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Wetlands are an effective green roof system

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ABSTRACT

Green roofs recently have garnered much attention as a means to reduce both the absorption of solar energy in summer and heat loss in winter, especially in urban areas with limited space for gardening. Constructed wetland roofs maintain more stable temperature profiles than terrestrial systems because of their slow heat transfer and high heat storage capacity. We found that wetland roofs were particularly efficient at decreasing the temperature of green roof systems on hot days. Wetland plants have high evaporation rates that are associated with their ability to cool buildings. Constructed wetland had excellent water holding ability, requiring less than 400 l water/m^2 of irrigation over the entire growing season, which was less than 20% of the expected irrigation requirement for terrestrial systems on green rooftops. Wetland macrophyte species demonstrated high tolerance to flooding and drought and showed great potential for regeneration by rhizomes, suggesting easy maintenance. Plants grown in the constructed wetland accumulated high biomass that can serve as a carbon sink. Wetlands on rooftops would not exceed the weight-bearing capacity of rooftops if water depths are designed and kept under 30 cm. Constructed-wetland roofs offer thermal benefits, a low amount of required irrigation, high tolerance of drought and flood, and flood-control capacities. They also can act as a carbon sink, are easy to manage, and provide other ecological services. Therefore, constructed wetlands are a reasonable choice for green rooftop systems.

1. Introduction

Urban development alters the environment in many ways, including raising temperatures in cities above those of surrounding areas. This "heat island effect" results from landscape modifications that replace green surfaces with buildings and pavements. These structures are made of materials that retain heat more than natural surfaces. Further, buildings discharge anthropogenic heat and gaseous pollutants that restrict normal patterns of airflow. Green spaces that are necessary to buffer these effects simultaneously disappear. Commensurate with its rapid development into the world's third largest megacity, Seoul, Korea, has experienced one of the highest rates of temperature increase over the last few decades [1].

The development of green areas may mitigate, to some extent, the heat island effect. However, in most cases, available space for greening is limited to rooftops and the outside walls of buildings [2]. Rooftop gardening can be used to create green, living roofs which are expected to reduce absorption of excessive solar energy, thus resulting in a significant savings in the energy used for air-conditioning in summer [3]. Green roofs also serve as insulation in cool weather [4]. Also, green roofs have other social costs benefits such as carbon reduction, air quality improvements, provision of recreational space and Habitat creation [5]. Green-roof methods have advanced with studies of appropriate species and growing media [3,6–8], system design [9,10], thermal and energy properties [11–13], and economic and environmental impacts [14,15]. However, the possible use of wetland plants or systems for green roofs has been largely overlooked.

Species of drought-adapted succulents (genus *Sedum*) currently are favorites for populating green roofs [16]. In comparison, the aqueous barrier provided by a wetland roof system should have better evaporation and insulation performance properties than the substrate used for terrestrial green roof systems. The higher water holding capacity of wetland plants, because of minimal leaching associated with them, increases their effectiveness. Therefore, using wetlands for green roofs offers distinct advantages in comparison to those provided by traditional green roof systems. Additional benefits of creating wetlands in urban areas include improvement in air quality, microclimate regulation, noise reduction, and added recreation-cultural value [17]. To evaluate these advantages, we studied the tolerance and performance of several wetland species

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under rooftop conditions. We then constructed a pilot-scale wetland to test its actual performance and features under rooftop conditions.

2. Materials and methods

2.1. Research site

Field measurements were carried out on the rooftop of a six-story building (the College of Natural Sciences building; 37°27′ 31.01″ N, 126°56′ 53.67″ E; 100 m above sea level) at Seoul National University, Seoul, Korea. The concrete rooftop was recently covered with urethane elastic water proofing coatings (top layer is covered with a mixture of trimethylopropane-neopentyl glycol-1,6-hexanediol-phthalic anhydride-adipic acid copolymer, toluene, methyl methcrylate, butyl acrylate-2-hydrooxyethyl methacrylate copolymer and other minor chemical compounds).

2.2. Selection of plant species

We selected four wetland species to study. These included two macrophyte, emerged plant species [18], *Iris laevigata* Fisch. (rabbit-ear iris) and *Iris pseudoacorus* L. (yellow flag iris). In addition, we used two riparian plants that are also found in terrestrial habitats, *Aster koraiensis* Nakai (Korean starwort) and *Astilbe chinensis* var. *davidii* Fr. (Chinese astilbe). *I. laevigata* and *I. pseudoacorus* were selected because they are shorter than other macrophytes, such as reeds and cattails [18], and therefore would not obstruct the view from rooftops. These species commonly are found in gardens [19] and survive well in a wide spectrum of environmental conditions [19,20]. Both species produce very attractive flowers [19] and have excellent water purification capabilities [20,21]. *Aster koraiensis* and *Astilbe chinensis* were selected because they are also commonly used for gardening and already have been trialed for use in terrestrial green roofs [22]. Like the chosen macrophytes, these riparian species provide no obstruction to rooftop views and produce beautiful flowers [18]. Only perennial species that would self-regenerate each year were selected, to reduce the cost of annual re-planting. The pictures of test species are presented in described in Supplementary material for this paper (Figs. S1–S4).

