EFFECTS OF SUBSTRATES AND PLANT SPECIES ON WATER QUALITY OF EXTENSIVE GREEN ROOFS

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Abstract. Green roofs have multiple environmental benefits, such as saving energy, improving air quality, mitigating noise, providing habitat, beautifying the landscape, and improving urban hydrology. Among the environmental benefits of green roofs, improving runoff quality is a controversial issue. Substrate and plant litter may be transported with green roof runoff, which would increase the risk of urban nonpoint source pollution. However, the soil substrates on green roofs can filter out pollutants that can then be taken up by plants, which would improve water quality. In the present study, experimental containers with 2 substrates and 8 plant species were constructed, and data were collected from 7 real rainfall events to analyze the effluent water quality. This outdoor site was unfortunately terminated by a strong typhoon, but the idea and some results of the study might give some lights for the future study. The total solid (TS), chemical oxygen demand (COD), and total nitrogen (TN) concentrations were greater during the earlier stage and gradually decreased. However, the total phosphorous (TP) concentrations did not change with time. The limited data did not show the expected effects of the combinations of substrates and plants, but the effect of substrates was significant on the COD and TP concentrations.

Keywords: *exetensive green roofs; substrate; plant species; water quality*

Introduction

Green roofs provide various environmental benefits regarding water, energy, air, ecology, and aesthetic value (Dunnett and Kingsbury, 2004; Oberndorfer et al., 2007; Getter et al., 2009). Therefore, green roofs are commonly used component of the design of sustainable cities. Unlike in other measures taken to increase green space in urban areas, no additional land is required to implement green roofs because they use underutilized rooftops. This unique feature promotes the development of green roofs (Peck, 2003; Villarreal and Bengtsson, 2005; Mentens et al., 2006; Dvorak and Volder, 2010). Some countries and cities provide incentives to encourage or enforce the use of green roofs, including Germany, Belgium (Dunnett and Kingsbury, 2004), Singapore (Wong et al., 2003), Japan (Osmundson, 1999), Hong Kong (Zhang et al., 2012), and some cities in Canada and the United States (Carter and Fowler, 2008). In Taiwan, green roofs are a component of several central and local governmental policies and regulations regarding development (Chen, 2013).

Green roofs can improve the urban environment; however, the factors affecting green roof performance remain unclear. For example, the selection of plant species, use of substrates, integration of rainwater harvesting systems, carbon sequestration, and human

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health benefits of green roofs have not yielded consistent research results (Lundholm et al., 2010; Roehr and Kong, 2010; Rowe, 2011). In particular, the overall benefit or harm of green roofs regarding runoff quality remains uncertain. A roof with soils and plants on it might flush out solids or pollutants with rainfall runoff and impair water quaity; howerver, in the other hands, the soils and plants might be able to filter pollutants and clean up water. The water quality of green roofs remains controversy and has been discussed. Several impact factors for water quality have been defined in previous research, including plant height, root density, and substrate properties. Plants reduce pollution levels by extending water retention time and taking up nutrients from the substrate. When grown in an appropriate substrate, plants are healthy and nutrient losses decrease. Thus, the combination of substrate and plant species is a crucial design factor that determines the level of water quality improvement. The objective of this study was to determine the effects of substrates, plant species, and their combinations on green roof water quality.

Review of literature

Water quality of green roofs is mainly influenced by the properties of substrates and plants and rainfall events. Moran et al. (2005) reported that pollutants can accumulate in the bottom layers of green roof substrates. These pollutants may be flushed out during intensive rainfall events, which would result in lower water quality. Teemusk and Mander (2007) claimed that the runoff flow rate determines whether water quality will be improved or worsened by green roofs; during moderate- and low-intensity rainfall events, water quality improves as rainwater traps nutrients and sediments on green roofs. The USEPA (2009) reported that high nutrient concentrations and low flow rates from green roofs may result in reduced pollutant mass loads. Bliss et al. (2009) and Wang et al. (2013) indicated that the first flush (a typical nonpoint source pollution characteristic) did not occur with green roofs. Most previous studies have indicated that green roof runoff has poor water quality. However, these studies have also indicated that the water quality is influenced by the age of the green roofs, the substrate used, the rainfall volume, and the fertilization practices used (Czerniel Berndtsson et al., 2006; Hathaway et al., 2008; Carpenter and Kaluvakolanu, 2011; Vijayaraghavan et al., 2013). In a review, Rowe (2011) reported that mature and well-maintained green roofs improve water quality, whereas new green roofs do not. New green roofs without full-grown plants typically have high substrate nutrient concentrations and are therefore regarded as pollution sources.

In addition to the effects of rainfall, substrate characteristics and plant composition affect the water quality of green roof runoff. Emilsson et al. (2007) emphasized that the use of conventional fertilizers would reduce water quality, whereas plants are capable of reducing pollutant leaching. The health and nutrient use of plants largely affect the performance of green roofs (Rowe, 2011). Tall stems and dense roots help retain rainwater and soil and effectively reduce water runoff (Nagase and Dunnett, 2012). Diverse plant species create various ecological habitats, and the use of mixed plant species results in improved performance (Dunnett et al., 2008; Lundholm et al., 2010). Monterusso et al. (2004) tested the water quality from sedum and herbaceous plant species and found that nitrate concentrations were greater on sedum green roofs than on herbaceous green roofs. However, no changes in phosphorus concentrations were observed. Furthermore, the depth and material of the substrate affect water quality

(Moran et al., 2005; Teemusk and Mander, 2007; Getter and Rowe, 2009; Alsup et al., 2010; Wang et al., 2013). Nutrients in the substrate are required for plant growth but should be limited to prevent the detachment and transport of nutrients from the substrate.

