Interception of Photosynthetically Active on Cocoa Plantations in Mexico

Rutilo López-López[1], Waldo Ojeda-Bustamante[2], Mario Rodríguez-Cuevas[3], Marco Antonio Ibarra Inzunza[4], José Alfredo Jiménez-Chong[5]

[1,3,5]National Institute of Forestry, Agricultural and Animal Husbandry Research in Mexico (INIFAP). Experimental Station Huimanguillo. Km 1. Carretera Huimanguillo Cárdenas. Ap. 86400. Huimanguillo, Tabasco, México. Tel: 01 800 0882222 ext. 87515

[2]Mexican Institute of Water Technology. Jiutepec Morelos, México. C.P. 62550. Paseo Cuauhnáhuac 8532, Colonia Progreso. Jiutepec, Morelos, México

[4]Centro Nacional de Investigación Disciplinaria en Relación Agua Suelo Planta Atmósfera (CENID RASPA). INIFAP. Canal Sacramento km 6.5, margen derecha. Gómez Palacio, Dgo., México. 35140.

***Abstract*— *The cocoa or cacao tree (Theobroma cacao L.) requires shade to efficiently perform its physiological processes. The objectives of this study were to characterize the shading on cocoa plantations in the Chontalpa region of Tabasco to generate possible pruning and phytosanitary control recommendations, and to measure the PAR in three strata of the cocoa agroecosystems to determine the shade percentage and the amount of PAR intercepted by shade and cocoa trees in the sampled plots. PAR was measured in units of µmol/m^2/s using a ceptometer. PAR readings were taken on sunny days in three vertical strata, namely the upper, middle and lower parts, and an average of five readings per stratum were considered for plantations with 1 to 10 acres, and 25 to 30 readings per stratum for plantations greater than 10 hectares. The results for the plantations studied indicate that on average 49.1% of the PAR reaches the cocoa plants and only 10.3% reaches the soil surface. The PAR used by cocoa averaged 620 µmol/cm^2/s, which represent only 38.9% of the total incident radiation. The PAR measured in the middle and lower strata of the cocoa plantations has a negative logarithmic effect on the shade percentage and is a reliable indicator for estimating the shade percentage in cocoa plantations. There is a direct relationship between the intercepted PAR or shade percentage and the pruning practices performed by the producer on the cocoa plantations.*

***Keywords*— Cocoa productivity, Photosynthetically active radiation, Shade percentage, Shade trees.**

I. INTRODUCTION

Cocoa (*Theobroma cacao* L.) is the main source of income for 40-50 million people in producing areas located primarily in Africa, Asia, and Central and South America (within the tropical belt extending 20 degrees north and south from the equator) (Nadurille, 2010).

World production is distributed among the countries of South America, Central America, the Caribbean, Africa, Asia and Oceania, plus Mexico, and all of these countries have tropical wet forests. Cocoa cultivation originated in the Americas but the exact place of origin cannot be pinpointed (Batista, 2009). The cocoa is a native Amazonian species from neotropical lowlands and tropical rain forests and is now grown in more than 50 countries in the humid tropics (Motamayor *et al*., 2008).

The cocoa requires shading to efficiently perform its physiological processes. Traditionally cocoa has been grown under the protection of fast-growing species and other leguminous trees, including palm trees and tropical fruit trees. The association of timber trees with cocoa production systems maximizes the economic benefits to the farmer, making the system more sustainable in terms of conserving natural resources such as soil, water and biodiversity (Vanhovea *et al*., 2016).

Besides protecting the crop, shade trees offer additional benefits and services to the agroforestry system, such as nitrogen fixation (in the case of leguminous trees) and the production of leaf litter that becomes soil organic matter, which buffers against extreme weather conditions, such as temperature, wind and humidity. Cocoa associated with larger species creates stable conditions especially against the sun's heat effect, promotes nutrient recycling and therefore contributes to the sustainability of this system (Santana and Cábala 1987). In addition, cocoa producers generally benefit from shade tree species by using them as a source of energy (firewood) and tropical fine woods. This allows the system to be more sustainable from an economic standpoint, as it provides additional income (Somarriba *et al*., 2014), and ecologically contributes to the protection and conservation of soil and water resources, as well as to carbon sequestration and oxygen release (Abou Rajab, 2016).

