An Enlightened View on Protected Cultivation of Shade-Tolerant Pot-Plants: Benefits of Higher Light Levels

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Abstract

Commercial protected cultivation of shade-tolerant pot-plants in The Netherlands has expanded enormously in the last decade. Typically, very low daily light integrals are applied (3-5 mol PAR m^{-2} day^{-1}), which are achieved by use of heavy screening and application of a layer of chalk ($CaCO_3$) on the outside of the greenhouse to increase reflection of incoming irradiance. Although these low daily light integrals are meant to avoid damage by high light intensities and/or high temperatures, it is clear that they carry a production penalty, since potential crop growth is directly related to the amount of light that can be captured and efficiently used. Additionally, it remains unclear whether current daily light integrals are too conservative, which would create room for optimisation. Recently, a number of experiments have been carried out to examine the possibilities and limitations for cultivation of several shade-tolerant pot-plants at higher daily light integrals. For most species, plants could be grown faster when more light was allowed. Also, a significant reduction in energy use for heating could be achieved if more natural irradiance was allowed to enter the greenhouse. However, use of more light required higher levels of relative humidity to avoid light damage. In this paper, we present a synthesis of experiments, as well as an outlook to further improvements.

INTRODUCTION

Commercial protected cultivation of shade-tolerant pot-plants represents a rapidly increasing industry in The Netherlands. The production value of the three largest pot plant crops (*Phalaenopsis*, *Anthurium*, *Bromeliad*) together represented approximately 423 million euro in 2010. Typically these pot-plants are cultivated at very low daily light integrals (DLI, 3-5 mol PAR m^{-2} day^{-1}) inside the greenhouse. In this paper we compare 5 recent studies, which have looked at the possibilities of increasing DLI in the cultivation of a wide range of commercially relevant shade-tolerant pot-plant species. We have compiled the responses of biomass growth to DLI, as well as effects of DLI on developmental rate and the effect of timing is considered. We also present some recommendations to further improve the cultivation strategy, including high DLI.

MATERIALS AND METHODS

We analysed 5 different experiments (Van Telgen et al., 2004; Garcia and Driever, 2010; Warmenhoven and Garcia, 2010; Dueck et al., 2011; Van Noort et al., 2011) looking at the influence of Daily Light Integral (DLI, mol PAR m^{-2} day^{-1}) on the growth and development of a wide variety of potplants (Table 1). All of the experiments were carried out at the facilities of Wageningen UR Greenhouse Horticulture in Bleiswijk, except for Van Telgen et al. (2004) which was done at the facilities of Wageningen UR Greenhouse Horticulture in Aalsmeer.

Although all the studies looked specifically at changes in plant growth and development as a result of increasing DLI, the results are often not straight-forward to compare within and between studies due to the differences in growth and development between each pot-plant species. However, each study used a designated reference treatment to represent the state of the art in commercial practice at the time of the experiment. Therefore, for this report we have decided to normalise data using the reference treatment as an index to visualise general trends. We refer to the original reports for the absolute data. We have used the fact that *Anthurium* has been used in more than one study, to compare findings between studies (Figs. 2 and 4).

RESULTS AND DISCUSSION

Growth in Relation to Daily Light Integral

Growth can be analysed in a number of different ways. A common feature of all studies was the use of destructive growth analysis (among other techniques) to define biomass accumulation. A summary of biomass growth (fresh and dry weight) is shown in Figure 1. All *Phalaenopsis* cultivars accumulated more biomass at higher DLI, showing increases in biomass of 10-30% compared to the reference treatment (Fig. 1A and D). The only exception was *Phalaenopsis* 'White Moon', which only showed increased growth at DLI above 4.5 mol m^{-2} day^{-1}. These treatments were all done on the first stage of *Phalaenopsis* cultivation, which involves purely vegetative growth. In the study by Van Noort et al. there is more differentiation between species (Fig. 1B and E), with a pronounced increase in biomass accumulation with increasing DLI for *Anthurium* 'Baby talk', *Areca, Calathea* 'Bicajoux' and *Ficus* 'Danielle', a small increase for *Ficus* 'Tineke', *Guzmania* 'Hilda' and *Dendrobium* and no increase or even a small decrease for *Dracaena* 'Lemon lime' and *Oncidium*. In the study by Warmenhoven and Garcia (2010) all species accumulated more freshweight biomass at higher DLI (Fig. 1C), although in some cases the increase was small (3% for *Vriesea* 'Miranda') or not observed in dryweight biomass (*Vriesea* 'Miranda' and *Tillandsia cyanea* 'Anita' highest DLI, Fig. 1F). However, in this study, only above-ground biomass was determined, which makes comparing their findings to the other studies difficult.

