Artificial lighting technologies to support aquatic plants in rivers which are shaded by bridges and culverts

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DOI: https://doi.org/10.52201/CEJ20/QHUI1774

SUMMARY

Aquatic plant communities are important components of river ecosystems, providing food sources and functional habitats through the provision of refuge and spawning substrate for animals including fish and macroinvertebrates. Types of urban infrastructure including bridges and culverts present a major challenge to rivers; for example, the shading effects of these structures can exclude aquatic and wetland plants, degrade and fragment habitats and inhibit the movement of aquatic and riparian species in rivers.

Few studies have investigated the potential to reconnect riverine habitats through artificial lighting technologies. In this study, a 12-month controlled laboratory trial was undertaken to investigate the potential for using artificial lighting to support aquatic plants shaded by urban infrastructure. Two artificial lighting scenarios were compared to a natural light (control) scenario to determine the potential for supporting eight aquatic plant species common in UK rivers.

Overall, growth rates, flower numbers and biomass values were higher for all species under the natural light scenario. However, the artificial lighting scenarios also enabled selected plants to grow and survive over the trial period with variable success in line with shade tolerance, suggesting that it is feasible to grow aquatic plants under urban infrastructure using artificial lighting. This study provides a basis of understanding on how to design an artificial lighting strategy that can support a community of aquatic plants; however, further study and in river trials are required to optimise such as system.

BACKGROUND

Rivers globally have been subjected to extensive historical and ongoing physical modification and fragmentation to enable flood protection, industrial development, urbanisation and increased agricultural yield (Walsh *et al*., 2005, Vörösmarty *et al*., 2010, Macklin & Lewin, 2019). Physical modifications affect hydrology, channel morphology and water quality (Walsh *et al*., 2005; Pennino *et al*., 2014; Booth *et al*., 2016; Vietz *et al*., 2016), all of which are intrinsically linked with the abundance and richness of aquatic communities (Hering *et al*., 2006, Newson 2002). In England, pressures including physical modification have resulted in just 14% of rivers achieving 'good' ecological status as defined by the Water Framework Directive (WFD) (Defra 2020).

River crossings associated with infrastructure such as bridges and culverts are commonly required where roads and railways intersect rivers. Additionally, in both urban and rural settings, rivers have often been built over with extensive reaches now underground in culverts and hidden from sight (Elmore & Kaushal 2008, Napieralski & Carvalhaes 2016). These human modifications can sever connections between upstream and downstream habitats (Foster & Keller 2011), influencing hydrological connectivity and impacting upon critical ecosystem functions (Arango *et al*., 2017). Shading from such structures may fundamentally change the river ecosystem locally, fragment habitats and subsequently inhibit the longitudinal movement of species along rivers (Environment Agency 2002, Neale & Moffett, 2016).

Light is an essential source of energy for photosynthetic species including periphyton, phytoplankton and aquatic plants which are autochthonous energy sources for the wider river ecosystem. The specific light spectrum needed by plants is called Photosynthetically Active Radiation' (PAR) and includes the visible light spectrum wavelength of 400-700 nanometers (nm), UV light 280-400 nm and far-red light 700-800 nm. Consequently, shading from daylight is a prominent factor influencing the abundance and distribution of aquatic plants in rivers (Lacoul & Freedman 2006). De-culverting or 'daylighting' is an increasingly common river restoration technique in the urban environment (Wild *et al*. 2011; Wild *et al*., 2019). Nevertheless, culvert construction continues to be widespread where alternatives such as clear span bridges are considered disproportionately expensive or technically unfeasible.

 ISSN 1758-2067

In many scenarios, there are few options for introducing natural light into culvert design to mitigate the negative impacts of shading. There is no existing evidence on the benefits of artificial lighting to culverted rivers on the Conservation Evidence website. This study therefore aims to provide evidence for the use of artificial lighting as a viable form of mitigation for culverts and bridges. Using laboratory trials, we show how aquatic plant species respond to artificial lighting scenarios and recommend the next steps to optimise the technology. This will assist engineers and ecologists to integrate artificial lighting into river crossing infrastructure and retrofit existing river crossings.

