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**Abstract**  
Recent research has shown that increasing the photosynthetic daily light integral (DLI) during propagation of cuttings increases root growth and overall quality of rooted cuttings. Our objectives were to determine how biomass accumulation and allocation and leaf morphology of *Impatiens hawkeri* (New Guinea impatiens) cuttings were influenced by the photosynthetic DLI during root development in propagation. Cuttings of New Guinea impatiens ‘Magnum Salmon’ were inserted into propagation substrate in cell trays and placed under mist in environmental conditions for callus development (approximately 5 mol·m⁻²·d⁻¹) for 7 days. After 7 days, cuttings were placed under DLIs of 2.5, 8.5, or 15.6 mol·m⁻²·d⁻¹ for 14 days. Total, leaf, stem, and root dry mass increased for cuttings within each DLI over time, and dry mass generally increased with DLI. Dry mass partitioning was greatest into leaves for cuttings under 2.5 mol·m⁻²·d⁻¹ and roots for cuttings under 8.5 and 15.6 mol·m⁻²·d⁻¹. Total leaf area increased throughout the experiment for all cuttings, while final total leaf area was highest under 15.6 mol·m⁻²·d⁻¹. The leaf area ratio and specific leaf area increased for cuttings under 2.5 mol·m⁻²·d⁻¹, but not under higher-light treatments. These results suggest cutting morphology and physiology is plastic in response to DLI during root development.

**INTRODUCTION**  
Many flowering bedding and garden plants are propagated from herbaceous shoot-tip cuttings. Some of the advantages of producing bedding plants from cuttings as opposed to seeds include increased genetic uniformity, no juvenile stage to pass before flowering, shorter production time, and production of sterile or seedless cultivars (Erwin, 1994). However, one of the challenges associated with cuttings is the need for rapid, complete, and uniform rooting during propagation.

In northern latitudes, un-rooted cuttings are received and propagated by greenhouse crop producers in winter and early spring in order to make spring sales dates. During these times of the year the outdoor photosynthetic daily light integral (DLI) is at seasonally low levels (Korczynski et al., 2002), and may be further reduced by over 50% by the greenhouse glazing material and super structure (Han, 1998). In order to promote root development during propagation, current photosynthesis must supply carbohydrates to the developing roots (Davis, 1988). Therefore, while low DLIs in the greenhouse during propagation may be beneficial for minimizing stress and developing callus at the base of cuttings during the initial stages of propagation, low DLIs during root development do not result in maximum photosynthesis to promote subsequent root growth (Loach, 1988). Supplemental lighting has been shown to accelerate growth and development of seedlings during propagation (Graper and Healy, 1991; Pramuk and Runkle, 2005; Oh et al., 2010) and has been widely accepted in the greenhouse industry for seedling production of bedding plants. Only recently has research demonstrated that increasing the DLI during propagation of herbaceous un-rooted cuttings can improve growth and quality of rooted cuttings (Lopez and Runkle, 2008; Currey et al., 2012).
Research has shown that increasing the photosynthetic DLI can increase root (RDM) and shoot dry mass (SDM) and the root:shoot dry mass ratio (R:S ratio). However, we have not found more detailed analyses of trends and patterns in biomass production, partitioning, leaf morphology, and photosynthesis of cuttings in response to DLI. Therefore, the objectives of this research were to identify the impact of DLI during the root development phase of propagation on biomass accumulation, partitioning, development, and photosynthesis of New Guinea impatiens.

MATERIALS AND METHODS

On 3 March 2011, 400 stem-tip cuttings of Impatiens hawkeri W. Bull ‘Magnum Salmon’ were received from a commercial propagator (Dümmen; Las Mercedes, El Salvador) at Purdue University (West Lafayette, IN, USA; 40°N). Cuttings were individually placed in 105-cell propagation trays (28-ml individual cell volume) filled with a substrate composed of (v/v) 50% soilless substrate (containing peat and perlite) and 50% coarse perlite. Cuttings were sprayed to runoff with a solution containing 300 mg L⁻¹ non-ionic surfactant so that water would not accumulate on the plant foliage. Mist was supplemented with 93% sulfuric acid at 0.08 ml·L⁻¹ to reduce alkalinity to 100 mg L⁻¹ and pH to a range of 5.7 to 6.0.