In summary, the water quality of green roofs can be imporved in low rainfall intensity event. The new bulit green roofs produce bad water quality because of abundant nutrients blended in substrates. But the studies on the details of substrates and plants effects on water quality are still rare. Theoretically, the deep depth of substrates and the dense roots of plants strengthen filtration level and benefit water quailty. The clarification of effects of substrates and plant species would help to develop a satisfactory green roof.

Materials and Methods

Experimental containers

To collect rainwater from different substrates and plants, individual containers were used for each experimental unit. We designed a transparent experimental container constructed of acrylic materials (*Fig. 1*). The dimensions of the container were 30×30×30 cm (length×width×height). Each container was 5 mm thick. The standard green roof structure was used, including plants, substrate, filter, and a drainage layer. The drainage layer was composed of acrylic material with 81 drainage holes (2 cm diameter). A PE material filter net was placed above the drainage layer. Next, the substrate was spread on the filter net to a depth of 10 cm. The container included a removal drawer at the bottom of the container to receive outflow water from the drainage holes.

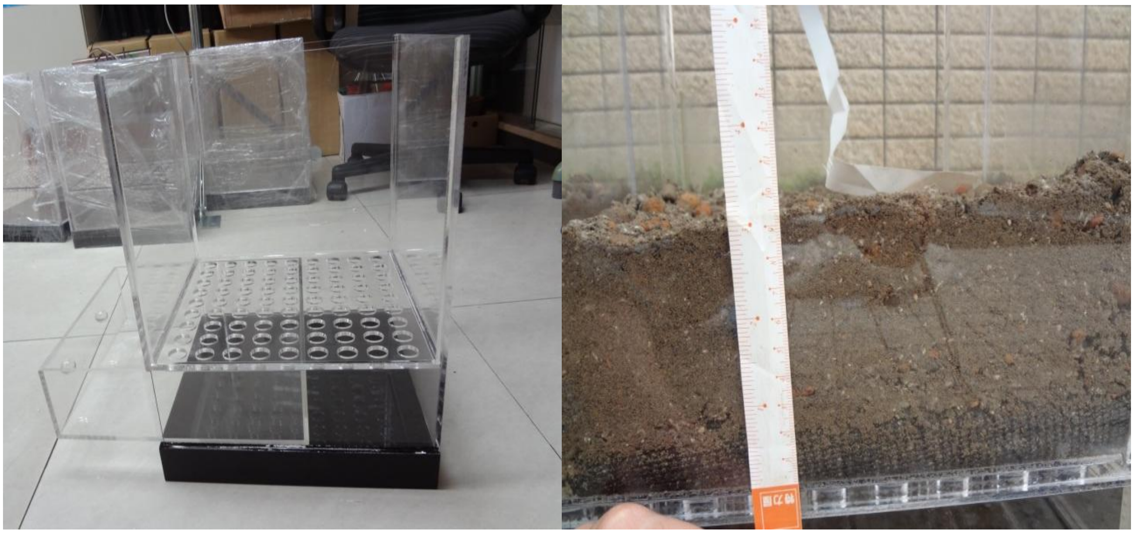

Figure 1. *The left is the experimental container. At the bottom is a removal drawer to collect outflow water. The right shows the filter net and the substrate.*

Substrates

Two substrates were tested, including a traditional cultivated soil from Taiwan and a soil that was specifically designed for green roofs by a local green roof company in Taiwan. The latter substrate was designed to mitigate roof loads by achieving improved drainage capacity and lighter weight. Recycled fiber and pottery stone were mixed for the light green roof (GR) soil. The chemical and physical properties of the two substrates are listed in *Table 1*. The GR soil is lighter than the traditional cultivated soil. The results of a particle analysis indicated that the two soils had very different particle distributions. Although 90% of the cultivated soil passed through a 4 mm sieve, only 60% of the light GR passed through a 4 mm sieve. In both soils, 45% of the particles were smaller than 1 mm. The cultivated soil was uniform, with particle sizes of 1 to 4 mm. However, the light GR soil included large particles, such as pottery stones, that were larger than 4 mm. The uneven particle distribution in the GR soil was used to increase the soil porosity and enhance water and air movement in the substrate layer. The result of particle size analysis is in *Fig. 2*. Becasue of the loose texture the GR soil has higher water holding capacity than the traditional cultivated soil. The organic matters, mass percentages of total organic carbon (TOC), total Kjeldahl nitrogen (TKN), and total phosphorous (TP) in the two substrates were very different. The nutrient concentrations in the light GR soil were approximately 3 times greater than those in the cultivated soil.