2.3. Experimental design

2.3.1. Tank experiment

In early May 2012, mats containing 25 plants grown in a 40 cm × 40 cm fiber net (Supplementary material, Fig. S5) filled with peat moss and pearlite (Uri-seed, Korea) were placed over a polystyrene foam bed to provide buoyancy. Then, the mat and bed were placed into a 46.5 cm × 68.5 cm × 38.5 cm (interior measurements) high-density polypropylene tank. The picture and cross-sectional view of tanks are shown in Fig. 1A and B. Five mats were prepared for each study species. Five additional mats without plants were prepared as controls. Water was added to the tanks to a depth of 20 cm, and the entire surface except the growing mat was covered with polystyrene foam to prevent evaporation. Large tanks were used to provide enough room for water collection and storage during any flooding that might occur upon rainfall and to prevent a rapid decrease of water depth due to transpiration. Water levels were checked every two weeks and also were measured after any special events, such as heavy rainfall, between early May and the end of October 2012. Water was added to the tanks whenever the water level fell below 10 cm. Water loss (mm) was transformed to volume (l) and then calculated as volume per unit area (l water/m^2). At the end of September, when the biomass had reached its peak, one-third of the plants were harvested for measurement of biomass. Measurements of tank evaporation in October were corrected to take into account the mass of the harvested plants.

The nitrogen (N) and carbon (C) contents of the original mats were 0.67 ± 0.02% and 28.19 ± 1.08%, respectively (values represent mean ± SE of three replicates). The average height and above ground biomass (fresh weight) of the plants in May were 12.1 ± 2.1 cm and 8.9 ± 1.4 g for *Aster koraiensis*, 18.5 ± 1.4 cm and 17.3 ± 2.4 g for *I. laevigata*, 17.2 ± 1.7 cm and 15.0 ± 1.9 g for *I. pseudoacorus* and 8.4 ± 2.2 cm and 2.1 ± 0.4 g for *Astilbe chinensis*

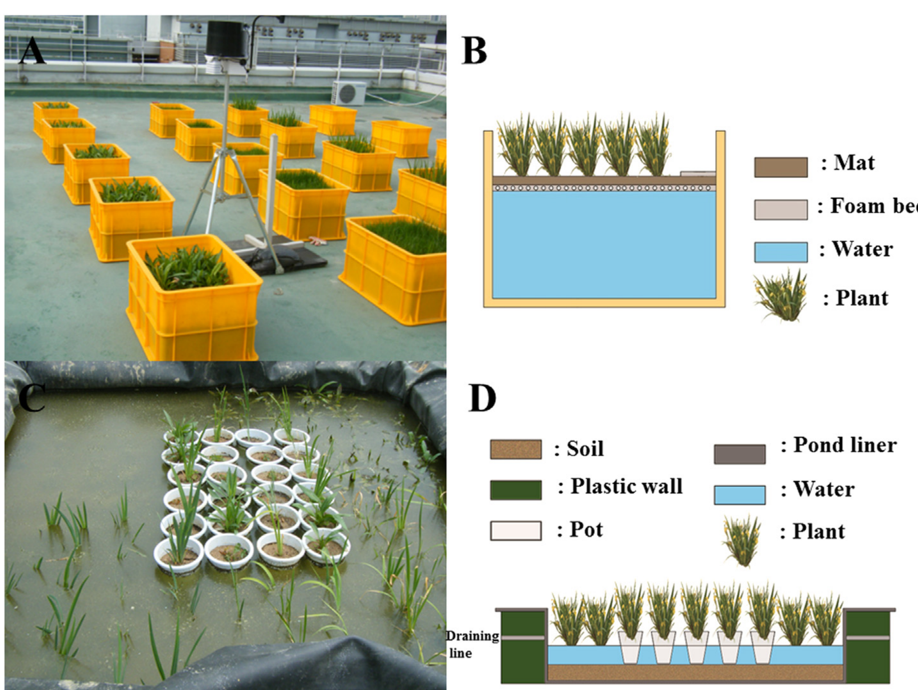

Fig. 1. Pictures and cross-sectional views of tanks and the wetland.

(values represent mean ± SE of ten replicates for height and three replicates for biomass).

