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Determination of light and nitrogen extinction coefficient for coffee plant at different growth stages and canopy layers

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Abstract
The experiment was undertaken to estimate light and nitrogen extinction coefficient at different growth stages and across canopy layers for each growing stage and to analyze the effect of the Leaf Area Index on canopy light interception of the coffee plant. It was super imposed on those which were planted in a 3 x 3 factorial arrangement in a randomized complete block design with four replications and a total of 36 experimental units. Leaf area index and a fraction of light intercepted (Fi) by the coffee plant there was significant variation among growing stage. The highest LAI (2.75) was obtained from coffee with the age of five years followed by three years old (0.684). The highest Fi (0.63) was also obtained from a plant five years old. The highest LA (43.72 m^2) was from five years old and the lowest (22.76 m^2) from one year age coffee. The effect of the growing stage for leaf area of coffee was highly significant variation. The light extinction coefficient shows significant variation. The study revealed on nitrogen extinction coefficient very highly significant variations between treatments. Generally, there was a significant influence of variation in growth stages on the light and nitrogen extinction coefficient of the coffee plant.

Keywords: *coffee, leaf area index, light extinction coefficient, nitrogen extinction coefficient*

Introduction
Coffee is the most important commodity in the global agricultural trade for developing countries [1]. Its acceptance and volume of drinking are growing each year, and coffee shops are the fastest-growing part of the cafeteria business. Today, coffee is both a part of our community experiences as well as an accepted norm for doing business. Economically, coffee is the second highly exported commodity next to oil, and employed over 100 million people globally [2, 3, 4], with worldwide marketing sales estimated to be US$ 90 billion and it is the major export product of some countries such as Uganda, Burundi, Rwanda and Ethiopia [5]. More than 80 developing countries mainly earn their foreign currency from coffee [6, 7, 8]. For Ethiopia, coffee is the most important export commodity, with a share of 20-25% of the total foreign exchange earnings [9]. At least 15 million people also directly or indirectly depend on coffee for their living [2].

Arabica coffee will thrive under a wide range of environmental conditions; however, there are limits to the environment within which this crop can be grown economically. The inherent growth of coffee is affected by several factors, including drought, temperature, photo period, waterlogging, and leaching of nitrates by high rainfall. The major climatic factors include temperature, light, water, and wind [9], the first two are different forms of energy: i.e., radiant and thermal. Quanta of visible light represent relatively large amounts of energy. For instance, blue light has about five to six times more energy per mole of photons (260 KJ mol^{-1} at 460 nm) than the covalent chemical energy in ATP (40 to 50 KJ mol^{-1}). This high energy allows reactions that otherwise would be impossible if they depended on chemical energy. Radiant energy is converted to chemical energy through photosynthesis and stored in molecules that can be used later to power cellular processes and serve as the initial energy source for all forms of life [10].

Light is one of the environmental factors which plays a significant role in plant growth and development. As producers in most ecosystems, plants rely heavily on some sort of light source [11, 12]. The occurrence of light plays a vital character in plant morphology. Thus, the response of green plants always to the light components such as quality, quantity, and direction of light. Light is required in photosynthesis, a plant's process of creating food and energy [13, 14]. Although light is a crucial environmental resource that affects photosynthesis and ultimately influences plant growth, low and high light can limit plant performance. Shortages of key resources, such as light, can compromise survival and growth; however, plants face heat, desiccation, and excessive irradiance under high sunlight. The consequences of variable light environments on plant growth and photosynthesis are currently best understood in the case of sun flecks, in which the duration and frequency of light patches affect carbon assimilation and biomass accumulation through responses to an array of physiological and morphological processes [15].

In its natural habitat, coffee is found in shaded or semi-shaded situations. Its response to light has caused it to be traditionally considered a heterophobic plant, requiring high, somewhat dense cover in a plantation. Later on, it will be shown that this shade practice, which was debated for a long time, is generally being abandoned today. It is known that coffee trees with high productivity potential (selections) are capable of particularly high yields when they are cultivated intensively without shade [16]. Only about 1 percent of the light can penetrate the foliage of a thick coffee bush. As shade can limit the flowering capability of arabica trees and so restrict the yield potential, its use is restricted to the area of low fertility; where the diurnal temperature fluctuation is large; and where weed growth is serious [9]. In crop plants, the effects of different light environments have been examined by comparing plants grown entirely at high light with individuals grown at a fixed level of shade (e.g., using netting with varying degrees of light transmittance) or in agroforestry systems with homogeneous ground cover that varies from sparse to deep shade depending on the shelter tree attributes and management (e.g., crown architecture, spacing and pruning). Thus, local photo synthetically active radiation conditions to which individual leaves are exposed can vary tremendously throughout the canopy of a tree [17].