The studies by Van Telgen et al. (2004), Van Noort et al. (2011) and Garcia and Driever (2010) all used various *Anthurium* species to investigate the response to DLI. Their results are shown in Figure 2, normalised against their own reference treatment. It is interesting to see that the growth increase in Van Telgen and colleagues appears to saturate at DLIs above 4 mol PAR m^{-2} day^{-1}. In other words, all growth benefits were obtained from simply adding artificial light on top of their reference treatment, which used only daylight. The applied amount of artificial lighting, was not found to cause significant changes as it increased the DLI for all treatments to values of at least 4 mol PAR m^{-2} day^{-1}. However, this response does not appear to be generic, when the results of both other studies are taken into account. These studies use a higher reference treatment (5 mol PAR m^{-2} day^{-1} for Van Noort et al. (2011), 5.8 mol PAR m^{-2} day^{-1} for Garcia and Driever) and still large increases in biomass accumulation are observed when DLI is increased. In these studies, the increase in biomass accumulation only appears to reach a plateau at DLIs above 8 mol m^{-2} day^{-1}. Although these different responses to DLI could be (partly) due to genotypical differences, we think they can also be explained by the interaction of other growth factors with light and will elaborate on these interactions in the paragraph on future improvements.

Development Rate in Relation to Daily Light Integral

All studies have incorporated a measure for developmental rate. Dueck et al. (2011) have measured the number of new leaves during the course of the experiment. They show an increase in the number of new leaves with an increase in DLI for all four *Phalaenopsis* cultivars (Fig. 3A). In Van Noort et al. (2011) and Warmenhoven and Garcia (2010) total number of leaves was determined at the end of each treatment. In Van Noort et al. (2011) this was only determined for three representative species (Fig. 3B). *Anthurium* 'Baby talk' showed a severe increase of up to 42% in total number of leaves at the highest DLI. *Calethea* 'Bicajoux' showed a more moderate increase of approximately 20% and also did not increase between DLI treatments. *Dracaena* 'Lemon lime' did not increase at the moderate DLI and showed an increase of 10% at the highest DLI.

Warmenhoven and Garcia show moderate increases (5-10%, Fig. 3C) in the total number of leaves of all species, except for *Vriesea* 'Miranda'.

Similar to the biomass analysis in Figure 2, we have also analysed normalised developmental rate measurements of the *Anthurium* species from Van Telgen et al. (2004), Garcia and Driever (2010) and Van Noort et al. (2011) together. Van Telgen and colleagues only report leaf developmental period, which is therefore shown in a separate figure (Fig. 4A). Figure 4B shows normalised total number of leaves for the *Anthurium* cultivars used in Van Noort et al. (2011) and Garcia and Driever (2010). Decreases in leaf developmental period saturate at DLI above 4 mol PAR m^{-2} day^{-1} in Figure 4A, whereas increases in total numbers of leaves only saturate at DLI above 10 mol PAR m^{-2} day^{-1} (Fig. 4B). It is not clear if these findings contradict, because leaf appearance rate was not measured by any of the studies except for Dueck et al. (2011), which prohibits a true comparison.

One remarkable finding is the apparent increase in development rate (assessed by the related variables mentioned above) as a result of increasing DLI. According to conventional physiological dogma's temperature would be the main controlling factor. The amount of light captured is traditionally only associated with the increase in growth of biomass via sink-source relations. However, it seems that development rate of a number of pot-plants was also affected by DLI, also in the studies where temperature was kept constant between treatments (Van Telgen et al., 2004; Dueck et al., 2011; Warmenhoven and Garcia, 2010). It seems therefore that pot-plants could be more flexible in the rate of organ initiation, perhaps allowing for more plasticity in growth strategy. In particular, such plasticity could be beneficial to the epiphytic species in an ecological sense. In their original natural habitat, these species often have very limited access to water and nutrients as well as light, which may also be distributed very unevenly over the growing period. The observed plasticity in development rate may help to adapt the growth strategy to these external conditions.