Target greenhouse air and substrate temperatures set points and DLI were 23°C and approximately 5.0 mol·m⁻²·d⁻¹, respectively, for callusing. Resistance-based sensors (External Temperature Sensor; Spectrum Technologies, Inc., Plainfield, IL, USA) recorded air and soil temperatures under each treatment every 30 s and averages were logged every 15 min by a data logger (WatchDog 2800 Weather Station; Spectrum Technologies, Inc.). Amplified quantum sensors (SQ-212; Apogee Instruments, Inc., Logan, UT) measured photosynthetic photon flux (PPF) every 30 s under each lighting treatment and the average of each sensor was logged every 15 min by a data logger (WatchDog 2800 Weather Station; Spectrum Technologies, Inc.). Actual air and substrate temperatures and DLI during callusing were 22.8±0.8 and 23.1±0.9°C and 4.9±2.9 mol·m⁻²·d⁻¹, respectively.

Seven days from the beginning of propagation, cuttings were divided and placed under no shade or fixed shade cloth providing approximately 38 or 86% shade (XLS F-14 or -16; Ludvig Svensson, Inc., Charlotte, NC, USA) under ambient daylight supplemented with a PPF of 83.3±2.1, 37.7±2.5, or 15.0±2.0 µmol·m⁻²·d⁻¹ at plant height [as measured with a quantum sensor (LI-COR Biosciences, Lincoln, NE, USA)], respectively, delivered from high-pressure sodium lamps from 06:00-20:00 hr (16-h photoperiod) to create high, medium, and low DLI treatments. Mist was applied consisting of acidified tap water supplemented with a water-soluble fertilizer providing (in mg·L⁻¹) with each misting event: 50 N, 5 P, 39 K, 9 Ca, 4.7 Mg, 0.05 B, 0.025 Cu, 0.25 Fe, 0.125 Mn, 0.025 Mo, and 0.125 Zn. Greenhouse air and substrate temperature set points were 23 and 22°C, respectively. Environmental data were recorded as previously described and are reported in Table 1.

Morphological data were collected at -1, 2, 5, 8, 11, and 14 days after transfer (DAT) to DLI treatments. Total leaf area (LA) was determined by removing all of the leaves and scanning them through a leaf-area meter (LI-3000; LI-COR Biosciences) three times and the recording the mean. Roots were excised from the cutting and roots, shoots, and leaves were dried separately in an oven at 70°C for 3 days. After 3 days roots, stems, and leaves were weighed to determine root (RDM), stem (SDM), and leaf dry mass (LDM), respectively. Data calculated for each cutting included total dry mass (TDM; TDM=RDM+SDM+LDM), root:shoot dry-mass ratio [R:S; R:S=RDM/(SDM+LDM)], leaf mass ratio (LMR; LMR=LDM/TDM), stem mass ratio (SMR; SMW=SDM/TDM), root mass ratio (RMR; RMR=RDM/TDM), leaf area ratio (LAR; LAR=LA/TDM), specific leaf area (SLA; SLA=LA/LDM), and leaf mass area (LMA; LMA=LDM/LA).

The experiment was designed as a randomized complete block design in a factorial arrangement with DLI (3 levels) and DAT as factors (6 factors for morphological and growth data). There were two replications (individual benches) per DLI treatment.
There were 5 samples (individual cuttings) per DLI per replication. Analyses of variance (ANOVA) and mean separation by Tukey’s HSD ($P \leq 0.05$) were performed for all data using SPSS 18.0 software (SPSS Inc., Chicago, IL, USA).