2.3.2. Wetland experiment

On May 21, 2012, a pilot scale (2 m × 2 m) wetland was constructed using ethylene propylene diene monomer (EPDM) pond liner (Firestone Building Products USA) surrounded by plastic walls that were supported by earth bags. The wetland was filled to a depth of 10 cm with a commercial bed soil for paddy rice (Pungnong, Korea) designed to grow plants under flood conditions. The wetland was divided into four sections, and each test-plant species was planted in a separate section. Plants were planted at a density of 30 plants/m^2. Twenty-four pots were placed in the middle of the wetland, 6 pots (20 cm diameter and 27 cm height) for each plant species (covering about 1 m^2), to investigate plant performance in the absence of flooding. Pots were placed so that at maximum flooding, there would be −1 cm of water level in each pot. Water was added to the wetland to a depth of 12 cm and the water depth was maintained at ≤12 cm for a month, to prevent plants from becoming completely submerged. The picture and cross-sectional view of the wetland are shown in Fig. 1C and D. After the first 30 days, a draining line was installed 15 cm above the top of the soil to prevent water levels from exceeding 15 cm. Water levels were checked every two weeks and measured after any special events, such as heavy rainfall, until the end of September when they were harvested.

The N and C content of the commercial soil were: N: 0.10 ± 0.01% and C: 1.28 ± 0.15% (values represent mean ± SE of three replicates). The average height (leaf length) of the plants immediately after transplanting were: 14.1 ± 1.2 cm for *Aster koraiensis*, 23.2 ± 2.0 cm for *I. laevigata*, 20.7 ± 1.8 cm for *I. pseudoacorus* and 12.4 ± 2.5 cm for *Astilbe chinensis* (values represent mean ± SE of ten replicates).

2.3.3. Tolerance to flood and drought

To test the tolerance of *I. laevigata*, *I. pseudoacorus*, *Aster koraiensis*, and *Astilbe chinensis* to flooding, drought, and low irrigation, plants were grown in pots. For the flooding experiment, plants were placed into containers at 25 cm water depth, to simulate flooding conditions, in late May. Plants were flooded for one week, two weeks, or three weeks and then observed for a month while being watered daily, to create optimal conditions with which to infer whether they would survive after flooding. For the drought experiment, plants were not irrigated for 5, 10, or 15 days in late May. During the experiment, plants were covered in rainy weather to keep them dry. After treatment, plants were observed for a month in optimal conditions.

2.3.4. Minimum irrigation experiment

We compared levels of irrigation necessary to run a green-roof wetland system with those required for a green-roof terrestrial system. For this experiment, we selected two species that we used in the wetland system, *I. pseudoacorus* and *Aster koraiensis*, but compared results with those that we obtained from a third species, *Zoysia japonica* (Korean lawn grass). *Z. japonica* was selected because the species is often used for green roofs [23,24] and minimum and optimal local irrigation rates for this species already have been delineated [24].

The experiment was run with four treatments that provided varied amounts of irrigation: A: 20 l water/m^2 every other day, B: 40 l water/m^2 every other day, C: 60 l water/m^2 every other day, and D: 10 l water/m^2 daily. We initially considered treatment D as the baseline treatment, because we recorded the maximum evaporation rate of the wetland in late June and early July to be about 10 l water/m^2. Moreover, we recorded transpiration rates of *I.* of 8.3 ± 0.4 l water/m^2 day (mean ± SE of five replicates) June 28–30 and 8.7 ± 0.3 l water/m^2 day (mean ± SE of five replicates) July 7–9. However, because 10 l water/m^2 for a day did not appear to wet the soil at the bottom of the pots, we used treatment A as an additional baseline treatment. As the minimum irrigation rates for *Z. japonica* are reported to be about 20 l water/m^2 per day [24], we included treatments B and C in case plants did not survive in treatments A and D. Survival of the plants was checked every second day. Plants were considered dead when every leaf had withered and dried.

2.4. Soil and plant analysis

Plants in tanks and wetlands were sampled at the end of September. Plants biomass was measured immediately after harvesting. The C and N content of soil and plant samples were analyzed using an elemental analyzer (Flash EA 1112; Thermo Finnigan, United States). To measure density, the soil was sampled with a 100 ml soil core sampler (Eijkelkamp, Netherlands) and the sample was weighed [25].

2.5. Temperature, humidity and precipitation

Temperature and relative humidity were monitored by sensors connected to dataloggers (HOBO H08-003-02, Onset Computer, USA). Ambient rooftop data were collected by sensors placed in an instrument shelter. Wetland data were collected by sensors placed on the soil surface which was submerged. Precipitation during the study was measured using a rain gauge set in the middle of the tanks. The data of daily solar radiation and external temperature were provided by Korea Meteorological Administration, taken from a nearest weather station to the study site (Jongno station for radiation and Sillim station for temperature).

2.6. Statistical analysis

Treatment means were compared by one-way ANOVA and Tukey's HSD post hoc test using SAS 9.1. Differences were considered significant if $P < 0.05$.

3. Results

3.1. Temperature, humidity and precipitation

The mean rooftop and wetland temperature and precipitation on the rooftop are shown in Fig. 2. The mean rooftop temperature during the experiment was 21.7 °C and the mean relative humidity was 46.3%. The average external temperature during the experiment was 21.1 °C. The highest rooftop temperature recorded was 38.0 °C on August 5, and the highest wetland temperature was 33.1 °C on the same day. The highest one-day mean rooftop temperature was 32.3 °C on August 3, and the lowest mean one-day rooftop temperature was 9.1 °C on October 23. In May, the rooftop temperature was measured for 20 days following the beginning of the tank experiment, and the wetland temperature was measured for 10 days after wetland construction. However, due to a data logger malfunction, wetland temperatures readings only were obtained for 10 days in September.