ACTION

Tank Setup

The study was undertaken at an agricultural and horticultural research centre in the UK over a 12-month period between October 2019 and October 2020. The costs for undertaking this project are not available for publication. The growth response of eight plant species considered common and widespread in UK rivers (common reed *Phragmites australis; g*reater pond sedge *Carex riparia*; water mint *Mentha aquatica*; brooklime *Veronica beccabunga*; branched bur-reed *Sparganium erectum*; common bulrush *Typha latifolia*; unbranched bur-reed *Sparganium emersum* and common club-rush *Schoenoplectus lacustris*) were tested in three lighting scenarios: two artificial and one natural.

The experiment consisted of interconnected water tanks placed inside a daylight-excluded warehouse for the artificial lighting scenarios and outside of the warehouse for the natural light scenario. The plastic tanks were new and measured 1.1 m x 1.0 m and approximately 1.1m in height. All tanks were interconnected by plastic pipework and water was pumped through the connected tanks via a central bulk storage tank, providing a continuous flow of water to all tanks. This meant that the entire study was a closed system, delivering water of a consistent physico-chemical condition to all tanks both inside and outside the warehouse. The pump and pipe arrangement was designed to provide a target flow rate of 6 litres per minute into each tank. Tank setups are photographed in Figure 1a-f.

The plant species chosen for the experiment were considered to represent aquatic plants found across the depth profile of a typical mid-reach river found in the UK, from channel margin wetland plants to deeper central channel plants.

Tanks were designed to simulate typical water depths for these species. Plant species studied and preferred water depths are detailed in Table 1. The limited tank size prohibited creation of greater water depths as are found in lower-reach rivers. Two replicates of the tank setup were studied for each lighting scenario.

The substrate was comprised of layers of pebbles, sand, grit, loamy soil and a final pebble layer to mimic typical river substrate. The containers were filled with the required depth of substrate to accommodate the water depths above as stated in Table 1. Tanks were filled with mains tap water and allowed to recirculate for two weeks. After two weeks, plant specimens of the eight plant species were supplied from a specialist wetland plant nursery in pre-planted coir matting. These were submerged into the tanks and anchored onto the bed substrate.

Table 1: List of species that were included in the trial and their typical habitat / depth requirement

Common name	Scientific Name	Habitat	Water Depth
Common reed	*Phragmites australis*	Wetland	10 mm
Greater pond sedge	*Carex riparia*	Wetland	10 mm
Water mint	*Mentha aquatica*	Shallow	250 mm
Brooklime	*Veronica beccabunga*	Shallow	250 mm
Branched bur-reed	*Sparganium erectum*	Medium	500 mm
Common bulrush	*Typha latifolia*	Medium	500 mm
Unbranched bur-reed	*Sparganium emersum*	Deep	750 mm
Common club-rush	*Schoenoplectus lacustris*	Deep	750 mm

