Research Article

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Altitude, shading, and management intensity effect on Arabica coffee yields in Aceh, Indonesia

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Abstract: The productivity of Arabica coffee in the Gayo Highlands, Aceh, Indonesia is far below its potential because of climate change and inadequate agricultural practices. To develop a strategy on sustainable coffee yield and improvements of smallholder farming systems, we investigated coffee productivity in three classes of shade densities and three classes of total management intensities index (TMI) along six altitude gradients (1,000–1,600 m above sea level) over 234 farmers' plots. Coffee productivity was significantly affected by altitude, shade density, and TMI. Our results showed a stronger positive altitudinal effect with coffee productivity in middle and higher altitudes than in lower altitudes and were related to shade density and TMI. Increasing elevation of coffee plantation from lower to middle altitudes and shade from low to medium density increased in coffee productivity but further increase to higher altitude seemed to depress coffee productivity. Increasing TMI positively increased coffee productivity across altitudes. Shade density and TMI played significant roles in coffee productivity in lower altitudes; therefore, coffee farmers have to increase the shade to medium or higher density and at the same time improve plantation management to medium or high TMI.

Keywords: agroforestry, multipurpose tree, climate change, adaptation strategy

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1 Introduction

Indonesia, the fourth largest coffee producer in the world, produced 685.8 thousand tons of coffee in 2018, of which 116.6 thousand tons are Arabica coffee (BPS-Statistics Indonesia 2019). The Gayo Highlands in Aceh, the largest producer of Arabica coffee in Indonesia, produces 40.8 thousand tons/year from a total area of 103,000 ha. As one of Indonesia's strategic commodities, Arabica coffee production faces challenges to its sustainability because of its productivity and its sensitivity to climate change (Läderach et al. 2011). The yield quantity and quality of Arabica coffee declined outside its optimum temperature ranges. The increase in temperature results in a condition that is more vulnerable to the production of Arabica coffee compared to the change in annual or sessional precipitation (Gay et al. 2006; Ovalle-Rivera et al. 2015). In modeling studies, Schroth et al. (2015) reported that land suitable for coffee development in Indonesia by 2050 would be drastically reduced, even the coffee area in the Gayo Highlands will reduce up to 91% compared to the currently suitable area.

Coffee in the Gayo Highlands, Aceh is generally cultivated in agroforestry systems with *Leucaena* (*Leucaena leucocephal*a (Lam.) de Wild) as shade trees. Farmers also grow other multipurpose plants between their coffee, such as avocado (*Persea americana*), citrus (*Citrus reticulata*), and banana (*Musa* sp.), used as alternative additional income. In practice, farmers have begun to reduce shade trees to increase coffee productivity. However, shade trees are useful for creating a microclimate, reducing the amount of fruit that falls (DaMatta 2004), reducing erosion, increasing plant nutrition (especially shade trees derived from legumes) (Sauvaded et al. 2019), as well as food security (Tscharntke et al. 2011). To maintain the sustainability of Arabica coffee production in the Gayo Highlands, adaptation strategies for existing coffee plantation need to be developed; if not, farmers probably will need to switch to other economically suitable crops.

To understand how coffee productivity can sustain climate change, especially the increase in temperature, we analyzed the effect of altitude, shade tree density, and management intensity on coffee productivity. We hypothesized that (i) altitude, shade tree density, and management intensity had a significant effect on coffee productivity; and (ii) there was a strong relationship among altitude, shade tree density, and management intensity on coffee productivity.

2 Materials and methods

2.1 Study area

The study was conducted in two districts in Gayo Highlands, i.e., Aceh Tengah located geographically between 4°22′14.42″–4°42′40.80″N and 96°15′23.60″–97°22′10.76″E, and Bener Meriah located geographically between 4°33′50″–4°54′50″N and 96°40′75″–97°17′50″E (Figure 1).

The total area of the two districts is 6,432.1 km^2, where 37.0% is less than 1,000 m asl (above sea level), 20.7% is from 1,000 to 1,600 m asl, and 42.3% is more than 1,600 m asl. The area between 1,000 and 1,600 m asl is usually an ideal area for Arabica coffee cultivation. The mean annual rainfall in the area is 1,575 mm, with one peak in February–March and another one in October–November. The mean annual temperature in the study site is 19.1°C, with a high variation between the daily and nightly temperatures (BMKG 2016). The soil in the lower elevations is classified as Ultisols, while Inceptisols are found in higher elevations, and Andisols are found in the lower and higher elevations. The terrain is hilly, with more than 42% with a slope of more than 25%. However, coffee plantations may be found on hills with a 60% slope.