RESULTS

Total, leaf, stem, and root dry mass were affected by the interaction of DLI during root development and DAT (Figs. 1A-D). For example, though there were no differences in total dry mass of cuttings -1 DAT, total dry weights increased to 149.2, 179.5, and 304.3 mg by 14 DAT for cuttings grown under 2.5, 8.5, and 15.6 mol·m$^{-2}$·d$^{-1}$, respectively (Fig. 1A). Leaf dry mass increased by 44.0, 53.9, and 137.5 mg from -1 to 14 DAT for cuttings grown under 2.5, 8.5, and 15.6 mol·m$^{-2}$·d$^{-1}$, respectively (Fig. 1B). There were no differences in stem dry mass among cuttings at -1 and 2 DAT, but at 14 DAT, stem dry mass was 6.6 and 24.1 mg greater for cuttings under 8.5 and 15.6 mol·m$^{-2}$·d$^{-1}$, respectively, compared to cuttings grown under 2.5 mol·m$^{-2}$·d$^{-1}$ (Fig. 1C). The increase in root dry mass by 3.7-4.2 mg from -1 to 2 DAT was similar for cuttings under each DLI, root dry mass 14 DAT was 19.0, 37.0, and 59.7 mg for cuttings grown under 2.5, 8.5, and 15.6 mol·m$^{-2}$·d$^{-1}$, respectively (Fig. 1D).

Though there were no differences in the LMR for cuttings (0.85-0.86) across DLI treatments from -1 to 5 DAT, LMR for cuttings grown under 2.5 mol·m$^{-2}$·d$^{-1}$ decreased by 0.11 from -1 to 5 DAT with no further reductions, while LMR for cuttings grown under 8.5 and 15.6 mol·m$^{-2}$·d$^{-1}$ decreased by 0.30 from -1 to 11 DAT with no further reduction (Fig. 1E). The SMR was unaffected by DLI, DAT, or their interaction and ranged from 0.13-0.15 throughout the experiment (Fig. 1F). As DAT increased, RMR increased for cuttings under all DLIs for different durations (Fig. 1G). For cuttings grown under 2.5 mol·m$^{-2}$·d$^{-1}$ RMR increased by 0.11 from -1 to 5 DAT with no further changes, while RMR of cuttings grown under 8.5 and 15.6 mol·m$^{-2}$·d$^{-1}$ increased by 0.19 and 0.20, respectively, from -1 to 11 DAT (Fig. 1G). The trend in R:S ratio was similar to RMR (Figs. 1G and H). As DAT increased from -1 to 5 the R:S ratio of cuttings grown under 2.5 mol·m$^{-2}$·d$^{-1}$ increased, while the R:S ratio of plants grown under 8.5 and 15.6 mol·m$^{-2}$·d$^{-1}$ increased until 11 DAT (Fig. 1H).

Total leaf area increased for all species throughout the experiment (Fig. 2A). At 14 DAT, leaf area was greatest for cuttings grown under 15.6 mol·m$^{-2}$·d$^{-1}$. Time interacted with DLI to affect LAR differently (Fig. 2B). For example, while LAR of cuttings under 8.5 and 15.6 mol·m$^{-2}$·d$^{-1}$ was unaffected by DLI from -1 to 2 DAT, LAR decreased after 2 DAT to a consistent value (Fig. 2B). Alternatively, LAR of cuttings under 2.5 mol·m$^{-2}$·d$^{-1}$ did not change initially, then increased until 11 DAT (Fig. 2B). The SLA of cuttings was affected by the interaction of time and DLI (Fig. 2C). There was little change in SLA of cuttings grown under 8.5 and 15.6 mol·m$^{-2}$·d$^{-1}$ (Fig. 2C). The SLA of cuttings grown under 2.5 mol·m$^{-2}$·d$^{-1}$ increased from -1 to 11 DAT (Fig. 2C). The DLI interacted with time to affect the LMA of cuttings (Fig. 4D). While LMA of cuttings under 15.6 mol·m$^{-2}$·d$^{-1}$ changed little from -1 to 14 DAT, LMA of cuttings under 2.5 mol·m$^{-2}$·d$^{-1}$ decreased until 11 DAT. At 8 to 14 DAT, LMA increased with DLI.