Table 1. *Properties of the studied substrates*

Substrates Properties	Cultivated soil	Light GR soil
Bulk density (g/cm^3)	1.13	0.84
Water holding capacity (%)	39.1	53.7
Diameter size>1mm (%)	42	52
D_{10} (mm)	0.12	0.07
D_{50} (mm)	0.7	1.2
Organic matters (g/L)	35	63
TOC (%)	1.82	4.39
TKN(mg/kg)	628	1,150
TP (mg/kg)	6.53	20.1

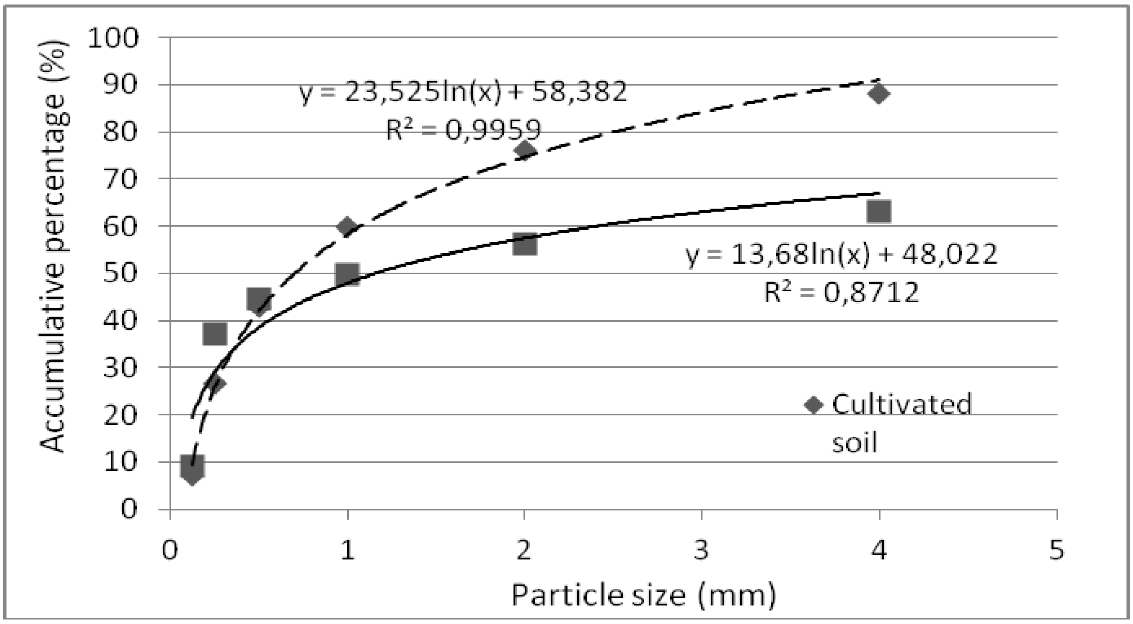

Figure 2. *Particle size analyses for the two substrates*

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This study started in 2013 and at that time, no design guideline was provided in Taiwan to follow. However, a latest official technic design guideline of green roofs was established in 2015 to suggest local design factors used in Taiwan (Architecture and Building Research Institute, 2015). This guildeline referred to the German Landscape Research, Development and Construction Society (FLL) green roof technology standards and made adjustments for Taiwanese cases. The suggestions for substrates are shown in *Table 2.* The physical properties and the organic matters percentage of the two studied substrates are fit in the range of the criteria.

Table 2. *Suggested properties of the substrates of green roofs in Taiwan(Architecture and Building Research Institute, 2015)*

Propeties	Suggested values
Diameter size>1mm	≧30%
Bulk density	0.7-1.0 g/cm^3
Permeable rate	>3.6 cm/hr
Water holding capacity	≧50% volume
Organic matter	≦65 g/L
pH	6-8.5
Electrical Conductivity	<2.5 mS/cm
Cation exchange capacity	>10 meg/100g

Plants

Sedum and herbs are generally planted on green roofs. Here, we studied plants that are commonly used on extensive green roofs in Taiwan. To examine the effects of plant species, we used plants with substantially different appearances and growth characteristics. After reviewing commonly used plants on local green roofs, we chose four types of plants and two species of each plant type. The selected plant species are also listed in the 2015 local technic guideline (Architecture and Building Research Institute, 2015). The first type of plant was the creeper forb. Creeper forbs are tiny, have dense root systems, and can grow extensively to cover the surface quickly. The creeper forb species *Ficus pumila* and *Portulaca 'Hana Misteria'* were chosen for this study. The second type of plant was sedum. *Sedum lineare* and *Sedum mexicanum* are the two most widely used plants for green roofs in Taiwan and were thus chosen for this study. The third type of plant was non-sedum succulents. *Sansevieria trifasciata* and *Aloe* were selected because they have large blade areas and a low irrigation requirement. The fourth type of plant was evergreen shrubs. Shrubs are planted one at a time and cannot fully cover the substrate surface. However, shrubs have longer and thicker roots relative to the other three plant types. We selected the shrub species *Adenium obesum* and *Euphorbia milii Desm*. *Adenium obesum* has a succulent stem, and *Euphorbia milii Desm.* is drought tolerant.