2.2 Sampling and surveying method

2.2.1 Farmer interview

A mixed and stratified household survey was conducted in 2019–2020 of 234 farmers' coffee farms. The survey was conducted by direct interviews based on a set of structured questionnaires. Pre-test and focus group discussions were conducted before the survey to finalize the survey instrument. The interviewers were trained by the same person, and surveys lasted between 45 and 60 min

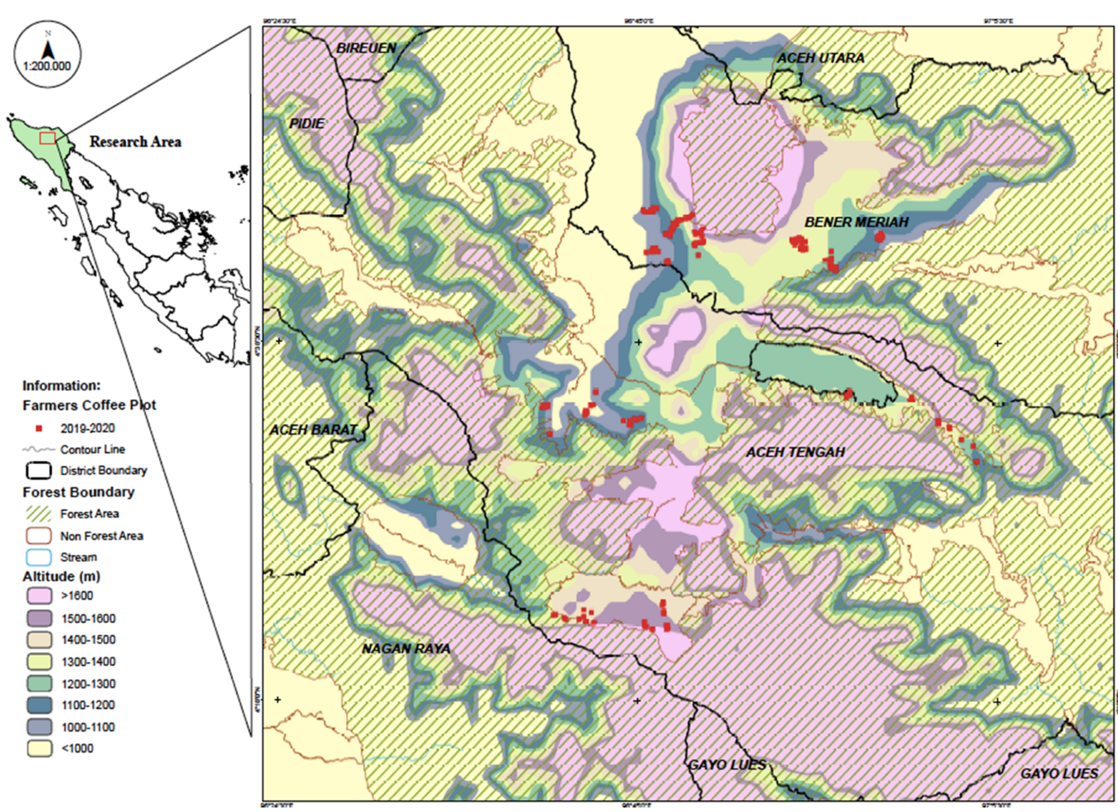

Figure 1: Map of Sumatera island, Indonesia, and research area with farmers' plots (234 plots).

per farmer. The interviewers directly observed the farmer's farms, recorded the altitude (using GPS), and counted density and type of shade trees, age of the coffee plants, plant spacing, and land conditions (flat or slope).

2.2.2 Plot selection and altitude

The main target of this study was to understand the effect of shade tree density and management practices carried out by coffee smallholder farmers across the altitude from 1,000 to 1,600 m asl, as well as their correlation with coffee productivity. Therefore, sampling plots were categorized by 100 m altitude gradient, i.e., category 1 (1,000–1,100 m asl), category 2 (1,100–1,200 m asl), category 3 (1,200–1,300 m asl), category 4 (1,300–1,400 m asl), category 5 (1,400–1,500 m asl), and category 6 (1,500–1,600 m asl). We examined 234 plots consisting of 52, 26, 48, 36, 39, and 33 plots in each category, respectively. The plots were the entire farmers' coffee farms, which had a size of at least 0.25 ha, ages of coffee plants between 5 and 30 years, and a minimum coffee plant population of 300 plants/ha.