Leaf area index (LAI, the total one-sided foliage area per unit soil surface area) is one of the most important characteristics of canopy structure. An accurate estimate of LAI is critical for the estimation of a large number of key ecosystem processes, including rainfall interception and $C0_2$ and water-vapor fluxes. LAI is also a dynamic parameter that varies on time scales ranging from days to years [18]. Weiss [19] also stated in their work that a leaf area index is a unit less measure of the area of photosynthetic material per unit area of the soil surface, which is to say the quantity of leaf–atmosphere interface per unit of soil surface area. According to Johnson [20], LAI is an important factor in determining photosynthesis and subsequent biomass production. A canopy’s fi PAR is also influenced by the canopy light extinction coefficient (*k*), which is primarily determined by leaf. So far, information about the light and nitrogen extinction coefficient of coffee at different growing stages and through the canopy layer is unknown in our country's case. Therefore, considering this fact the research was conducted with the following objectives;

- To estimate light and nitrogen extinction coefficient for the coffee plant at different growth stages
- To determine the light and nitrogen extinction coefficient for coffee plant across canopy layer for each growing stage
- To analyze the effect of LAI on canopy light interception of the coffee plant

Materials and Methods

Description of the Study Area

The research was conducted in the Horticulture Demonstration site and Horticulture Laboratory of Jimma University College of Agricultural Veterinary Medicine (JUCAVM). JUCAVM is geographically located at 346km southwest of Addis Ababa, lies at an elevation of 1710 meters above sea level and 7^0, 33’ N latitude and 36^0, 57’ E longitude. The mean annual rainfall of the area ranges from 1200 to 2000 mm. Within a year, the maximum temperature ranges from 25 ^{0}C to 30 ^{0}C from January to April while the minimum ranges from 7 ^{0}C to 12 ^{0}C, from October to December [21].

Experimental Materials

Different growing stages of the coffee plant (starting from seedlings to maturity) were selected from the horticulture demonstration site and these plants had the age of one, three, and five years. Then coffee plants were divided into three canopy layers (upper (C1), medium (C2), and lower canopies (C3). From each layer, five leaves were taken to measure leaf area and brought to the horticulture laboratory of JUCAVM to analyze nitrogen contents.

Treatments and Experimental Design

Nine treatments (three different growing stages, *i.e.*, one, three, and five-year aged plants each combine with three canopy layers (C1, C2 and C3) were used for the experiment. The experiment was laid out in a 3 x 3 factorial arrangement in Randomized Completely Block Design with four replications and a total of 36 experimental units.

Equipment and Tools

Equipment and tools were needed to facilitate the experiment and listed with their function in the following table.

Table 1: List of Equipment and Tools with their Functions

S. No	Equipment	Function
1	Analytical sensitive balance	To measure weight
2	Phenolphthalein ($C_{20}H_{14}O_4$)	Color indicator chemical
3	An oven	To dry sample of coffee leaves
4	Accu PAR LP-80 Ceptometer	To measure light interception in coffee canopies, and to calculate Leaf Area Index
5	Beaker	Mixing chemicals and sample
6	Flask	Distilled water and HCl holder
7	Dropper	Dropping sample and chemical
8	Burette	Titrating water measuring
9	Graduated cylinders	Measuring sample and distilled water
10	Kjeldahl	To analysis Nitrogen
11	Whatman filter papers	To filter digested leaves
12	0.1 N HCl solution	Titrating agent

Procedure

The selected coffee seedlings/plants were used to measure light intercepted and leaf area index to estimate light and nitrogen extinction coefficient. To avoid the poor quality of incident PAR, measurements were taken under clear skies with maximum sun height. Before taking the actual data, few measurements were taken above the canopy to check the reference sensor; thereby each canopy layer from each growing stage the actual measurement was taken by using an instrument AccuPAR LP-80 Ceptometer and data were recorded. From each growing stage and canopy layer, five green leaves were taken to measure leaf area, and these leaves were used to analyze total nitrogen concentration on both area and mass basis by using the Kjeldahl method after drying the leaves at 70^{o}C to constant weight. Finally, light and nitrogen extinction coefficients were estimated at each canopy layer and phonological stages.