Timing of Daily Light Integral

Interestingly, some of the studies also looked at the timing effect of DLI during the cultivation period. Contrary to the strong effects of DLI on growth and development in the vegetative period in cultivation of *Phalaenopsis*, no significant effects of DLI during the (relatively) cool phase (which is used to induce flowering) were observed by Dueck et al. (2011). Increasing DLI at this stage appeared to only marginally increase the development rate of the flowering shoot, leading to slightly shorter time to flower. Garcia and Driever specifically looked at the effect of timing of increased DLI, by dividing the cultivation in three distinct periods. They found for *Anthurium* that high DLI applied in the middle of the cultivation period was most beneficial for the quality of the produce (in particular of the colour of the flower), whereas high DLI applied towards the end of the cultivation period resulted in almost the same growth increases compared to high DLI applied during the middle and the end of the cultivation period. Perhaps similar effects also play a role in the study by Warmenhoven and Garcia (2010), in which the reference treatment was subject to a pronounced seasonal shift in natural DLI, whereas the artificial light treatments were more stable around a constant DLI. Van Noort et al. (2011) follow plants in four overlapping cultivation periods, in which the reference treatment performs remarkably better during the summer months, even though the average DLI is similar over all reference treatments. This could be due to variations in other growth factors, but also possible to a difference in spectral quality of the light, which was completely composed of natural irradiance over summer, but had a large contribution of HPS lamps in winter.

Energy Use

Beneficial effects of increasing DLI do not have to be accompanied by increasing energy spending. Garcia and Driever report costs of € 0.32 associated with energy use in their reference treatment, whereas DLI treatments vary between € 0.31 to 0.45. Overall an average increase of € 0.09/plant was associated with additional energy costs of their highest DLI treatment compared to the reference treatment. However, in Van Noort et al. (2011) saving energy was a specific goal of the research and reported savings were between 19.1 to 22.5% for the DLI treatments. Of course, many aspects play a role here, such as timing over the season. But Van Noort and colleagues also specifically designed a temperature integration regime allowing high daytime temperatures combined with high diurnal fluctuations to make maximal use of heating via incoming natural irradiance. At the same time, a significant part of the irradiance in the DLI treatments came from natural irradiance, which kept associated electricity costs low.

Interaction of Daily Light Integral with Other Growth Factors

The comparison between the *Anthurium* species in Figures 2 and 4 shows a different response of *Anthurium* in the studies by Van Telgen et al. (2004) and the studies by Van Noort *et al.* (2011) and Garcia and Driever (2010). Although these contrasting results may be explained by genotypic differences, this apparent contradiction could also be a result of differences in the way the other growth factors were applied between these studies. The DLI treatments by Van Telgen and colleagues shared the same greenhouse compartment, which did not allow differential control of temperature or humidity to coincide with DLI. Although nutrient solution was applied optimally for each treatment in the study, they did not humidify air in any treatment and it is not clear whether CO_2 enrichment of greenhouse air was applied. Garcia and Driever also supplied specific nutrient solution based on regular analysis of the potting soil. However, they also increased the temperature in the high DLI treatment, and humidity control was used to keep relative humidity at high stable values. Van Noort and colleagues also used humidity control used even more severe daytime temperature increases (compensated for by nocturnal temperature) to coincide with high DLI. It is important to realise that the increase in temperature also had a positive effect on the CO_2 concentration within the greenhouse, due to less cooling via ventilation. The interactive effect of high humidity (which keeps the stomata from closing), high daytime temperature (speeding up development rate) and associated high daytime CO_2 concentration may explain the increase in response to DLI found by the *Anthurium* studies of Garcia and Driever (2010) and Van Noort et al. (2011), compared to Van Telgen (2004).

