Plant Physiology Preview. Published on April 10, 2009, as DOI:10.1104/pp.109.135509

Running title: Phytochrome regulation of photosynthesis and transpiration

Corresponding author: Jorge J. Casal
IFEVA, Facultad de Agronomía, Universidad de Buenos Aires, and Consejo Nacional de
Investigaciones Científicas y Técnicas (CONICET), Av. San Martin 4453, 1417-Buenos Aires,
Argentina
Phone n° ++54 1145248070 ext 1223
Email casal@ifeva.edu.ar

Research Area
Whole Plant and Ecophysiology

Phytochrome B enhances photosynthesis at the expense of water use efficiency in Arabidopsis[1][OA]

Hernán E. Boccalandro[2, 3] Matías L. Rugnone[3], Javier E. Moreno, Edmundo L. Ploschuk, Laura Serna, Marcelo J. Yanovsky and Jorge J. Casal[*]

IFEVA, Facultad de Agronomía, Universidad de Buenos Aires, and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Av. San Martín 4453, 1417-Buenos Aires, Argentina (H.E.B., M.R., J.M., M.J.Y., J.J.C.), Cátedra de Cultivos Industriales, Departamento de Producción Vegetal, Facultad de Agronomía, Universidad de Buenos Aires, Av. San Martín 4453, 1417-Buenos Aires, Argentina (E.L.P) and Facultad de Ciencias Ambientales e ICAM, Universidad de Castilla-La Mancha, Toledo, Spain (L.S.).

[1] This work was supported by grants from the University of Buenos Aires (grant G044 to JJC), Agencia Nacional de Promoción Científica y Tecnológica (PICT 1026 to MY and PICT 32924 and 00492 to HEB), International Centre for Genetic Engineering and Technology (ICGEB, CRP/ARG07-02 to JJC), and CONICET (PIP5958 to JJC).

*Corresponding author: Jorge J. Casal; e-mail casal@ifeva.edu.ar
The author responsible for distribution of materials integral to the findings presented in this article in accordance with the policy described in the Instructions for Authors (www.plantphysiol.org) is: Jorge J. Casal (casal@ifeva.edu.ar)

[2] Present address: Cátedra de Química Orgánica y Biológica, Facultad de Ciencias Agrarias and Instituto de Ciencias Básicas, Universidad Nacional de Cuyo, Mendoza, Argentina

[3] These authors contributed equally to the article

[OA] Open Access articles can be viewed online without a subscription.

In open places, plants are exposed to higher fluence rates of photosynthetically active radiation and to higher red to far-red ratios than under the shade of neighbor plants. High fluence rates are known to increase stomata density. Here we show that high, compared to low red to far-red ratios, also increase stomata density in *Arabidopsis thaliana*. High red to far-red ratios increase the proportion of phytochrome B (phyB) in its active form and the *phyB* mutant exhibited a constitutively low stomata density. phyB increased the stomata index (the ratio between stomata and epidermal cells number) and the level of anphistomy (by increasing stomata density more intensively in the adaxial than in the abaxial face). phyB promoted the expression of *FAMA* and *TOO MANY MOUTHS* genes involved in the regulation of stomata development in young leaves. Increased stomata density resulted in increased transpiration per unit leaf area. However, phyB promoted photosynthesis rates only at high fluence rates of photosynthetically-active radiation. In accordance to these observations, phyB reduced long-term water use efficiency estimated by the analysis of isotopic discrimination against $^{13}CO_2$. We propose a model where active phyB promotes stomata differentiation in open places allowing plants to take advantage of the higher irradiances at the expense of a reduction of water use efficiency, which is compensated by a reduced leaf area.

Photosynthesis, transpiration and transpiration efficiency, the ratio of carbon fixation to water loss, are key physiological traits considered by plant breeders when selecting productive and water-use efficient plants (Rebetzke et al., 2002; Richards, 2006; Passioura, 2007). Opening of the stomata allows the uptake of CO_2 necessary for photosynthesis but it simultaneously increases the loss of water and the potential deterioration of the water status. Plants are finely tuned to efficiently face this dilemma. Under low levels of photosymthetically-active radiation (PAR), stomata open just enough to prevent the limitation of photosynthesis by CO_2 influx and the photochemical phase of photosynthesis is the limiting step. If PAR increases allowing higher rates of photochemical reactions, which leads to more ATP and NADPH, stomatal conductance also increases to allow sufficient CO_2 to use these products in the Calvin Cycle (Donahue et al., 1997; Yu et al., 2004). If instead of following this response coordinated to photosynthetic rates, stomata opened maximally in response to low PAR, more CO_2 than needed would be allowed to reach the chloroplast at the expense of unnecessary water loss.

Canopy shade-light is characterized not only by reduced PAR levels but also by a reduced proportion of red light (R) compared to far-red light (FR) caused by the selective absorption of visible light by photosynthetic pigments and the reflection and transmission of FR (Holmes and Smith, 1977). This low R/FR ratio compared to unfiltered sunlight is perceived by phytochromes (Smith, 1982; Ballaré et al., 1987; Pigliucci and Schmitt, 1999), mainly phytochrome B (phyB) (Yanovsky et al., 1995). In Arabidopsis, the high R/FR signals perceived by phyB decrease the length of the stem and petioles, cause a more prostrate position of the leaves, promote branching and delay flowering, among other responses (Reed et al., 1993; Franklin and Whitelam, 2005).

Transgenic plants of potato expressing the *PHYB* gene of *Arabidopsis thaliana* show higher stomatal conductance, transpiration rates and photosynthesis rates per unit leaf area than the wild type (WT) (Thiele et al., 1999; Boccalandro et al., 2003; Schittenhelm et al., 2004). Stomata density is unaffected, indicating that phyB enhances the aperture of the stomatal pore in these transgenic plants. Stomatal conductance is higher in *Fuchsia magellanica* plants exposed to R than to FR pulses at the end of the photoperiod (Aphalo et al., 1991). However, there are no general effects of R/FR treatments on the aperture of the stomatal pore. The stomata of *Commelina communis* (Roth-Bejerano, 1981) and of the orchid of the genus *Paphiopedilum* (Talbott et al., 2002) open in response to R and this effect is reversed by FR, indicating a control by phytochrome. Nevertheless, this FR reversal of the effect of R is absent in WT *Arabidopsis thaliana* (Talbott et al., 2003). In *Phaseolus vulgaris*, FR accelerates stomatal movements during dark to light (opening) and light to dark (closing) transitions and this effect is R reversible, but phytochrome status has no effects under constant conditions of light or darkness (Holmes and Klein, 1985). In the latter species, prolonged FR added to a white-light background promotes stomatal conductance but this effect cannot be ascribed to phytochrome (Holmes et al., 1986).

In addition to this rapid adjustment of the CO_2 and water vapor fluxes to daily fluctuations in light levels via the regulation of the stomatal pore aperture, plants acclimate to the prevailing PAR conditions by changing stomatal density (number of stomata per unit area) and stomatal index (the ratio between the number of stomata in a given area and the total number of stomata and other epidermal cells in that same area). Stomatal density and stomatal index are higher in plants grown in full sunlight at high levels of PAR than in plants grown in shade (Willmer and Fricker, 1996; Lake et al., 2001; Thomas et al., 2004; Casson and Gray, 2008). Mature leaves sense the environment (light intensity and CO_2) and produce a systemic signal that regulates stomatal density and index in young leaves (Coupe et al., 2006). A change in CO_2 concentrations or PAR levels affects photosynthesis and therefore it was suggested that a metabolic compound associated to this process (i.e. a sugar) may regulate stomatal development (Coupe et al., 2006). However, there is no correlation between photosynthetic rate and stomatal index in poplar (Miyazawa et al., 2006) and transgenic anti-SSU tobacco plants, show reduced photosynthesis and normal responses of stomatal density and stomatal index to PAR, suggesting that other photoreceptors could be involved in this regulation (Baroli et al., 2008).

Here we demonstrate that high, compared to low R/FR ratios, perceived by phyB increase stomata density, stomata index and amphistomy in the leaves of *Arabidopsis thaliana***.** This behavior results in an enhanced photosynthetic rate at high PAR at the expense of reduced water use efficiency.