Batista (2009) mentions that it is possible to cultivate cocoa without shade and even increase yield, but the disadvantages that this would entail in the long term have not been assessed. By removing the shade trees from cocoa plantations, it ceases to be a diversified agroecosystem and becomes a monoculture and is therefore no longer sustainable under current conditions; moreover, such a system requires the use of new technologies and application of crop inputs such as irrigation and chemical fertilizers.

Another factor that determines the shading level is pruning, is done to maintain the cocoa tree's proper shape, facilitate crop management tasks and decrease the presence of pests and diseases. The types of pruning performed on cocoa plantations include shape pruning, maintenance pruning and restoration and sanitation pruning (López *et al*., 2016).

Photosynthetically active radiation (PAR) is the radiation that crops use to perform their vital functions in allphenological stages. Unlike most crops, cocoa grows well under shaded conditions. The crop uses only a portion of the photosynthetically active radiation that reaches the plantation, as the rest is intercepted by the shade trees; therefore, correct management of the shading level on cocoa plantations is of utmost importance (Batista, 2009). The most accurate and practical method to indirectly estimate shading is the use of a ceptometer, which estimates the PAR at various heights of the plant to determine the interception of radiation when penetrating the foliage in an agroforestry system, and it can be used in studies which require quantitatively relating the effect of shade on production.

The level of shading or its opposite, the level of sunlight that penetrates the plantation, determines the photosynthetic rate of agricultural crops in the lower strata, their growth, their demand for nutrients and water, the dynamics of pests and diseases and ultimately the commercial production. Shade trees on cocoa plantations provide environmental, economic and social benefits to the home, the environment and society (Almeida *et al*. 2002).

Despite their importance, no studies have been conducted in Mexico related to shading levels on cocoa plantations. Consequently, the objectives of this study were: i) to characterize the shading level on cocoa plantations in the Chontalpa region of Tabasco, Mexico to generate possible recommendations related to agronomic management of the crop; ii) to measure the PAR in three strata of the cocoa agroecosystem to determine the shade percentage in producer plots and iii) to determine the interception percentage of the shade and cocoa trees (shade percentage).

II. MATERIAL AND METHOD

2.1 Study area

The study was conducted in the Chontalpa region of Tabasco, Mexico, consisting of the municipalities of Cárdenas, Comalcalco, Cunduacán, Huimanguillo, Jalpa de Méndez and Paraíso. The climate is hot and humid with summer rains; average rainfall is about 2000 mm per year, and the mean annual temperature is between 25 and 27°C, with the highest temperatures occurring in April and May. Throughout the year, Tabasco receives 20% of the radiation reaching the outside atmosphere on cloudy days, 58% of the radiation that should reach the surface on clear days and the radiation received on clear days is between 76 to 81% of what reaches the outside atmosphere. The predominant crops in the study area are cocoa, coconut, banana, citrus fruits, sugar cane, watermelon, cantaloupe, pineapple, corn for fodder or self-consumption and beans grown in small areas. Cocoa is a crop of great importance and is found in all the municipalities comprising the study region. A total of 32 plantations located in the municipalities of Huimanguillo, Cárdenas, Cunduacán and Comalcalco, all in the state of Tabasco, Mexico, were sampled. One plantation studied is located in the Huimanguillo Experimental Field in Huimanguillo, Tabasco, where there have been a variety of studies to understand the behavior and management of cocoa plantations.

2.2 Soils

The soils used for growing cocoa are derived from river, lake or marine sediments; they have organic carbon content that decreases irregularly with depth or remains above 0.20% at a depth of 1.25 m from the soil surface. The eutric and eutri-gleyic fluvisol subunits, the latter to separate the fluvisols presenting gleyic characteristics due to a high phreatic mantl eat some time during the year, have been identified. Both soil types are locally known as tierras de vega de rio (riverplain soils).

2.3 Determination of shade species

To designate the shade species present in the sampled plots, the following classification scheme based on the number and diversity of species in the agroecosystems was proposed: Single shade species, where there is only one tree species; main shade species, present in greatest proportion; secondary shade species in the agroecosystem in relation to the main species and low-proportion species, those species whose density is marginal.