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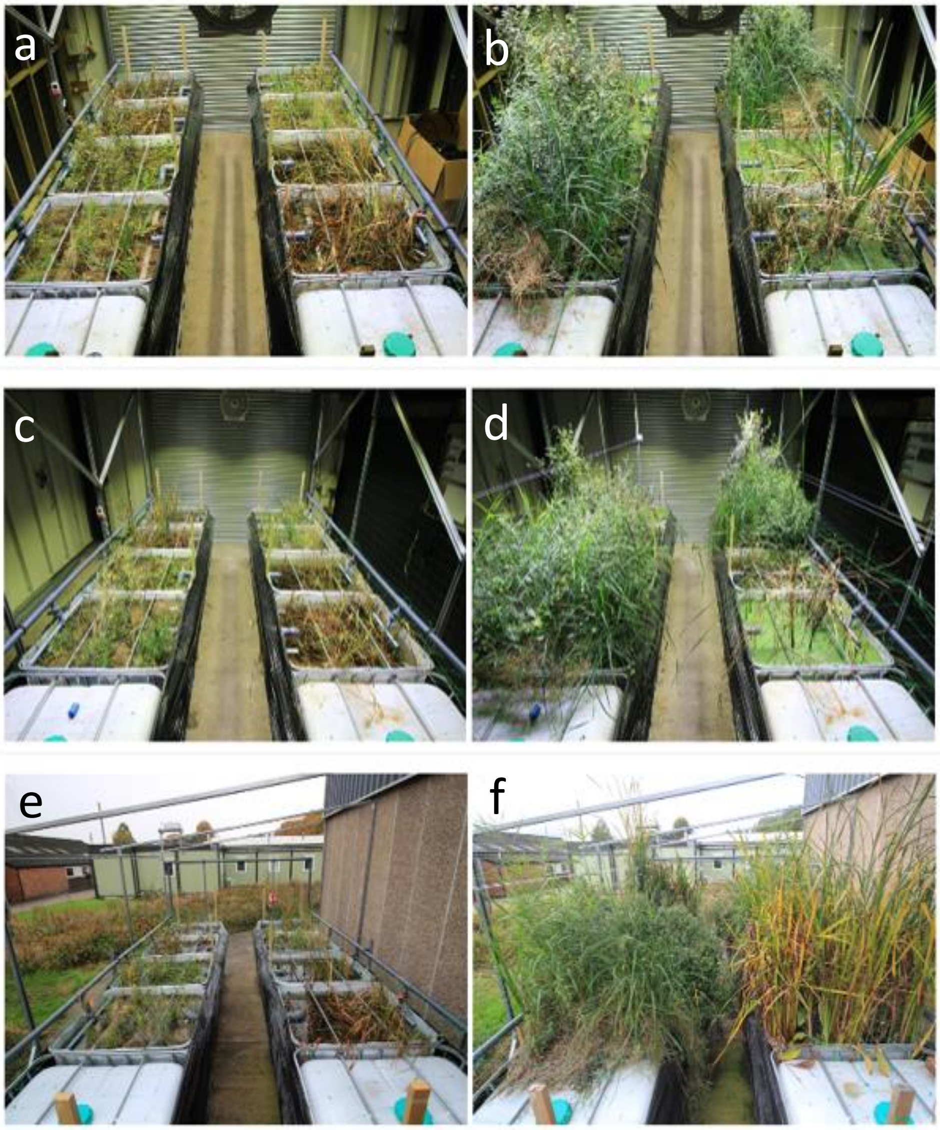

Figure 1a-1f. Site eye imagery for plants in artificial lighting scenario 1 (a-b) scenario 2 (c-d) and natural light (e-f) at 1 month and 12 months, from left to right.

Water quality within the experiment was maintained to simulate urban river water quality with typically high nutrient levels. This was considered appropriate as many culverted rivers are found in urban landscapes where they are also subject to anthropogenic pressures including wastewater discharges. Target water values were determined using existing in-river water quality data (Environment Agency 2021); with target total nitrogen values of 8-10 mg/l and orthophosphate of 0.3 mg/l. Water samples were collected weekly for external laboratory nutrient analysis to monitor compliance or deviation from target. Three fertilisers – calcium nitrate, potassium nitrate and mono potassium phosphate were used at different times depending on requirements to increase single or combined nutrient values.

Lighting Scenarios

Existing research formed a basis for understanding how much photosynthetically active radiation (PAR) should be delivered to the plants by the luminaires. A value of 25 µmol m^2 s^{-1} photosynthetic photon flux density (PPFD) for 16 hours per day was defined as a minimum light requirement for submerged macrophytes (Sand-Jensen & Madsen 1991). This equates to daily light integral (DLI) (mol m^2 d^{-1}) of 1.4. A higher target of 4.2 DLI was used in this study as the basis for the artificial lighting due to the range of species and to allow for the inherent uncertainty around applying lab-derived values in a potential real-world river environment in the future.