RESULTS

Light signals perceived by phyB increase transpiration rate

Plants of *Arabidopsis thaliana* of the WT L*er* and of the *phyB-4* and *phyB-5* mutants were grown under white light photoperiods (12 h) terminated with or without a pulse of FR (+FR). The classical end-of-day pulse of FR (Downs et al., 1957) provides a simulation of canopy shade-light that is more rudimentary than FR given simultaneously with white light throughout the photoperiod but it avoids potential effects linked to differential excitation of photosystems I and II by FR, which are known to be important in the acclimation of photosynthesis-related traits (Dietzel and Pfannschmidt, 2008; Wagner et al., 2008).

Transpiration per plant depends on leaf area per plant and transpiration per unit leaf area. The +FR treatment and the *phyB* mutation increased the leaf area per plant (Fig. 1A) and reduced the rate of transpiration per unit leaf area (Fig. 1B), compared to WT plants grown under the high R/FR ratio control conditions. A highly significant interaction occurred between light conditions and genotype because under the +FR conditions, the *phyB* mutation had no effects compared to the WT, and in the *phyB* mutant, the +FR treatment had no effect compared to the high R/FR ratio control. These observations indicate a control of leaf area and transpiration per unit leaf area by the +FR treatment perceived by phyB, without any obvious participation of other phytochromes in the response to R/FR ratio.

phyB increases stomata density

To investigate the basis for the differences in the rate of transpiration per unit leaf area we recorded the number of stomata per unit leaf area. The +FR treatment (Fig. 2A) and the *phyB* mutation (Fig. 2B) reduced stomata density compared to WT plants grown under the high R/FR ratio control conditions. Light and genotype effects on stomata density correlate positively with the effects on the rate of transpiration per unit leaf area (*cf* Fig. 2A, B, and Fig 1B). The *phyA-201* mutant presented a WT-like phenotype and the *phyB-5 phyA-201* double mutant behaved as the *phyB* single mutants (Fig. 2B), indicating no significant role of phyA.

phyB increases stomata index

Differences in stomata density can result either from a general effect on cell density per unit leaf area (larger cells would reduce density and account for the enhanced area in response to +FR or the *phyB* mutation) or from a specific reduction in stomata differentiation. We calculated the stomatal index, i.e. the ratio between the number of stomata and the number of epidermal cells in a given area. The +FR treatment (Fig. 2C) and the *phyB* mutation (Fig. 2D) reduced stomatal index revealing the existence of a specific control by phyB of the proportion of epidermal cells that differentiate into stomata. The *phyA-201* mutant presented a WT-like phenotype and the *phyB-5 phyA-201* double mutant was similar to the *phyB* single mutants (Fig. 2), indicating no significant role of phyA. The *phyA* and *phyB* mutant backgrounds caused small but statistically significant increments or reductions, respectively, of non-guard epidermal cell density (cells per mm^2, mean ±SE, WT L*er*: 764 ±19: *phyB-5*: 710 ±26; *phyB-4*: 772 ±25; *phyA-201*: 849 ±29; *phyB-5 phyA-201:* 772 ±21, $P < 0.05$ for *phyA* vs *PHYA* and *phyB* vs *PHYB*). The *phyB* mutation caused no obvious stomata aberrant distribution phenotype (e.g. contiguous stomata).

phyB enhances the amphistomy level

Arabidopsis has amphistomatous leaves, with higher stomata density in the abaxial respect to the adaxial leaf surface (Hetherington and Woodward, 2003). Depending on the species, PAR levels increases not only stomata density but also the level of amphistomy, a trait that affects acclimation to sunny environments (Mott et al., 1982; Mott and Michaelson, 1991). The +FR treatment and the *phyB* mutation reduced stomata density more in the adaxial than in the abaxial face of the leaf and therefore increased the abaxial / adaxial ratio (Fig. 3).

phyB reduces water use efficiency

Transpiration efficiency (the ratio between fixed CO_2 and water vapor lost by transpiration) was estimated through the analysis of isotopic discrimination against $^{13}CO_2$ respect to $^{12}CO_2$ (Δ). This parameter is a reliable and sensitive marker negatively correlated with water use efficiency or photosynthesis per unit transpiration (Farquhar and Richards, 1984; Masle et al., 2005). The *phyB* mutation decreased isotope discrimination (Δ) (Fig. 4), indicating that phyB decreases water use efficiency.

Overexpression of *PHYB* increases stomatal density and stomatal index and reduces water use efficiency

Transgenic plants overexpressing *PHYB* (*PHYB OX*) had a phenotype opposite in many respects to that of the *phyB* mutants (Supplementary Figure 1). Compared to the WT, the transgenic overexpressors showed reduced leaf area per plant, increased transpiration rate per unit leaf area, increased stomata density, increased stomatal index, increased amphistomatous character and increased isotope discrimination (Δ). The proportion between abaxial and adaxial stomata decreased because stomata density increased more in the adaxial (147 %) than in the abaxial face (76 %). In addition, *PHYB* overexpression increased total non-guard epidermal cell density (WT Nossen, 468±30; *PHYB* OX, 645±46, $P < 0.05$). *PHYB* overexpression caused no obvious aberrant stomata distribution phenotype (e.g. contiguous stomata).

phyB increases the expression of *FAMA* and *TMM*

FAMA (*FAMA*) causes the guard mother cell to divide into the guard cells that define the stomatal pore (MacAlister et al., 2007; Casson and Gray, 2008). *TOO MANY MOUTHS* (*TMM*) negatively regulates the development of supernumerary stomata and enhances spacing among stomata (Geisler et al., 2000; Nadeau and Sack, 2002). We investigated the level of expression of these genes in developing leaves of WT and *phyB* mutant plants. Other genes involved in stomatal development were also investigated but the expression levels did not allow a clear resolution. The *phyB* mutation reduced both *FAMA* and *TMM* expression compared to the WT (Fig. 5 A, B). At first glance it was surprising to see that both genes with contrasting consequences on stomata density were affected in the same direction in the *phyB* mutant, which shows reduced stomata density. To explore this issue in further detail we analyzed the correlation of expression between *FAMA* and *TMM* across 633 conditions representing different tissues, developmental stages and differentially treated plants (www.arabidopsis.org). Publicly available data for each of the two genes were normalized to the median of each experiment and ln (x+1) transformed as described (Buchovsky et al., 2008). This analysis demonstrates that a highly significant positive correlation between the expression of *FAMA* and *TMM* beyond the action of phyB (Figure 5C).

phyB promotes photosynthesis at high PAR

phyB increased stomata density and the level of amphistomy. Both traits potentially favor CO_2 diffusion from the atmosphere to the chloroplasts. We investigated whether phyB affects CO_2 uptake in WT and *phyB* mutant leaves exposed to a range of PAR (Fig. 6). Net CO_2 uptake was unaffected by the *phyB* mutation at or below the PAR that the plants had experienced during the growth period (250 μmol m^{-2} s^{-1}). However, the *phyB* mutants presented lower photosynthetic rates than the WT under higher PAR (380 μmol $^{-2}$ s^{-1} or more) (Fig. 6).

To investigate whether the differences in CO_2 uptake were caused by stomatal limitations to CO_2 diffusion, consistent with the lower stomata density, we obtained curves of net CO_2 uptake against the intercellular CO_2 concentration (Fig. 7A). The WT showed higher CO_2 than the *phyB-5* mutant (mean ±SE in mol m^{-2} s^{-1} for 400 μmol mol^{-1} of CO_2 in the reference infra-red gas analyzer; n= 5; WT= 0.36 ±0.02; *phyB-5*= 0.21 ±0.02; P <0.0005). The lower ratios between intercellular and ambient CO_2

concentrations in the *phyB* mutant compared to the WT indicate stomatal limitations to CO_2 diffusion (Fig. 7B). The residual differences in the curves of net CO_2 uptake against the intercellular CO_2 concentration (Fig. 7A) suggest that additional non-stomatal effects of phyB on photosynthesis could occur.