Eight plant species and 2 substrates were studied. Therefore, 16 experimental units and 2 control groups without plants were set up. *Fig. 3* provides photos of the experimental substrates and plants. The experimental units were placed outside to receive natural rainfall. Every rainfall event contributes one sample for each substrate and plant combination unit. While receiving multiple rainfalls, multiple samples are for each combination as replications. In this study period, 7 rainfall events were collected, meaning that 7 samples are for each combination unit. Because of the fixed collection volume, it is not able to analyze three replications for every water quality items for individual rainfall events. Therefore, we took multiple rainfall events as multiple samples of each experiment unit to run statistic.

Figure 3. *Photos of the experimental units. From left to right and top to bottom: cultivated soil, light GR soil, Ficus pumila, Portulaca 'Hana Misteria', Sedum lineare, Sedum mexicanum, Sansevieria trifasciata, Aloe, Adenium obesum, and Euphorbia milii Desm. (A total of 18 units were tested, including 9 units with each test substrate: 1 without plants and 8 with each of the different plant species).*

Water quality analysis

The water quality items in this study characterize sediment erosion and nutrient concentrations. NO_3-N, NH_4-N, TN, TP, COD, and TS were analyzed. Heavy metal concentrations were not assessed in this study. Heavy metals generally result from fertilizer and substrate materials. In this study, we did not add fertilizers and do not discuss the inherent heavy metal concentrations in the substrates. Therefore, only the nutrient concentrations and organic substances were examined. All analysis procedures and methods complied with the national standard methods.

Results

Collected rainfall events

The experiment began in January 2013. The first three months were used for plant growth, and the first rainfall data were collected on March 28, 2013. The experimental period was expected to last for at least one year. Unfortunately, a violent typhoon,

Typhoon Soulik, occurred on July 12, 2013, and destroyed the outdoor study sites. All experimental containers were blown away and broken, which forced the termination of the experiment. Before this unexpected event, 7 realistic rainfall events were examined between March and July 2013. *Fig. 4* shows the rainfall hyetograph during the experimental period. The rainfall volume, duration, and intensity of the sampling events were summarized in *Table 2*. We collected the waters from the bottom removal drawer of the experimental containers, which represented the mixed effluent of the sampling rainfall events. The total sample number should be 126 (7*18=126). However, some of the small rainfall events did not produce enough water for analysis, which resulted in a final total sample number of 118. Due to the only 7 sampling rainfall events, the effects of rainfall volume or intensity on water quality are not discussed.

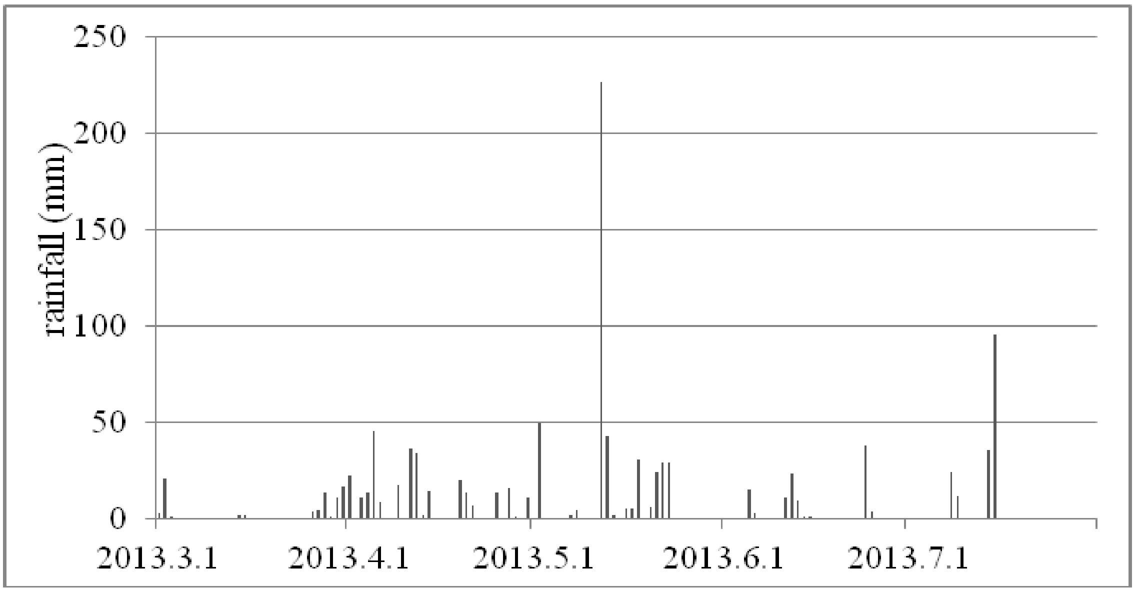


Figure 4. *Rainfall hyetograph during the experimental period.*

Table 2. *Water sampling events*

data	Rainfall volume (mm)	Rainfall duration (hr)	Rainfall intensity(mm/hr)
2013/3/28	23.0	7.0	3.29
2013/4/1	51.5	7.0	7.36
2013/4/14	87.5	13.0	6.73
2013/5/2	61.0	16.0	3.81
2013/5/13	269.5	48.0	5.61
2013/6/12	35.0	10.0	3.50
2013/7/9	36.5	8.0	4.56