Two artificial lighting scenarios provided different profiles of PAR delivery by luminaires above each of the water tanks. Each luminaire used

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white light Osram OSLON Square LED chips (version 1.3). Lighting scenario 1 provided a constant value of 4.2 DLI throughout the year (equivalent of 75 µmol m^2 s^{-1} over a 16-hour day). During the winter, when the days were shorter, this required a higher PPFD to deliver such energy (Figure 2). Lighting scenario 2 provided a constant PPFD value of 75 µmol m^2 s^{-1} during all daylight hours. This equated to a higher DLI in summer than in winter (Figure 2). The two artificial lighting scenarios were separated by an internal wall to prevent light spill between them.

The control scenario consisted of the same tank arrangement placed outside, adjacent to the warehouse, under natural light. PPFD values were collected every half hour externally to determine how much PAR the control experiment received from the natural light. Across all water tanks in all lighting scenarios, PPFD was measured with an illuminometer (LI-192SA, LI-COR, Lincoln, NE, USA).

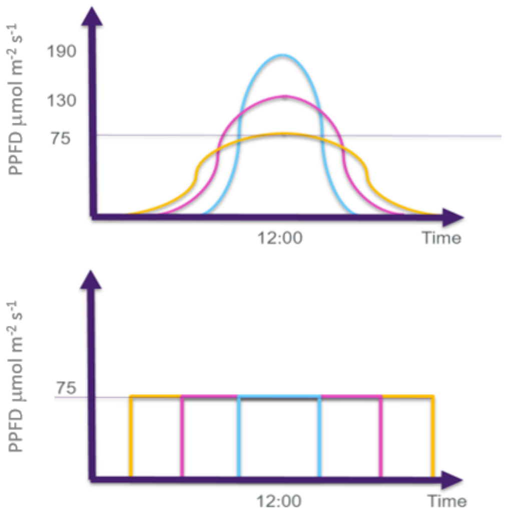

Figure 2: Artificial lighting scenarios 1 and 2 demonstrating seasonal variation between winter (blue), mid-season (pink) and summer (yellow). Scenario 1 (top): 4.2 mol m^{-2} d^{-1} DLI throughout the year resulting in variable PPFD peak between seasons. Scenario 2 (bottom): Constant peak PPFD (75 µmol m^{-2} s^{-1}) throughout the year. This results in a DLI value that varies throughout the year due to differing lengths of days.

Plant based assessments

In order to accurately monitor plant growth of all plant species, a number of parameters were assessed and recorded on a weekly or fortnightly basis. This included:

- *Biomass* (grams) following completion of the study to determine total live plant material (fresh weight) and total dead plant material (dead weight) for each species in each scenario;
- *Measures of plant height* on a subset of five tagged plants (centimetres) for each species in each scenario, measured from the base of the plant to the leaf tip (the same tagged leaf/stem was used at each assessment period). Plant height monitoring was not continuous throughout the study and only commenced when plant growth began to accelerate in the spring and summer such that peak growth rates could be captured. Consequently, the start of plant height monitoring varied between species. During the experiment, plant height monitoring in the control scenario had to be stopped where dense canopy cover impeded measurements, and;
- *Total numbers of flowers* across all individuals of each species in each scenario was recorded as a key indicator of plant health.

Data Analysis

Data analysis was carried out using R statistical software (R Core Team 2016). The overall biomass, fresh weight and dead weight of plant material in each scenario was analysed using a Kruskal-Wallis test. Plant growth was tested through comparison of the maximum plant heights recorded for each of the five tagged plants assessed from each species in each scenario using Analysis of Variance (ANOVA). Tukey's HSD Test was used for post-hoc analysis of ANOVA results for multiple comparisons between lighting scenarios.