DISCUSSION

In *Arabidopsis thaliana*, the density of stomata and the stomata index increase in response to PAR and in response to low CO_2 (Willmer and Fricker, 1996; Lake et al., 2001). Low R/FR ratios are typical of canopy shade-light and establish low proportions of active phytochrome (Holmes and Smith, 1977). Here we show that light treatments (+FR) that reduce the proportion of phytochrome in its active form also reduce stomata density and stomata index of *Arabidopsis thaliana* leaves (Fig. 2A, C). The *phyB* mutants having reduced or null levels of phyB, the main photoreceptor of R/FR ratios, showed low stomata density and stomata index under high R/FR ratios (Fig. 2B, D, E). The level of amphistomy (i.e. the presence of stomata on both leaf blade surfaces) can increase with PAR (Mott et al., 1982) . The +FR treatment and the *phyB* mutation reduced stomata density more in the adaxial than in the abaxial face and therefore reduced the level of amphistomy (Fig. 3). This picture is completed by the observation that lines overexpressing the *PHYB* gene increased stomata density, stomata index, and the level of amphistomy compared to the WT (Supplementary Fig. 1). Therefore, active phyB increases stomata density, stomata index and amphistomy in Arabidopsis.

Low irradiance or low R/FR ratio do not change stomata density in the leaves of *Commelina communis* (Assmann, 1992), indicating that not all the species follow the pattern of response to shade-light signals exhibited by Arabidopsis. However, given the contribution of Arabidopsis as a model experimental system to study the regulation of transpiration and drought tolerance (Nilson and Assmann, 2007) it is important to uncover the environmental signals and the receptors controlling stomatal density and the physiological consequences of this regulation in Arabidopsis.

Stomata index is defined relatively early during the development of the leaves (Larkin et al., 1997; Serna et al., 2002) and therefore, the adjustment to the future conditions that the leaf is more likely to face would be beneficial. In closing canopies, the reduction in R/FR ratio anticipates actual shading among neighbors due to selective FR reflection on green leaves (Ballaré et al., 1987). The perception of low R/FR signals by phyB would provide a mechanism to adjust stomata density of developing leaves to the likely occurrence of shade, before mutual shading (i.e. reduced irradiance) actually takes place.

We are largely ignorant of the genes that relate environmental signals to the control of stomata density (Wang et al., 2007). One exception is the *HIGH CARBON DIOXIDE* (*HIC*) gene, which encodes a putative 3-keto acyl coenzyme A synthase involved in the synthesis of very-long-chain fatty acids, involved in the response to carbon dioxide (Gray et al., 2000). Here we place phyB between light quality signals and genes involved in stomata differentiation. The expression of *FAMA*, a BHLH transcription factor that promotes stomata differentiation (MacAlister et al., 2007; Casson and Gray, 2008), is reduced in developing leaves of the *phyB* mutant compared to the WT (Fig. 5A). *SPEECHLESS* (*SPCH*) is a BHLH transcription factor that positively regulates the asymmetric divisions that form stomata and the expression of *FAMA* (MacAlister et al., 2007; Casson and Gray, 2008). The expression of *SPCH* in 8-days-old seedlings with very young primordia is reduced by exposure to 1 h or 4 d to low R/FR ratio (Carabelli et al., 2007). Based on these observations we propose a model where phyB-mediated promotion of stomata differentiation involves positive regulation of BHLH transcription factors that play a key role in stomata development. Interestingly, the expression of *TMM*, a putative cell-surface leucine-rich repeat (LRR)-containing receptor-like protein that negatively regulates stomata differentiation (Geisler et al., 2000; Nadeau and Sack, 2002) was also lower in the *phyB* mutant than in the WT (Fig. 5B). The analysis of the expression levels of *FAMA* and *TMM* across different developmental, abiotic and biotic conditions revealed that, despite their opposite effects on stomata density, the positive expression correlation between these genes is not limited to the comparison between the WT and the *phyB* mutant (Fig. 5C). *TMM* is not only a repressor of stomatal development, it also seems to provide competence to enter into the stomatal pathway (Nadeau and Sack, 2002). It is likely that phyB positively regulates stomata formation by increasing the number of cells from which the stomatal lineage may develop. The fact that *TMM* also represses stomatal development, playing an opposite role to phyB, suggests that its expression might be positively controlled by a feedback mechanism during stomata differentiation. These findings suggest that the expression of *TMM* might be positively controlled by a feedback mechanism during stomata differentiation. There are several examples where an environmental cue initiates downstream signaling and sets into motion mechanisms that negatively regulate that signaling (Casal et al., 2004). The complex interaction among *TMM* and three *ERECTA* family of leucine-rich repeat containing receptor kinases revealed by the mutant phenotypes is not fully understood (Nadeau, 2008) and this sort of feedback regulations could be part of the complexity. The *ERECTA* gene product is a putative partner of TMM in the regulation of stomata development (Casson and Gray, 2008). We observed changes in stomata density and index in response to

+FR or to the *phyB* mutation in the Landsberg *erecta* background indicating that phyB-mediated responses of these traits can occur in the absence of a functional *ERECTA* gene.

Changes in stomata density do not necessarily translate into changes in water vapor and carbon dioxide fluxes. In transgenic Arabidopsis plants over-expressing the *STOMATAL DENSITY AND DISTRIBUTION 1* (*SDD1*) gene and in the *sdd1* mutant stomata density is significantly decreased or increased, respectively, compared to the WT (Bussis et al., 2006). However, carbon dioxide assimilation rate and stomatal conductance of over-expressers and *sdd1* mutant were unchanged compared with WT because changes in stomatal density were compensated for by opposite changes in stomatal aperture (Bussis et al., 2006). Conversely, the control of stomatal density by phyB correlated with changes in the rate of transpiration when the WT is compared to either the *phyB* mutant (Fig. 1B) or the *PHYB OX* (Supplementary Fig. 1). This resulted in a negative regulation of water use efficiency by phyB (Fig. 4, Supplementary Fig. 1) consistent with the positive regulation by *ERECTA*, which reduces stomata density (Masle et al., 2005).

The activity of phyB is higher in open places, where the radiation load is stronger and atmospheric water demand is more intense. Therefore, the increased stomatal density caused by phyB, which results in reduced water use efficiency, cannot easily be associated with a strategy aimed to conserve water. Along the same line of arguments, increased amphistomy is a feature often linked to adequate water availability (Mott et al., 1982; Lynn and Waldren, 2002). Low R/FR ratios and the *phyB* mutation increased leaf area per plant (Figure 1A). Increased leaf area in response to +FR has been observed in other species such us *Cucumis sativus* (López Juez et al., 1990), *Taraxacum officinale* (Cogliatti and Sánchez, 1987), *Terminalia ivorensis* (Kwesiga and Grace, 1986) and *Petunia axilaris* (Casal et al., 1987), and for some leaf positions in *Arabidopsis thaliana* (Robson et al., 1993). However, the opposite pattern has also been found (Kasperbauer, 1971; Holmes and Smith, 1977; Frankland and Letendre, 1978; Robson et al., 1993; Devlin et al., 1999), suggesting that the actual effect may depend on the species and growing conditions. The negative regulation of leaf area by phyB observed here would help to reduce water loss per plant in open places. However, the opposite regulation of leaf area and transpiration per unit leaf area by phyB largely compensate each other, indicating that the main function of these changes is not the adjustment of water use. Rather, phyB perception of the high R/FR ratios of open places allows Arabidopsis plants to increase photosynthesis in response to the higher PAR levels that the plant may experience in those conditions (Fig. 6). The increased stomata density and amphistomy mediated by phyB would be an adaptation to the high PAR of open places by favoring the diffusion of carbon dioxide (Fig. 7B) and by facilitating leaf cooling due to the concomitant increase in transpiration rate reducing the stress imposed by high radiation loads (Mott et al., 1982; Parkhurst and Mott, 1990; Mott and Michaelson, 1991). Excitation energy that is not used for photochemistry and not dissipated as fluorescence or heat can be transferred to molecular oxygen, creating highly damaging reactive oxygen species ((Golan et al., 2006) and references therein). Therefore, the higher rate of photosynthesis at high PAR caused by phyB could also reduce the diversion of excitation energy to the generation of reactive species of oxygen in open places.