There were 4 days in May, 2 days in June, 6 days in July, 10 days in August, 4 days in September and 3 days in October that had more than 1 mm of precipitation.

3.2. Monthly evaporation from tanks and water depth fluctuation of wetland

During the 173-day research period, total measured evaporation measurements were: *Aster koraiensis*, 1272 l water/m^2; *I. laevigata*,

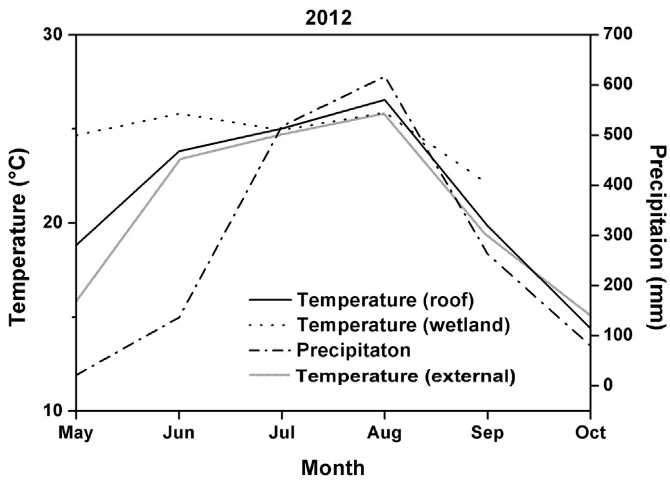

Fig. 2. Monthly mean temperature and precipitation of rooftop and rooftop wetland. The mean rooftop temperature for May is the mean of 20 days. The mean wetland temperatures for May and September are the means of 10 days. The external temperature data was provided by Korea Meteorological Administration, taken from a nearest weather station to the study site (Sillim station, 2 km distance).

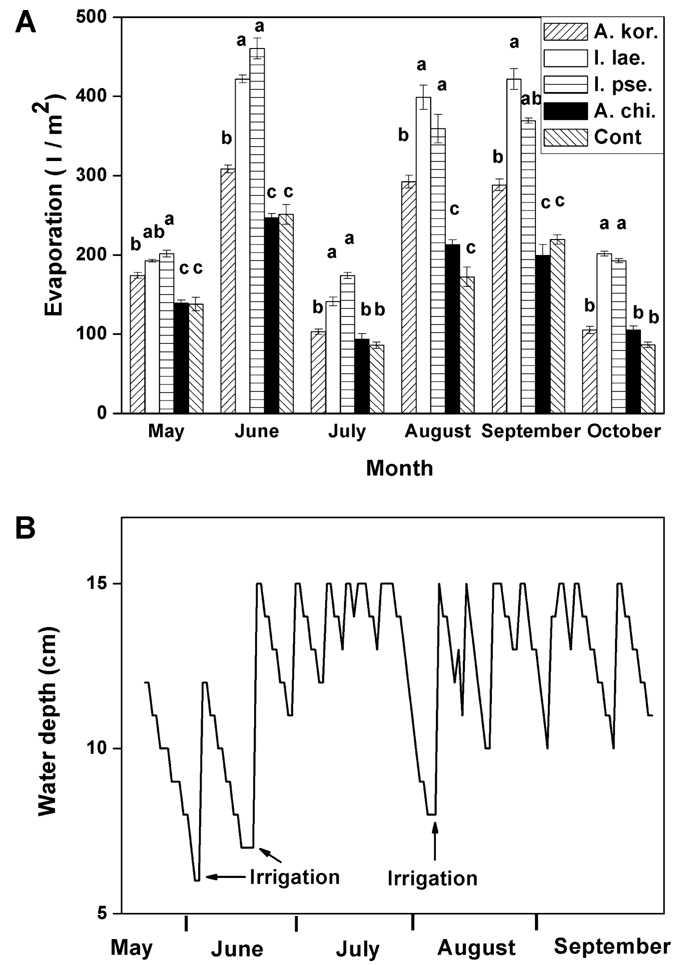

Fig. 3. Monthly evaporation and water depth of rooftop tanks and wetland. A: Monthly total evaporation amounts of tanks, B: monthly water depth fluctuation and irrigation pattern of wetland. The bars and error bars represent the mean ± SE of five replicates; different letters represent significant differences at the 0.05 level. The total evaporation value of tanks for May is the sum of 20 days. ※*A. koraiensis*: *Aster koraiensis*, *I. laevigata*: *Iris laevigata*, *I. pseudoacorus*: *Iris pseudoacorus*, *A. chinensis*: *Astilbe chinensis*.