To obtain the data on the shade species, the producers were surveyed and their information verified in the field. Once these data were obtained, the shade trees were then grouped according to their type (fruit, leguminous, timber and native trees).

2.4 Measurement of photosynthetically active radiation (PAR)

The measurement of photosynthetically active radiation (PAR) photons was performed using an AccuPar-LP80 model ceptometer, in units of µmol/m^2/s. This device can estimate leaf area index (LAI) once crop parameters are calibrated (Figure 1).

FIGURE 1. TREE SPECIES USED FOR SHADING COCOA AND ESTIMATION OF PHOTOSYNTHETICALLY ACTIVE RADIATION INTERCEPTION ON COCOA PLANTATIONS IN MEXICO.

PAR readings were taken in the three vertical strata of the sampled plantations: upper part (outside the plantation), middle part (to 2.5 m high), and lower part (to 0.5 m high), and an average of five readings per stratum were taken for plantations with areas from 1 to 10 hectares. In plantations with areas larger than 10 acres, between 25 and 30 readings per stratum were taken.

PAR measurements were made above the cocoa tree canopy using an aluminum ladder. As for obtaining the value of the PAR that reaches the upper part of the shade tree canopy, five readings were taken in an open area outside of the plantation, without any kind of interference, assuming that the radiation reaching the crown of these trees has no interference.

The readings were taken on sunny days with the fewest clouds possible. The plots were sampled from 11:00 to 15:00 h to take advantage of the hours when solar radiation is the highest. Data collection was carried out in the period from March 2 to July 18, 2012.

A survey was administered to the 32 producers of the sampled plots to learn about the characteristics and management of their plantations.

2.5 Measurement Variables

To determine the shade percentage (S*f*) of the plantations, the PAR interception percentage as expressed in the following equation was used:

$$Sf = 100 - \left(\frac{PARm}{PARu} \right) 100 \tag{1}$$

Where *PARm* is the photosynthetically active radiation of the middle stratum and *PARu* is the photosynthetically active radiation of the upper part open to the sky.

2.6 Statistical Analysis

Analysis of the shade percentage and shade tree species was performed by using descriptive statistics such as arithmetic mean, standard deviation, and obtaining maximum and minimum values. Once the continuous measurement variables were correlated, simple and multiple regression functions were obtained to quantitatively explain the effect of one or more variables on a continuous dependent variable. The parameters of the regression functions based on the probability of significance ($p<0.05$) were selected using the Statistical Analysis System, and through Excel software, simple or multiple regression models, which were selected from the coefficient of determination (R^2), were obtained.

III. RESULTS AND DISCUSSION

3.1 Tree species used for shading cocoa

Several authors have characterized cocoa as sciophilous or "shade-loving," indicating that it thrives where its foliage is not directly exposed to sunlight (Paredes and Montero, 2004). The cocoa requires shading mainly in places with clear skies for much of the year and that shading itself can classified into two types: temporary shading, which is used during the first three years, and permanent shading, which is used from three years onwards; therefore, the species used for this latter type of shading should have a useful life of 30 years or more. Shade trees should be planted before establishing the cocoa plantation. Below the shade species and their distribution percentage (Table 1) in the cocoa plantations sampled are described:

TABLE 1
SHADE SPECIES AND THEIR DISTRIBUTION PERCENTAGE IN THE COCOA PLANTATIONS SAMPLED.

Scientific name	Common name	Overall presence	Single species	Main species	Secondary species	Minimum proportion
		Total % of plots with the species				
Gliricidia sepium	Cocoite	40.6	3.1	18.8	18.8	0.0
Eritrhyna sp.	Mote or madre cacao	34.4	0.0	18.8	12.5	3.1
Diphysa Americana	Chipilín	28.1	0.0	15.6	12.5	0.0
Tabebuia Mexicana	Macuili	37.5	3.1	9.4	12.5	12.5
Cedrellaodorata	Spanish cedar	40.6	3.1	0.0	12.5	25.0
Colubrina arborescens	Wild coffee	21.8	3.1	0.0	9.4	9.4
Samanea samán Albizia samán	Saman	15.6	0.0	6.25	0.0	9.4
Others	Fruit and pepper trees	93.7	0.0	3,1	40.6	50.0
Native trees	Various species	59.4	0.0	9.4	15.6	34.4

The cocoite (*Gliricidia sepium)* is one of the species most commonly used in the region as the main shade tree for cocoa plantations, which is true for 18.8% of the plots sampled in this study. It is also sometimes used as the single shade species, which is the case for 3.1% of this sample, and it is a secondary shade species in 18.8% of the plots sampled. In total, the cocoite is present in 40.6% of the sampled plantations.