MATERIALS AND METHODS

Plant material

The accessions Landsberg *erecta* (L*er*), Columbia (Col) and Nossen (No) of Arabidopsis were used as WT in this study. The *phyA-201* (formerly *fre-1* (Nagatani et al., 1993) , *phyB-5* (formerly *hy3*), *phyB-4* (Koornneef et al., 1980; Reed et al., 1993) and the double mutant *phyA-201 phyB-5* are in the L*er* background; the transgenic line expressing *35S:PHYB:GFP* (*PHYB:GFP*) (Más et al., 2000) is in the Columbia background and the overexpressor line *35S:PHYB* (*PHYB* OX) is in the Nossen background (Wagner et al., 1991).

Seeds were sown on 0.8% agar-water and four-day-old seedlings were transplanted to 230 cm^3 pots containing equal amounts of perlite (Perlome, Perfiltra, Rosario, Argentina) peat moss (Cuidad floral, Escobar, Argentina) and vermiculite (Intersum, Aislater, Córdoba, Argentina) and watered as needed with a solution containing 1 g per L of Hakaphos R (COMPO, Spain).

Light conditions

Plants were grown under white light photoperiods of 12 h at 250 µmol m^{-2} s^{-1} of photosynthetically active radiation (LI-COR Li-188B sensor, Lincoln, Nebraska) provided by a combination of mercury and sodium lamps and temperature was 23±1°C. The R/FR ratio (Skye meter SKR 100, remote probe SKR110; Skye Instruments, England). was 4.1. During one hour after the end of white light photoperiod, FR (10 µmol m^{-2} s^{-1}, R/FR ratio = 0.04) was provided from one side of the plants by incandescent lamps in combination with a water filter (10 cm width), a red filter (Lee filters, number 026), and two blue acrylics filters (1mm thick, Paolini 2031, Buenos Aires Argentina).

Stomata density, stomata index and amphistomy

Fully expanded leaves of the first pair were collected from 25-d-old plants. The number of stomata and epidermal cells were counted in clarified leaves or in imprints performed with transparent nail varnish, under the microscope (40 X) in 6 portions of the adaxial surface of the leaf blade, at both sides of the midrib (two determinations in the distal, medium and proximal zone). In some experiments, epidermal cell counting was performed in the adaxial and abaxial sides of the second pair of leaves to investigate the amphistomy level (Fig. 3) or the effect of +FR on stomata density and index (Fig. 2). Representative photographs were taken using Nomarsky optics with a Leica DC 300F camera attached to a Leica DMIRB inverted microscope. To improve their visualization, cell walls were draw on the image, using the brush tool of the Photoshop v.7.0.

Carbon isotope discrimination

Analysis of carbon isotope composition was performed on 35-d-old rosette leaves (vegetative stage). Three plants per genotype were pooled for each independent biological replicate. Carbon isotope composition (δ) was measured at SIRFER (Stable Isotope Ratio Facility for Environmental Research, University of Utah) following the standard protocol to determinate stable isotopes (http://ecophys.biology.utah.edu/sirfer.html). The δ values were then converted to carbon isotopic discrimination values (Δ). Δ was calculated according to Masle et al., (2005), using the equation $\Delta = (\delta_a - \delta_p) / 1 + \delta_p$ where δ_a and δ_p are the δ of the source air and the plant, respectively. δ of the source air (δ_a) was assumed to be -8 per mil.

Gene expression

Total RNA was isolated from 200 mg of developing leaves (less than 5 mm in length), the upper part of the shoot and shoot apex of 25-days-old plants by using RNeasy kit (Qiagen). Complementary DNA was synthesized from 1 µg of total RNA using 0.1 µg oligo (dT) primer and reverse transcriptase (Super script 3, Invitrogen). RT-PCR was run for 40 cycles. Real Time RT-PCR analysis was carried out with a 7500 Real-Time PCR System with Fast Universal PCR Master Mix (Applied Biosystems). The expression of *TMM1* (At1g80080) and *FAMA* (At3g24140) was normalized to the expression of *ACT8*. The primers sequences were: *TMM1*Fw, 5´ AACAGTCTTCGGGTCCTTCAC 3´; *TMM1*Rv, 5´GCTTTCTCCTCATCCTCCACA 3´; *FAMA*1Fw, 5´GACCATAACCAAACCCAACA 3´; *FAMA1*Rv, 5´GCTCTCTTCCTCTTGCTCTTCA 3´; *ACT8*Fw, 5´AGTGGTCGTACAACCGGTATTGT 3´; *ACT8*Rv, 5´GAGGATAGCATGTGGAACTGAGAA 3´.

Correlation of expression of *FAMA* and *TMM*

The correlation between the expression of *FAMA* and *TMM* was analyzing using 633 data points corresponding to different developmental contexts and biotic or abiotic treatments (1 to 3 biological replicates per point) taken from 46 experiments (1388 microarrays, www.arabidopsis.org). Data were normalized to the median of each experiment and transformed as ln (x+1) as it was performed by Buchovsky et al., (2008).

Whole plant transpiration rate

Whole plant transpiration rate was measured as described (Masle et al., 2005). Briefly, the night before transpiration was assayed, the pots containing one 35 d old plant (vegetative stage) was watered at field capacity and the surface of the soil was wrapped with 0.025-mm thick transparent film (Rolopac, Buenos Aires, Argentina) to avoid evaporation. The next day, pots were weighted immediately prior to the beginning of the photoperiod and 12 h later. Relative humidity during the photoperiod was 70 ±4 %. The rosette leaves were harvested immediately and photographed to determinate leaf area of each plant using the Photoshop v.7.0. Transpiration per plant per hour (mg of water h^{-1}) was calculated as the difference between the initial and the final weight of each pot at the end of the photoperiod, divided by the number of hours of the photoperiod (12 h). The transpiration rate (mg of water cm^{-2} h^{-1}) was calculated dividing the former parameter by the total leaf area of each plant. Units were converted to mmol of water m^{-2} s^{-1}.

Leaf Photosynthesis

Leaf CO_2 exchange responses to PPF were obtained by using a closed infrared gas analysis system (LI-COR 6200, LI-COR Inc., Lincoln, NE.). CO_2 exchange at 0, 200, 380, 710 and 1,150 µmol m^{-2} s^{-1} PAR was measured in fully expanded leaves of *phyB-4, phyB-5* and WT L*er* 30-d-old plants, using a 0.25-L chamber attached to a regulated portable red light power (QB1205LI-670, Quantum Devices Inc., Barneveld, WI). Actual leaf temperature during measurements was between 27 and 29 °C and CO_2 concentration was 390 µmol mol^{-1}.

A portable gas exchange system (LI-COR 6400; LI-COR, Lincoln, NE) was used to obtain curves of leaf CO_2 exchange against intercellular CO_2 concentration in fully expanded leaves of *phyB-5* and WT L*er* 30-d-old plants. The area included in the 6 cm^2 chamber was recorded for each leaf. Measurements of leaf CO_2 exchange started at 400 µmol mol^{-1} CO_2 in the reference chamber, decreased stepwise to 50 µmol mol^{-1}, returned to 400 µmol mol^{-1} and increased stepwise to 1,200 µmol mol^{-1} CO_2. PPFD was 1,200 µmol m^{-2} s^{-1} provided by the red al blue diodes of the gas-exchange system (6400-02B LED Light Source). Actual leaf temperature during measurements was between 27 and 29 °C. The flow rate of air was set at 300 µmol s^{-1}. Ambient and reference CO_2 concentrations are the concentration in the sample and reference infrared gas analyzers, respectively.

Additional Note

While this paper was under review Casson et al. (2009) have demonstrated a role of phyB in the promotion of stomata density by irradiance. The latter is consistent with and complements the function of phyB in the response to light quality reported here.

ACKNOWLEDGEMENTS

We thank Juan Pablo Sáez and Carina Verónica González for their help with stomata determinations, Amy Austin for helping in the processing and analysis of the samples for isotope discrimination, Paloma Más (Instituto de Biología Molecular de Barcelona, Spain) for her kind provision of seeds of the *35S:PHYB:GFP* line and Antonio Hall (IFEVA, Buenos Aires, Argentina) and Pedro Aphalo (Helsinki University for their helpful comments. We are grateful to Instrumentalia S.A. (Argentina) for their kind lending of the LI-COR 6400.