1778 l water/m^2; *I. pseudoacorus*, 1757 l water/m^2; *Astilbe chinensis*, 997 l water/m^2; and control (mat only), 953 l water/m^2. Monthly tank evaporation measurements are shown in Fig. 3A. Fluctuations in water depth and irrigation patterns of the constructed wetland are shown in Fig. 3B. The wetland was irrigated three times during the research period (132 days). All other increases in water levels were due to precipitation.

3.3. Survival rates of plants after flooding, drought and controlled irrigation treatments

Aster koraiensis and *Astilbe chinensis* had low survival rates after flooding (Fig. 4A). However, all *I. laevigata* and *I. pseudoacorus* survived, even after 3 weeks of flooding. Similarly, *Aster koraiensis* and *Astilbe chinensis* had low survival rates under drought treatments (Fig. 4B), but all *I. laevigata* and *I. pseudoacorus* survived, even after 15 days without irrigation.

I. pseudoacorus had longer survival periods with controlled irrigation (Table 1) than the other two species. However, *Aster koraiensis* and *Z. japonica* survived only for a short period when irrigation was controlled. *Z. japonica* survived fewer than 8 days, even at the highest irrigation rate (60 l water/m^2 every other day).

3.4. Biomass and C and N content of plants

The average biomass of the plants in tanks is shown in Fig. 5A. In wetlands, plants had much higher biomass than those in tanks, even though they had a shorter growing period (Fig. 5B). The C and N contents of plants grown in wetlands were significantly higher than those grown in tanks (Table 2).

4. Discussion

Rooftop temperatures (ranging from 14.4 °C in October to 26.6 °C in August) fluctuated considerably more than those in the wetland (ranging from 22.1 °C in September to 25.8 °C in August). Although the wetland temperature was not measured in October, the average rooftop temperature in September was 19.8 °C, much lower than that of the wetland. The highest recorded rooftop temperature, at 38.0 °C, was five degrees warmer than that of the wetland, 33.1 °C. As water is a slow transfer medium for the delay of heat intrusion, rooftop wetland can prevent excessive temperature increase of building rooftops in summer. In summer, wetland in rooftop can retard heat entrance through the roof [26] and will assist natural air conditioning. Moreover, our wetland experiment was conducted only on a pilot scale, so we expect that temperature stability would be even greater in a full-scale wetland as other green roofs, or even better. Our results clearly demonstrate that the heat releasing by evaporation [27] and heat intrusion delay properties of wetlands modulate temperature changes and should confer benefits on buildings that utilize them.

During the study, rainfall was heavy but intermittent. For 29 days, total precipitation exceeded 1 mm. While there was more than 500 mm of precipitation in July (Fig. 2), it rained on only six days. Without a means to store excess water, rainwater leaches from the system. Korea receives most of its summer precipitation as intense heavy rainfall, perhaps exacerbated by climate change, and a large portion of the annual precipitation falls during the summer season [28]. The water holding capacity of wetlands thus would useful not only for flood control [29] but also in supplying rainfall for irrigation during dry periods.

Most urban areas are covered with an impermeable layer that can cause flooding without drainage systems. Drainage systems

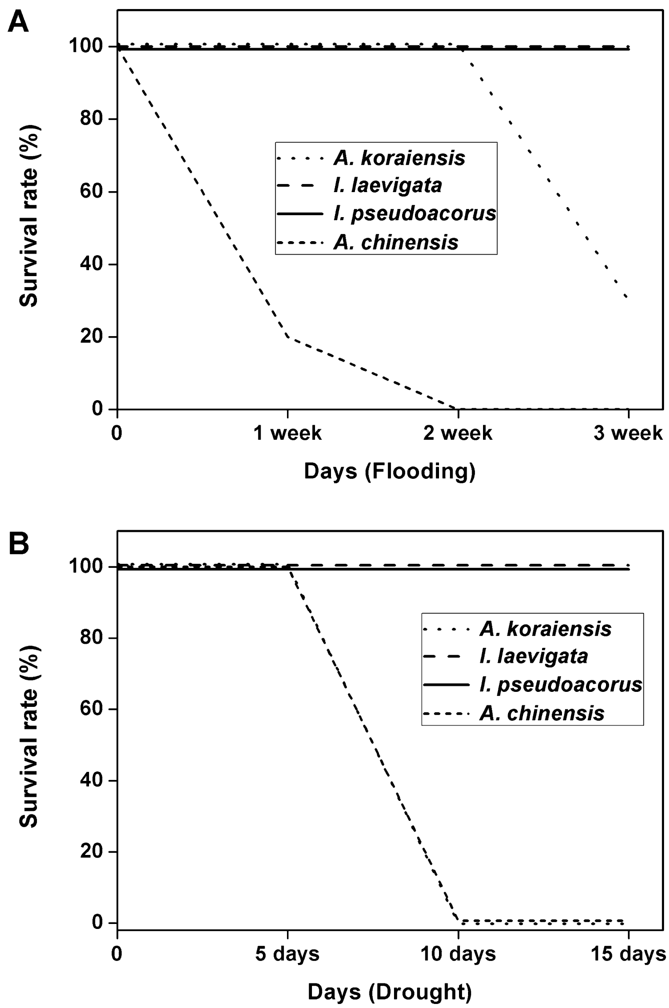

Fig. 4. Survival rates of plants after flood or drought. A: Survival rates of plants by duration of flooding, B: Survival rates of plants by duration of drought. ※*A. koraiensis*: *Aster koraiensis*, *I. laevigata*: *Iris laevigata*, *I. pseudoacorus*: *Iris pseudoacorus*, *A. chinensis*: *Astilbe chinensis*.

