouadio et al., 2021). Modeling assists in designing, planning, and evaluating applied agroforestry systems. Agroforestry system modeling can be achieved through dynamic plant modeling concepts (Hussain et al., 2016). Dynamic plant modeling is useful for assessing the long-term effects of a complex system, integrating both biophysical and socio-economic components (Hussain et al., 2016). Furthermore, plant-based dynamic modeling has been developed to understand the dynamic processes influenced by weather and nutrition, facilitating the simulation of interactions between components such as soil, water, plants, light, and management practices (Kouadio et al., 2021; Chitsiko et al., 2022). Modeling provides a better understanding of the processes and interactions among soil, water, and plants in the long term (Wang et al., 2022; Boote et al., 2023). The use of models in research is crucial for testing new technologies, understanding climate change factors, decision-making determinants, and as a cost-effective alternative to long-term field experiments (Wijayanto et al., 2022; Zewdie et al., 2022; Chen et al., 2023).

The WaNuLCAS model (Water, Nutrient, Light Capture in Agroforestry Systems) is a plant-based model developed to depict the dynamics and interactions among trees, crops, light, and soil at plot and field scales (Hussain et al., 2016; Onsamrarn et al., 2020). WaNuLCAS can simulate interactions among trees, crops, and soil with four lateral zones and four soil depths. Hussain et al. (2016) used WaNuLCAS to assess conservation efforts on sloping land and their impact on maize productivity. Additionally, WaNuLCAS has been utilized to estimate nutrient leaching rates, runoff rates, soil structure, and erosion rates at various levels of land cover and shade in tropical ecosystems (Cahyo et al., 2016; Onsamrarn et al., 2020; Kraft et al., 2021). However, the use of WaNuLCAS for predicting coffee production levels under various agroforestry system management combinations (e.g., plant-tree spacing, fertilization, pruning, and organic matter addition) has not been reported.

This research aimed to a) evaluate the ability and efficiency of the WaNuLCAS model in depicting actual events, b) use the model to assess dynamic processes influencing coffee production levels, and c) use the model to formulate the best agroforestry system management scenarios to enhance coffee production.

Materials and Methods

Study site

This research was conducted from June to December 2022, located in the Special Purpose Forest Area of Brawijaya University (KHDTK-UB) or UB Forest, in Malang, East Java. The elevation of the research location ranges from 900 to 1100 meters above sea level (m asl), with an average annual air temperature of 21.9°C and an annual rainfall of 4,725 mm. UB Forest has been identified as having Andisols as the soil order. The research location is presented in (Figure 1). Laboratory analysis was carried out at the Soil Physics Laboratory of Brawijaya University.

Research design and data collection

This study was conducted using a survey method in five different agroforestry management interventions in the UB Forest production forest area. Sampling was conducted by random purposive sampling in the form of five different management interventions (fertilization, pruning, and thinning), with repetition three times on the same management intervention in different locations (Table 1), with a plot size of 20 x 20 m. Next, select and measure the parameters to be used in the WaNuLCAS model simulation in accordance with the research objectives. The measurements, indicators, and variables measured were soil water content, soil texture, soil bulk density, diameter breast height (DBH) as coffee plant growth, and yields due to different management. These data were also used for parameterization, calibration, validation, and testing of the WaNuLCAS model.

Sampling was conducted in each plot with three replicates at each sampling point, resulting in a total of 15 sampling points. Random purposive sampling was conducted on soil samples with a depth of 0-10 cm. Water content measurements were carried out at a depth of 0-0.2 m in each observation plot using a sensor logger that has been installed in each plot for six months (April-September 2022); the sensor measurement data were used to validate the WaNuLCAS model. Samples of coffee growth and production were conducted by inventorying DBH (Diameter Breast Height) and harvesting the entire population of coffee plants in a 20 x 20 m plot area. Harvesting was carried out in stages (a total of 4 harvests) until the ripe coffee fruit was harvested, weighed, and converted in units of hectares.

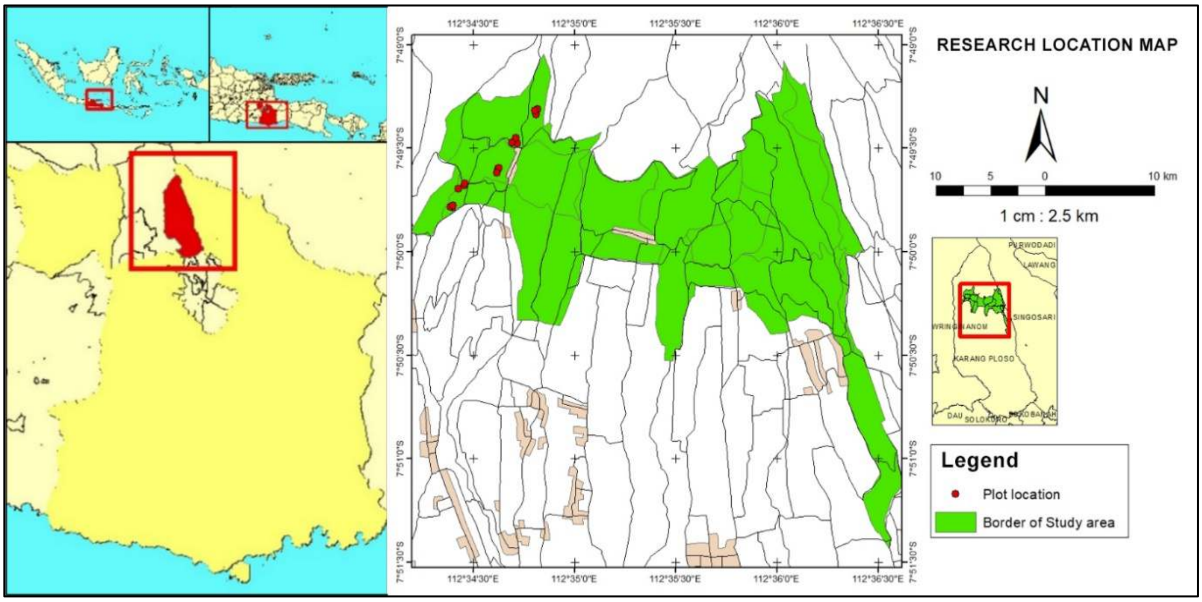


Figure 1. Research site.