LITERATURE CITED

Aphalo PJ, Gibson D, Di Benedetto AH (1991) Responses of growth, photosynthesis, and leaf conductance to white light irradiance and end-of-day red and far-red pulses in *Fuchsia magellanica* Lam. New Phytol **117:** 461-471

Assmann SM (1992) Effects of light quantity and quality during development on the morphology and stomatal physiology of *Commelina communis*. Oecologia **92:** 188-195

Ballaré CL, Sánchez RA, Scopel AL, casal JJ, Ghersa CM (1987) Early detection of neighbour plants by phytochrome perception of spectral changes in reflected sunlight. Plant Cell Environ **10:** 551-557.

Baroli I, Dean Price G, Badger M, von Caemmerer S (2008) The Contribution of Photosynthesis to the Red Light Response of Stomatal Conductance. Plant Physiol **146:** 737-747

Boccalandro HE, Ploschuk EL, Yanovsky MJ, Sanchez RA, Gatz C, Casal JJ (2003) Increased Phytochrome B Alleviates Density Effects on Tuber Yield of Field Potato Crops. Plant Physiol **133:** 1539-1546

Buchovsky AS, Strasser B, Cerdán PD, Casal JJ (2008) Suppression of Pleiotropic Effects of Functional CRYPTOCHROME Genes by TERMINAL FLOWER 1. Genetics **180:** 1467–1474

Bussis D, Von Groll U, Fisahn J, Altmann T (2006) Stomatal aperture can compensate altered stomatal density in Arabidopsis thaliana at growth light conditions Funct Plant Biol **33** 1037-1043

Carabelli M, Possenti M, Sessa G, Ciolfi A, Sassi M, Morelli G, Ruberti I (2007) Canopy shade causes a rapid and transient arrest in leaf development through auxin-induced cytokinin oxidase activity. Genes Dev **21:** 1863-1868

Casal JJ, Aphalo PJ, Sánchez RA (1987) Phytochrome effects on leaf growth and chlorophyll content in *Petunia axillaris*. Plant Cell Environ **10:** 509-514

Casal JJ, Fankhauser C, Coupland G, Blázquez MA (2004) Signalling for developmental plasticity. Trends Plant Sci **9:** 309-314

Casson S, Gray JE (2008) Influence of environmental factors on stomatal development. New Phytol **178:** 9–23

Casson SA, Franklin KA, Gray JE, Grierson CS, Whitelam GC, Hetherington AM (2009) phytochrome B and PIF4 Regulate Stomatal Development in Response to Light Quantity. Current Biology **19:** 229-234

Cogliatti DH, Sánchez RA (1987) Influencia del fitocromo sobre el crecimiento foliar en *Taraxacum officinale*. Phyton **42:** 191-199

Coupe SA, Palmer BG, Lake JA, Overy SA, Oxborough K, Woodward FI, Gray JE, Quick WP (2006) Systemic signalling of environmental cues in Arabidopsis leaves. J Exp Bot **57:** 329-341

Devlin PF, Robson PRH, Patel SR, Goosey L, Sharrock RA, Whitelam GC (1999) Phytochrome D acts in the shade-avoidance syndrome in Arabidopsis by controlling elongation growth and flowering time. Plant Physiol **119:** 909-915

Dietzel L, Pfannschmidt T (2008) Photosynthetic acclimation to light gradients in plant stands comes out of shade. Plant Signal Behavior **3:** 1-3

Donahue RA, Poulson ME, Edwards GE (1997) A method for measuring whole plant photosynthesis in Arabidopsis thaliana. Photosynth Res **52:** 263–269

Downs RJ, Hendricks SB, Borthwick HA (1957) Photoreversible control of elongation of pinto beans and other plants under normal conditions of growth. Bot Gaz **118:** 199-208.

Farquhar GD, Richards RA (1984) Isotopic composition of plant carbon correlates with water-use efficiency of wheat genotypes. Aust J Plant Physiol **11:** 539–-552

Frankland B, Letendre RJ (1978) Phytochrome and effects of shading on growth of woodland plants. Photochem Photobiol **27:** 223-230

Franklin KA, Whitelam G (2005) Phytochromes and Shade-avoidance Responses in Plants. Ann Bot (Lond) **96:** 169–175

Geisler M, Nadeau J, Sack FD (2000) Oriented asymmetric divisions that generate the stomatal spacing pattern in Arabidopsis are disrupted by the too many mouths mutation. Plant Cell **12:** 2075–2086

Golan T, Mu□ller-Moulé P, Niyogi KK (2006) Photoprotection mutants of Arabidopsis thaliana acclimate to high light by increasing photosynthesis and specific antioxidants Plant Cell Environ **29:** 879-887

Gray J, Holroyd G, van der Lee F, Bahrami A, Sijmons P, Woodward F, Schuch W, Hetherington A (2000) The HIC signalling pathway links CO2 perception to stomatal development. Nature **408:** 713–716

Hetherington A, Woodward F (2003) The role of stomata in sensing and driving environmental change. Nature **424:** 901-908

Holmes M, Smith H (1977) The function of phytochrome in the natural environment--III. Measurement and calculation of phytochrome photoequilibria. Photochem Photobiol **25:** 547 - 550

Holmes MG, Klein WH (1985) Evidences for phytochrome involvement in light-mediated stomatal movement in *Phaseolus vulgaris* L. Planta **166:** 348-353

Holmes MG, Sager JC, Klein WH (1986) Sensivity to far-red radiation in stomata of Phaseolus vulgaris L.: rhythmic effects on conductance and photosynthesis. Planta **168:** 516-522

Holmes MG, Smith H (1977) The function of phytochrome in the natural environment. I Characterization of daylight for studies in photomorphogenesis and photoperiodism. Photochem Photobiol **25:** 533-538

Kasperbauer MJ (1971) Spectral distribution of light in a tobacco canopy and effects of end-of-day light quality on growth and development. Plant Physiol **47:** 775-778

Koornneef M, Rolf E, Spruit CJP (1980) Genetic control of light-inhibited hypocotyl elongation in Arabidopsis thaliana (L.) Heynh. Z Pflanzenphys **100:** 147-160

Kwesiga F, Grace J (1986) The role of red/far-red ratio in the response of tropical tree seedlings to shade. Ann Bot (Lond) **57:** 283-290

Lake JA, Quick WP, Beerling DJ, Woodward FI (2001) Plant development: Signals from mature to new leaves. Nature **411:** 154-154

Larkin J, Marks M, Nadeau J, Sack F (1997) Epidermal cell fate and patterning in leaves. Plant Cell **9:** 1109–1120.

López Juez E, Buurmeijer WF, Heeringa GH, Kendrick RE, Wesselius JC (1990) Response of light-grown wild type and long hypocotyl mutant cucumber plants to end-of-day far-red light. Photochem Photobiol **52:** 143-149

Lynn D, Waldren S (2002) Physiological Variation in Populations of Ranunculus repens L. (Creeping Buttercup) from the Temporary Limestone Lakes (Turloughs) in the West of Ireland. Ann Bot (Lond) **89:** 707-714

MacAlister CA, Ohashi-Ito K, Bergmann DC (2007) Transcription factor control of asymmetric cell divisions that establish the stomatal lineage. Nature **445:** 537–540

Más P, Devlin P, Panda S, Kay S (2000) Functional interaction of phytochrome B and cryptochrome 2. Nature **408:** 207-211

Masle J, Gilmore SR, Farquhar GD (2005) The ERECTA gene regulates plant transpiration efficiency in Arabidopsis. Nature **436:** 866–870

Miyazawa S-I, Livingston NJ, Turpin DH (2006) Stomatal development in new leaves is related to the stomatal conductance of mature leaves in poplar (Populus trichocarpa x P. deltoides). J Exp Bot **57:** 373-380

Mott K, Gibson A, O'Leary J (1982) The adaptative significance of amphistomatic leaves. Plant Cell Environ **5:** 455-460

Mott KA, Michaelson O (1991) Amphistomy as an Adaptation to High Light Intensity in *Ambrosia cordifolia* (Compositae). Am J Bot **78:** 76-79

Nadeau JA (2008) Stomatal development: new signals and fate determinants. Curr Op Plant Biol **12:** 1–7

Nadeau JA, Sack FD (2002) Control of stomatal distribution on the Arabidopsis leaf surface. Science **296:** 1697–1700.