CONCLUSIONS AND FUTURE IMPROVEMENTS

Although increases in growth and development rate are often perceived as positive, we realise that quality traits have not been mentioned in this review. However, in particular in potplants, these traits determine the final market value. In some respects the increases in growth and development associated with high DLI led to increases in quality due to generally bigger or heavier plants with more flowers. However, sometimes high DLI also led to negative quality aspects, such as increasing number of young side-shoots in the *Vriesea* cultivars, as well as less intense colour of the flower at high DLI in many of the *Anthurium* cultivars. Also, the highest DLI in the study by Van Noort and colleagues led to mild (discolouring *Anthurium* ‘Baby talk’, *Areca*) to severe (burned necrotic spots *Guzmania* ‘Hilda’) leaf damage. This is probably a result of uneven distribution of direct irradiance, leading to local light flecks with high intensity. As these peaks are more intense when high DLI is part of the cultivation strategy we have two recommendations for future improvements.

Firstly, diffuse light is more evenly distributed than direct light, and the use of light scattering materials for greenhouse cover or shade screens to change the ratio direct/diffuse is therefore a focus for current research. The more advanced Fresnel technique, in which the direct fraction of the incident irradiance is focused on photovoltaic cells, leaving the diffuse fraction to be used for crop photosynthesis has also become interesting in this respect. Initial results reported by Van Noort (2011) look very promising. Secondly, when increasing DLI is considered, monitoring of the leaf status to prevent leaf damage to occur becomes more important. Monitoring based on chlorophyll fluorescence is a good example of a popular plant physiological technique, which is also available for commercial growers. These techniques should be considered when high DLI is incorporated in cultivation practices.

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Tables

Table 1. Studies that were used in this meta-analysis.

Study	Plant species	Cultivation period (dd/mm/yyyy)	Daily light integral (mol PAR m^{-2} day^{-1}) (approximate average over the complete cultivation period)	Number of plants used for averages
Van Telgen et al. (2004)	*Anthurium* 'Champion' *Anthurium* 'Bonina' *Anthurium* 'Orange Love'	5/9/2003-1/4/2004	2.2, 4, 4.46, 5.1	Destructive: 10 plants Non-destructive: 20 plants
Van Noort et al. (2011)	*Anthurium* 'Baby talk' *Areca* *Calathea* 'Bicajoux' *Dracaena* 'Lemon lime' *Ficus* 'Tineke' *Ficus* 'Danielle' *Guzmania* 'Hilda' *Dendrobium* *Oncidium*	10/2009-10/2010	5, 7.5, 10 (averages over 4 growing periods). Per period: 5, 5.5, 6, 5, 6, 6.5, 5, 8, 10.5 5, 9, 12	10 plants
Warmenhoven and Garcia (2010)	*Guzmania* 'Tempo' *Guzmania* 'Rana' *Guzmania* 'Hilda' *Vriesea* 'Stream' *Vriesea* 'Charlotte' *Vriesea* 'Miranda' *Aechmea fasciata* 'Primera' *Aechmea* 'Felicia' *Tillandsia cyanea* 'Anita'	24/9/2008-14/5/2009	4.5, 5, 5.6	Prior treatment: 10 plants Post-treatment: 20 plants
Garcia and Driever (2010)	*Anthurium* 'Leny' *Anthurium* 'Vito' *Anthurium* 'Pandola' *Anthurium* 'True Love'	7/11/2008-6/2009 (variable end date)	Two different greenhouse setups: 5.8, 6.5, 6.8, 7.5 6, 7, 7, 8	Destructive: 10 plants Non-destructive: 25 plants
Dueck et al. (2011)	*Phalaenopsis* 'Golden Treasure' *Phalaenopsis* 'Las Palmas' *Phalaenopsis* 'White Moon' *Phalaenopsis* 'Promise'	24/2/2010-9/7/2010	3.5, 4.5, 5.5	10 plants