CONSEQUENCES

Lighting scenarios

Throughout the 12-month period, the average DLI for lighting scenarios 1 and 2 were 4.0 and 3.4 mol m^2 d^{-1} respectively, compared to 19.3 mol m^2 d^1 in the external control scenario. This translated to an annual total for lighting scenarios 1 and 2 of 1460 and 1241 mol m^2 respectively, compared to an annual total of 7045 mol m^2 for the external control.

It must be noted that as plants grow taller and get closer to the light source, they will be subjected to higher levels of PPFD. In the natural environment, this does not affect plant exposure as the distance of the sun is so great that small variations in height are negligible. Nevertheless, the set-up in the study is similar to what is envisaged for future adoption of such a system to artificially light a culvert and so provides a realistic baseline study.

Biomass

Biomass values obtained at the end of the trial in week 52 provided an indication of the total fresh weight and dead weight of plants at that moment in time (Figure 3). Overall biomass of all species combined was found to be significantly greater in the natural light scenario compared to the artificial lighting scenarios ($H(2) = 14.72$, $p = 0.0006$). Two

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species, common club-rush and common bulrush recorded no biomass in the artificial lighting scenario. Common club-rush showed negligible growth in both artificial lighting scenarios. Common bulrush showed a small amount of growth before dying back between week 34 and week 44. Consequently, plant material had decayed thereby preventing biomass measurements. Greater pond sedge (scenario 1 – 793.7g; scenario 2 – 659 g) and water mint (scenario 1 – 3896 g; scenario 2 – 2971.5 g) provided substantial average biomass measurements within the artificial lighting scenarios with no dead weight biomass recorded indicating no dieback. Branched bur-reed, unbranched bur-reed and brooklime grew throughout the experiment, however low biomass values were recorded in artificial lighting scenarios. Water tanks supporting common reed were taken over by an unidentified grass species which compromised the data. Consequently, this species is not discussed any further.

Plant Growth

Branched bur-reed plant height was similar between the artificial and the natural light scenarios up to week 34, at which point plant growth rapidly accelerated under natural light (Figure 4a). Average growth rate between week 34 and week 38 was 1.99 cm per day under natural light, compared to the artificial lighting scenarios 1 and 2 which recorded 0.46 cm and 0.44 cm per day respectively during this period. Average maximum plant heights recorded for each lighting scenario prior to cessation of monitoring in week 42 were 112 cm (SD ± 34.7) and 111.4 cm (SD ± 28.5) for artificial lighting scenarios 1 and 2 respectively and 162.1 cm (SD ± 14.7) for the natural light scenario. This reflects greater maximum plant height in the natural light compared to plants in artificial lighting ($F(2, 27) = 11.37$, $p < 0.0002$) (Table 2).

Unbranched bur-reed showed similar results to branched bur-reed with similar growth rates across all scenarios until week 36. At week 36, plant growth rate began to decline in artificial lighting scenario 1 and 2 to 0.37 cm per day and 0.22 cm per day respectively yet the growth rate continued to increase in natural light to 1.42 cm per day. Average maximum plant heights recorded for each lighting scenario prior to cessation of monitoring in week 42 were 110.15 cm (SD ± 17.5) and 118.25 cm (SD ± 13.1) for artificial lighting scenario 1 and 2 respectively and 164.15 (SD ± 14.0) for the natural light scenario, again reflecting greater plant height under natural light compared to in artificial lighting scenarios ($F(2, 27) = 33.97$, $p < 0.0002$).