Nagatani A, Reed JW, Chory J (1993) Isolation and initial characterization of Arabidopsis mutants that are deficient in phytochrome A. Plant Physiol **102:** 269-277.

Nilson S, Assmann SM (2007) The control of transpiration. Insights from Arabidopsis. Plant Physiol **143:** 19-27

Parkhurst DF, Mott KA (1990) Intercellular diffusion limits to CO_2 uptake in leaves. Plant Physiol **94:** 1024-1032

Passioura J (2007) The drought environment: physical, biological and agricultural perspectives. J Exp Bot **58:** 113-117

Pigliucci M, Schmitt J (1999) Genes affecting phenotypic plasticity in Arabidopsis: pleiotropic effects and reproductive fitness of photomorphogenic mutants. J Evol Biol **12** 551-562

Rebetzke GJ, Condon AG, Richards RA, Farquhar GD (2002) Selection for Reduced Carbon Isotope Discrimination Increases Aerial Biomass and Grain Yield of Rainfed Bread Wheat. J Exp Bot **42:** 739-745

Reed JW, Nagpal P, Poole DS, Furuya M, Chory J (1993) Mutations in the gene for the Red/Far-Red light receptor phytochrome B alter cell elongation and physiological responses throughout Arabidopsis development. Plant Cell **5:** 147-157

Richards RA (2006) Physiological traits used in the breeding of new cultivars for water-scarce environments. Agric Water Manag **80:** 197-211

Robson PRH, Whitelam GC, Smith H (1993) Selected components of the shade-avoidance syndrome are displayed in a normal manner in mutants of Arabidopsis thaliana and Brassica rapa deficient in phytochrome B. Plant Physiol **102:** 1179-1184.

Roth-Bejerano C (1981) Involvement of phytochrome in stomatal movement: Effect of blue and red light. Physiol Plant **52:** 201-206

Schittenhelm S, Menge-Hartmann U, Oldenburg E (2004) Photosynthesis, Carbohydrate Metabolism, and Yield of Phytochrome-B-Overexpressing Potatoes under Different Light Regimes. Crop Sci **44:** 131-143

Serna L, Torres-Contreras J, Fenoll C (2002) Clonal analysis of stomatal development and patterning in Arabidopsis leaves. Dev Biol **241:** 24–33.

Smith H (1982) Light quality, photoperception and plant strategy. Ann Rev Plant Physiol **33:** 481-518.

Talbott LD, Shmayevich IJ, Chung Y, Hammad JW, Zeiger E (2003) Blue Light and Phytochrome-Mediated Stomatal Opening in the npq1 and phot1 phot2 Mutants of Arabidopsis. Plant Physiol **133:** 1522-1529

Talbott LD, Zhu J, Han SW, E Z (2002) Phytochrome and blue light-mediated stomatal opening in the orchid, Paphiopedilum. Plant Cell Physiol **43:** 639–646

Thiele A, Herold M, Lenk I, Quail PH, Gatz C (1999) Heterologous expression of Arabidopsis phytochrome B in transgenic potato influences photosynthetic performance and tuber development. Plant Physiol **120:** 73-82

Thomas P, Woodward FI, Quick WP (2004) Systemic signalling in tobacco. New Phytol **161:** 193-198

Wagner D, Tepperman JM, Quail PH (1991) Overexpression of phytochrome B induces a short hypocotyl phenotype in transgenic *Arabidopsis*. Plant Cell **3:** 1275-1288

Wagner R, Dietzel L, Brautigam K, Pfannschmidt T (2008) The long-term response to fluctuating light quality is an important and distinct light acclimation mechanism that supports survival of *Arabidopsis thaliana* under low light conditions. Planta **228:** 573–587

Wang Y, Chen X, Xiang C-B (2007) Stomatal Density and Bio-water Saving. J Int Plant Biol **49** 1435–1444

Willmer C, Fricker M (1996) Stomata. Chapman and Hall. **2nd ed. London**

Yanovsky MJ, Casal JJ, Salerno GL, Sánchez RA (1995) Are phytochrome-mediated effects on leaf growth, carbon partitioning and extractable sucrose-phosphate synthase activity the mere connsequence of stem-growth responses in light-grown mustard? J Exp Bot **46:** 753-757

Yu Q, Zhang Y, Liu Y, Shi P (2004) Simulation of the Stomatal Conductance of Winter Wheat in Response to Light, Temperature and CO2 Changes. J Exp Bot **93:** 435-441

Figure legends

Figure 1. Phytochrome controls leaf transpiration rate. Leaf area per plant (A) and transpiration per unit leaf area (B) in seedlings of the WT and of the *phyB* mutants grown under white light with or without exposure to FR at the end of the photoperiod. Data are means and SE of at least 21 plant replicates. Factorial ANOVA indicates significant interaction (P <0.0001) between the effects of the *phyB* mutations and the + FR treatment because the *phyB* mutation had effects under white light but not under white light +FR (A, B). Different letters denote significant differences (P <0.05) among means according to Bonferroni post-tests.

Figure 2. Phytochrome controls stomata density (A, B) and stomata index (C, D). Plants of the WT were grown under white light and white light +FR (A, C) and plants of the *phyA*, *phyB*, *phyA phyB* mutants (B, D) were grown with their respective WT under white light. Data are means and SE of at least 12 plant replicates. * denotes significant differences (P <0.05) between the indicated condition or genotype and its control according to ANOVA followed by Bonferroni post tests. Representative sections of the epidermis are shown for a *phyB* mutant and its WT (E). Stomata density, index and images correspond to the adaxial epidermis of fully expanded leaves.

Figure 3. Phytochrome increases the level of amphistomy (A, B). The abaxial and abaxial stomatal densities and the percent decrease caused by +FR or by the *phyB* mutation are also shown (C, D). Plants of the WT were grown under white light and white light +FR (A, C) and plants of the *phyB* mutant were grown with its WT under white light (B, D). Data are means and SE of at least 12 plant replicates. * denotes significant differences (P <0.05) according to ANOVA. *** denotes significant differences (P <0.001) according to Bonferroni post tests.

Figure 4. Phytochrome reduces water use efficiency. Plants of the *phyB* mutant and its WT were grown under white light. Data are means and SE of 3 plant replicates (pool of 3 plants each one). * denotes significant differences (P <0.05) according to ANOVA.

Figure 5. Phytochrome promotes the expression of *FAMA* and *TMM* in the leaves and the positive correlation in the expression of these two genes extends beyond phyB action. (A, B) Plants of the *phyB* mutant and its WT were grown under white light. Data are means and SE of 3 biological replicates. * denotes significant differences (P <0.05)

according to ANOVA. (C) Positive correlation between the expression of *FAMA* and *TMM*. The figure includes 633 data points corresponding to different developmental contexts and biotic or abiotic treatments (1 to 3 biological replicates per point) taken from 46 experiments (1388 microarrays, www.arabidopsis.org). Data were normalized to the median of each experiment and transformed as ln (x+1) (Buchovsky et al., 2008). The line shows least square linear fit of the 633 points and the significance is indicated.

Figure 6. Phytochrome promotes photosynthesis in Arabidopsis. Plants of the WT and of the *phyB* mutants were grown under white light and then exposed to the indicated PAR during measurements. Data are means and SE of 6 plant replicates. * denotes significant differences ($P < 0.05$) according to ANOVA and Bonferroni post tests.

Figure 7. Analysis of stomatic and non-stomatic limitations to photosynthesis. (A) Curves of leaf net CO_2 uptake against intercellular CO_2 concentrations were obtained with a Li-COR 6400 system for the WT and the *phyB-5* mutant. (B) Ratio between intercellular and ambient CO_2 concentrations plotted against ambient CO_2 concentration (i.e. the concentration in the sample infrared gas analyzer of the Li-COR 6400 system). Data are means and SE of 5 plant replicates. * denotes significant differences ($P < 0.05$) according to *t* tests. The tests were done between WT and the *phyB* having the closest intercellular (A) or ambient (B) CO_2 concentrations (in A, this overestimates the significance of the difference for the samples around 280 $\mu mol.mol^{-1}$).