Table 1. Description of management intervention on research location.

Plot	Management Intervention
Without Management (WM)	Pine forest aged 41 years with a tree planting distance of 3 m x 2 m with coffee plants aged 11 years, no management efforts were made.
Management Without Fertilizer (WF)	Pine forest aged 41 years with a tree spacing of 3 m x 2 m with coffee plants aged 11 years, pruned, not fertilized, or thinned.
Organic Fertilizer Management (OF)	Pine forest aged 41 years with a tree spacing of 3 m x 2 m with coffee plants aged 11 years, pruned, fertilized organic matter, and not thinned.
Mixed Fertilizer Management (MF)	Pine forest aged 41 years with a tree spacing of 3 m x 2 m with coffee plants aged 11 years, pruning, fertilizing organic matter and inorganic fertilizers, and not thinning.
Recommended Management (RM) by Perhutani	Pine forest aged 41 years with a tree spacing of 3 m x 2 m with coffee plants aged 11 years, routine pruning, organic and inorganic fertilization, and thinning so that the spacing of pine trees becomes 6 m x 2 m.

Soil analysis that was carried out included analysis of bulk density, texture, and soil organic matter. The gravimetric method was used to analyze soil bulk density (Blake and Hartge, 1986), the Walkley and Black method was used to analyze soil organic matter (Walkley and Black, 1934), and the pipette method was used to analyze soil texture (Blake and Hartge, 1986).

WaNuLCAS model structure and input data

WaNuLCAS describes tree, soil, and crop interactions in agroforestry systems where trees and crops overlap and compete in space and time (Cahyo et al., 2016; Onsamrarn et al., 2020). These interactions can be simulated with the WaNuLCAS model in four lateral zones at the soil surface (horizontally) and four soil layers (vertically). The WaNuLCAS model structure can describe the conditions of competition between plants both above and below the soil surface based on factors that affect plant growth, for example, water availability, nutrient availability (N and P), and light capture by plants on a broad space and time scale. The four lateral zones (horizontally) represent management conditions such as monoculture, polyculture, intercropping, agroforestry, hedgerows, fallow, and others. These four lateral zones can be arranged based on the level of plant spacing and the type of crop planted; for example, shade crops (pine) are planted within zone 1, then cultivated crops (coffee) are planted within zones 2, and 3, such as in plots WM, WF, OF, and MF with a distance of 1 m (Figure 2) or coffee is planted in zones 2 and 3 with a distance between pine-coffee plants of 2 m and a distance between coffee-coffee plants of 1 m (Figure 3).

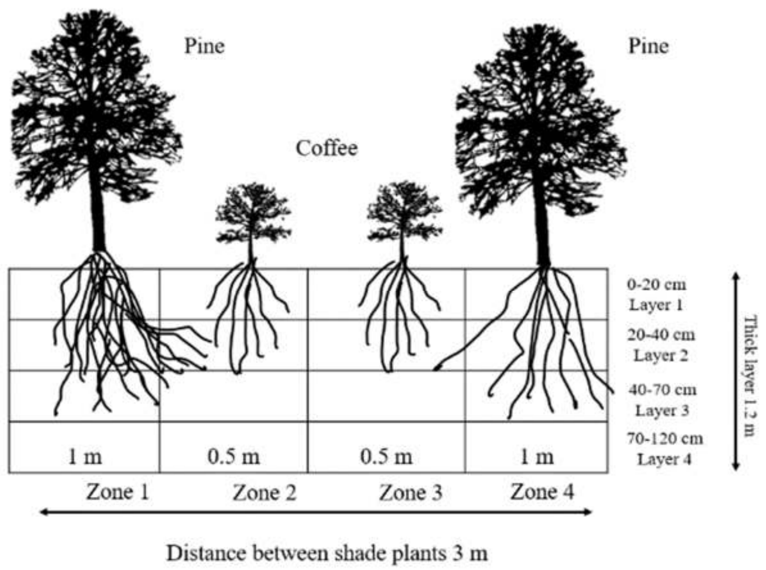


Figure 2. The model settings are based on the actual conditions of the research applied in the WM, WF, OF, and MF plots.

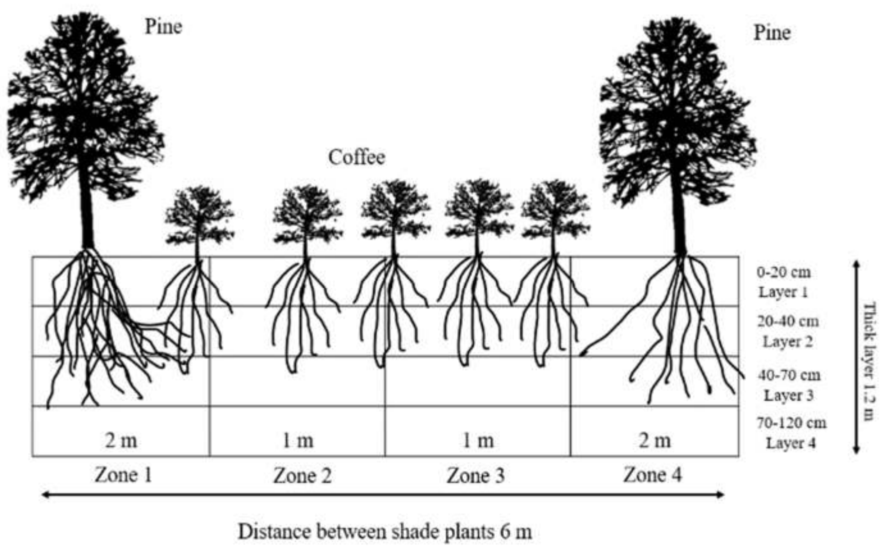


Figure 3. The model settings are based on the actual research conditions applied in RM plots.

With such arrangements, it is possible to regulate the level of competition between crops to represent different management patterns. In addition, the four soil layers (vertically) make it possible to see the effect of the level of competition present in the soil between zones at different depths (layers). The distance between zones can be adjusted according to the actual conditions of the study or based on recommended scenarios.