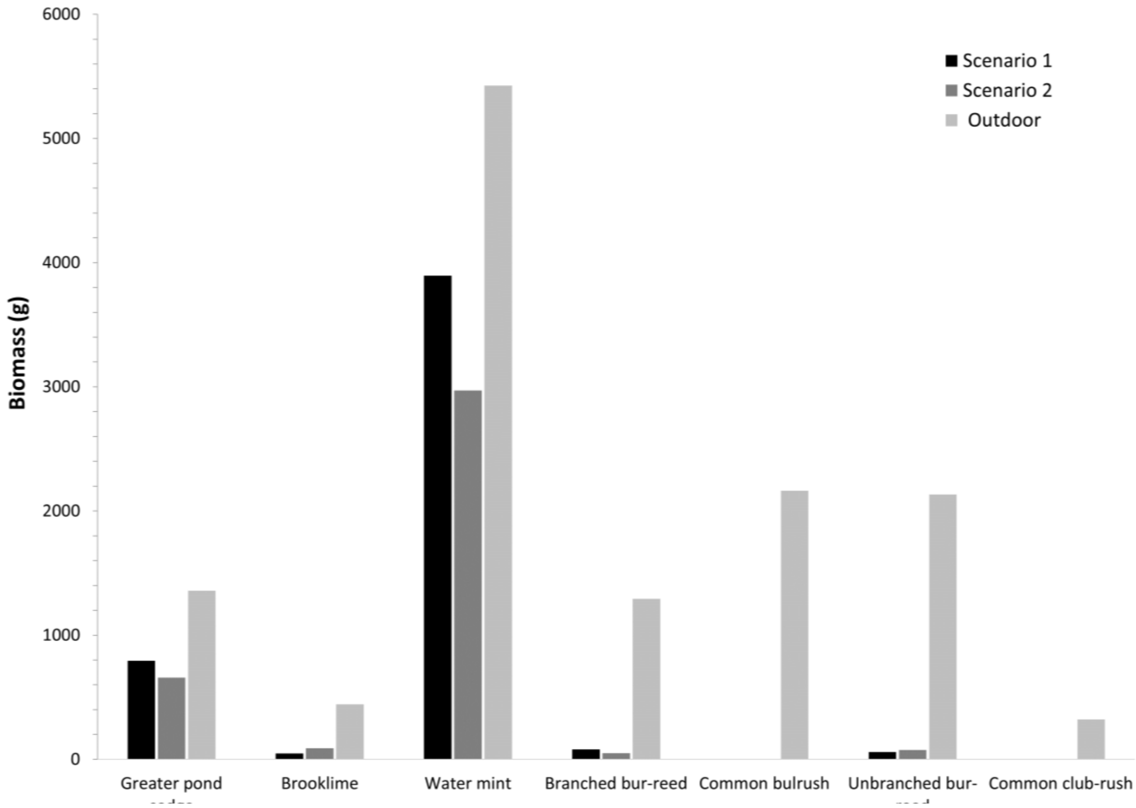

Figure 3. Average biomass from harvest at 12 months across species for the artificial and natural light scenarios

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Common bulrush plant height was considerably greater under natural light compared to in artificial lighting scenarios, with comparable growth between the scenario groups until week 28 only. At this point, growth rates accelerated under natural light with an average growth rate of 1.66 cm per day between week 28 and week 40, compared to 0.69 cm per day and 0.18 cm per day and in lighting scenarios 1 and 2, respectively (Figure 4b). Low growth rates recorded in artificial lighting scenario 2 were the result of some specimens dying back during this period. Average maximum plant heights recorded for each lighting scenario prior to cessation of monitoring in week 46 were 104.95 cm (SD ± 22.6) and 120 cm (SD ± 24.5) for artificial lighting scenario 1 and 2 respectively and 223 cm (SD ± 37.3) for the natural light scenario. This again reflects greater plant height on the plants in natural light compared to the plants in artificial lighting ($F(2, 27) = 49.56$, $p < 0.0001$).

Conversely, greater pond sedge plant height remained comparable in artificial lighting and natural light throughout the study with maximum growth rates of 1.07 cm and 1.01 cm in artificial lighting scenario 1 and 2 respectively and 0.71 cm in the natural light scenario (Figure 4c). Average maximum plant heights recorded for each scenario group were 125.9 cm and 126.5 cm in the artificial lighting scenario 1 and 2 and 124.6 in the natural light scenario, reflecting comparable growth both in artificial lighting and natural light ($F(2, 27) = 0.027$, $p = 0.973$).