Supplementary Figure 1. Phytochrome B overexpression increases transpiration per area, stomata density, stomata index, and amphistomy level and reduces leaf area per plant and transpiration efficiency. Leaf area per plant (A) and transpiration per unit leaf area (B) in plants of the WT and in the *PHYB OX* line grown under white light with or without exposure to FR at the end of the photoperiod. Data are means and SE of at least 21 plant replicates. Factorial ANOVA indicates significant interaction ($P < 0.0001$) between the effects of the *PHYB* overexpression and the +FR treatment in the control of leaf area because the latter had larger effects in the *PHYB OX* than in the WT; and significant effects of *PHYB* overexpression ($P < 0.0001$) and of the +FR treatment ($P < 0.01$) but no interaction in the control of transpiration rate. Stomata density (C), amphistomy level (D) and stomata index (E) in two *PHYB OX* lines and their respective WT grown under white light. Data are means and SE of at least 12 plant replicates.

Water use efficiency of *PHYB OX* plants and their respective WT (F) grown under white light. Data are means and SE of 3 plant replicates (pool of 3 plants each one). * denotes significant differences (P <0.05) according to ANOVA. Stomata density and index were determined in the adaxial epidermis of fully expanded leaves.

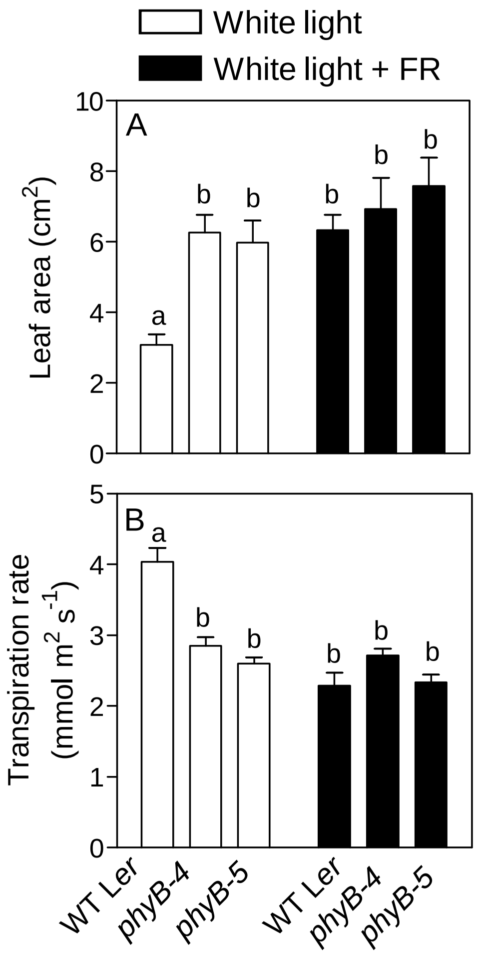

Figure 1. Phytochrome controls leaf transpiration rate. Leaf area per plant (A) and transpiration per unit leaf area (B) in seedlings of the WT and of the *phyB* mutants grown under white light with or without exposure to FR at the end of the photoperiod. Data are means and SE of at least 21 plant replicates. Factorial ANOVA indicates significant interaction ($P < 0.0001$) between the effects of the *phyB* mutations and the FR treatment because the phyB mutation had effects under white light but not under white light +FR (A, B). Different letters denote significant differences ($P < 0.05$) among means according to Bonferroni post-tests.

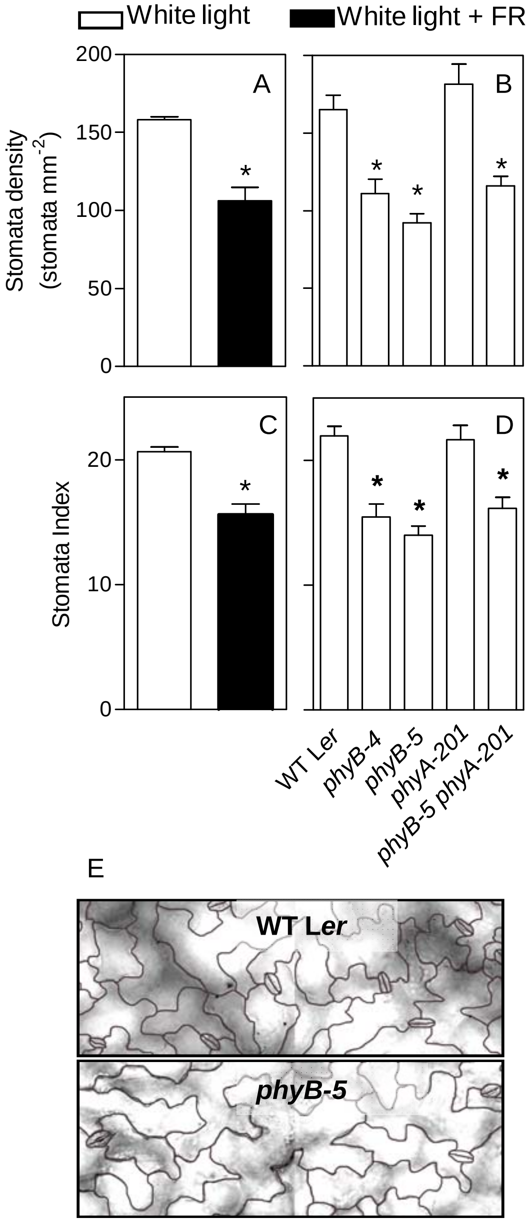

Figure 2. Phytochrome controls stomata density (A, B) and stomata index (C, D). Plants of the WT were grown under white light and white light +FR (A, C) and plants of the *phyA*, *phyB*, *phyA phyB* mutants (B, D) were grown with their respective WT under white light. Data are means and SE of at least 12 plant replicates. * denotes significant differences (P <0.05) between the indicated condition or genotype and its control according to ANOVA followed by Bonferroni post tests. Representative sections of the epidermis are shown for a phyB mutant and its WT (E). Stomata density, index and images correspond to the adaxial epidermis of fully expanded leaves.

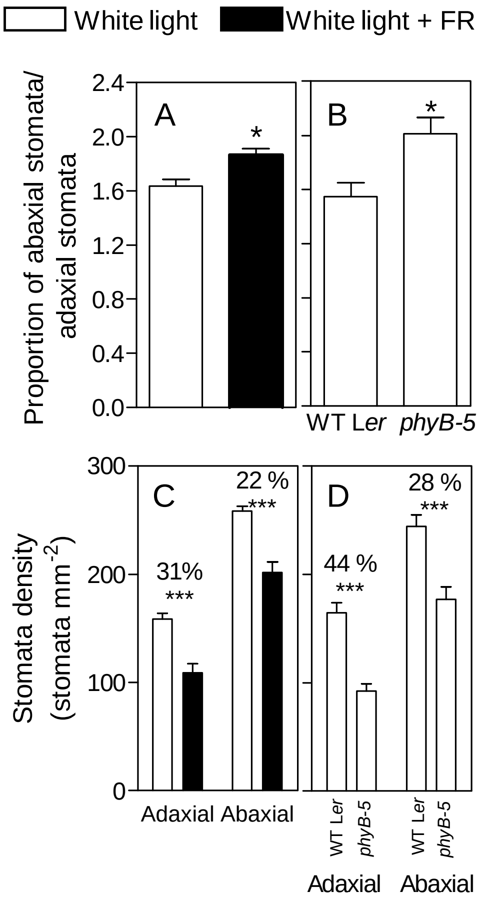

Figure 3. Phytochrome increases the level of amphistomy (A, B). The abaxial and abaxial stomatal densities and the percent decrease caused by +FR or by the *phyB* mutation are also shown (C, D). Plants of the WT were grown under white light and white light +FR (A, C) and plants of the *phyB* mutant were grown with its WT under white light (B, D). Data are means and SE of at least 12 plant replicates. * denotes significant differences ($P < 0.05$) according to ANOVA. *** denotes significant differences ($P < 0.001$) according to Bonferroni post tests.