designed to cope with extreme rainfall conditions are expensive to build and operate [30]. This further argues for the use of rooftop wetlands to store rainfall as a more economical solution for urban development. Like green rooftops can serve to reduce urban stormwater runoff [27], rooftop wetland with more water holding capacity will show considerable performance on flooding control. The wetland in our experiment was only 15 cm deep, yet effectively contained potential flooding from every heavy rain (Fig. 3B). If the wetlands were designed to have greater depth, they would be able to store more rainfall. The 15 cm depth we used in our experiments accommodated the height of *Aster koraiensis* and *Astilbe chinensis*. However, other macrophyte species (*I. laevigata* and *I. pseudoacorus*) suffered no mortality even after 3 weeks of

Table 1
Survival period of plants with different irrigation treatments.

Treatment	*Aster koraiensis*	*Iris pseudoacorus*	*Zoysia japonica*
20 l water/m^2 every two days	6.4 ± 0.4	24.4 ± 0.4	5.6 ± 0.4
40 l water/m^2 every two days	22.4 ± 0.7	30 ± 0.6	6.0 ± 0.0
60 l water/m^2 every two days	23.6 ± 0.4	35.6 ± 0.4	6.8 ± 0.5
10 l water/m^2 each day	24.8 ± 0.5	30 ± 0.6	5.6 ± 0.4

The data are presented as the mean ± SE of five replicates.

flooding over 25 cm (Fig. 5A). Therefore, if roof load-bearing capacity allows, wetlands can be designed to have greater maximum water depth, and thus, more water-holding capacity.

Evaporation rates of plants were higher than those of controls (Fig. 3A). Since the coverage of the plants was almost 100%, the evaporation values reflect water lost by plants themselves, not the growing mat. Evaporation in July was lower than in other months, because it was rainy and cloudy. In July, there were 6 rainy days and 10 cloudy days which showed low solar radiation (Fig. S6 in Supplementary materials) that reduced evaporation. August showed high evaporation because of the hot temperature (Fig. 2) and high radiation (Fig. S6 in Supplementary materials). October also had low evaporation because the weather became cold and the physiological activity of plants decreased. Overall, the total evaporation of the macrophyte plants was over 1700 l water/m^2 for macrophyte plants, providing a greater cooling effect than wet mats alone (control).

The constructed wetland required irrigation only three times during the 132- day research period. The water holding capacity of the wetlands thus reduces the needs for irrigation. In another study, the Korean lawn grass *Zoysia japonica* required a minimum irrigation rate of 20.7 l water/m^2 per day [24]. In our wetlands experiment, 109 days ensued without any precipitation. Assuming that irrigation would be required on these days, 2262 l water (109