WaNuLCAS is based on the Stella application linked to Microsoft Excel for input and output processing (Hussain et al., 2016; Onsamrarn et al., 2020). The Stella application is open source so that users can customize and calibrate the WaNuLCAS model. The principles and processes in agroforestry systems are described separately by each module, for example, climate inputs, nutrient balance, water balance, erosion processes, runoff processes, soil organic matter dynamics, tree and plant growth, pedotransfer, light reception, and others.

This study focussed on the water balance, growth, and crop production modules. All simulations in this study used WaNuLCAS 4.0 and Stella version 7.0.3 models to explore the effect of agroforestry system management (spacing, fertilization, pruning, and litter addition) on coffee production. Plant production levels are influenced by water availability, nutrient availability, and optimal light reception. Water and nutrient availability are influenced by water balance and nutrient balance. In this modeling, the output that is run in the model is the total moisture content in the soil or in the model with the output code "BW_StockTot" and the total tree biomass above the surface or in the model with the output code "T_Biom". In the process, the water and nutrient balance is influenced by the soil conditions in each layer. The WaNuLCAS model simulates the soil component as a pedotransfer process in the model based on the van Genutchen equation (Hussain et al., 2016).

Plant growth and development factors were simulated with WaNuLCAS on a continuous basis (daily basis simulation) under the influence of three main factors, namely light, water, and nutrients (N and P).

WaNuLCAS model calibration and validation

The WaNuLCAS model is calibrated using a one-year field data set (for climatic conditions) obtained from the Karangploso climatology station, Malang, East Java, as well as several other components in accordance with actual conditions in the field, with the aim that the expected output results match actual conditions. Some of the components calibrated in the WaNuLCAS model include the following (Table 2). After calibration, a running test model was conducted with five management intervention scenarios according to those in the field; then, to validate the model output, a comparison was made between observational data in the field and data from the running test model. The data used for model validation in this study were observational data on the dynamics of soil moisture content and coffee production in five different management interventions.

Table 2. Description of WaNuLCAS parameters, default values, and modified values used for model calibration.

Parameters in the WaNuLCAS Model	Default value	Modification value	Description
Zone width	0	Adjusted to the distance between coffee and pine plants in each observation plot.	Apply the scenario conditions that exist in the field.
Tree position across the zone	0	Tree species 1 (pine) is set in zone 1, and tree species 2 (coffee) is set in zone 4.	Apply the plant position according to the scenario in the field.
Tree position within the zone	0	The pine position is located to the left of the zone (value 0), and the coffee position is located to the right of the zone (value 1) in all plot scenarios.	Apply the plant position according to the scenario in the field.
Tree density	0	Adjusted to the population density of each plant in an area of 1 ha.	Apply the number of plants according to the scenario in the field.
Soil layer thickness	0	The entire soil thickness is 1.2 m set with depths of 0.2 m in layer 1; 0.2 m in layer 2; 0.4 m in layer 3; and 0.4 m in layer 4.	Optimal depth conditions for pine and coffee growth.
Amount of rain per day (weather)	0	Adjusted for 1 year of rainfall in 2022.	The amount of rain affects the condition of the water in the soil.
Bulk density, silt, dan clay	0	Adjusted according to field observations (each plot).	Soil properties influences pedotransfer processes that affect soil water dynamics and crop production.
Year of planting and day of planting	100	0 and based on Julian Day	To set the time to be simulated in the model.
T WoodBiomInit	0	Conversion from DBH value to Dry weight (DW) with the equation (1-2) DW Coffee = 0.281 x $DBH^{2.06}$ …(1) DW Pine = 0.0417 x $DBH^{2.6576}$… (2) (Suprayogo et al., 2020).	To determine the actual age of the plants when performing model simulations.

Data analysis

Correlation and regression analyses were conducted to evaluate the observations using the WaNuLCAS model results. In addition, model evaluation analysis was conducted using the Goodness of Fit (GoF) model fit indicator. This procedure was proposed by Loague and Green (1991), with a graphical representation of quantiles or Q-Q that was used to compare coffee production results and moisture content dynamics observed in the field with model simulation results; this is for model validation and to show whether the model is representative of actual conditions in the field or not. The mathematical equations are as follows (Equations 3-6).

$$\text{Model efficiency (EF)} = \left(\sum_{i=1}^{n}(Oi - \bar{O})^2 - \sum_{i=1}^{n}(Pi - Oi)^2\right)/\sum_{i=1}^{n}(Oi - \bar{O})^2 \quad \text{.......... (3)}$$

$$\text{Root mean square error (RMSE)} = \left[\sum_{i=1}^{n}(Pi - \bar{O})^2/n\right]^{0.5} x \frac{100}{\bar{O}} \quad \text{.......... (4)}$$

$$\text{Maximum error (ME)} = \text{Max}|Pi - Oi|_{i=1}^{n} \quad \text{.......... (5)}$$

$$\text{Coefficient of Residual Mass (CRM)} = \left(\sum_{i=1}^{n} Oi - \sum_{i=1}^{n} Pi\right)/\sum_{i=1}^{n} Oi \quad \text{.......... (6)}$$

Oi is the observed value, *Pi* is the predicted value, n is the number of observations or samples and $\bar{O}$ is the average of the observed values. Good model performance is indicated by EF, RMSE, ME, and CRM values as close as possible to 1, 0, 0, and 0, respectively.

Model simulation

Model simulation is carried out if the model is valid based on the results of statistical analysis. The purpose of the model simulation is to run the model with various scenarios of coffee cultivation management intervention to determine the best management scenario intervention that optimizes coffee production. The scenarios of coffee cultivation management intervention simulated in the WaNuLCAS model are presented in Table 3.

Table 3. Patterns of coffee cultivation scenarios in agroforestry systems to be simulated in the WaNuLCAS model.