2.2.3 Shade density

Shade density varies among farms. Coffee farmers usually plant shade trees with a density from 100 trees/ha (10.0 × 10.0 m) to 400 trees/ha (5.0 × 5.0 m). However, some farmers have reduced the number of shade trees and replaced them with multipurpose plants such as avocado, citrus, and banana. Our observation showed that minimum shade tree density was 31 trees/ha, while maximum tree density was 332 trees/ha (the range was 301). Therefore, we divided the range of shade tree density into three classes, with an interval of 100 trees/ha, namely low density (<100 trees/ha), medium density (100–200 trees/ha), and high density (>200 trees/ha). There were 64, 104, and 66 plots for low, medium, and high density, respectively.

2.2.4 Management intensity index

Management intensity index (MII) is calculated based on the information provided by farmers for each farmer's coffee plot, similar to indices used by Cerda et al. (2017) and Jezeer et al. (2018). In this study, MII was constructed as an aggregate of six management variables, i.e., land conservation (sloped and no conservation = 1, flat or sloped with conservation = 2), age of coffee plant (age >25 years = 1, age 5–<10 years = 2, and age 10–25 years = 3), pruning of coffee plants (no = 1, yes = 2), weeding (no = 1, yes = 2), applications of fertilizers (no = 1, organic or non-organic fertilizer = 2, both organic and non-organic fertilizers = 3), and application of pest and disease control (no = 1, yes = 2). The age of coffee plant category was based on the coffee planting cycle usually practiced by farmers in the region. The most productive age of coffee plant was between 10 and 25 years (the pick period of production). The second productive age of coffee plant was 5 to <10 years (the initial period of production). The lowest productive age of coffee plant was >25 years (the period when coffee production starts to decline).

These management practice variables were transformed to range between 0 and 1, with 0 representing the lowest inputs and 1 the highest, using the MII:

$$\text{MII} = \frac{(\text{value observed} - \text{minimum value})}{(\text{maximum value} - \text{minimum value})}.$$

The total management intensity index (TMI) corresponds to the sum of the MII of each farm's six variables. Based on the result, we classified TMI of each farm into three classes, i.e., low TMI (<2.0), medium TMI (2.0–4.0), and high TMI (>4.0). There were 20, 123, and 91 plots for low-, medium-, and high-TMI plots, respectively.

2.2.5 Coffee productivity

Coffee productivity (kg/ha) was calculated by dividing the yield of dry coffee beans (reported by farmers from January to December 2019), to the total area of the coffee farm owned by farmers.

2.3 Data analysis

To analyze the effect of altitude, shade density, and TMI on coffee productivity, we used a general linear model analyses. We used six categorical altitudes, three class shade densities, and three classes of TMI. Before analyses, data of coffee productivity were log-transformed to decrease variability (Steel and Torrie 1980). In the case of statistically significant effects, a comparison of means using the least significant difference (LSD) *post hoc* test ($P < 0.05$) was applied. To asses which of the altitude, shade density, and TMI had a significant relationship on coffee productivity, a stepwise linear regression was used ($P < 0.05$). For this analysis, we used continuous data of altitudes, shade tree density, and coffee productivity, while for TMI we used the TMI score of each farm. Statistical analyses were performed with SPSS v. 23.0.

3 Results

3.1 Farmer and coffee plots characteristics

Farmers' characteristics are presented in Table 1. The average gender of coffee farmers interviewed was 1.10 ± 0.30, male (63.33%) and female (36.67%). The average age category of the farmers was 1.98 ± 0.73, in category 2 (>35–54 years old), the very productive age category. The level of education respondent was quite good, with 95 respondents (40.60%) getting an education in senior high school and 24 respondents (10.30%) in university, while 46 respondents (19.70%) in junior high school and 69 respondents (29.50%) in elementary school. The majority of farmers had a good experience in the coffee plantation, 116 farmers (49.60%) in category 2 (>5–20 years), 99 farmers (42.3%) in category 3 (>20 years), and only 19 farmers (8.10%) in category 1 (0–5 years). The average household size was 3.82 ± 1.39, 162 farmers (69.20) had one to four persons, 65 farmers (27.80%) had four to six persons, and only seven farmers (3.0%) had more than six persons. The average land size was 0.95 ± 0.52.