Water mint also showed strong growth with increasing height in both artificial lighting scenarios observed until week 48 (Figure 4d). Water mint plant height could not be recorded in the natural light tanks over this period due to dense plant growth obstructing access to the five tagged plants, monitoring data for the artificial lighting scenarios is provided. Average maximum heights recorded in artificial lighting scenarios 1 and 2 were 120 cm (SD ± 54.3) and 145.4 cm (SD ± 43.7), respectively.

Brooklime plant height was not assessed as the plants became detached from the substrate and plants appeared to break off from the main stems. It is possible that the plants failed to grow root systems which sustained their form on the bed substrate, however this appeared to be associated with the experimental design as plant fragmentation was recorded both in artificial and natural light scenarios. Growth for common club-rush was also very limited and as such plant height was not assessed.

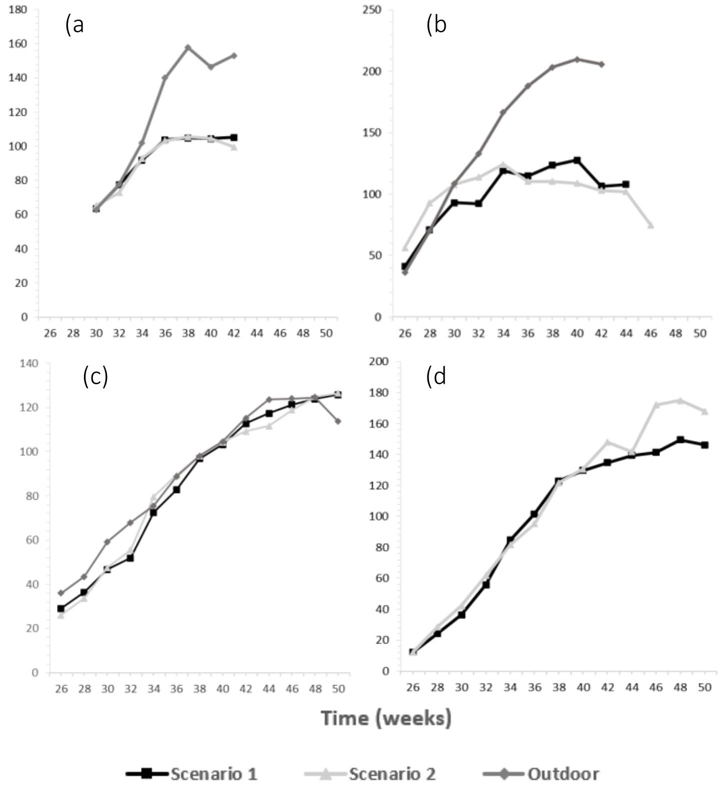

Figure 4. Mean plant heights (cm) recorded for (a) branched bur-reed (top left), (b) common bulrush (top right), (c) greater pond sedge (bottom left) and (d) water mint (bottom right) in the three lighting scenarios: artificial scenarios 1 and 2 and natural light scenario.

Flowering

Overall total flowers recorded across all species was found to be significantly greater in natural light compared to artificial light ($H(2) = 12.644$, $p = 0.0018$). Counts of flowers produced in each lighting scenario determined that six out of seven species flowered in the natural light scenario; only common bulrush failed to flower in natural light. In artificial lighting, greater pond sedge and water mint flowered successfully, with water mint producing the greater number of flowers in scenarios 1 and 2 with 45 (SD ± 28) and 21.5 (SD ± 12.5) flowers respectively and 92.5 (SD ± 8.5) flowers in natural light. Notably, flowering began earlier in the natural light scenario, with peak flower numbers being recorded between week 42 and 46; peak flower numbers were recorded later in the artificial lighting scenarios between week 50 and 52. Greater pond sedge recorded just one flower overall in artificial lighting scenario 1, compared to 9.5 (SD ± 0.5) flowers recorded in natural light.