Management Intervention Scenario	Description
Management of pine pruning once a year.	1. Coffee plant spacing of 2x1 m. 2. Pine plant spacing 3x2 m. 3. Pruning pine crowns with: a. 10% pruning (P10) b. 30% pruning (P30) c. 50% pruning (P50)
Management of pine pruning once a month.	1. Coffee plant spacing of 2x1 m. 2. Pine plant spacing 3x2 m. 3. Pruning pine crowns with: a. 10% pruning (P10R) b. 30% pruning (P30R) c. 50% pruning (P50R)
Fertilizer management.	1. Coffee plant spacing of 2x1 m. 2. Pine plant spacing 3x2 m. 3. Fertilization management with: a. N fertilization 80 kg ha^{-1} $year^{-1}$, with an interval of 40 kg ha^{-1} at the end of the rainy season, and 40 kg ha^{-1} at the beginning of the rainy season (N). b. N fertilization 80 kg ha^{-1} $year^{-1}$ and manure 5 t ha^{-1} $year^{-1}$ (NO).
Shade spacing management.	1. Coffee plant spacing of 2x1 m. 2. Pine plant spacing with: a. Spacing of pines to 6x2 m without fertilization (T). b. Spacing of pines to 6x2 m and fertilized with 80 kg ha^{-1} $year^{-1}$ N (TN). c. Spacing of pines to 6x2 m, fertilized with N 80 kg ha^{-1} $year^{-1}$ and manure 5 t $ha^{-1}$$year^{-1}$ (TNO). d. Spacing of pines to 6x2 m, fertilized with N 80 kg ha^{-1} $year^{-1}$, manure 5 t ha^{-1} $year^{-1}$, and pruned 30% every month (TNOP).

WaNuLCAS model validation

After the parameterization and calibration process, the model validation was carried out, WaNuLCAS simulated five patterns of coffee cultivation management interventions in the agroforestry system in UB Forest. The model output used to validate the model is the output of soil water dynamics (BW_StockTot) and total coffee plant biomass (T_Biom), then converted into wet coffee bean production results with Equation 7.

$$\text{Coffee bean yield}\left(\frac{\text{kg}}{\text{ha}}\right) = \left(\frac{\text{DWx10}}{0.4}\right)\text{x}2.04 + 160 \qquad (7)$$

Results and Discussion

WaNuLCAS model performance

The results of the comparison between the moisture content of field observations and the moisture content of the WaNuLCAS model simulation results for three years and analyzed by Goodness of Fit (GoF) show that the WaNuLCAS model is able to simulate the dynamics of water in the soil quite accurately, with model efficiency (EF) ranging from 0.71-0.88 with a correlation coefficient level of 0.75-0.88 (Table 4), while the ability of the WaNuLCAS model to model coffee production is very accurate, with a model efficiency level of 0.99 and a correlation coefficient of 0.99 (Table 4). Based on the results of GoF analysis and simple regression-correlation, it shows that the WaNuLCAS model is able to simulate the processes that occur in agroforestry systems, especially in the research location, namely UB Forest, well and acceptable, with a tendency to overestimate or exceed the actual conditions in the field. This is because the model efficiency level (EF) ranges from 0.71 to 0.88 for the dynamics of water content and 0.99 for production; these values are categorized that the model simulation results are acceptable, while the results of regression-correlation analysis show that the coefficient of determination (R^2) ranges from 0.75-0.88 for soil water dynamics, and 0.99 for coffee production. EF values close to 1 indicate a satisfactory relationship between model simulation results and field observations, and R^2 values greater than 0.5 indicate that the model simulates results well (García de Jalón et al., 2018; Onsamrarn et al., 2020). Regression-correlation analysis not only illustrates the fit of values between observations and modeling results but also, through scatter plots, can show the similarity of trends between observations and modeling (Hussain et al., 2016).

Table 4. Model performance statistics for soil water dynamics in five coffee cultivation management intervention patterns in agroforestry systems and coffee production yield.

	RM	WM	WF	OF	MF	Coffee bean yield	Optimum
N	136	136	136	136	136	15	-
RMSE	0.71	0.58	0.74	0.49	0.72	0.50	0
EF	0.72	0.82	0.78	0.88	0.77	0.99	1
CD	3.53	5.66	4.55	8.66	4.35	295.54	1
ME	1.63	1.99	2.05	1.27	1.83	29.10	0
CRM	0.002	0.002	0.002	0.001	0.002	0.011	0
R^2	0.75	0.85	0.80	0.88	0.78	0.99	1

Remarks: N = Number of observations; ME = Maximum Error; RMSE = Root Mean Square Error; CD = Coefficient of Determination; EF = Modeling Efficiency; CRM = Coefficient of Mass Residual; R^2 = Correlation Coefficient; RM = Recommended Management by Perhutani; WM = Without Management; WF = Management Without Fertilizer; OF = Organic Fertilizer Management; MF= Mixed Fertilizer Management.

Management of coffee-pine-based agroforestry through WaNuLCAS model simulation

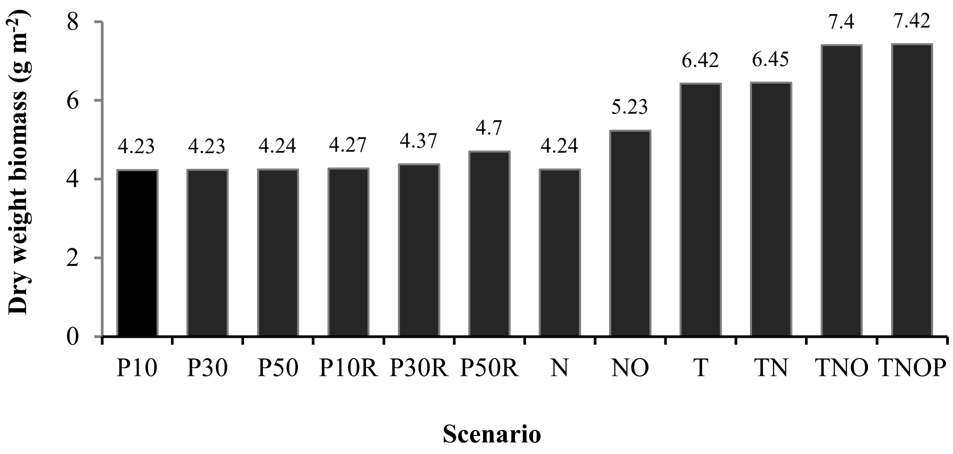
The development of coffee-pine-based agroforestry system management with the WaNuLCAS model through scenarios of a) pruning once a year, b) routine pruning once a month, c) fertilization, and d) thinning, with scenario schemes described in Table 3. Through the WaNuLCAS model, this study analyzed these scenarios by comparing the production outputs and environmental returns of the scenarios. Further details of the model outputs are discussed below.