The average coffee productivity was 545.40 ± 161.99 kg/ha, ranging from 264.4 to 1,136 kg/ha (Table 2). The high variability of coffee productivity among the farmer plots suggests that some farmers in the same agro-ecological condition could also obtain higher yields. By knowing the reasons why some farmers get higher yields, we could develop simple techniques and technologies to improve the coffee yields of other smallholder farmers.

The average altitude of the plots was 1,282.39 ± 186.19 m asl, with the lowest farm lied at 1,002 m asl, while the highest plot lied at 1,598 m asl. The average shade density was 146.90 ± 77.76 plants/ha, with the lowest density was 31 plants/ha and the highest density was 332 plants/ha. Management practices carried out by farmers vary greatly from one to another. The average score of land conservation was 1.6 ± 0.51. The average age of the coffee plant (15.1 ± 7.3 years) was in class 2, with an average score of 2.5 ± 0.62. Pruning had an average score of 1.5 ± 0.50, while the average of weeding score, and pest and disease control score were 1.8 ± 0.36 and 1.5 ± 0.50, respectively. The average of application of the fertilizer score was 2.3 ± 0.82, out of a possible score between 1.0 and 3.0 (data are not shown). After calculation, we found that the average of TMI was 3.90 ± 1.14 with a minimum score of 0.50 and a maximum score of 6.00 (Table 2).

3.2 Effect of altitude, shade density, and TMI on coffee productivity

Coffee productivity was significantly affected by altitude, shade density, and TMI. The effect of altitude on log coffee productivity is shown in Figure 2, the effect of shade density on log coffee productivity is shown in Figure 3, and the effect of TMI on log coffee productivity is shown in Figure 4.

The average of log coffee productivity (Figure 2) at altitudes >1,200–1,300 m asl was significantly higher than those at altitudes >1,000–1,100, >1,100–1,200, >1,400–1,500, and >1,500–1,600 m asl but was not than those at >1,300–1,400 m asl. The average of coffee productivity at altitudes >1,400–1,500 and >1,500–1,600 m asl tended to higher than those at altitudes >1,000–1,100

Table 1: Farmer characteristics (n = 234 farmers)

Variable	Type of variable	Mean	SD	Min.	Max.
Gender	(1 = male, 2 = female)	1.10	0.30	1	2
Age	(1 = >15–35 years, 2 = >35–54 years, 3 = >54 years)	1.98	0.73	1	3
Education	(1 = Preliminary school, 2 = Junior high school, 3 = Senior high school, 4 = University)	2.32	1.01	1	4
Experience as coffee farmer	(1 = 0–5 years, 2 = >5–20 years, 3 = >20 years)	2.34	0.62	1	3
Household size	(Continuous)	3.83	1.39	1	8
Land size	(Continuous)	0.95	0.52	0.25	3.00

SD, standard deviation; Min., minimum; Max., maximum.

Table 2: Coffee plot characteristics (n = 234 farmers' plots)

Variable	Type of variable	Mean	SD	Min.	Max.
Coffee productivity (kg/ha)	Continuous	545.40	161.99	264.4	1,136
Altitude (m asl)	Continuous	1,282.39	186.19	1,002	1,598
Shade density (trees/ha)	Continuous	146.90	77.76	31	332
Total management intensity index		3.90	1.14	0.50	6.0

SD, standard deviation; Min., minimum; Max., maximum.

and >1,100–1,200 m asl, although those were not significantly different.

The average of log coffee productivity (Figure 3) at medium- and high-shade densities was significantly higher than those at low-shade density. The average of log coffee productivity at medium-shade density was not significantly higher than those at high-shade density.

The average of log coffee productivity (Figure 4) at high TMI was significantly higher than those at medium TMI and low TMI. The average of log coffee productivity at medium TMI was significantly higher than those at low TMI.