Figures

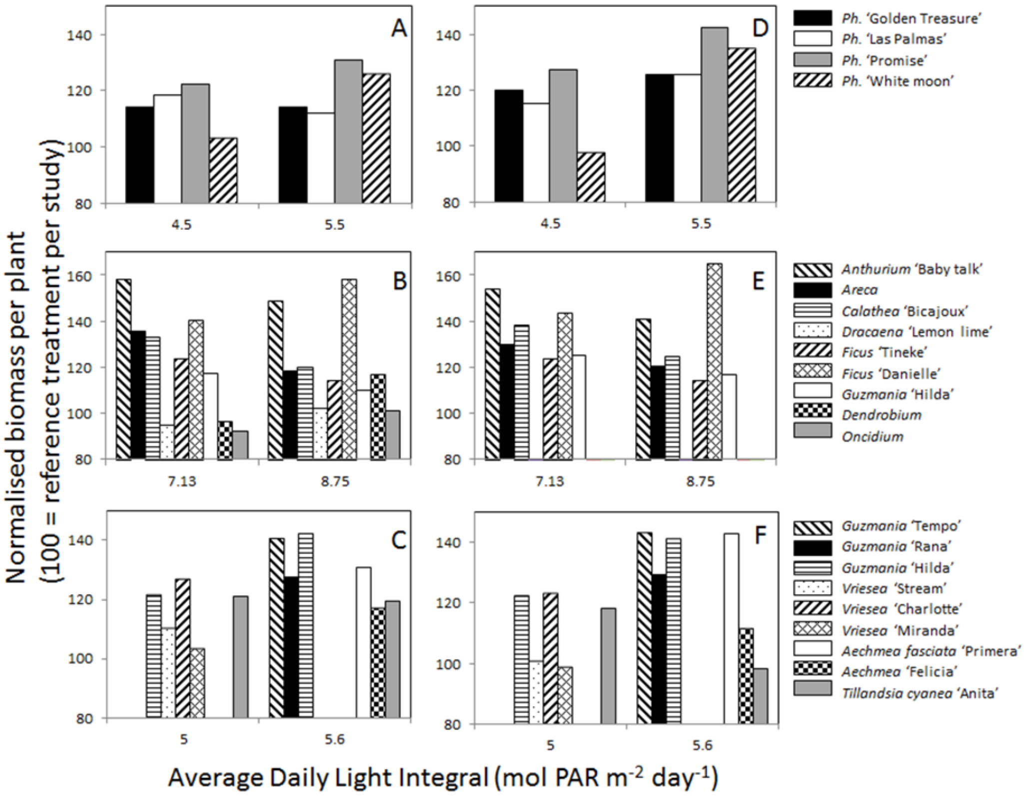

Fig. 1. Normalised plant biomass fresh weight (A,B,C)and dry weight (D,E,F) per Daily Light Integral treatment. Results from Van Noort et al. (2011) in B are averages from 4 cultivation periods. Reference treatments are taken as 100. C and F only show data for aboveground biomass, since belowground was not measured.

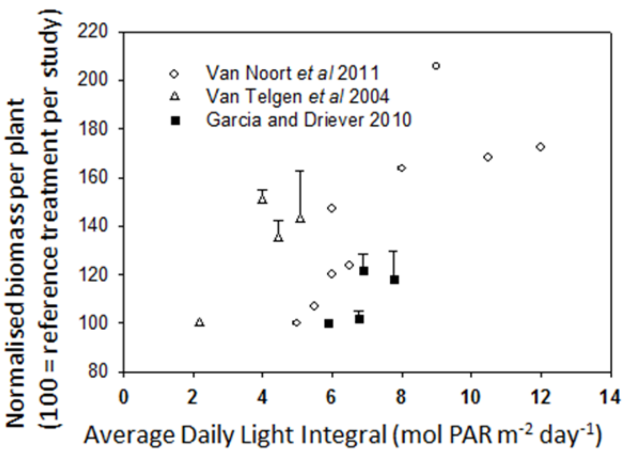

Fig. 2. Normalised *Anthurium* dry weight biomass as a function of DLI. Data were obtained from Van Telgen et al. 2004 (normalised against 2.2 mol PAR m^{-2} day^{-1}, average of 3 cultivars, error bars denote 1 standard deviation), Van Noort et al. 2011 (normalised against 5 mol PAR m^{-2} day^{-1}, 1 cultivar) and Garcia and Driever 2010 (normalised against 5.8 PAR mol m^{-2} day^{-1}, average of 4 cultivars, error bars denote 1 standard deviation).