The mote ormadre de cacao *(Eritrhyna sp.)* is also one of the species most commonly used as a permanent shade tree in cocoa farming. In the Chontal paregion, it is also one of the species most widely used as the main shade tree (Sánchez *et al*., 2016). When cocoa was introduced into the area, the mote tree was also propagated in the region using cuttings of this species to establish them in cocoa plantations. This species was found in 18.8% of the plantations as the main shade species, in 2.5% as a secondary shade species and in 3.1% as a low-proportion shade species. The mote is present in 34.3% of the sampled plots. In this regard, *Erytrina sp* is considered as a tropical species that is used for shading in cocoa farming to improve productivity.

Another common species used as the main shade tree in the agroecosystems studied is the chipilin (*Diphysa americana*). One of the main problems with this species is that they are old trees that have lost a lot of their foliage and branches, so they have a low crop shade percentage. This species was found in 15.6% of the plantations as the main shade species and in 12.5% as a secondary shade species. It is present in 28.1% of the sampled plantations.

The macuili (*Tabebuia mexicana*) was found in 3.1% of the plantations as the single shade species, in 9.4% as the main shade species, in 12.5% as a secondary species and in 12.5% as a low-proportion shade tree. It is found in 37.5% of the sampled plantations.

The Spanish cedar (*Cedrela odorata*) is one the most important timber species in the region (Sánchez *et al*., 2016). It is the single shade species in 3.1% of the plantations sampled, a secondary shade tree in 12.5% and a low-proportion shade tree in 25%. As are (2005) recommends the use of forest tree species suitable for the cocoa agroecosystem that can be sustainable in the long term, through restoration, addition and recycling of soil nutrients. It is present in 40.6% of the sampled plantations.

The wild coffee tree (*Colubrina arborescens*) was found in 21.8% of the plantations, in only 3.12% as the single shade tree, in 9.4% as a secondary shade tree and in the same proportion as a low-proportion shade tree.

The saman (*Samanea samán* or *Albiziasamán*) was present in 15.6% of the sampled plantations, distributed in 6.3% of the plots as the single shade species and in 9.4% as a low-proportion shade tree.

Currently promoting the use of commercial tree species to replace the traditionally recommended species, such as the genera *Gliricidia* and *Erythrina cassias*, among others, that offer limited additional benefits. Timber species (Sánchez *et al*., 2016), in addition to shading cocoa, provide products such as timber, logs, poles and other secondary products such as seeds. Cocoa production has undergone an interesting twist as a result of the recommended use of permanent shade trees, which, as well as shade, generate additional benefits such as timber and tropical fruits.

Fruit trees such as avocado, citruses, pepper, *pan de sopa*, sapote and mango, to name the most important, are the species with the largest presence in the cocoa plantations sampled. They were found in 3.1% as the main shade tree, in 40.6% as a secondary shade species and in 50% as a low-proportion shade tree; they were present in a total of 93.7% of the sampled plots.

Native trees, such as the guácimo (*Guazuma ulmifolia*), are widely used as firewood due to their quick regeneration. They rank second in terms of their presence in the agroecosystems, and are found as the main shade tree in 9.4% of the plots, as a secondary tree in 15.6% and as a low-proportion shade species in 34.4% of the plots; they are present in 59.4% of the sampled plantations.

3.2 Interception of photosynthetically active radiation (PAR) by shade trees and cocoa

In the Huimanguillo Experimental Field plot, photosynthetically active radiation readings were taken at one-hour intervals on a clear day (July 16, 2012), from 8:00 am to 14:00 h.