Biomass and coffee bean yield

The simulation results of the WaNuLCAS model showed that routine monthly pine pruning increased coffee plant biomass (Figure 4a) and coffee bean production (Figure 4b) by an average of 1.5% compared to once-a-year pine pruning. Pruning pine routinely every month had a positive impact on biomass and coffee bean production with increasing percentage of pruning, increasing 0.5% with 10% monthly pruning (P10R), 1.5% with 30% monthly pruning (P30R), and 3.1% with 50% monthly pruning (P50R) compared to 10% pine pruning once a year (P10) (Figures 5a and 5b).

The addition of N fertilizer did not increase biomass and coffee bean yield compared to the 10% pine pruning once a year (P10) treatment; thinning pine plants (T) were able to increase 52%, with the combination of fertilization and pruning (TNOP) increasing 75% biomass and coffee bean yield compared to 10% pine pruning once a year (P10) (Figures 4a and 4b).

a.



b.

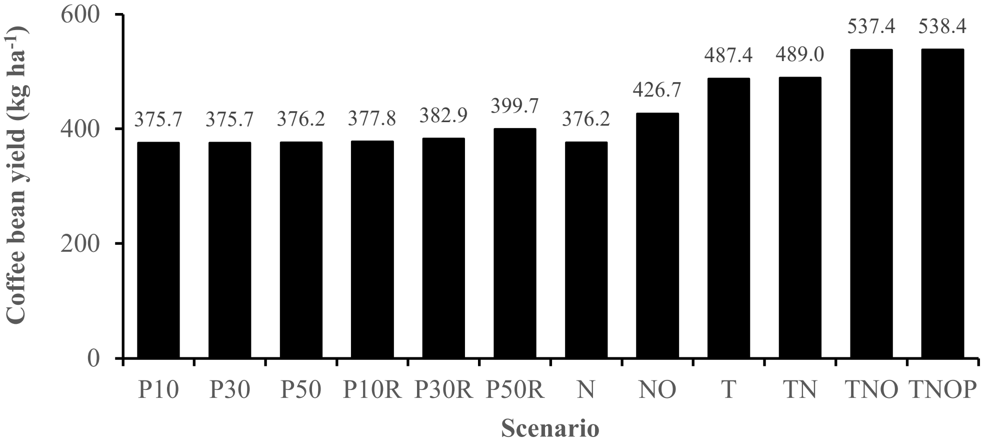


Figure 4. (a) Coffee plant biomass and (b) coffee bean yield in coffee-pine based agroforestry pine pruning once a year with 10% (P10) compared to 30% (P30) and 50% (P50) pruning; pine pruning once a month with 10% (P10R), 30% (P30R) and 50% (P50R) pruning; 80 kg ha^{-1} $year^{-1}$ N fertilization was applied twice 40 kg ha^{-1} at the end of the rainy season and 40 kg ha^{-1} at the beginning of the rainy season (N) and 80 kg ha^{-1} $year^{-1}$ N + 5 t ha^{-1} $year^{-1}$ manure (NO); pine spaced from 3 m x 2 m to 6 m x 2 m (T); pine spaced + 80 kg ha^{-1} $year^{-1}$ N fertilization (TN); pine spaced + 80 kg ha^{-1} $year^{-1}$ N fertilization + 5 t ha^{-1} $year^{-1}$ manure (TNO), and pine spaced + 80 kg ha^{-1} $year^{-1}$ N fertilization + 5 t ha^{-1} $year^{-1}$ manure + pine pruned 30% every month (TNOP)

Combined management of routine pruning once a month, thinning or spacing of shade plants, and fertilization (TNOP) positively affected biomass yield and coffee bean production when compared to the management pattern of pruning once a year with various percentages without thinning (P10, P30, and P50), coffee requires appropriate environmental conditions to produce coffee beans. Regular pruning of shade plants will maintain moisture and light intensity in the system (Chatterjee et al., 2018), maintaining optimal environmental conditions for coffee plants will optimize the photosynthesis process, optimizing the photosynthesis process will increase the formation of biomass and coffee beans (Valencia et al., 2014). Coffee plants produce optimally with a shade density between 50-60% (Saputra et al., 2018). In addition to reducing the level of shade density in coffee plant cultivation through pruning, the option of thinning pine plants can also be done to reduce shade density in coffee plant cultivation; the optimal shade condition for coffee plants is with a crown density of 35-50% or with a distance between shade plants of 3x5 m (Firmansyah et al., 2023; Lalani et al., 2024). Thinning of shade plants also reduces competition for water and nutrient uptake between pine and coffee plants, resulting in optimal growth and production of coffee beans (Wilkinson et al., 2016).

Pine biomass

The simulation results of the WaNuLCAS model show that pine pruning will reduce the biomass of the pine itself (Figure 5). Pine pruning, which is only done once a year with different percentages (P30 and P50), does not have a different impact compared to pine biomass with once-a-year pruning with a percentage of 10% (P10). Pruning pine regularly every month decreased pine biomass as the percentage of pruning increased, which decreased by 6% with 10% pruning regularly a month (P10R), 12.7% with 30% pruning regularly a month (P30R), and 15% with 50% pruning regularly a month (P50R) compared to 10% pine pruning once a year (P10). The addition of N fertilizer and organic fertilizer had no impact on the addition of pine biomass compared to 10% pine pruning once a year (P10). Thinning pine plants (T) reduced pine plant biomass by 27%, with a combination of 30% pine pruning (TNOP) reducing pine biomass by 35% compared to 10% pine pruning in a year (P10) (Figure 5).