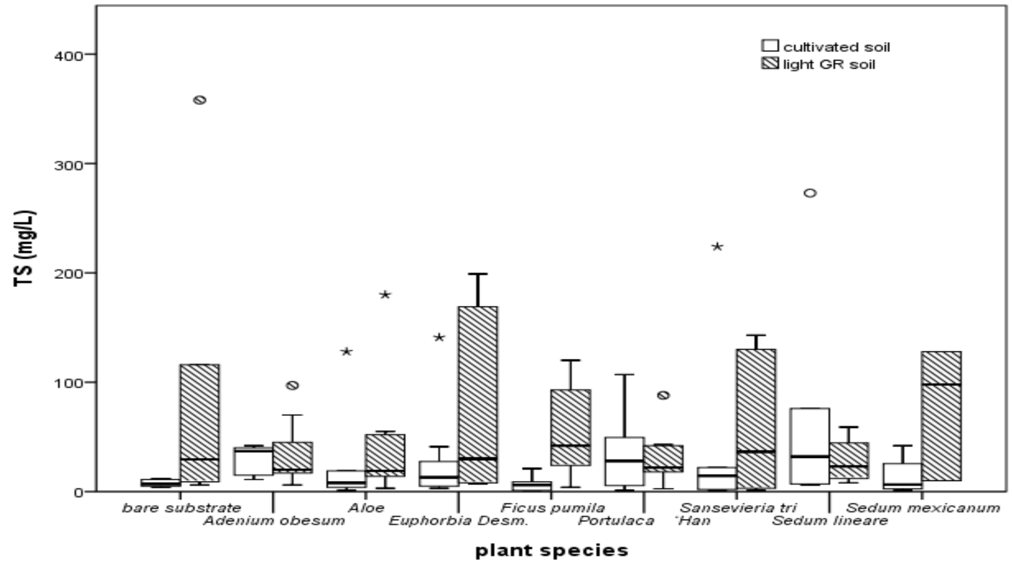
Water quality results

The water quality results that derived from the 7 rainfall events are depicted in a box-plot in *Fig. 5*. The average TS concentrations in the cultivated and light GR soils were 7.80 and 260.71 mg/L, respectively. Out of more than 100 water samples, four samples had TS concentrations of greater than 500 mg/L. Of these four samples, two were collected during the first sampling event. During this event, the substrate was not completely compacted and the plant roots had not effectively stabilized the soil. The other two turbid water events occurred on June 11. Before June 11, outflow had not occurred for one month and the gravitative substrate had accumulated at the receiving end of the container, which resulted in the high TS concentrations in the water.

The COD concentrations from the light GR soil were approximately twice as high as the COD concentrations from the cultivated soil in all plants units. The variability of the COD concentrations in the light GR soil was high, whereas the variability of the COD concentrations in the cultivated soil units was low. The COD concentrations from the sedum plants were slightly higher than those from the other plants. The average COD concentrations for *Sedum lineare* and *Sedum mexicanum* were 55.20 and 75.60 mg/L in the cultivated soil and 165 mg/L and 144 mg/L in the light GR soil, respectively.

The TN concentrations in the substrate and plant species units were not obviously different. The TN concentration variability in the light GR soil units was high. However, the average TN concentrations among the different plant species were similar for both substrates. The average TN concentrations from the bare cultivated and light GR soils were 1.22 and 10.37 mg/L, respectively. This finding potentially resulted from the 2-fold greater original TN concentration in the light GR soil relative to the cultivated soil.

The TP concentrations were 3 times higher in the light GR soil series relative to the cultivated soil series. The average TP concentration in the bare cultivated soil unit was 0.25 mg/L, whereas the average TP concentration in the bare light GR soil was 2.88 mg/L. The cultivated soil units with plants resulted in average TP concentrations that were less than 1 mg/L, except for *Sedum mexicanum*. The average TP concentrations in the light GR soil units with plants were greater than 3 mg/L, except for *Ficus pumila*, which had an average TP concentration of 1.96 mg/L. In both substrate units, *Ficus pumila* resulted in the lowest TP concentrations.