Figure 2 shows that the highest PAR values occurred from 12:00 to 13:00 h; PAR increases from 9:00 to 12:00 h and decreases from 13:00 h onwards. The opposite occurs with shading: when PAR is higher in the upper part of the agroecosystem, the shade percentage is lower; therefore, shading is the inverse of PAR. Table 2 shows the PAR average values in the three strata sampled in the cocoa plantations studied (n=32) and their shade percentage or radiation intercepted by the shade and cocoa trees. It can be seen that there is a 50.9% shading average in the upper part; this value is high to achieve satisfactory productivity and adequate phytosanitary control. The standard deviation (S) was 15.7%, which expresses the degree of data dispersion, with a maximum value (79.7%) and minimum (14.3%) value. The PAR used by cocoa averaged 620 $\mu mol/cm^2/s$, which represents only 38.9% of the total incident radiation. In the lower layer, the average shade percentage or intercepted PAR is 89.7% with S=9.28%. These values showed cacao plants increasing rates of net photosynthesis as the PAR increases to values in the range from near 400 to 750 (Da Matta *et al*., 2001) $\mu mol/cm^2/s$, corresponding to 20-30% of PAR at full sunlight.

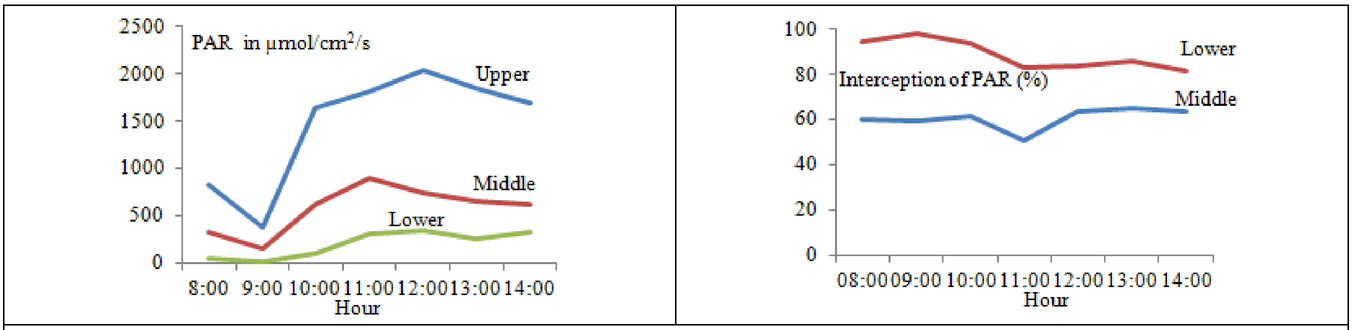

FIGURE 2. A) VARIATION IN PHOTOSYNTHETICALLY ACTIVE RADIATION. B) THE AMOUNT OF PAR INTERCEPTED OR SHADE PERCENTAGE ON A CLEAR DAY (JULY 16, 2012) AT THE HUIMANGUILLO EXPERIMENTAL FIELD, HUIMANGUILLO, TABASCO, MEXICO.

Regarding the potential yield of cacao beans under different shading conditions, Zuidema *et al*. (2005) used the Simple and Universal Crop Growth Simulator (SUCROS) model. They showed that moderate shade levels hardly affected bean yield, while shading greater than 60% reduced yields by more than one-third.

TABLE 2
PHOTOSYNTHETICALLY ACTIVE RADIATION (PAR) VALUES IN THE UPPER (PARu), MIDDLE (PARm) AND LOWER (PARl) STRATA, AND INTERCEPTION PERCENTAGE OR SHADE PERCENTAGE IN THE MIDDLE PART (Spm) AND LOWER PART (Spl) OF THE COCOA AGROECOSYSTEM AND SHADE TREES.