DISCUSSION

Increases in total, root, stem, and shoot dry mass can be attributed to increasing DLI during root development, as dry mass is positively correlated with DLI (Warrington and Norton, 1991). Similar reports of increasing total, shoot, and root dry masses in response to DLI during propagation of herbaceous cuttings and seeds have been reported (Lopez and Runkle, 2008; Torres and Lopez, 2011; Currey et al., 2012). For example, Torres and Lopez (2011) reported that as DLI during propagation increased from 0.75 to 25.2 mol·m$^{-2}$·d$^{-1}$ RDM of *Tecoma stans* (L.) Juss. ex Kunth ‘Mayan Gold’ increased by 107.5 mg. Similarly, Lopez and Runkle (2008) reported after 16 days in propagation RDM of ‘Harmony White’, ‘Harmony Magenta’, and ‘Celebrette Red’ New Guinea impatiens increased by 867, 604, and 580%, respectively, and shoot dry mass increased by 53, 32, and 40%, respectively, as DLI increased from 1.3 to 6.1 mol·m$^{-2}$·d$^{-1}$. Our
results are in agreement with Lopez and Runkle (2008), as RDM and shoot dry mass (LDM+SDM) at 14 DAT increased by 214 and 89%, respectively, as DLI increased from 2.5 to 15.6 mol·m⁻²·d⁻¹. While these studies provided insight to final dry mass in response to DLI, Svenson et al. (1995) also reported TDM, LDM, and apical and basal (lowest 1 cm of stem plus roots) dry mass over 23 days in propagation. All dry weights increased as time in propagation increased. Taken together with other studies, our results indicate that increasing the DLI during propagation clearly increases biomass accumulation of rooting cuttings throughout propagation.

Assessing dry matter partitioning throughout root development may provide insight into how DLI can affect trends or patterns in growth. Though we have found some reports of R:S ratios in response to DLI at the termination of an experiment (Lopez and Runkle, 2008; Torres and Lopez, 2011; Currey et al., 2012), we have not found studies that have reported a more detailed analysis of biomass partitioning over time during propagation in response to DLI. Initially, LMR decreased after -1 DAT for cuttings under all DLIs. However, LMR decreased until 5 DAT, for cuttings under 2.5 mol·m⁻²·d⁻¹ and 11 DAT for cuttings under 8.5 and 15.6 mol·m⁻²·d⁻¹, after which LMR did not change. From -1 to 5 DAT the LMR for cuttings was similar across DLIs, however, from 5 to 14 DAT LMR was greater for cuttings grown under 2.5 mol·m⁻²·d⁻¹ compared to cuttings grown under 8.5 or 15.6 mol·m⁻²·d⁻¹. This suggests that more biomass was invested in leaves relative to stems and roots. Though RMR increased for all species starting at -1 DAT, RMR remained constant after 5 DAT for cuttings under 2.5 mol·m⁻²·d⁻¹ and 11 DAT for cuttings grown under 8.5 and 15.6 mol·m⁻²·d⁻¹. After 5 DAT, cuttings under 8.5 and 15.6 mol·m⁻²·d⁻¹ have higher RMR than cuttings under 2.5 mol·m⁻²·d⁻¹.

