NET PHOTOSYNTHESIS AND CO$_2$ 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 Hibrido 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 CO$_2$ compensation concentrations ($\Gamma_{CO_2}$) were measured. $P_N$ in coffee leaves was similar for the three genotypes at 15°C [5.0 – 5.3 µmol(CO$_2$) m$^{-2}$s$^{-1}$] and 35°C [4.9 – 5.5 µmol(CO$_2$) m$^{-2}$s$^{-1}$], but lower at 25°C [5.4 – 11.7 µmol(CO$_2$) m$^{-2}$s$^{-1}$]. $\Gamma_{CO_2}$ increased with temperature in coffee and bean, while in maize no effect was observed. $P_N$ and $\Gamma_{CO_2}$ values documented in coffee genotypes were typical for C$_3$ plants.

Key words: Coffee, Coffea arabica L., CO$_2$ compensation concentration, leaf temperature, net photosynthesis, bean, maize.
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 Hibrido 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 (PN) y se obtuvo la concentración de compensación de CO₂ (ΓCO₂). PN en las hojas de café fueron similares para los tres genotipos a 15 °C [5,0 – 5,3 µmol(CO₂) m⁻²s⁻¹] y 35 °C [4,9 – 5,5 µmol(CO₂) m⁻²s⁻¹] pero más bajas a 25 °C [5,4 – 11,7 µmol(CO₂) m⁻²s⁻¹]. El ΓCO₂ en café y fríjol se incrementó con la temperatura, mientras en maíz no se presentó ningún efecto. Los valores observados PN y de ΓCO₂ 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; Pᵢ – inorganic phosphate; PN – net photosynthesis; RuDP – Ribulose 1,5-diphosphate; VPD – vapour pressure deficit; ΓCO₂ – 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 ΓCO₂ 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). ΓCO₂ has been used to estimate photosynthetic efficiency: In C₃ plants this value is near to zero, which makes them photosynthetically more efficient than C₄ plants, which have ΓCO₂ values above [30 µmol(CO₂)mol⁻¹(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 PN 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,
Net photosynthesis and CO₂ compensation...

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 Γ\textsubscript{CO₂} as an estimate for photosynthesis efficiency involving photorespiration, and found Γ\textsubscript{CO₂} values close to [65 \text{µmol(CO}_2\text{)mol}^{-1}\text{(air)}] at 25°C.

The objective of this research was to study the behavior of P\textsubscript{N} and Γ\textsubscript{CO₂}, under different temperatures, in three coffee (\textit{Coffea arabica} L.) genotypes, bean (\textit{Phaseolus vulgaris} L.), and maize (\textit{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.

Eight months \textit{Coffea arabica} L. cv. Caturra, Colombia, and interspecific natural hybrid “Hibrindo de Timor” - plants; bean (\textit{Phaseolus vulgaris} L. cv. Ica Cafetero PVA 916) and maize (\textit{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\textsubscript{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\textsubscript{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 \text{µmol(photon) 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 \text{µmol(CO}_2\text{) mol}^{-1}\text{(air)}] and P\textsubscript{N} was recorded for every [50 \text{µmol(CO}_2\text{) mol}^{-1}\text{(air)}] decrease inside the leaf chamber until a constant CO₂ concentration (Γ\textsubscript{CO₂}) was reached.

**RESULTS AND DISCUSSION**

The highest P\textsubscript{N} observed for the three genotypes [11,7 \text{µmol(CO}_2\text{)m}^{-2}\text{s}^{-1}] was reached at 25°C and [350 \text{µmol(CO}_2\text{) mol}^{-1}\text{(air)}] (Figure 1a), with values higher than those reported by Nutman (1937) [0,44 - 2,84 \text{µmol(CO}_2\text{) m}^{-2}\text{s}^{-1}] at 25°C; Nunes \textit{et al.} (1968) [3,51 - 4,41 \text{µmol(CO}_2\text{) m}^{-2}\text{s}^{-1}] at 24°C; Sondhal (1976) [3,87 \text{µmol(CO}_2\text{) m}^{-2}\text{s}^{-1}] at 20°C; Yamaguchi and Friend (1979) [3,5 \text{µmol(CO}_2\text{) m}^{-2}\text{s}^{-1}] at 25°C and Friend (1984) [4,4 \text{µmol(CO}_2\text{) m}^{-2}\text{s}^{-1}]. Temperature influenced P\textsubscript{N} directly, when measured at [350 \text{µmol(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\textsubscript{N} would be limited by RuDP regeneration, because electronic transport velocity diminishes and consequently ATP and NADH formation are limited, and P\textsubscript{N}...
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 El-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 \( \Gamma CO_2 \) 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 Coleman, 1987). In coffee and bean, \( \Gamma CO_2 \) increased with temperature, while in maize no changes were observed (Table 2). This increase in \( \Gamma CO_2 \) 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 \( \Gamma CO_2 \) 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, \( \Gamma CO_2 \) 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. \( \Gamma CO_2 \) 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 $\Gamma_{CO_2}$, while in maize only 25 min were needed (Figure 3). Comparison of times necessary to reach $\Gamma_{CO_2}$ in $C_3$ and $C_4$ plants is an evidence of the level of competition caused by photorespiration in $C_3$ plants, which is poorly reported in literature. Under the same temperature and initial $CO_2$ concentration in a closed system, more time is required by $C_3$ plants due to significant return of the $CO_2$ fixed to the environment by photorespiration (Zelitch, 1971; Tolbert, 1980; Ogren, 1984). In maize, a $C_4$ plant, where $CO_2$ lost by photorespiration is recycled; time necessary to reach $\Gamma_{CO_2}$ is shorter, allowing higher net $CO_2$ input rates than those in $C_3$ plants (Canvin, 1979).

Results indicate that in coffee plants, similar to what happens with other $C_3$ plants, $\Gamma_{CO_2}$ is dependent on temperature and that there is a wide range of variation in photosynthetic activity directly related to photorespiratory 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 $C_3$ 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 (Pn) of Coffea sp genotypes, bean and maize under three temperatures and [350 µmol(CO₂) mol⁻¹(air)]. Means ± SD of ten measurements.
Table 2. CO₂ compensation point (ΓCO₂) in Coffea arabica L. cvs. Caturra and Colombia, Hibrido de Timor, bean and maize, for 15 °C, 25 °C, and 35 °C. Means ± SD of ten measurements.

<table>
<thead>
<tr>
<th>Genotype</th>
<th>CO₂ compensation point (ΓCO₂)</th>
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<tbody>
<tr>
<td></td>
<td>μmol(CO₂)·mol⁻¹aired</td>
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<tr>
<td></td>
<td>15</td>
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<tr>
<td>Coffea arabica L. cv. Colombia</td>
<td>38.2 ± 1.1</td>
</tr>
<tr>
<td>Coffea arabica L. cv. Caturra</td>
<td>40.5 ± 1.2</td>
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<tr>
<td>Hibrido de Timor</td>
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<tr>
<td>Bean (Phaseolus vulgaris)</td>
<td>37.9 ± 2.0</td>
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<tr>
<td>Maize (Zea mays)</td>
<td>0.8 ± 0.3</td>
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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 CO$_2$ concentrations [µmol (CO$_2$) 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 [CO$_2$ compensation point ($Γ$CO$_2$)] at 25 °C.