Plot	*PARu*	*PARm*	*PARl*	*Spm*	*Spl*
1	1941	972	442	49.92	77.23
2	1884	957	437	49.2	76.80
3	1793	834	284	53.48	84.16
4	1751	807	274	53.91	84.35
5	1970	1013	508	48.57	74.21
6	1716	718	214	58.15	87.53
7	1758	921	133	47.61	92.43
8	1954	1134	180	41.96	90.79
9	2021	834	179	58.73	91.14
10	2272	1150	133	49.38	94.15
11	2014	1100	124	45.38	93.84
12	1837	1369	705	25.47	61.62
13	1880	1050	600	44.14	68.09
14	845	222	15	73.72	98.22
15	692	140	10	79.76	98.55
16	1075	644	16	40.09	98.51
17	612	397	13	35.13	97.88
18	1031	883	16	14.35	98.45
19	920	631	75	31.41	91.85
20	816	527	126	35.41	84.56
21	2241	1594	35	28.87	98.44
22	2057	850	39	58.67	98.10
23	1952	689	173	64.7	91.14
24	1800	433	54	75.94	97.00
25	1052	608	71	42.2	93.25
26	2005	1085	155	45.88	92.27
27	2045	980	220	52.07	89.24
28	1380	576	137	58.26	90.07
29	1645	881	94	46.44	94.29
30	1772	436	50	75.39	97.18
31	2157	668	180	69.03	91.66
32	2035	503	89	75.28	95.63
Average	1653.8	800.2	180.6	50.9	89.8
Standard Deviation (S)	490.9	317.5	177.8	15.7	9.3
Max. Value	2272	1594	705	79.8	98.5
Min. Value	612	140	10	14.3	61.6

PARu is the PAR in the upper part of the agroecosystem; *PARm* is the PAR in the middle part; *PARl* is the PAR in the lower part, and *Sfm* and *Sfl* are the shade percentage of the middle and lower strata, respectively, of the plantation.

Figure 3 A shows the effect of lower-stratum PAR on the shade percentage of the cocoa plantations. It can be seen that it has a negative logarithmic trendline ($Sf=-8.9\ ln(x)+100.5$) with a coefficient of determination (R^2) equal to 0.65. The model explains the relationship between the lower-stratum PAR and the behavior of the shade percentage of the cocoa plantations, which is as follows: the higher the radiation, the lower the shade percentage tends to be due to the interception of the shade trees and cocoa.

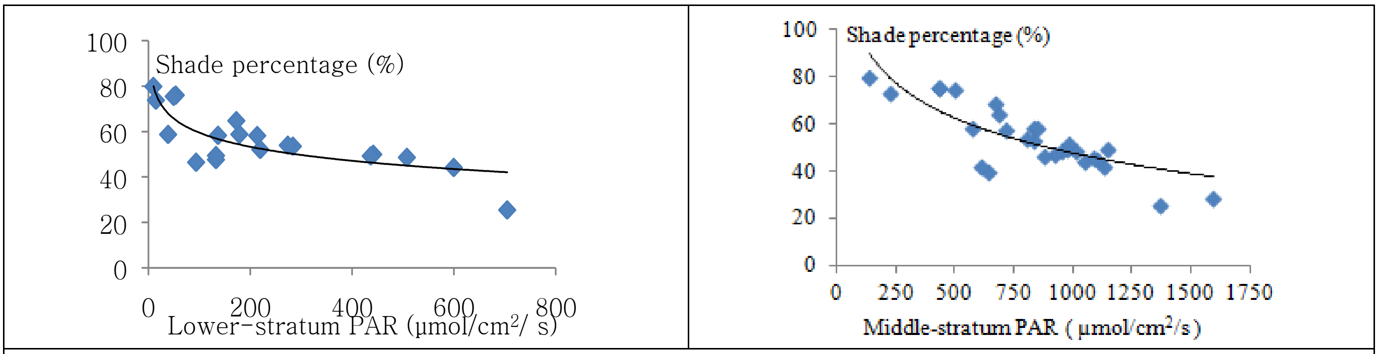

FIGURE 3. A) EFFECT OF LOWER-STRATUM AND B) MIDDLE-STRATUM PHOTOSYNTHETICALLY ACTIVE RADIATION ON THE SHADE PERCENTAGE OF THE COCOA PLANTATIONS.

