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UNDERSTANDING THE PERFORMANCE OF PLANTS ON NON-IRRIGATED GREEN ROOFS IN SINGAPORE USING A BIOMASS YIELD APPROACH

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INTRODUCTION

Rooftop greenery has increasingly been advocated as a component of green buildings that can provide multiple social, environmental and ecological contributions to improve the quality of life in the urban environment (Peck & Wieditz 2003; Oberndorfer et al., 2007). Rooftop greenery, particularly the 'extensive' type, or green roof, has seen the most widespread implementation in European cities, especially those in Germany since the 1970s. Green roofs are characterised by the use of small, ground cover plants grown on a shallow substrate, in systems that are lightweight and which require a low level of maintenance, compared to rooftop gardens which tend to be 'intensive' or more manicured (Kohler et al., 2005).

Singapore, as in several highly urbanised cities, has begun to evaluate the applicability of green roofs under its climatic conditions. In seeking to utilise green roof technology developed in European countries to a vastly different climate like that of the Tropics, the single most important and challenging consideration is the biological component, i.e. the choice of plants, because the other components of the green roof, such as drainage, water reservoir elements and growing substrate properties, are physical elements that can be engineered to match known performance criteria (such as infiltration rate, water holding capacity, drainage rate, nutrient holding capacity, amongst others). Alternatively, suitable plants that can be used on green roofs in different climates, still remain largely unknown in places where green roofs have yet to be implemented, but they have a large influence on the successful delivery of green roof installations. In the selection of suitable plants under different climates, apart from aesthetic considerations in the use of plants to meet the landscape design intent, an ecological approach could be taken based on an understanding of the factor(s) that most limit plant growth imposed by the local conditions.

This article describes a biomass yield approach that is adapted from a commonly used relationship relating plant yield to plant water relations in water-limited agriculture, to describe plant performance on green roofs in Singapore, as a representative country in the Tropics. The objective is to conceptualize the most important factors that affect the rate of coverage of green roofs and the long-term growth of plants, and thereby encourage suitable plant selection and best practices that can be put in place to achieve these objectives.

RESULTS AND OBSERVATIONS

***Green Roofs in the Singapore Experience Xeric Conditions.* –** Based on the European experience, it has been suggested that water availability is the most important factor affecting plant growth on green roofs (Kohler, 2003). It is shown here that even in a tropical country like Singapore, with a climate characterised by high rainfall and humidity (Table 1), periods of water deficit in the substrate do occur, and is also a limiting factor to plant growth.

Table 1. Evaporation, humidity and rainfall of Singapore.

Ambient Air Temperature (°C)	Annual Average Rainfall[1] (mm)	Annual Average Evaporation[1] (mm)	Relative Humidity (%)
Minimum: 23–26 Maximum: 31–34	2,078	1,802	64–96

[1]Data are averages of 1991–1995 from the Changi Meteorological Station, Singapore. Pan A evaporation data was used.

The reason for this is that it is the periodicity of water availability rather than total amount of available water that is important for plant growth in green roofs. Thus, even though the atmospheric water balance, which is the difference between precipitation and evaporation (Blight, 1997), indicates an annual surplus of 276 mm, the actual amount of water available for plant growth is determined by the distribution of water supply over time in relation to the amount of water that can be retained by the green roofs. Green roofs, being lightweight, typically have a shallow growing substrate