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ISCUSSION

The results of this study show that artificial lighting can be used to support riverine aquatic plants under laboratory conditions, providing an evidence base for its use where natural light is limited by urban infrastructure. However, the response of the species tested varied considerably under artificial lighting. Plant heights under natural light were greater than those in the two artificial lighting scenarios for branched bur-reed, unbranched bur-reed, common bulrush and common club-rush. Common bulrush was the poorest performing species alongside common club-rush which showed negligible growth. It is notable that these two species are associated with high light levels, rarely found where relative illumination in summer is less than 40%, corresponding to an Ellenberg light value of 8 (Ellenberg 1991). All other species (See Table 1) within the study are considered to be plants generally located in well-lit environments, but also occurring in partial shade, corresponding to an Ellenberg light value of 7. Greater pond sedge heights were comparable for plants under both natural and artificial lighting, whereas water mint performed well under artificial light but could not be compared to plants under natural light due to dense growth inhibiting height measurements. Successful flowering was generally observed in species that also responded well under artificial light, with both greater pond sedge and water mint developing flowers under artificial light, even though total flower numbers were less than the control. Similarly, relative biomass was greatest for these shade tolerant species including greater pond sedge and water mint.

As may be expected, shade tolerance of aquatic plant species appears to be a key factor determining plant growth under artificial light. Results suggest that within a natural river environment, provision of artificial lighting technologies under urban infrastructure may allow for shade tolerant species such as greater pond sedge and water mint to establish and grow, resulting in a community of aquatic plants reflecting that present under dense riparian tree cover, where natural light is limited. The value of such a plant community as functional habitat and its ability to connect habitats severed by urban infrastructure requires further research.

This study provides a basis for understanding how to design a lighting strategy which could support a community of plants species and deliver wider habitat benefits. However, there remains considerable uncertainty around how to optimise such a strategy to ensure that a diverse community of species can be supported across all life stages to ensure a healthy and self-sustaining community across multiple years. It is recommended that future work should look at testing lighting scenarios that provide higher light levels, including PPFD and DLI in summer, which is considered the peak growth period for most aquatic plants; such a scenario may also be more effective in supporting plant growth in species with lower shade tolerance. In addition, it is recommended that future research is carried out over multiple years to understand natural

Table 2: ANOVA and Tukey HSD results for comparisons of plant heights in the lighting scenarios; Artificial Lighting Scenario 1 (A1), Artificial Lighting Scenario 2 (A2) and Natural Light Scenario (N)

	Average Plant Height (cm) (SD)			**ANOVA**		**Tukey HSD**		
Species	**A1**	**A2**	**N**	**F Value**	**P Value**	**A1 x A2**	**N x A1**	**N x A2**
Brooklime	-	-	-	-	-	-	-	-
Common bulrush	104.95 (21.4)	119.95 (23.2)	222.95 (35.4)	49.56	**<0.001**	0.485	**<0.001**	**<0.001**
Branched bur-reed	112 (34.7)	111.4 (28.5)	162.1 (14.7)	11.37	**<0.001**	0.997	**<0.001**	**<0.001**
Unbranched bur-reed	110.15 (17.5)	118.25 (13.1)	164.15 (14.0)	33.97	**<0.001**	0.495	**<0.001**	**<0.001**
Greater pond sedge	125.9 (11.9)	126.7 (22.2)	124.8 (16.2)	0.027	0.973	0.995	0.97	0.99
Water mint	120 (54.3)	145.4 (53.7)	-	-	-	-	-	-
Common club-rush	-	-	-	-	-	-	-	-

ISSN 1758-2067

regeneration and seeding in artificial light; this would provide evidence that artificial light could be used to support a self-sustaining plant community, mitigating the effects of river shading and connecting habitats severed by river crossings.

ACKNOWLEDGEMENTS

The laboratory trials were funded by Heathrow Airport Ltd (HAL) and carried out at Stockbridge Technology Centre, Selby, North Yorkshire. Stockbridge Technology Centre specialise in undertaking applied research and development projects in horticulture and agriculture for a range of commercial clients. The write-up of this paper was supported by internal Arup research funds.

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