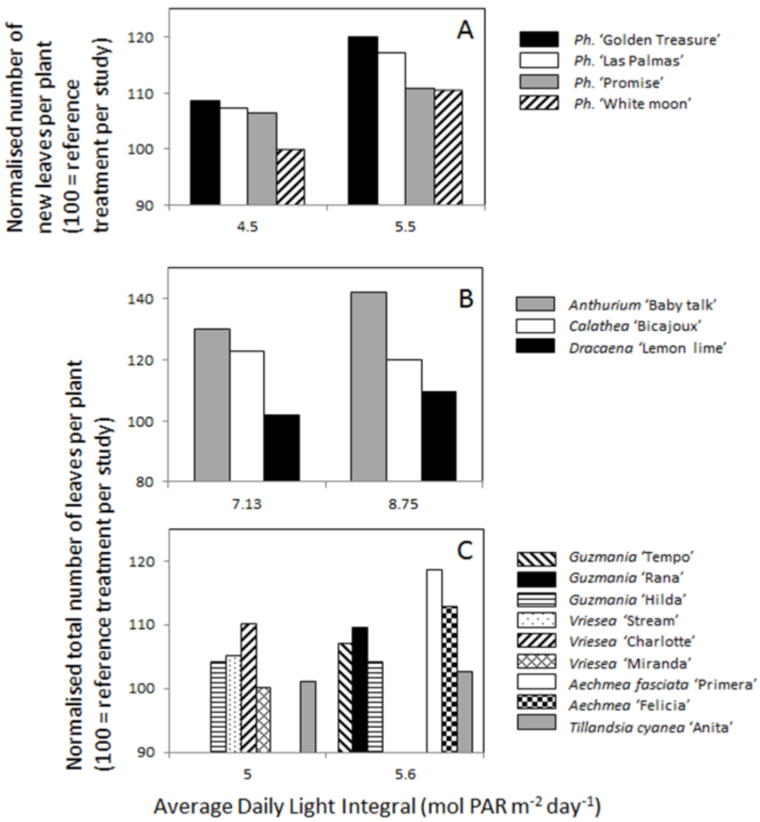

Fig. 3. (A) Normalised number of new leaves of *Phalaenopsis* as a function of DLI (Dueck et al., 2011). (B) Normalised total number of leaves of *Anthurium* 'Baby Talk', *Calathea* 'Bicajoux', and *Dracaena* 'Lemon lime' as a function of DLI (Van Noort et al., 2011). Results from 4 cultivation periods have been averaged. (C) Normalised number of total leaves for all species in Garcia and Warmenhoven (2010) as a function of DLI.

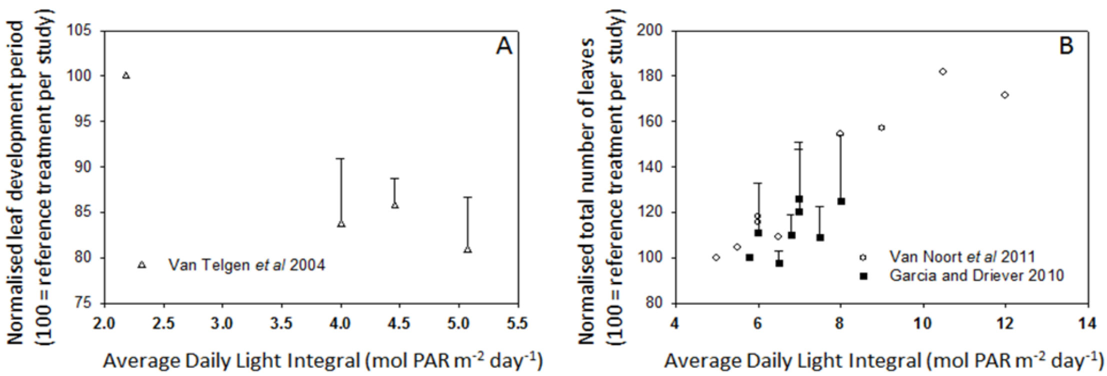

Fig. 4. (A) Normalised *Anthurium* leaf developmental period as a function of DLI. Data from Van Telgen et al. 2004 (normalised against 2.2 mol PAR m^{-2} day^{-1}, average of 3 cultivars, error bars denote 1 sd). (B) Normalised *Anthurium* total number of leaves as a function of DLI. Data from Van Noort et al. (2011) (diamond symbols, 1 cultivar, normalised against 5 mol PAR m^{-2} day^{-1}) and Garcia and Driever (2010) (circles, normalised against 5.8 PAR mol m^{-2} day^{-1}, average of 4 cultivars, error bars denote 1 sd).