3.3 Relationship among attitude, shade density, and TMI on coffee productivity

Based on the result of the effect of altitude on coffee productivity (Figure 2), to find the best fit of relationship of altitude, shade density, and TMI on coffee productivity, we clustered the altitudes into three categories, i.e., lower altitudes (>1,000–1,100 m asl and >1,100–1,200 m asl), middle altitudes (>1,200–1,300 m asl and >1,300–1,400 m asl), and higher altitudes (>1,400–1,500 m asl and >1,500–1,600 m asl).

The characteristics of coffee plots at lower, middle, and higher altitudes are shown in Table 3. In lower altitudes, shade density and TMI were positively correlated with log coffee productivity. The result showed that shade density and TMI played an important role in coffee productivity. This result was also consistent with the result of stepwise multiple regression analysis on shade density, where TMI and shade density significantly affect log coffee productivity ($P < 0.000$, adjusted $R^2 = 0.495$, Table 4). The function that described the relation between TMI, shade density, and coffee productivity was: $Y = 2.398 + 0.050$ TMI + 0.001 shade density, where Y = log coffee productivity (kg/ha). This equation indicated that the coffee productivity in lower altitudes was mainly determined by TMI and shade density.

4 Discussion

4.1 Effect of altitude, shade density, and TMI on coffee productivity

These results (Figure 2) showed that optimum growth, development, and yield of coffee were found in middle

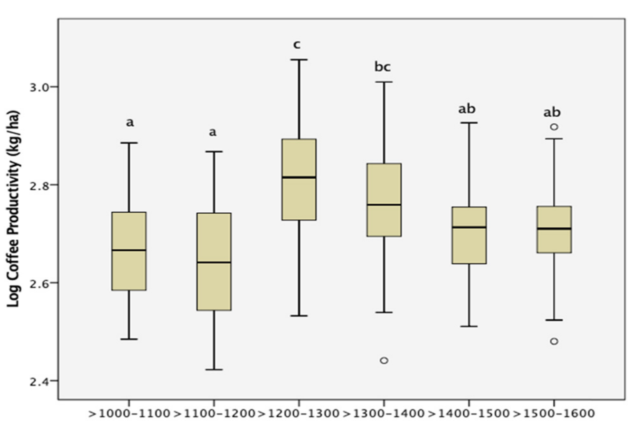

Figure 2: The effect of altitudes on log coffee productivity; general linear model ($P < 0.000$); means followed by the same letter did not differ (LSD $P < 0.05$).

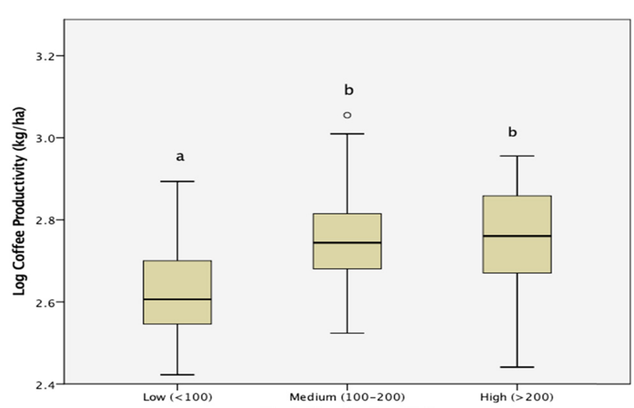

Figure 3: The effect of shade density on log coffee productivity; general linear model ($P < 0.000$); means followed by the same letter did not differ (LSD $P < 0.05$).

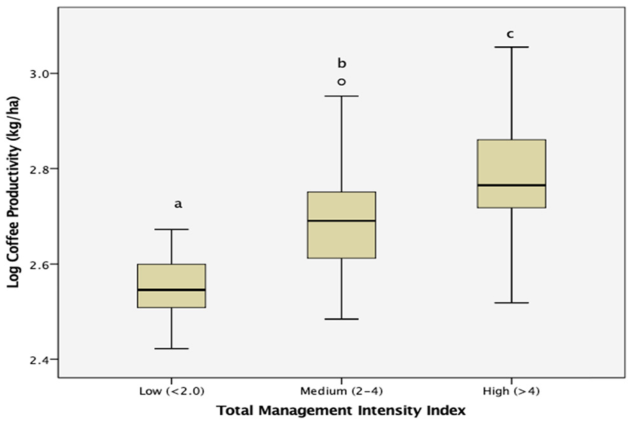

Figure 4: The effect of total management intensity index on log coffee productivity; general linear model ($P < 0.000$); means followed by the same letter did not differ (LSD $P < 0.05$).