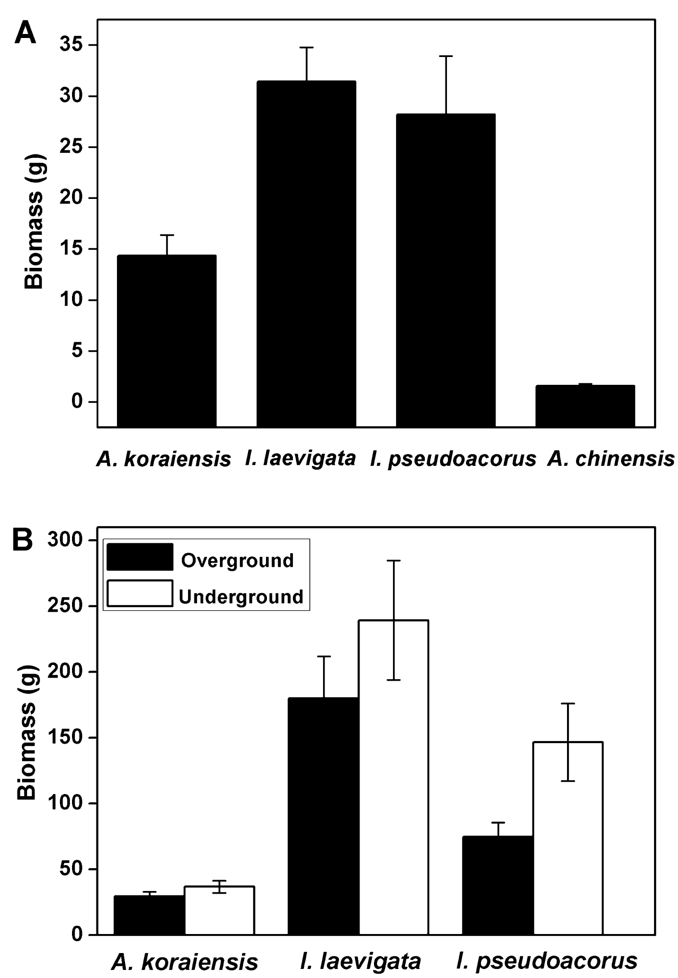

Fig. 5. Harvested biomass of plants. A: Harvested biomass of plants grown in tanks, B: Harvested biomass of plants grown in wetland. The bars and error bars represent the mean ± SE of ten replicates. ※*A. koraiensis*: *Aster koraiensis*, *I. laevigata*: *Iris laevigata*, *I. pseudoacorus*: *Iris pseudoacorus*, *A. chinensis*: *Astilbe chinensis*.

Table 2
C and N content of plant leaves after harvesting.

Species	Tank O		Wetland O		Wetland U	
	C (%)	N (%)	C (%)	N (%)	C (%)	N (%)
A. koraiensis	41.4 ± 0.2[b]	0.4 ± 0.1[b]	39.5 ± 0.5[a]	1.0 ± 0.2[a]	34.8 ± 0.8	0.4 ± 0.1
I. laevigata	41.3 ± 0.1[b]	0.5 ± 0.0[b]	43.1 ± 0.2[a]	1.7 ± 0.3[a]	40.1 ± 0.3	1.0 ± 0.1
I. pseudoacorus	41.7 ± 0.3[b]	0.1 ± 0.1[b]	43.3 ± 0.3[a]	1.6 ± 0.3[a]	40.2 ± 0.2	0.8 ± 0.2
A. chinensis	45.5 ± 0.4	0.5 ± 0.1	Dead	Dead	Dead	Dead

The data are presented as the mean ± SE of four replicates.
Means within a row followed by different letters are significantly different at $p < 0.05$ (Tukey's HSD test; C and *N* values were analyzed separately).
※*A. koraiensis*: *Aster koraiensis*, *I. laevigata*: *Iris laevigata*, *I. pseudoacorus*: *Iris pseudoacorus*, *A. chinensis*: *Astilbe chinensis*.
※O: Overground, U: Underground.

days × 20 l water/m^2) might be needed for each square meter of terrestrial green roof, an order of magnitude than the irrigation that we provided. Even assuming that less irrigation is required in May and June than during the summer months in which *Z. japonica* was studied, irrigation requirements would be much greater than those of a woodland system. As we have shown, less irrigation would be needed still if wetlands were constructed with a higher maximum water depth.

Tanks containing *I. laevigata* and *I. pseudoacorus* similarly required only three days of irrigation (62.5 l water/m^2 each time). Including the initial irrigation (200 l water/m^2), the total required amount of water was less than 400 l water/m^2, much less than the expected irrigation requirement of terrestrial systems (2262 l water/m^2). Because the maximum water depth of the tanks was larger, they required the addition of much less water than the wetlands did. The average water depth of the tanks at the end of October was over 33 cm, indicating that they had stored more than 130 l water/m^2 of water in addition to the initial amount added to the tanks.

The advantages of wetland systems also are apparent in measures of plant survival (Table 1). Plants that were given water at the same rate used it wetlands (10 l water/m^2 per day treatment or 20 l water/m^2 every two days) could not survive in a terrestrial system. Even those plants that were provided with three times that amount of water (60 l water/m^2 every two days) were unable to survive. Although the macrophyte plants had great drought tolerance (Fig. 4A), they failed to survive in irrigated terrestrial systems because of leaching and draining. *Z. japonica* survived only a short time, even in the highest irrigation treatment. In contrast, two wetland macrophytes, *I. laevigata* and *I. pseudoacorus*, tolerated drought and flooding, suggesting that they would be suitable to populate the harsh environment of green rooftops (Fig. 4).

We tested non-macrophyte species, *Aster koraiensis* and *Astilbe chinensis*, to promote biodiversity on the edge of designed wetlands. However, these species showed only limited drought and flood tolerance, so did not grow as well as the macrophytes (Fig. 5). *Astilbe chinensis* did not survive though we considered adjusting periods. Because most of the macrophytes can live in both flooded and terrestrial conditions, non-macrophyte plants probably need not be included in designed wetlands. Nonetheless biodiversity should be preserved by planting more than one species, Over all, because the wetland system would create permanent flooding conditions, flood-tolerant macrophytes that have the appropriate biomass and height are the best choice for rooftop wetlands.

Using wetlands for green rooftops offers other advantages. First, flooding may control weeds. During this study we removed weeds twice each month from test pots and wetlands. Weeds were less a problem in flooded portions of the wetlands than elsewhere. However, the rapid growth of weeds interfered with our ability to measure growth of test plants in pots of in the wetland. On the mats in tanks, we found more that wetland conditions inhibit weed germination.