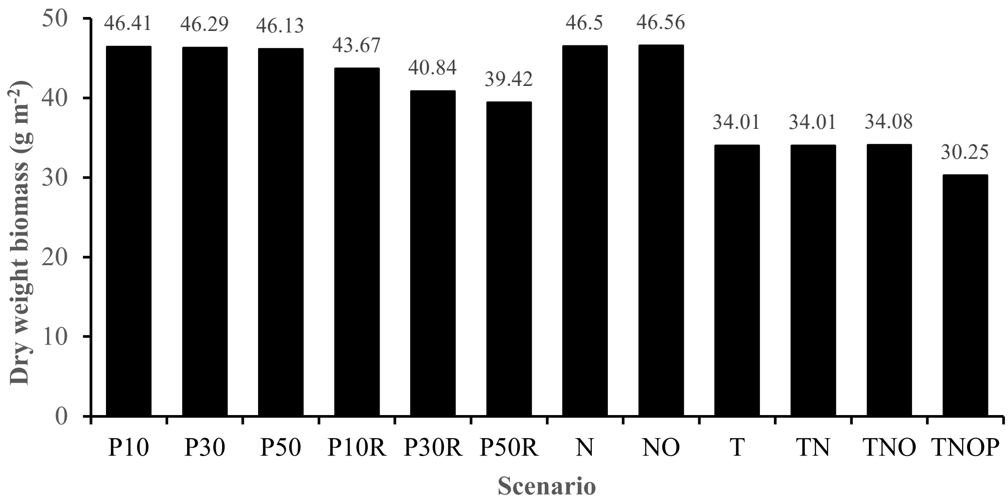


Figure 5. Pine biomass in coffee-pine based agroforestry pine pruning once a year with 10% (P10) compared to 30% (P30) and 50% (P50) pruning; pine pruning once a month with 10% (P10R), 30% (P30R) and 50% (P50R) pruning; 80 kg ha^{-1} year^{-1} N fertilization was applied twice 40 kg ha^{-1} at the end of the rainy season and 40 kg ha^{-1} at the beginning of the rainy season (N) and 80 kg ha^{-1} year^{-1} N + 5 t ha^{-1} year^{-1} manure (NO); pine spaced from 3 m x 2 m to 6 m x 2 m (T); pine spaced + 80 kg ha^{-1} year^{-1} N fertilization (TN); pine spaced + 80 kg ha^{-1} year^{-1} N fertilization + 5 t ha^{-1} year^{-1} manure (TNO), and pine spaced + 80 kg ha^{-1} year^{-1} N fertilization + 5 t ha^{-1} year^{-1} manure + pine pruned 30% every month (TNOP)

Management of pruning and thinning pine will directly affect the decrease in the amount of pine biomass in the agroforestry system; the decrease in the amount of pine biomass will reduce the amount of water and nutrient uptake in the soil, thereby reducing competition between pine plants and coffee plants (Syano et al., 2023).

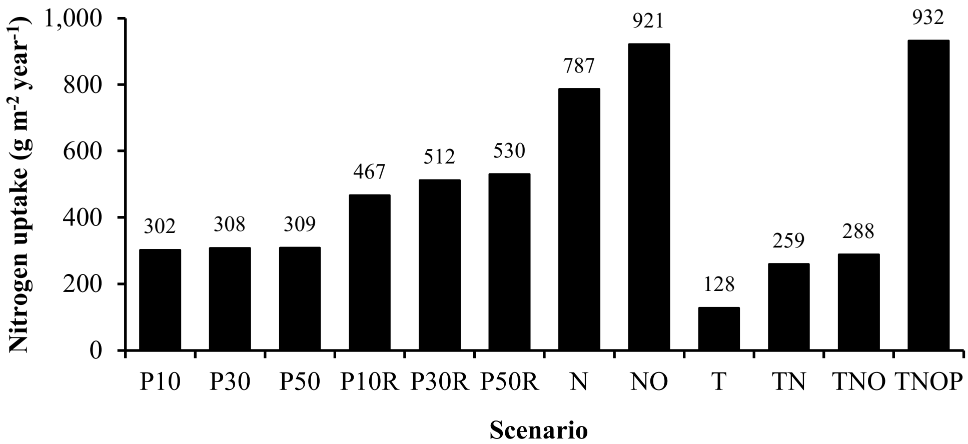
In addition to modifying the agroforestry environmental system through pruning and thinning management, the addition of both organic and inorganic N fertilizers also has a positive impact on the addition of coffee biomass and coffee bean yield; the addition of fertilizers increases the amount of N in the soil in the form of available N (Rusli et al., 2015). The increase in N in the soil due to fertilization will stimulate the process of plant vegetation and result in the optimization of the photosynthesis process, thereby increasing food reserves and the formation of coffee beans (Negash et al., 2022).

Soil nitrogen uptake

The simulation results of the WaNuLCAS model showed that pruning pine once a year with a percentage of 30% (P30) and 50% (P50) did not increase the amount of soil nitrogen uptake by coffee and pine plants compared to pruning once a year with a percentage of 10% (P10) (Figures 6a and 6b). Routine monthly pruning of pine increased the uptake of soil nitrogen by coffee and pine plants as the percentage of pruning increased, increasing 35% of coffee plant uptake and 31% of pine uptake with 10% monthly pruning (P10R), increasing 41% of coffee plant uptake and 35% of pine uptake with 30% monthly pruning (P30R), increasing 43% of coffee plant uptake and 36% of pine uptake with 50% monthly pruning (P50R) compared to once-a-year pruning with a percentage of 10% (P10) (Figures 6a and 6b).

The addition of inorganic fertilizer (N) increased 62% of coffee plant uptake and decreased 48% of pine uptake, and the addition of a combination of inorganic and organic fertilizers (NO) increased 67% of coffee plant uptake and decreased 60% of pine uptake compared to once-a-year pruning at 10% (P10). Thinning and the combination of fertilization (T), (TN), and (TNO) did not increase nitrogen uptake by either coffee or pine, but the combination of thinning, inorganic and organic fertilization, and 30% pine pruning (TNOP) increased 70% of coffee plant uptake and decreased 63% of pine uptake compared to 10% pine pruning in a year (P10) (Figures 6a and 6b).

a.



b.

