

NET PHOTOSYNTHESIS AND CO₂ COMPENSATION CONCENTRATION IN THREE COFFEE (*Coffea* sp.) GENOTYPES, BEAN AND MAIZE UNDER THREE TEMPERATURES

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ABSTRACT

*The coffee (**Coffea arabica** L.) genotypes Colombia, Caturra, and Híbrido de Timor, and bean (**Phaseolus vulgaris** L.) and maize (**Zea mays** L.) plants were exposed to three temperatures (15°C, 25°C and 35°C), and net photosynthetic rates (P_N) and CO₂ compensation concentrations (Γ CO₂) were measured. P_N in coffee leaves was similar for the three genotypes at 15 °C [5,0 – 5,3 $\mu\text{mol}(\text{CO}_2) \text{ m}^{-2}\text{s}^{-1}$] and 35 °C [4,9 – 5,5 $\mu\text{mol}(\text{CO}_2) \text{ m}^{-2}\text{s}^{-1}$], but lower at 25 °C [5,4 – 11,7 $\mu\text{mol}(\text{CO}_2) \text{ m}^{-2}\text{s}^{-1}$]. Γ CO₂ increased with temperature in coffee and bean, while in maize no effect was observed. P_N and Γ CO₂ values documented in coffee genotypes were typical for C₃ plants.*

Key words: Coffee, *Coffea arabica* L., CO₂ compensation concentration, leaf temperature, net photosynthesis, bean, maize.

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RESUMEN

FOTOSÍNTESIS NETA Y CONCENTRACIÓN DE COMPENSACIÓN DE CO₂ EN TRES GENOTIPOS DE CAFÉ (*Coffea sp.*), FRÍJOL Y MAÍZ BAJO TRES TEMPERATURAS

Se expusieron plantas de café *Coffea arabica* L. de los genotipos Colombia, Caturra e Híbrido de Timor, fríjol (*Phaseolus vulgaris* L.), maíz (*Zea mays* L.), a tres temperaturas (15 °C, 25 °C y 35 °C); se midió la fotosíntesis neta (P_N) y se obtuvo la concentración de compensación de CO₂ (Γ CO₂). P_N en las hojas de café fueron similares para los tres genotipos a 15 °C [$5,0 - 5,3 \mu\text{mol}(\text{CO}_2) \text{ m}^{-2}\text{s}^{-1}$] y 35 °C [$4,9 - 5,5 \mu\text{mol}(\text{CO}_2) \text{ m}^{-2}\text{s}^{-1}$] pero más bajas a 25 °C [$5,4 - 11,7 \mu\text{mol}(\text{CO}_2) \text{ m}^{-2}\text{s}^{-1}$]. El Γ CO₂ en café y fríjol se incrementó con la temperatura, mientras en maíz no se presentó ningún efecto. Los valores observados P_N y de Γ CO₂ en los genotipos de café fueron los típicos de plantas C₃.

Palabras clave: Café, *Coffea arabica* L., concentración de compensación de CO₂, temperatura de la hoja, fotosíntesis neta, fríjol, maíz.

Abbreviations: ATP – adenosine triphosphate; NADH – nicotinamide adenine dinucleotide reduced form; PAR – photosynthetic active radiation; P_i – inorganic phosphate; P_N – net photosynthesis; RuDP – Ribulose 1,5-diphosphate; VPD – vapour pressure deficit; Γ CO₂ – CO₂ compensation concentration.

Continuous increase in concentration of CO₂ and other atmospheric gases are contributing to the rise of global air temperature, causing variations in plant growth (Kimball *et al.*, 1993; Taylor *et al.*, 1994).

The effect of temperature on photosynthesis depends on plant species and environmental conditions under which the plant is growing (Kimball *et al.*, 1993; Larcher, 1995). In general, optimum temperatures for photosynthesis in C₃ plants with high Γ CO₂ are between 20 °C and 25 °C, while for C₄ plants optimum temperature is between 30 °C and 40 °C (Fitter and Hay, 1987; Kimball *et al.*, 1993). Γ CO₂ has been used to estimate photosynthetic efficiency: In C₄ plants this value is near to zero, which makes them photosynthetically more efficient than C₃

plants, which have Γ CO₂ values above [$30 \mu\text{mol}(\text{CO}_2)\text{mol}^{-1}(\text{air})$] (Kennedy 1976, Ogren, 1984, Kimball *et al.*, 1993; Taylor *et al.*, 1994).