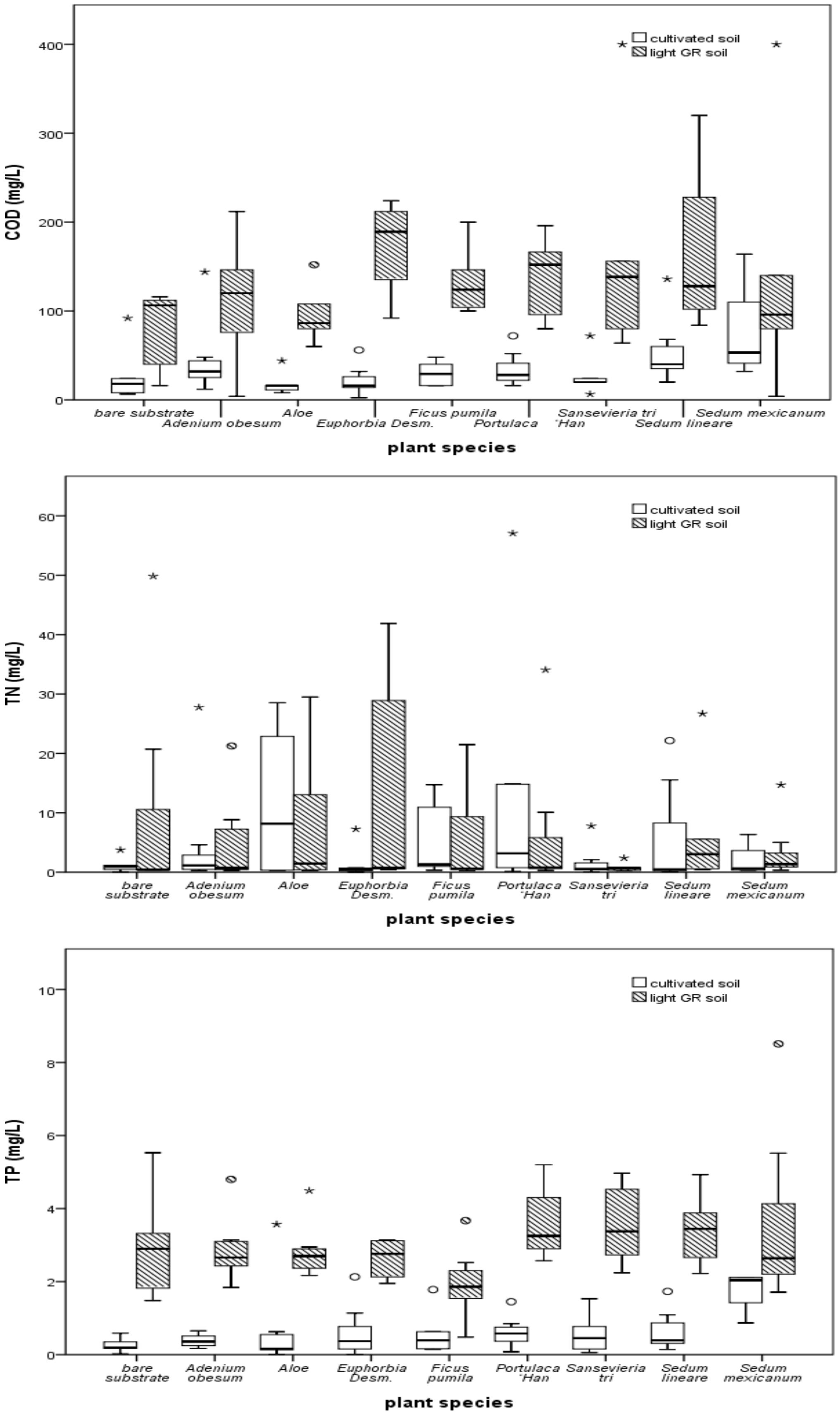
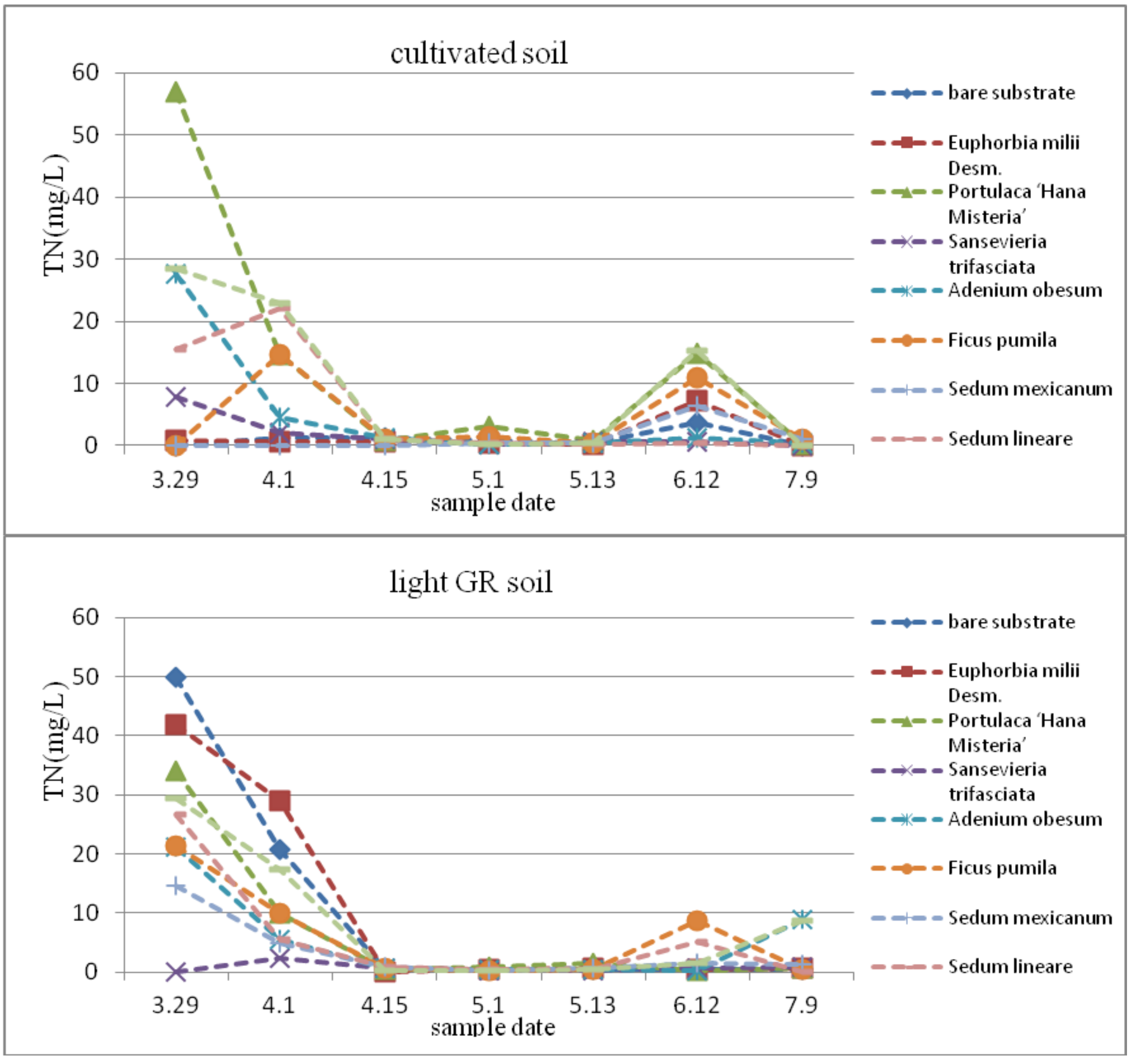