Throughout the experiment, there were no differences in SMR among treatments or over time, suggesting that SMR remains static for herbaceous cuttings during propagation, regardless of DLI. Cuttings grown under 8.5 or 15.6 mol·m⁻²·d⁻¹ had higher R:S ratios than cuttings grown under 2.5 mol·m⁻²·d⁻¹ after 5 DAT. The trend observed in the R:S ratio is similar to that seen for the RMR and inversely related to the LMR. This indicates that, since SMR was unaffected over time or across DLI, root and leaf biomass production enters a pattern of coordinated development during propagation. However, it is clear that cuttings grown under 2.5 mol·m⁻²·d⁻¹ partition more biomass into leaf production relative to total biomass, while cuttings grown under 8.5 and 15.6 mol·m⁻²·d⁻¹ partition more biomass into roots. Furthermore, there appeared to be a saturation in the relative amount of biomass partitioning into roots as DLI exceeded 8.5 mol·m⁻²·d⁻¹, as there were no differences in RMR and SMR of cuttings grown under 8.5 and 15.6 mol·m⁻²·d⁻¹.

Total leaf area increased for all cuttings from -1 to 14 DAT (Fig. 2A). While the TLA of cuttings under 15.6 mol·m⁻²·d⁻¹ was greater than cuttings under the other DLIs at 14 DAT, this may be attributed to having approximately 1 additional leaf unfolded and a slightly larger average individual leaf area (data not shown). The LMA of cuttings, a measurement of leaf mass per unit leaf area, increased with DLI in this experiment. While not measured in this study, leaf thickness has a large impact on LMA (Lambers et al., 2008). More specifically, for leaves under higher light an increase in LMA is attributed to an increase in the palisade parenchyma of the leaf. When we look at the SLA, a measurement of leaf area per unit leaf mass, compared to LMA, the inverse of SLA, we observed an increase in response to increasing DLIs. Leaves developing under a low-light environment tend to be larger sinks for photosynthates in comparison with other plant organs (Lambers et al., 2008). This may be further supported with our data on LAR and LMR. The LAR and LMR, the ratios of TLA or LDM to TDM, respectively, increased for cuttings under 2.5 mol·m⁻²·d⁻¹ and decreased for cuttings under 8.5 and 15.6 mol·m⁻²·d⁻¹ (Fig. 2).

CONCLUSIONS

It appears that while total, leaf, stem, and root biomass accumulation increases over time during root development, increasing the DLI can result in greater biomass
accumulation. Similarly, cuttings exhibit plasticity in dry mass allocation and can alter allocation of biomass into leaves or roots in response to DLI during root development.

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**Literature Cited**


Tables

Table 1. Shade cloth percentage, daily light integral (DLI), and air and substrate temperatures for *Impatiens hawkeri* ‘Magnum Salmon’ cuttings under three different DLI treatments during root development.

<table>
<thead>
<tr>
<th>Shade (%)</th>
<th>DLI (mol·m⁻²·d⁻¹)</th>
<th>Temperature (°C)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Air</td>
<td>Substrate</td>
</tr>
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<td>None</td>
<td>15.6±3.0</td>
<td>23.3±0.8</td>
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<tr>
<td>38</td>
<td>8.5±2.1</td>
<td>22.2±1.0</td>
</tr>
<tr>
<td>86</td>
<td>2.5±0.7</td>
<td>22.4±1.2</td>
</tr>
</tbody>
</table>

Figures

Fig. 1. Total, leaf, stem, and root dry mass (A-D) and leaf, stem, and root dry mass ratios and root:shoot ratios (E-H) of *Impatiens hawkeri* ‘Magnum’ cuttings from -1 to 14 days after transfer (DAT) to DLIs of 2.5, 8.5 or 15.6 mol·m⁻²·d⁻¹. Each symbol represents the mean of 10 cuttings and error bars represent SE of the mean.
Fig. 2. Total leaf area, leaf area ratio, leaf mass ratio, specific leaf area, and leaf mass area of *Impatiens hawkeri* ‘Magnum Salmon’ cuttings from -1 to 14 days after transfer (DAT) to DLIs of 2.5, 8.5 or 15.6 mol·m⁻²·d⁻¹. Each symbol represents the mean of 10 cuttings and error bars represent SE of the mean.