During the study period, we observed several species of birds (dove, black-billed magpie, and rufous turtle dove) drinking water from the wetlands. We also found the nymphs of dragonflies, mayflies, and other insects. Dragonflies, ladybugs, and butterflies were found resting in the wetlands. This rooftop wetland showed benefit of habitat creation like other terrestrial green rooftops [5]. Although the study site was within 100 m of a mountain stream and larger constructed wetlands, we observed the rooftop wetlands serving as breeding place, water source, and shelter. If wetlands are constructed in urban areas that do not currently contain much green space, the wetlands would be much more utilized. Constructed wetlands also filter the air and offer recreational and cultural value [17], further adding to their overall benefits.

Along with the advantages come some disadvantages. Wetlands equally provide a breeding ground for pest species, such as mosquitoes. Indeed, we observed many mosquito nymphs during the experiment. In a pilot study, we attempted to solve this problem by introducing a natural enemy, mudfish (*Misgurnus anguillicaudatus*). On June 11, there was average 25.6 ± 3.4 mosquito nymphs per l (mean ± SE of five samples). However, three days after introducing 20 mudfish into the wetland, there were only 1.4 ± 0.2 mosquito nymphs per l. We checked numbers of nymphs of mosquitoes for a month, and never found any more nymphs beyond 6 days from the introduction of the mudfish.

Although weeds did not thrive in wetlands, the weeds that established themselves there grew large. We did not remove weeds after July, and 3 *Echinochloa crus-galli* and 4 *Eleusin indica* grew to about 1 m in height in September. The weeds were larger than their typical sizes in terrestrial conditions. Therefore, even though flood conditions reduce the number of weeds, weeds should be managed in constructed wetlands during the growing season.

Wetland provided better growing conditions than tanks. Plant biomass in the wetlands was much greater than that in tanks (Fig. 5). Plants preferred real soil than mats filled with other growing media, as is evident in the C and N content of the plants. Plants grown in the wetland had a higher concentration of N in their tissues than did plants grown in tanks (Table 2), indicating better growing conditions [31]. In the wetlands the biomass of *I. laevigata* was over 400 g, including above and underground biomass. Such plants, with C content typically over 40%, would serve well as a carbon sink and oxygen releaser during the growing season. The relatively large biomass of the underground portion of the plants (Fig. 5B) results from the large biomass of rhizomes. This indicates that the plants would easily regenerate the following season [32]. Therefore, macrophytes with large rhizomes would be useful for easy green rooftop management.

Despite their many advantages, wetland systems are heavier than systems that use dry media and the construction of wetland green roofs systems is limited by the load-bearing capacity of the underlying roof [33]. Maximum loading of rooftop garden, both prescribed in Korea [34] and by the International Green Roof Association, is 500 kg/m^2 [35]. This loading would support constructed wetland systems to appropriate specifications. As the liner used for wetland construction weighs less than 2 kg/m^2 it does not critically affect loading. The density of the water-saturated soil used in this experiment was less than 1.6 kg/l (1.57 $\pm$ 0.12 kg/l, mean $\pm$ SE of three samples), or 16 kg for 1 cm of water saturated soil per m^2. As we used about 10 cm of soil in the constructed wetland, 340 kg/m^2 may remain for water loading. This suggests that a wetland system to 30 cm depth would fall within allowable loadings.

Other arguments against the use of wetland green roofs include the expected amount of irrigation. But this is based on the misunderstanding that wetlands require more irrigation than terrestrial systems, or that construction of irrigation for them is costly. However, because irrigation needs are reduced by wetland systems and green roof techniques involve substantial costs, perhaps 10–14% more expensive than conventional roofs [36], constructing wetlands would not be expensive compared to other green roof systems. Locally, green roofs typically use expensive mat or block-type beds to overcome problems with drought and dispersion [34], so the construction cost of a wetland roof would not be greater than that of other green roof systems.

5. Conclusions

The temperature of a constructed wetland on a rooftop was more stable than that of the ambient air of the rooftop, due to the high heat release and insulation ability of water. The highest rooftop temperature recorded during the study 38.0 °C, but was only 33.1 °C in the wetlands, clearly demonstrating he thermal benefits of the wetland system. The total evaporation of macrophyte plants during the study period was about 1700 l water/m^2, indicating their ability for cooling. The constructed wetland had excellent water holding ability, and three days of irrigation were required during the study period. The required irrigation during the growing season was less than 400 l water/m^2, which is less than 20% of the expected irrigation requirement for terrestrial systems on green rooftops. Wetland species (macrophytes) showed high tolerance to flooding and drought, and this facilitated weed control in the wetland. Wetland species would be easy to manage because they regenerate in subsequent seasons through rhizomes. Rooftop wetland systems with water depths $\leq$30 cm would not exceed the load-bearing capacity of rooftops and the construction cost would be comparable to, or lower than, that for terrestrial green roof systems. Therefore, with their thermal benefits, low irrigation requirement, high tolerance to drought and flood, flood-control abilities, carbon sink potential, easy management, weed control, and other ecological benefits, constructed wetlands are a reasonable choice for green rooftop systems.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2013.04.024.

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