Figure 3B shows the relationship between the middle-stratum PAR and the shade percentage of the plantations. It can also be seen that it has a negative logarithmic trendline ($Sf=-21.6\ ln(x)\ +196.7$) with a coefficient of determination (R^2) equal to 0.65. This means that the model adequately explains the effect of middle-stratum PAR on the behavior of the shade percentage of cocoa plantations. The shade percentage is lower than in the lower stratum. The relationship between the shade percentage and the middle-stratum PAR is similar to that of the lower stratum, where the shade percentage tends to decrease logarithmically with increasing PAR.

The most important parameters determinants of yield which are related are the light interception and photosynthesis, events that can be modified by abiotic factors (Almeida and Valle 2007). Cocoa is a shade tolerant species, in which appropriate shading leads to relatively high photosynthetic rates, growth and seed yield. However, heavy shade reduces seed yield and increases incidence of diseases; in fact, cacao yields and light interception are tightly related when nutrient availability is not limiting. High production of non-shaded cacao requires high inputs in protection and nutrition of the crop.

3.3 Phytosanitary pruning and shade tree pruning

Phytosanitary pruning involves removing dead or diseased branches. In total, 92% of surveyed producers carry out phytosanitary pruning on their crop and 8% do not. The removal of damaged or diseased fruit from cocoa trees in order to avoid contaminating the healthy fruit is a recommended disease management and control practice. Most producers do this work primarily to prevent damage caused by *Moniliophthor aroreri*, causal agent of frosty pod rot of cacao, is the main parasitic infestation that limits cacao production in the state; losses caused by this parasite exceed 75% of the annual production, thus causing social, economic and environmental negative effects (Ortíz-García *et al.*, 2015) and black pod (*Phytoptora palmivora*). To combat these diseases, various researchers recommend regulating the permanent shading level of cocoa plantations to facilitate the passage of light and air, by pruning the shade trees (López *et al.*, 2016), mainly the branches that are very close to the cocoa plants to reduce moisture, no relationship was found between phytosanitary pruning and cocoa bean yield, or with intercepted PAR or the shade percentage in the middle and lower strata ($P>0.05$).

About 16% of surveyed farmers prune their shade trees (PR), 20% have done thinning and 64% do not perform this task, which clearly explains why the average shade percentage obtained in the middle and lower parts are high (50.9 and 89.7%, respectively). Based on Dubón and Sánchez (2013) recommendation, this should be 30% to obtain good cocoa production. Pruning shade trees is important for growing cocoa because it allows in more light and this helps to control diseases such as frosty pod rot (*Moniliophthor aroreri*), witches' broom (*Crinipellisperniciosa*) and black pod (*Phytoptora palmivora*).

Shade tree pruning has a highly significant ($P=0.005$) relationship with cocoa yield ($R=0.53$) with a linear function $Y=303.85+129.5(PR)$. This relationship indicates that the greater the number of prunings in the shade trees, the higher the cocoa yield.

The interception of PAR or shade percentage in the middle and lower strata has a negative linear relationship with shade tree pruning [*Spm=52.7-7.3(PR)* and *Spl=92.2-4.79(PR)*, respectively]. These functions indicate that the shading level on cocoa plantations decreases when the number of shade tree prunings increases. In this regard, Paredes and Montero (2004) indicated that the effect of shade when starting a plantation is not only to reduce the light, but also to protect the plants from strong air currents that harm them just as much or more than the combined effect of temperature and light. Once the plant's development enables self-shading, shading should be gradually phased out until an equilibrium point is reached. To achieve this, the shade trees should be pruned once or twice a year. The cocoa crop needs shade for good development; in the first years, the amount of shade required by the crop is greater than when it reaches its production stage. For this reason, it is important to regulate shading based on the age of the plantation (López *et al*., 2016).

IV. CONCLUSION

The shade percentage present in the cocoa plantations, based on the PAR measured, averaged 50.9% and 89.7% in the middle and lower strata, respectively. The PAR used by cocoa averaged 620 µmol/cm^2/s, which represents only 38.9% of the total incident radiation.

The photosynthetically active radiation measured in the middle and lower strata of the cocoa plantations has a negative logarithmic effect on the shade percentage and is a reliable indicator for estimating the shade percentage.

There is a direct relationship between the intercepted PAR or shade percentage and the pruning practices performed by the producer on the cocoa plantations. Increased shading is closely related to less pruning and consequently greater damage from fungal diseases.

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