altitudes (the elevation between 1,200 and 1,500 m asl). The lower coffee productivity in lower altitudes (>1,000–1,200 m asl) than those in middle and higher altitudes might be because of the higher temperature in the lower altitudes. Study in coffee plantation in Uganda (Sarmiento-Soler et al. 2019) showed that higher temperature and vapor pressure deficit in lower altitudes lead to sub-optimum growing conditions. On the other hands, DaMatta et al. (2018) reported that coffee can resist higher temperature if ample water supply is available. The lower coffee productivity in higher altitudes (>1,500–1,600 m asl) than those in middle altitudes (1,200–1,500 m asl) might be because of the cooler temperatures and lower incoming radiation that resulted in limiting coffee yield. Farmers in the area reported that there was occasion where temperature at night might drop down to 10°C that affected coffee plant growth and yield.

Low-shade density (Figure 3) resulted in significantly lower coffee productivity than those at medium- and high-shade density. The result showed that in the agroforestry coffee system, shade density plays an important role in coffee production especially in lower altitude. Medium- and high-shade density resulted in better coffee productivity. Shade cover has the potential to keep coffee plants closer to their ideal temperature ranges and to prevent damage from extreme minimum and maximum temperatures (Lin 2006).

An increase in the level of TMI (Figure 4) resulted in significantly higher coffee productivity. Jezeer et al. (2018) reported that coffee yields were higher in plantations with higher maintenance cost (higher management intensity). Study of yield gap analysis of Arabica coffee in Costa Rica showed that altitudes and management practices were the limiting factor of coffee yield (Bhattarai et al. 2017)

These results showed that the area at higher altitudes would not always be the most potential area for coffee plantation in the future, concerning climate change. However, it is generally known that higher altitude has a positive coffee quality (Avelino et al. 2005). Better price of better quality coffee in higher altitudes could be a trade-off to lower coffee quantity than those in middle altitudes. However, coffee pests and diseases are likely to follow the migration of the host to expand their geographic range to the same future suitable coffee growing areas (Rosenzweig et al. 2001). Therefore, shade density,

Table 3: Coffee plot characteristics in lower altitudes (>1,000–1,200 m asl, $n = 78$), middle altitudes (>1,200–1,400 m asl, $n = 84$), and higher altitudes (>1,400–1,600 m asl, $n = 72$)

Variable	Type of variable	Mean	SD	Min.	Max.	Corr.
Lower altitude category						
Altitude (m asl)	Continuous	1,064.15	54.42	1,002	1,179	—
Log coffee productivity (kg/ha)	Continuous	2.66	10.11	2.42	2.89	—
Shade density (trees/ha)	Continuous	136.92	78.87	31	300	0.49**
Total management intensity index		3.78	1.11	1.00	6.00	0.60**
Middle altitude category						
Altitude (m asl)	Continuous	1,292.64	58.15	1,209	1,389	—
Log coffee productivity (kg/ha)	Continuous	2.79	1.13	2.44	3.06	—
Shade density (trees/ha)	Continuous	149.09	72.71	40	311	0.21ns
Total management intensity index		4.21	1.05	1.50	6.00	0.56**
Higher altitude category						
Altitude (m asl)	Continuous	1,506.86	55.33	1,413	1,598	—
Log coffee productivity (kg/ha)	Continuous	2.70	0.10	2.48	2.93	—
Shade density (trees/ha)	Continuous	155.15	82.05	50	332	0.18ns
Total management intensity index		3.67	1.19	0.50	6.00	0.63**

SD, standard deviation; Min., minimum; Max., maximum.; Corr., Pearson's correlation analyses; **, highly significant; ns, not significant.

Table 4: Analysis of multiple regression of shade density and total management intensity index on coffee productivity at lower altitude category (>1,000–1,200 m asl, n = 78), middle altitude category (>1,200–1,400 m asl, n = 84), and higher altitude category (>1,400–1,600 m asl, n = 72)

Variable	Coefficient ß	*t*-test	*P*-value
Lower altitude categories; R^2 = 0.495, adj. R^2 = 0.481			
Constant	2.398	74.53	0.000
Total management intensity index	0.050	6.20	0.000
Shading density	0.001	4.50	0.000
Middle altitude categories; R^2 = 0.324, adj. R^2 = 0.303			
Constant	2.505	52.10	0.000
Total management intensity index	0.067	6.09	0.000
Higher altitude categories; R^2 = 0.438, adj. R^2 = 0.422			
Constant	2.472	72.93	0.000
Total management intensity index	0.052	7.07	0.000

management practices, and strategies have to be developed specifically for each altitude to sustain coffee yield in regard to climate change.