***Figure 5.** Water quality results from the different substrates and experimental plant units.*

Temporal variability of water quality

Analyzing the temporal variability allowed us determine the effects of green roof age on water quality. The results showed that TS, COD, and TN concentrations decreased with time. However, TP concentrations did not substantially change. *Fig. 6* shows the temporal trends of the TN and TP concentrations. In both substrate series, the TN concentrations were higher before May 2013, which corresponded to five months after the green roof units were positioned. In contrast, the TP concentrations did not dramatically change. As the results above, the TN concentrations can be affected by both the substrate and plant types. However, the TP concentrations were only affected by the substrates. As plants grow, high TN concentrations may be reduced. The percentage of nitrate in the TN pool was 96% (on average) during the earliest stages and was reduced to less than 50% during the latest stages. This result implies that the nitrogen was effectively used by the plants. The TP concentrations in the runoff did not depend on plant growth and did not change with green roof age.



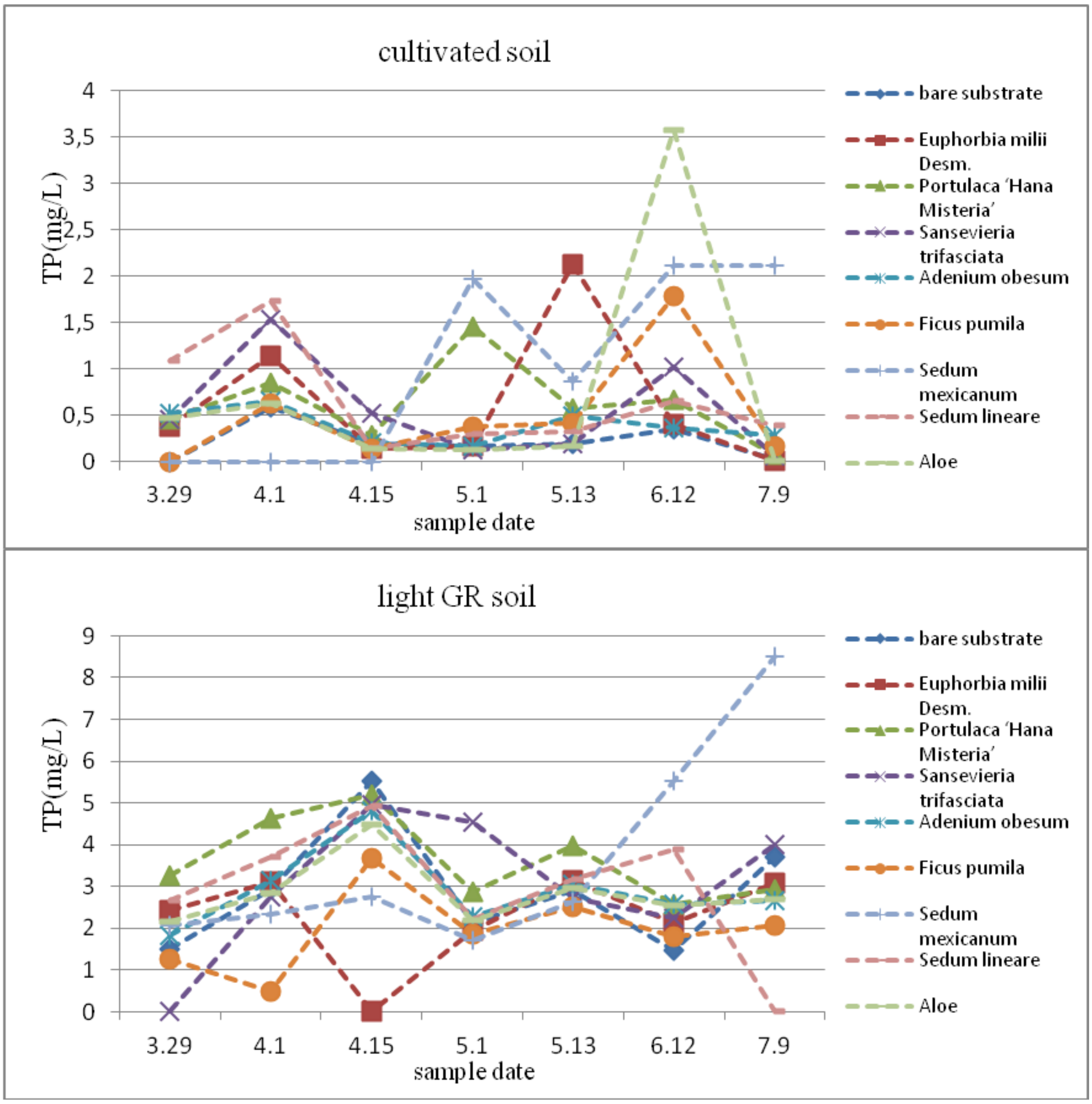


Figure 6. *Temporal trends of average TN and TP concentrations in the experimental series.*

Discussion

We used 2 substrates and 8 plants as independent variables, and 4 water quality items (TS, COD, TN, and TP) as dependent variables, to test the significant level of the interactions of substrates and plants. However, the results of the ANOVA analysis did not reach the expected significant level. There are only 7 samples for each combination and the few samples are not sufficient to reveal the combination effects. Therefore, we tested the single effects of substrates and of plants. When testing the effects of substrates, difference of plants was ignored and each substrate had a maximum total of 56 samples (8 plants and 7 rainfall events). Taking 2 substrates as independent variables and 4 water quality items as dependent variables, the results showed that the influence of substrate on the COD and TP concentrations was significant ($F(1, 99) = 63.063$, $p < 0.001$ for COD, and $F(1,116) = 155.460$, $p < 0.001$ for TP). Using the same method to test the effects of plants, each plant had a maximum total of 14 samples (2 substrates and 7 rainfall events). However, no significant differences in TS, COD, TP, and TN concentrations among plant species were observed.

The effect of substrate on TP concentrations was significant but no consistent effects were observed among the different plant species. Plants use phosphorus in the form of phosphate. Although we did not measure phosphate concentrations, when higher TP concentrations corresponded with higher COD and TS concentrations, we hypothesized that organic phosphate was the dominant form of phosphorous, which is mainly transported with solids (Logan, 2000). Therefore, the TP concentrations highly depend on substrate properties, such as the original phosphorous concentration and erodibility. The effects of plant species on TP concentrations were relatively small. Thus, proper filter maintenance and reducing substrate loss have a greater effect than plan growth on TP concentrations.