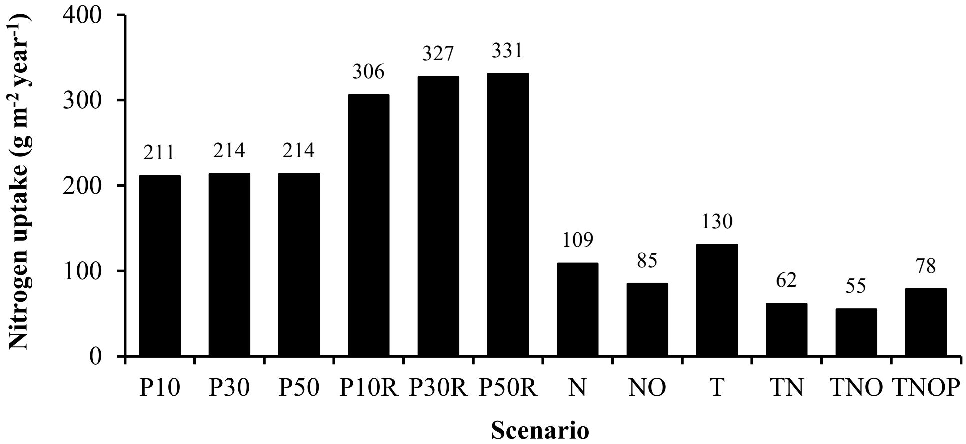


Figure 6. (a) Coffee N uptake and (b) pine N uptake in coffee-pine based agroforestry pine pruning once a year with 10% (P10) compared to 30% (P30) and 50% (P50) pruning; pine pruning once a month with 10% (P10R), 30% (P30R) and 50% (P50R) pruning; 80 kg ha^{-1} $year^{-1}$ N fertilization was applied twice 40 kg ha^{-1} at the end of the rainy season and 40 kg ha^{-1} at the beginning of the rainy season (N) and 80 kg ha^{-1} $year^{-1}$ N + 5 t ha^{-1} $year^{-1}$ manure (NO); pine spaced from 3 m x 2 m to 6 m x 2 m (T); pine spaced + 80 kg ha^{-1} $year^{-1}$ N fertilization (TN); pine spaced + 80 kg ha^{-1} $year^{-1}$ N fertilization + 5 t ha^{-1} $year^{-1}$ manure (TNO), and pine spaced + 80 kg ha^{-1} $year^{-1}$ N fertilization + 5 t ha^{-1} $year^{-1}$ manure + pine pruned 30% every month (TNOP).

Management of pine pruning once a year with various percentages (P10, P30, and P50) does not affect the amount of N uptake for both coffee and pine caused by pruning once a year does not have an impact on optimal environmental conditions for coffee plants, besides that, there is still competition for nutrients. Pruning the upper part of the trunk and branches (pine), if done only once, can trigger the growth of proximal roots, which is the first root branch on the main root; this root will trigger nutrient competition between coffee and pine plant roots (Ollinaho and Kröger, 2021; Purnamasari et al., 2022). In contrast to routine monthly pine pruning (P10R, P30R, and P30R), this pruning management positively increases the uptake of soil nitrogen by coffee plants and pine nitrogen. Routine pruning will maintain suitable environmental conditions for coffee plants, resulting in optimal soil nitrogen uptake (Schmitt and Perfecto, 2021). Fertilizer application is also very effective for increasing soil nitrogen uptake by coffee plants but does not increase nitrogen uptake by pine. This is because fertilizer application is carried out in the topsoil, which is where the roots of coffee plants are mostly found in part close to the topsoil, so coffee plants get an abundance of available nitrogen due to fertilization, which has an impact on increasing nitrogen uptake by coffee plants (Ollinaho and Kröger, 2021; Negash et al., 2022). Management of thinning or setting a wide shade distance without pruning (T, TN, and TNO) is not effective in increasing the uptake of soil nitrogen by coffee plants. The thinning management is not optimal for the suitability of coffee plant growth. As a result, coffee plants are less optimal for the absorption of nitrogen in the soil

(Anhar et al., 2020). In addition, the decrease in pine population due to thinning increases the level of volatilization, or nitrogen evaporation, and increases the leaching of nitrogen in the soil during rainfall, resulting in ineffective nutrient uptake by plants (Charbonnier et al., 2017). However, this is different when thinning management is combined with pruning management (TNOP); pruning management will optimize the receipt of sunlight into the system for coffee plants; this will have an impact on creating ideal environmental conditions for coffee plants, which impact on the uptake of soil nitrogen by coffee plants (Negash et al., 2022).

Drainage and runoff

The simulation results of the WaNuLCAS model showed that once-a-year pine pruning with a percentage of 30% (P30) and 50% (P50) did not increase the soil drainage rate compared to once-a-year pruning with a percentage of 10% (P10) (Figure 7a). Regular pruning of pine every month with a percentage of 10% and 30% did not increase the drainage rate compared to pruning once a year with a percentage of 10% (P10), but regular pruning of pine every month with a percentage of 50% (P50R) increased 15% of the drainage rate compared to pruning once a year with a percentage of 10% (P10).