4.2 Relationship among attitude, shade density, and TMI on coffee productivity

Maintaining shade density was an economically feasible way to protect coffee plants from an extreme microclimate and soil moisture and should be considered a potential adaptive strategy for farmers in areas that would suffer from extreme climate (Lin 2006). Therefore, in lower altitudes, maintaining shade to medium or high density could be an adaptation strategy to climate change. Shade density maintained better canopies and lower temperatures under the shade which resulted in more stable coffee yields over time, which also ensured a more stable income for coffee farmers (DaMatta 2004). However, an increase in shade to medium and high density should be followed by an increase in TMI to increase coffee productivity. Shade trees provide sufficient ecosystem services to justify their integration in even intensively managed plantations (Meyland et al. 2017). Shade-tree coffee systems at Mt. Elgon had been proven to provide several ecosystem services and were used by low-income farmers to reduce risks, in particular at low altitudes (Rahn et al. 2018).

In middle and higher altitudes, shade density did not correlate with log coffee productivity. Analysis of stepwise multiple regression also shows that shade density does not significantly affect log coffee productivity. TMI significantly affects log coffee productivity in middle altitudes (P < 0.000, adjusted R^2 = 0.303) and in higher altitudes (P < 0.000, adjusted R^2 = 0.422). The function that described the relation between TMI and log coffee productivity in middle and higher altitudes was: $Y = 2.505 + 0.067$ TMI and $Y = 2.472 + 0.052$ TMI, respectively. These equations indicated that the coffee productivity was mainly determined by TMI in middle and higher altitudes (Table 4). An increase in TMI would significantly increase coffee productivity. However, in higher altitudes, high-shade density slightly reduced coffee productivity, even with an increase in TMI. This reduction was most likely caused by a decrease in incoming radiation and temperature under the canopy (DaMatta 2004). Therefore, in higher altitudes, shade density needs to be maintained at least at medium level. Shade trees can provide other ecosystem services such as pest and diseases regulation or carbon sequestration and contribute to the cropping system sustainability (Cerda et al. 2017).

The fact that coffee productivity was affected by shade density, and TMI in lower altitudes, and in middle or higher altitudes in different ways, it indicates that the combination of these three factors should always be considered in developing strategies for sustainable coffee production in the region.

In lower altitudes, maintaining shade at medium or high density followed by increasing management intensity will improve coffee productivity. Adding shade density with multipurpose plants such as avocado and citrus is the best option. The practices will produce not only microclimate conditions that are ideal for coffee growth and development but can also be an additional income for farmers.

In middle and higher altitudes, maintaining shade at a medium or high density and increasing management intensity will result in an optimum coffee productivity. The practice of reducing the shade density must be avoided, considering that the middle altitudes might also experience an increase in temperature because of the current trends of climate change.

Smallholder farmers should be able to plan and manage shade trees without undermining their productive and economic objectives and at the same time ensure the delivery of other ecosystem services. The decision on the type and the density of shade and management intensity to be implemented at a given altitude must also consider pest and disease control protocol and their responses to environmental conditions. The adaptation strategies to sustain coffee productivity must also pay attention to the land and environment carrying capacity.

5 Conclusions

Our results suggest that altitude, shade density, and TMI influenced coffee productivity. Increasing elevation of coffee plantation from lower to middle altitudes and shade from low to medium density increased in coffee productivity, but further increase in elevation to higher altitude seemed to depress coffee productivity. Increasing management intensity positively increased coffee productivity across altitudes.

Shade density and TMI played significant roles in coffee productivity in lower altitudes. To obtain better coffee productivity in lower altitudes, coffee farmers have to increase the shade to medium or high density and at the same time improve plantation management to medium or high TMI.

In middle and higher altitudes, only TMI significantly affected coffee productivity. Therefore, improving management intensity to high TMI, while keeping shade to medium or high density, will improve and sustain coffee productivity in the area.

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Data availability statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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