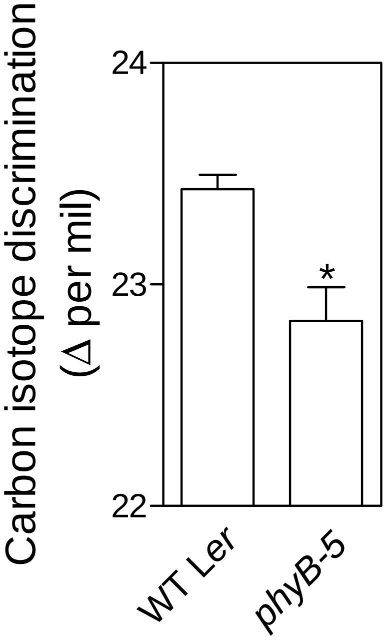

Figure 4. Phytochrome reduces water use efficiency. Plants of the *phyB* mutant and its WT were grown under white light. Data are means and SE of 3 plant replicates (pool of 3 plants each one). * denotes significant differences (P <0.05) according to ANOVA.

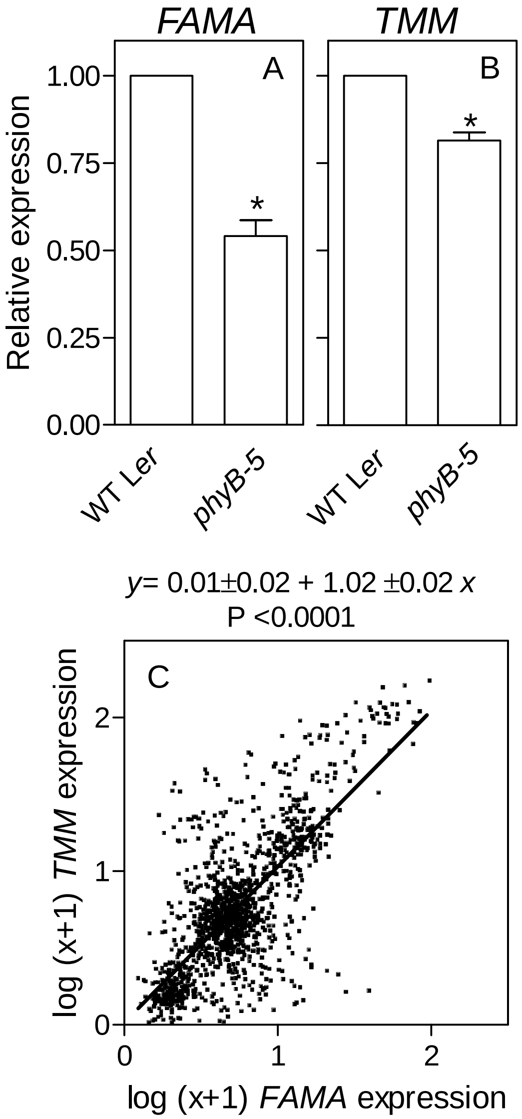

Figure 5. Phytochrome promotes the expression of *FAMA* and *TMM* in the leaves and the positive correlation between the expression of these two genes extends beyond phyB action. (A, B) Plants of the *phyB* mutant and its WT were grown under white light. Data are means and SE of 3 biological replicates. * denotes significant differences ($P < 0.05$) according to ANOVA. (C) Positive correlation between the expression of *FAMA* and *TMM*. The figure includes 633 data points corresponding to different developmental contexts and biotic or abiotic treatments (1 to 3 biological replicates per point) taken from 46 experiments (1388 microarrays, www.arabidopsis.org). Data were normalized to the median of each experiment and transformed as ln (x+1) (Buchovsky et al., 2008). The line shows least square linear fit of the 633 points and the significance is indicated.

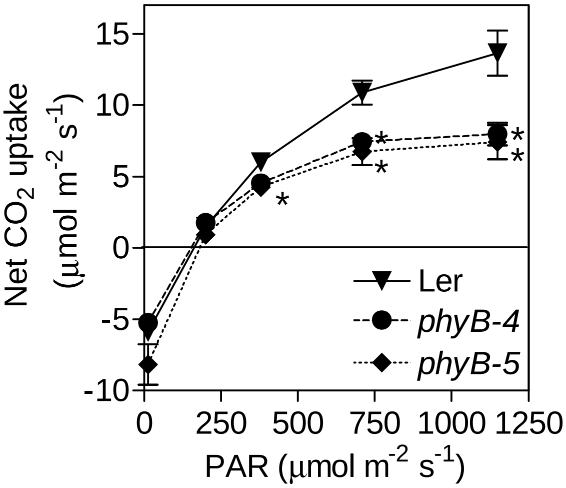

Figure 6. Phytochrome promotes photosynthesis in Arabidopsis. Plants of the WT and of the *phyB* mutants were grown under white light and then exposed to the indicated PAR during measurements. Data are means and SE of 6 plant replicates. * denotes significant differences ($P < 0.05$) according to ANOVA and Bonferroni post tests.

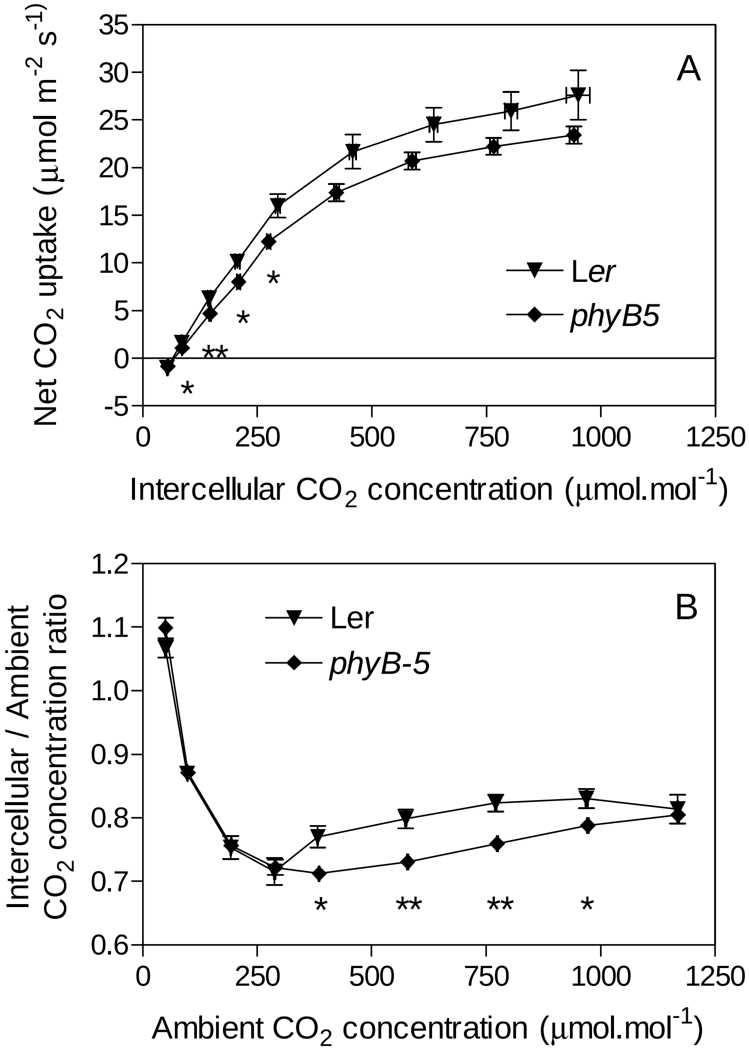

Figure 7. Analysis of stomatic and non-stomatic limitations to photosynthesis. (A) Curves of leaf net CO_2 uptake against intercellular CO_2 concentrations were obtained with a Li-COR 6400 system for the WT and the *phyB-5* mutant. (B) Ratio between intercellular and ambient CO_2 concentrations plotted against ambient CO_2 concentration (i.e. the concentration in the sample infrared gas analyzer of the Li-COR 6400 system). Data are means and SE of 5 plant replicates. * denotes significant differences (P <0.05) according to *t* tests. The tests were done between WT and the *phyB* having the closest intercellular (A) or ambient (B) CO_2 concentrations (in A, this overestimates the significance of the difference for the samples around 280 µmol.mol^{-1}).