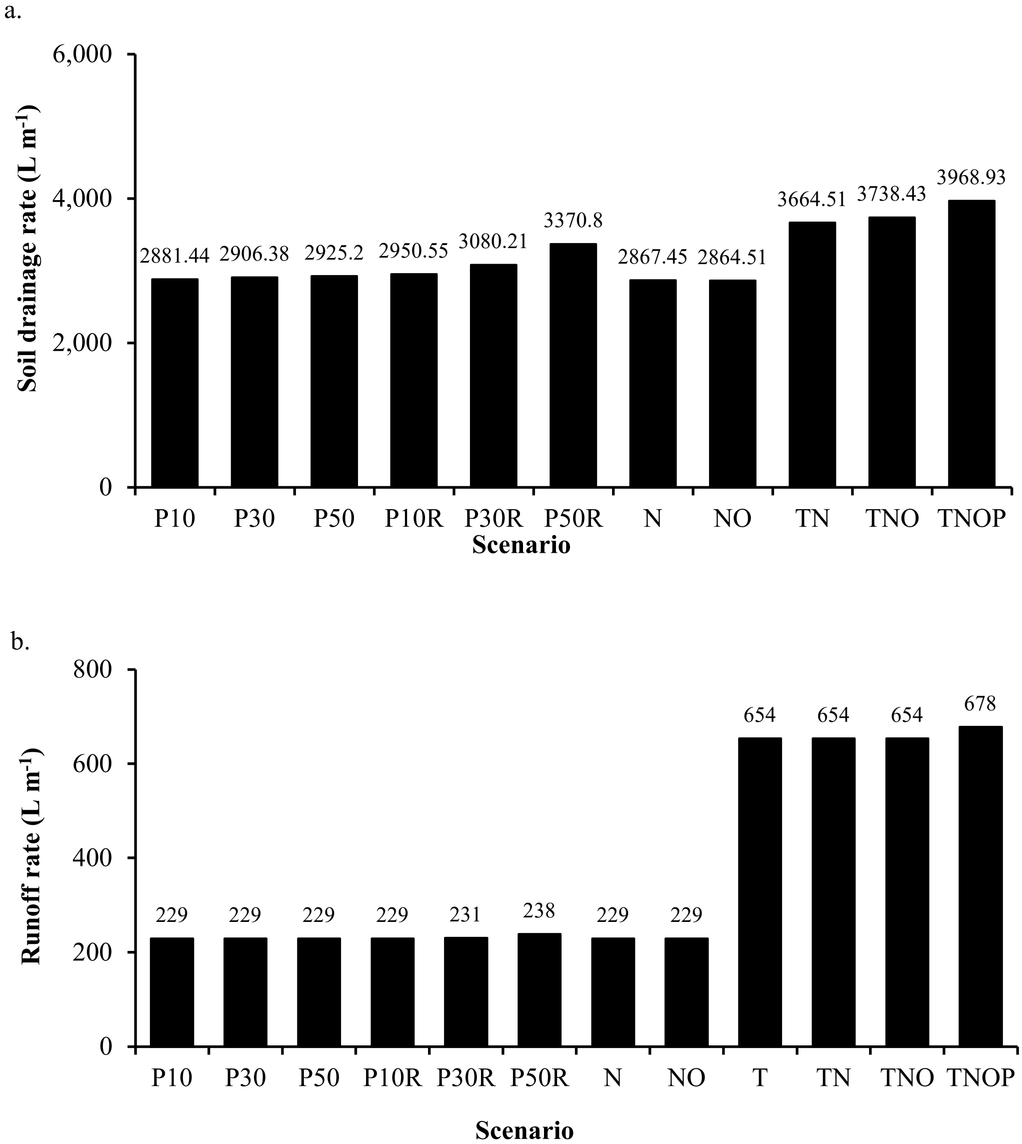


Figure 7. (a) Soil drainage rate and (b) soil runoff rate in coffee-pine based agroforestry pine pruning once a year with 10% (P10) compared to 30% (P30) and 50% (P50) pruning; pine pruning once a month with 10% (P10R), 30% (P30R) and 50% (P50R) pruning; 80 kg ha^{-1} $year^{-1}$ N fertilization was applied twice 40 kg ha^{-1} at the end of the rainy season and 40 kg ha^{-1} at the beginning of the rainy season (N) and 80 kg ha^{-1} $year^{-1}$ N + 5 t ha^{-1} $year^{-1}$ manure (NO); pine spaced from 3 m x 2 m to 6 m x 2 m (T); pine spaced + 80 kg ha^{-1} $year^{-1}$ N fertilization (TN); Pine spaced + 80 kg ha^{-1} $year^{-1}$ N fertilization + 5 t ha^{-1} $year^{-1}$ manure (TNO), and pine spaced + 80 kg ha^{-1} $year^{-1}$ N fertilization + 5 t ha^{-1} $year^{-1}$ manure + pine pruned 30% every month (TNOP).

The addition of inorganic fertilizer (N) and the addition of a combination of organic and inorganic fertilizers (NO) did not increase the soil drainage rate compared to once-a-year pruning with a percentage of 10% (P10) (Figure 7a). Thinning and the combination of thinning and pruning (T), (TN), (TNO), and (TNOP) increased the drainage rate by an average of 30% compared to once-a-year pruning at 10% (P10). Thinning pine trees (T, TN, TNO, and TNOP) had a negative impact on surface runoff rates, increasing by 65% the average runoff rate in the system compared to no thinning (P10, P30, P50, P10R, P30R, P50R, N, and NO) (Figure 7b).

Drainage ability and soil runoff rates in agroforestry systems are indicators of sustainability in agroforestry farming practices. Routine pruning management once a year with different percentage levels has no impact on drainage rates when compared to routine pruning management once a month it caused by pruning management at the top of the pine will stimulate the formation of new roots in pine plants so that many new roots are formed in the apical meristem, this root formation will indirectly affect soil structure which will improve soil drainage (Cannavo et al., 2011). The combination of thinning and pruning pine effectively increases the rate of soil drainage, reducing the amount of pine shade and reducing competition between pine plants and the coffee itself by creating a suitable environment for coffee and pine, and root growth is also optimal. Optimizing root growth as a result of suitable conditions for the plant growth environment impacts improving soil structure, which affects soil drainage ability (Pinto et al., 2015).

The level of runoff or surface flow is influenced by two components: canopy density and surface roughness (Sakai et al., 2015). Pruning management (T, TN, TNO, and TNOP) has a higher runoff rate than management without pruning. This is driven by the reduction of pine trees, which will reduce the interception of rainwater by both the canopy and trunk of the pine, leading to higher runoff rates in the system. The function of stands is to increase the interception of rainwater by plants, thereby reducing the kinetic energy of rainwater and slowing the rate of surface flow (Perron et al., 2023). Runoff rates can also be reduced by adding cover crops and litter to the soil surface to increase surface roughness (Sakai et al., 2015).

Conclusion

Modeling agroforestry systems requires balancing processes and patterns that are adjusted through parameterization and model calibration. Based on the results of this study, the WaNuLCAS model can represent the processes in the agroforestry system temporally and spatially with an acceptable level of accuracy so that the WaNuLCAS model can be used as a tool for optimizing production and environmental return impacts as a consequence of implementation with various management patterns. Through the simulation of the WaNuLCAS model, we can see that in optimizing coffee production, the right management pattern is to create optimal environmental suitability for coffee plant growth, including through thinning of shade plants and routine pruning and fertilization, but on the other hand thinning and pruning will increase the runoff rate or surface runoff rate in the system. So, in its actual application, it can be combined by adding grasses or cover crops to reduce the level of surface runoff rate. This research provides valuable insights for farmers and forest managers that modeling can be used as one of the foundations for decision-making in the management of agroforestry systems.

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