Unlike TP results, neither substrate nor plant species did not result in significant influence on TN concentrations. The TN concentrations include various compounds of organic nitrogen, ammonia-nitrogen, and nitrate. The distribution of these compounds should allow us to determine whether the TN results from soil nutrients or nitrification. The insufficient number of collection events and the highly variable water quality precluded the use of our data to determine the sources of TN. But, the results showed that the units with plants produce higher TN concentrations in the cultivated soil series. This implies that nitrate would be generated by nitrification and leached out. The light GR soil series demonstrated opposite results because organic nitrogen was transported with fine soil solids, which increased the TN concentration. In both substrates, *Sansevieria trifasciata*, *Sedum lineare*, and *Sedum mexicanum* resulted in the lowest TN concentrations. *Sansevieria trifasciata* was the only C4 plant that was used in this study, and the two sedum plants are CAM plants. These three plants exhibited different carbon transformation reactions relative to the other studied plants. However, it is unclear whether these reactions affected plant nitrogen use or resulted in different TN concentrations in the water.

In the results of TS, four samples had TS concentrations of greater than 500 mg/L. The four high TS samples came from the light GR soil units, which indicates that the larger pore space for water retention and root growth allowed the fine particles to pass through the filter layer and be carried out with the runoff. Thus, to avoid contaminating the runoff with the substrate itself, the substrate particle size distribution should be seriously considered.

Conclusions

The design of substrates and plants is an important factor to advance the green roof performance and the effect of such combinations is expected to influence the effluent water quality. In this preliminary study, the limited data did not reveal the expected effects, but the results presented that the substrates significantly affect water quality. Based on the nature of substrates that were used in this study, the highly porous soil was designed for better root growth, air movement, and water retention. However, high porosity may increase soil erosion and contaminate runoff during the early stages of green roof establishment. Although the experiment period is not long enough, it is obvious that poor water quality is unavoidable for newly built green roofs. Water quality, such as TS, COD, and TN improves with time. It might be caused by the substrates are more compact and roots develop after 5 or more months, and organic matters in substrates are utilized and are decreased. In order to mitigate the water quality concentration, a well-maintained filter layer is important to prevent the loss of substrate and the associated pollutants. The effects of plant species on these substances are not clear in this study; although, the factors impacting TN concentrations are related to substrate and plant types. Details regarding the effects of plants on water quality did not be analyzed, but based on the current results, C4 and CAM plants (which have special carbon transformation processes) resulted in the lowest TN concentrations. Future studies could continue to study the effects of plants on nitrogen runoff and water quality.

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ELECTRONIC APPENDIX

This article has an electronic appendix with basic data.