In coffee, the study of factors that influence photosynthesis started with the works of Nutman (1937), who established that P_N is higher under low light intensities and leaf temperatures because stomatal opening is not affected. Nunes *et al.* (1968) and Kumar and Tieszen (1980), confirmed Nutman's observations and found that optimum temperature for photosynthetic activity is between 20 °C and 25 °C.

Photosynthesis in C₃ plants is limited by photorespiration and most of this activity is closely related to temperature (Zelitch, 1971; Long, 1991 and Pastenes, 1996).

Pioneer works of Decker and Tio (1959) showed that photosynthesis in coffee leaves were cancelled almost immediately by respiration in the presence of light (photorespiration) and only a small fraction was left as net gain. Heath and Orchard (1957), Jones and Mansfield (1970), and Sondhal (1976) studied ΓCO_2 as an estimate for photosynthesis efficiency involving photorespiration, and found ΓCO_2 values close to $[65 \mu\text{mol}(\text{CO}_2)\text{mol}^{-1}(\text{air})]$ at 25°C.

The objective of this research was to study the behavior of P_N and ΓCO_2 , under different temperatures, in three coffee (*Coffea arabica* L.) genotypes, bean (*Phaseolus vulgaris* L.), and maize (*Zea mays* L.), under conditions of the Colombian central coffee-growing zone.

MATERIALS AND METHODS

This research was performed at the Centro Nacional de Investigaciones de Café CENICAFE, Chinchiná, Colombia, 5°01' N, 75°36' W, altitude of 1425 m, mean annual temperature of 20,6 °C, 2530 mm cumulative rainfall and 1830 hours cumulative sunshine.

8 months *Coffea arabica* L. cv. Caturra, Colombia, and interspecific natural hybrid "Híbrido de Timor" - plants; bean (*Phaseolus vulgaris* L. cv. Ica Cafetero PVA 916) and maize (*Zea mays* L. cv. ICA V305) plants were 45 days old. All were planted in individual pots with soil and decomposed coffee fruit pericarp (3:1), and growing under full exposition to sunlight. Net photosynthesis rate (P_N) was measured with a portable photosynthesis system

(model 6200, LI-COR, Lincoln, NE, U.S.A.), infrared gas analyzer (IRGA), data logger, and a 4 L Plexiglas leaf chamber. P_N was measured on two mature leaves of the higher part of five plants per genotype, between 08:00 hours and 12:00 hours, with photosynthetic active radiation (PAR) above $[600 \mu\text{mol}(\text{photon}) \text{m}^{-2} \text{s}^{-1}]$, measured with a quantum sensor (model LI-190S-1, LI-COR, Lincoln, NE, U.S.A.). Air and leaf temperatures inside the chamber (15 °C, 25 °C, and 35 °C) were maintained with a JULABO-J10 recirculation water system. Measurement started with air containing $[450 \mu\text{mol}(\text{CO}_2) \text{mol}^{-1}(\text{air})]$ and P_N was recorded for every $[50 \mu\text{mol}(\text{CO}_2) \text{mol}^{-1}(\text{air})]$ decrease inside the leaf chamber until a constant CO₂ concentration (ΓCO_2) was reached.

RESULTS AND DISCUSSION

The highest P_N observed for the three genotypes $[11,7 \mu\text{mol}(\text{CO}_2)\text{m}^{-2} \text{s}^{-1}]$ was reached at 25°C and $[350 \mu\text{mol}(\text{CO}_2) \text{mol}^{-1}(\text{air})]$ (Figure 1a), with values higher than those reported by Nutman (1937) $[0,44 - 2,84 \mu\text{mol}(\text{CO}_2) \text{m}^{-2}\text{s}^{-1}]$ at 25°C; Nunes *et al.*, (1968) $[3,51 - 4,41 \mu\text{mol}(\text{CO}_2) \text{m}^{-2}\text{s}^{-1}]$ at 24°C; Sondhal (1976) $[3,87 \mu\text{mol}(\text{CO}_2) \text{m}^{-2}\text{s}^{-1}]$ at 20°C; Yamaguchi and Friend (1979) $[3,5 \mu\text{mol}(\text{CO}_2) \text{m}^{-2}\text{s}^{-1}]$ at 25°C and Friend (1984) $[4,4 \mu\text{mol}(\text{CO}_2) \text{m}^{-2}\text{s}^{-1}]$. Temperature influenced P_N directly, when measured at $[350 \mu\text{mol}(\text{CO}_2) \text{mol}^{-1}(\text{air})]$ (Table 1), values obtained at 15 °C and 35 °C were similar, but lower than those at 25 °C. At 15 °C, P_N would be limited by RuDP regeneration, because electronic transport velocity diminishes and consequently ATP and NADH formation are limited, and P_i regeneration capacity during starch and sucrose synthesis is lowered, as well as