Data Collected

Light interception measurements

The most common method of measuring the fraction of radiation intercepted by the crop canopy is using a line-source quantum sensor [26]. Fraction light interception from each canopy layer and growing stage were measured with AccuPAR LP-80 light rod. The ceptometer measures and calculates the average PAR incident on 80 sensors located at lcm intervals along with a narrow, 80-cm probe. Four measurements were taken circularly (≈90” intervals) at each height interval and averaged to provide a mean PAR value. The light rod was positioned horizontally and holding the rod from the edge to the center of the plant. Measurements were taken between 11:00 am to 3:00 pm during times with relatively stable incident solar radiation (without intermittent clouds) and the fraction light interception was calculated by the formula proposed by Board [22]:

$$LI = 1 – (I_t / I_0)$$

Where, I_t is incident photo synthetically active radiation (PAR) just below the lowest layer of photo synthetically active leaves, and I_0 is incident PAR at the top of the canopy.

Leaf Area Index (LAI)

LAI in this study was measured with a portable AccuPAR Ceptometer (Model LP-80, Decagon Devices, Inc.) and the instrument calculates LAI based on the above and below-canopy PAR measurements along with other variables that relate to the canopy architecture and position of the sun.

Leaf nitrogen content

Nitrogen content was determined using the micro Kjeldahl method. One gram of oven-dried material was placed in the digestion flask, 10g of powdered potassium sulfate, 0.5g of copper sulfate, and 25 ml of concentrated Sulphuric acid were added to it, and digestion conducted by placing the flask in an inclined position and heating it below the boiling point of acid for 10minutes. The temperature was raised until the acid boiled briskly. A funnel was placed in the mouth of the flask to restrict the circulation of air. Heating was continued till the solution became clear. The contents were cooled and diluted by adding 200 ml of water. 0.5g of Zinc and 50 ml of 40 % NaOH solution were added to make the reaction strongly alkaline. The contents were mixed and at once attached to the distillation apparatus. In the receiving flask 25 ml, 0.1 N HCl was taken. When two-thirds of the liquid had been distilled, it was tested for completion of the reaction. The flask was removed and titrated against 0.1 N HCl solution using methyl red indicator for determination of Kjeldahl nitrogen, which in turn gave the protein content [23].

$$\%N = \frac{(V - B)xNxRx14.01}{WtxCF}$$

Where, V = Volume of 0.01 N HCl titrated for the sample (mL), B = Digested blank titration volume (mL), N = Normality of HCl solution, 14.01= Atomic weight of N, CF = Correction factor for Atomic weight of N, Wt = Weight of sample (g)

The crude protein content was determined with a conversion factor of 6.25 [24]:

$$CP = CF \times TN$$

Where, CP = Crude protein, CF = Correction factor, TN = Total nitrogen

Light extinction coefficient

The extinction coefficient k depends upon the angle distribution of the leaves in the canopy and the angle of radiation (zenith solar angle) and has been reported to be specific to crop type and stage of development [25].

According to Kiniry [26], the light extinction coefficient (k) for Beer's law was determined from the Fraction light interception (LI) and the leaf area index (LAI) values. The light extinction coefficient k was calculated from transmitted (I_tPAR) and incoming (I_0PAR) as proposed by Flénet [27]:

$$TPAR/I_0PAR = 1- \exp(-k \times LAI)$$

By rearranging the above relationship, the following formula was obtained as reviewed by Kiniry [26]:

$$KL = -\ln(T)/LAI$$

Where, k_L= light extinction coefficient; T = transmittance fraction of incoming radiation; LAI = leaf area index.

Nitrogen extinction coefficient

The vertical *nitrogen* profile can be described with the nitrogen extinction coefficient (k_N), expressing an attenuation of light per unit leaf nitrogen and calculated by the formula stated by Jongschaap and Booij [28]:

$$K_{N} = \frac{-\ln(T)}{Leaf N}$$

Where, K_N= nitrogen extinction coefficient; T= transmittance fraction of incoming radiation; Leaf N= leaf nitrogen content.

Statistical Analysis

Analysis of variance was computed for each parameter to estimate light and nitrogen extinction coefficient at different canopy layers of the different growing stages of coffee based on the procedures described by Analysis of Variance (ANOVA) and computed using SAS version 9.2 [29]. For significant parameters, multiple comparisons of means were conducted to separate the means of significant effects including control by using the LSD (Least Significance Difference) test at $P < 5$ % probability levels.