carbohydrate transport from chloroplasts (Azcon-Bieto, 1983; Makino, Nakano and Mae, 1994). Another limitation is Rubisco activity because its optimum activation temperature in coffee is between 25 °C and 28 °C (Riaño and López, 1998), similar to what has been reported for other perennial species (Woodrow and Berry, 1988). At 35 °C, decrease in P_N would be related to stomatal closure, leaf sensitivity to increase in water vapor pressure deficit (VPD) as reported by Hernández, Cock and E-Sharkawy (1989), and the increase of photorespiration due to increase of oxygenase activity on RuBPCO, caused by higher diffusion of O_2 to the active site, which causes an additional CO_2 loss (Zelitch, 1971; Ogren, 1984; Lawlor, 1987; Poorter, 1993; Pearson and Brooks, 1995; Pastenes and Horton, 1996a,b), thus lowering photosynthetic efficiency. Additionally, temperatures above the optimum reduce RuBPCO content, as reported by Vu *et al.*, (1997) in soybean and rice.

In bean plants (Figure 1b), P_N increased slightly with temperature variation despite being considered a C_3 plant. The genotype used, ICA Cafetero PVA 916, adapted to the Colombian central coffee-growing zone conditions, [1000 - 2000 m of altitude], accounts for this behavior, even though ΓCO_2 was within the range for C_3 plants (Table 2).

Maize (C_4 photosynthetic metabolism), showed an increase in P_N with temperature increase, reaching highest values at 35 °C (Figure 1c). High temperatures induced higher activity of phosphoenol pyruvate carboxylase (PEPC) in this species (Tolbert, 1980; Ogren, 1984).

Two groups, according to photosynthetic activity are formed (Figure 2) for 25 °C and several CO_2 concentrations. The first group is conformed by coffee and bean with P_N between [5,4 and 13 $\mu mol(CO_2) m^{-2}s^{-1}$], and the second group is represented by maize with higher rates [18,6 $\mu mol(CO_2) m^{-2}s^{-1}$].

For the species studied, the lower the CO_2 concentration at the three temperatures (15 °C, 25 °C, and 35 °C), the lower the P_N , until CO_2 compensation point is reached, where photosynthesis rate is equal to CO_2 release by photorespiration and mitochondrial respiration (Espie and Colman, 1987). In coffee and bean, ΓCO_2 increased with temperature, while in maize no changes were observed (Table 2). This increase in ΓCO_2 with higher temperatures in coffee and bean indicates the occurrence of photorespiration, not detected in maize (Zelitch, 1971; Canvin, 1979; Tolbert, 1980; Ogren, 1984).

Highest ΓCO_2 value at 25 °C in coffee was observed with Híbrido de Timor [$80,1 \pm 1,9 \mu mol(CO_2) mol^{-1}(air)$], suggesting the occurrence of a higher photorespiration rate in this genotype, followed by Caturra [$45,6 \pm 1,3 \mu mol(CO_2) mol^{-1}(air)$] and Colombia [$40,6 \pm 1,0 \mu mol(CO_2) mol^{-1}(air)$]. For the last two genotypes, ΓCO_2 values are lower than those found by Jones and Mansfield (1970) [$85 \mu mol(CO_2) mol^{-1}(air)$] and Sondhal (1976) [$65 \mu mol(CO_2) mol^{-1}(air)$], at 23 °C and 25 °C, respectively. ΓCO_2 at 25 °C in bean plants [$36,05 \pm 0,5 \mu mol(CO_2) mol^{-1}(air)$], and maize [$0,8 \pm 0,3 \mu mol(CO_2) mol^{-1}(air)$] are similar to the values presented by Zelitch (1971).