Results and Discussion

Leaf Area, Leaf Area Index, Fraction of Light Intercepted, and Nitrogen Content of Leaf

The results obtained from the experiment revealed that the leaf area of a coffee plant at different canopy layers and the growing stage was measured. The effect of the growing stage for leaf area of coffee was highly significant ($P< 0.0006$) variation (Table 2). The highest LA (43.72 m^2) was obtained from five years old and the lowest (22.76 m^2) from one year age coffee. From this investigation, statistically, there is no variation across canopy layers for each growing stage even though numerically there is variation for LA. Leaf area index (LAI) and a fraction of light intercepted (Fi) by the coffee plant were measured and highly significant ($P< 0.0001$) variation among growing stage. The highest LAI (2.75) was obtained from coffee with the age of five years followed by three years old (0.684). The highest Fi (0.63) was also obtained from a plant five years old.

Table 2: Effect of growing stages on leaf area, leaf area index, a fraction of light intercepted, and nitrogen content of leaf of the coffee plant

Growing stages (in a year)	Leaf Area (m^2)	LAI	Fi	LN
Five	43.72^a	2.75^a	0.63^a	8.90^{Ns}
Three	30.62^b	0.684^b	0.21^b	7.68
One	22.76^c	0.513^b	0.22^b	7.56
LSD 5%	4.665	0.324	0.061	1.542

Ns= non-significance, *Means followed by the same letter(s) across row are not significantly different at ($P < 5\%$) As stated, LAI is an important factor in determining photosynthesis and subsequent biomass production. The present study revealed that there is a positive relationship between LAI and FI. This is in line with the work of [27] which is quantified that the increase in leaf area index, the light absorption of the canopy increases. Similarly, plants with high Fi may produce high photo assimilation, because it is directly related to the amount of biomass of the plant that is directly related to the growth of the plant. The present work also showed that there is a positive relationship between FI and leaf nitrogen concentration.

Likewise, Wong [30] in a similar way reported that in many plants, a positive relationship between photosynthetic capacity and leaf nitrogen concentration is observed. Some researchers believe that the leaf nitrogen distribution in a canopy light distribution pattern is similar; the canopy photosynthesis reaches its maximum [31]. The distribution pattern of nitrogen allocation to leaves is more exposed and thus the amount of photosynthesis per unit leaf area and canopy were optimized in wheat cultivars [32].

Light Extinction Coefficient (KL)

From the present finding, the light extinction coefficient (*K*L) for the coffee plant was estimated and the result revealed that highly significant (P<0.0003) variation (Figure 1) among the coffee with different growth stages. The highest value (0.506) was recorded from a plant with one year and the lowest (0.335) obtained from the plant with three years even though statistically no difference with the plant of five years. On the other hand, statistically, there is no difference within the canopy layer for each growing stage.

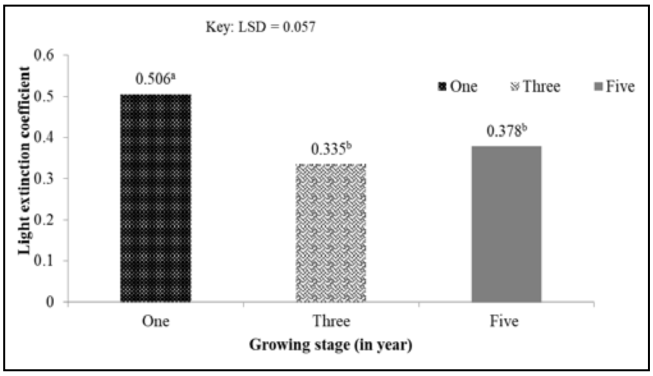

Fig 1: Mean light extinction coefficient of the *coffee* plant as influenced by growing stage (*Means followed by different alphabets differ significantly at P < 5%)*

The value of *K*L was estimated for each growing stage at different canopy layers and this value is inversely associated with LAI and Fi. Coffee plants of five years showed the highest LAI and Fi, but the value of *K*L for this growth stage is the lowest even though statistically similar to that of three years old plants. The reason why *K*L is largest for the plant with one year may be the data was taken at the mid-day when the solar angle is small.

Similarly, Flénet [27] reported in their work extinction coefficients decreased significantly as the solar angle increased during the day and the k-value was smallest at noon. Although we were unable to establish positive relationships between *K*L and LAI and Fi for the growing stage as well as the canopy layer of the coffee plant in our study, a more extensive and intensive study might reveal predictable relationships. For instance, [33] reported that a high amount of nitrogen (150 Kg h^{-1}) for wheat cultivars compared to control, produced the highest LAI higher light absorption and also [34, 35] reported that light extinction coefficient of the canopy is the absolute maximum. On the other hand, [28] found that the *K*L values decreased with increasing nitrogen supply and they also reported that relatively high *K*L values imply steep light gradients, i.e., relatively low light intensities deeper in the canopy, which is characteristic for potato crops [36].

Nitrogen Extinction Coefficient (KN)

The data on the nitrogen extinction coefficient of coffee with a different growing stage at different canopy layers was measured from randomly selected five normal leaves that were used for analyzing leaf nitrogen. The result revealed that very highly significant (P<0.0002) variations (Figure 2) between treatments. The highest *K*N (0.202) was obtained from coffee with an age of one year and the lowest (0.053) was obtained from the plant with five years even though statistically no difference with the plant of three years.

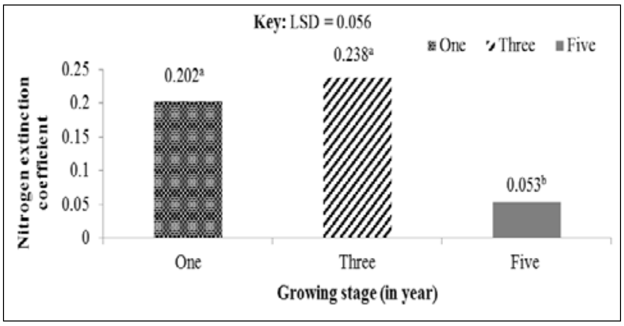

Fig 2: Mean nitrogen extinction coefficient of the *coffee* plant as influenced by growing stage (*Means followed by different alphabets differ significantly at P < 5%)*

Similarly, the value of *K*N across the canopy layer for the coffee plant with the different growing stage was estimated and as observed from the result (Figure 3), even though there is a numerical difference among canopy layer for the growing stage of one and three years, statistically there is no difference. On the other hand, for the coffee plant five years old, there is a significant difference variation in the canopy layer. Overall, the highest *K*N value (0.28) was recorded from the upper canopy layer (C1) of the plant with an age of three years and the lowest (0.037) from the lower canopy layer (C3) of the plant with an age of five years.

From the present finding, the value of *K*N was estimated and the relationship with leaf nitrogen at different growing stages and canopy layers did not follow a normal pattern. But as reported by [28] lower nitrogen supply resulted in higher *K*N values with time, indicating translocation of leaf nitrogen from lower leaf layers to top layers in the course of the growing season for the potato crop.

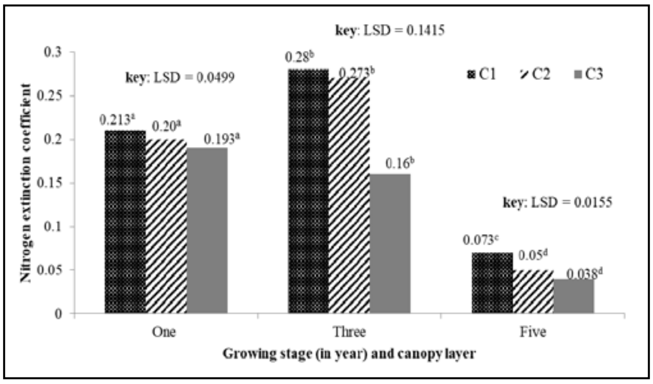

Fig 3: Mean nitrogen extinction coefficient of the *coffee* plant as influenced by canopy layer of each growing stage (*Means followed by different alphabets within a growing stage differ significantly at P < 5%)*

Summary and Conclusion

In crop plants, the effects of different light environments have been examined by comparing plants grown entirely at high light with individuals grown at a fixed level of shade or in agroforestry systems with homogeneous ground cover that varies from sparse to deep shade depending on the shelter tree attributes and management. Under favorable conditions, the radiation develops a decisive role for vegetal growth and development. This way, the radiant energy variation inside the culture field can provide a way to create conditions of canopy saturation, with the purpose of efficient use of solar energy for agricultural production. To generate such information, coffee plants at different growth stages at different canopy layers were tested in randomized complete block design at JUCAVM in the year 2018 main season. Results of analysis of variance revealed a static significance difference ($p<0.005$) for all parameters under study except for leaf area and leaf area index across canopy layer for each growth stage of the coffee plant. The range and mean values were medium to high for most of the parameters indicating the existence of variation among the different growing stages of the coffee plant. The highest leaf area, leaf area index, a fraction of light interception, and leaf nitrogen content were obtained from five years old coffee plant which indicating that as plants getting matured the leaf morphology of the crop increase and it directly affect light interception and nitrogen holding capacity of crops.

The present study generally implied that there is a significant influence of variation in growth stages on the light and nitrogen extinction coefficient of the coffee plant. Thus, younger plants can have high nitrogen and light extinction coefficient as compared to older plants.

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Conflicts of Interest

The authors have declared that there is no conflict of interest existing.

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