In *Coffea arabica* L. cv. Colombia and bean, 60-65 minutes were necessary to reach ΓCO_2 , while in maize only 25 min were needed (Figure 3). Comparison of times necessary to reach ΓCO_2 in C₃ and C₄ plants is an evidence of the level of competition caused by photo-respiration in C₃ plants, which is poorly reported in literature. Under the same temperature and initial CO₂ concentration in a closed system, more time is required by C₃ plants due to significant return of the CO₂ fixed to the environment by photorespiration (Zelitch, 1971; Tolbert, 1980; Ogren, 1984). In maize, a C₄ plant, where CO₂ lost by photorespiration is recycled; time necessary to reach ΓCO_2 is shorter, allowing higher net CO₂ input rates than those in C₃ plants (Canvin, 1979).

Results indicate that in coffee plants, similar to what happens with other C₃ plants, ΓCO_2 is dependent on temperature and that there is a wide range of variation in photosynthetic activity directly related to photo-respiratory competition. The study of different genotypes of *Coffea arabica* L., species and *Coffea* genus would allow identification of photosynthetically efficient genotypes to be used in breeding programs in order to increase productivity. Photosynthetic behavior of the plants studied was that of a typical C₃ plant, and optimum leaf temperature for photosynthesis under conditions of the Colombian central coffee-growing zone is around 25 °C.

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Table 1. Net photosynthesis (P_N) of *Coffea* sp genotypes, bean and maize under three temperatures and [350 $\mu\text{mol}(\text{CO}_2)$ $\text{mol}^{-1}(\text{air})$]. Means \pm SD of ten measurements.

	Net photosynthesis (PN) [$\mu\text{mol}(\text{CO}_2)$ $\text{m}^{-2}\text{s}^{-1}$]		
	Temperature (°C)		
	15	25	35
<i>Coffea arabica</i> L. cv. Colombia	5,3 \pm 0,4	11,7 \pm 0,6	5,5 \pm 0,5
<i>Coffea arabica</i> L. cv. Caturra	5,2 \pm 0,4	10,9 \pm 0,5	5,2 \pm 0,2
Híbrido de Timor	5,0 \pm 0,5	5,4 \pm 0,3	4,9 \pm 0,7
Bean (<i>Phaseolus vulgaris</i>)	10,6 \pm 0,4	11,0 \pm 1,0	12,8 \pm 1,5
Maize (<i>Zea mays</i>)	5,3 \pm 1,1	18,6 \pm 0,4	23,5 \pm 1,0

Table 2. CO₂ compensation point (Γ CO₂) in *Coffea arabica* L. cvs. Caturra and Colombia, Híbrido de Timor, bean and maize, for 15 °C, 25 °C, and 35 °C. Means \pm SD of ten measurements.

Genotype [$\mu\text{mol}(\text{CO}_2)\text{mol}^{-1}(\text{air})$]	Temperature (°C)	CO ₂ compensation point (Γ CO ₂)
<i>Coffea arabica</i> L. cv. Colombia	15	38,2 \pm 1,1
	25	40,6 \pm 1,0
	35	48,5 \pm 0,7
<i>Coffea arabica</i> L. cv. Caturra	15	40,5 \pm 1,2
	25	45,6 \pm 1,3
	35	86,0 \pm 0,6
Híbrido de Timor	15	75,9 \pm 1,8
	25	80,1 \pm 1,9
	35	99,8 \pm 1,8
Bean (<i>Phaseolus vulgaris</i>)	15	37,9 \pm 2,0
	25	47,2 \pm 2,3
	35	77,5 \pm 2,5
Maize (<i>Zea mays</i>)	15	0,8 \pm 0,3
	25	0,8 \pm 0,0
	35	0,9 \pm 0,2

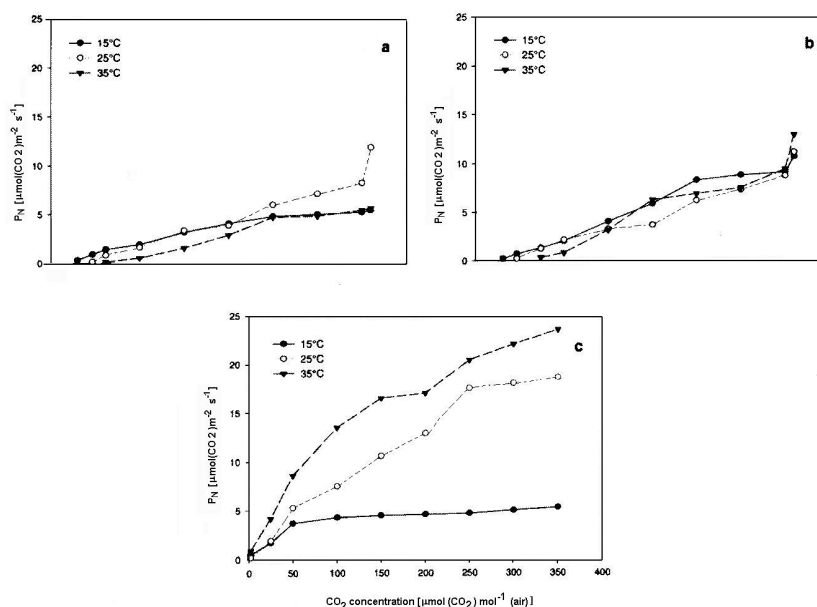


Figure 1. Net photosynthesis (PN) under 15 °C, 25 °C, 35 °C and different CO₂ concentrations in (a) coffee (*Coffea arabica* L.) cv. Caturra, (b) bean (*Phaseolus vulgaris* L.) (c) maize (*Zea mays* L.).

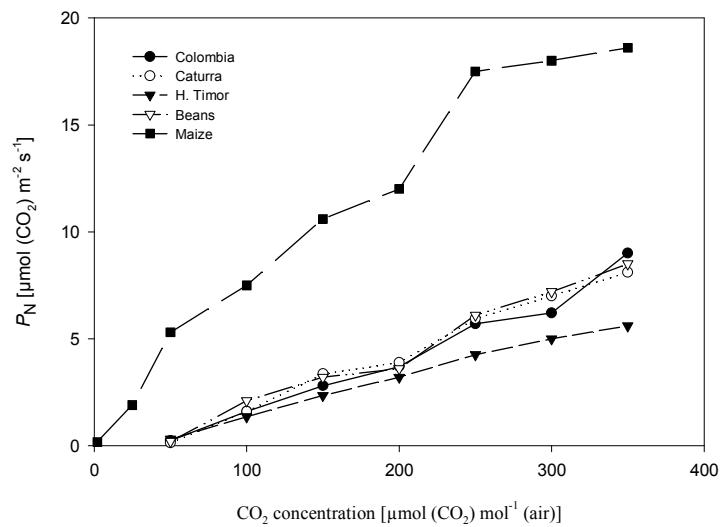


Figure 2. Net photosynthesis (P_N) of coffee (*Coffea arabica* L.) cv. Caturra, Colombia, Híbrido de Timor, bean (*Phaseolus vulgaris* L.) and maize (*Zea mays* L.) at 25 °C and several CO₂ concentrations [μmol (CO₂) mol⁻¹(air)].

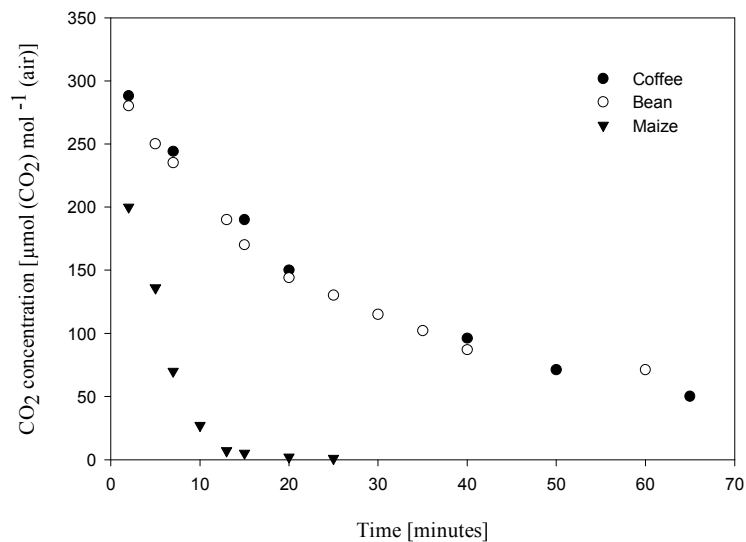


Figure 3. Time required for coffee *Coffea arabica* L. cv. Caturra, bean *Phaseolus vulgaris* L. and maize *Zea mays* L. to reach photosynthesis and (dark respiration + photorespiration) balance [CO₂ compensation point (I'CO₂)] at 25 °C.