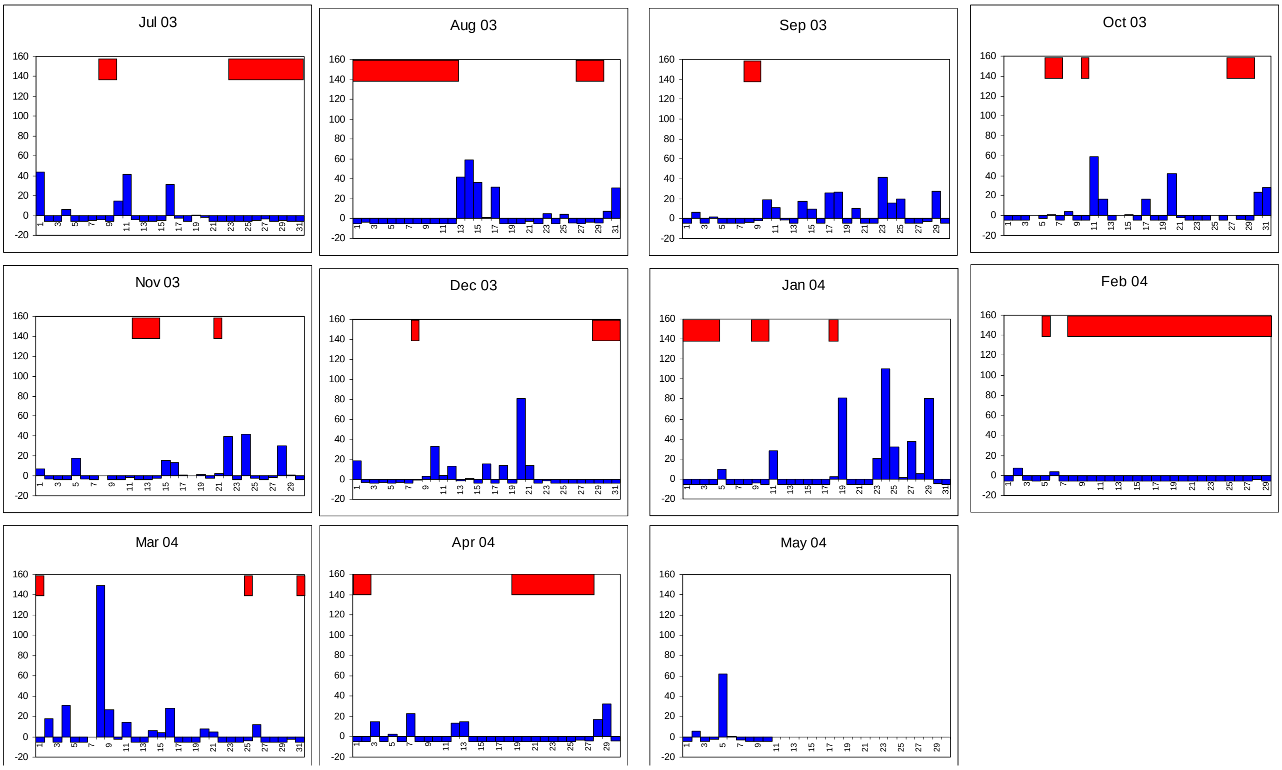

Fig. 1. Daily atmospheric water balance (mm) (difference between daily rainfall and evaporation) for the Punggol (north-eastern) region of Singapore. Daily evaporation is estimated from the average monthly evaporation data of 1991–1995 divided by number of days in the month (Table 1). Daily rainfall values were obtained from the Punggol Weather Station from Jul.2003–Jun.2004. The shaded box on top of each chart indicates the likely periods when the substrate would have depleted moisture, based on an evapotranspiration of 5 mm/day and a water-holding capacity of 30 l/ m^2 for an average green roof system. The total number of days with predicted water stress for the period Jul.03 to May 2004 is 85.

with a depth of between 80–150 mm. The shallow substrate imposes a limit on the amount of moisture that can be held. Based on systems currently tested in Singapore, the maximum water holding capacity of the substrate is between 24–35 l/m^2 for substrate depths of 80–100 mm. In most green roof systems, substrate moisture is supplemented by additional water retention in the drainage-cum-water reservoir layer, which contributes an additional 10–20% of water over that held by the substrate. Green roofs theoretically, under a potential evapotranspiration rate of 5–6 mm/day (estimated from data from the Meteorological Services Division, National Environment Agency, Singapore), hold sufficient moisture for plant's needs for a period of 5–8 days before the available water is depleted.

When the atmospheric water balance is analysed on a daily basis (Fig. 1), it is clear that significant periods of atmospheric water deficits are experienced. Even in the months of Apr. and Dec. when rainfall is higher during the monsoon seasons in Singapore, there are periods of up to nine consecutive days when the plants on the green roofs are experiencing depleted moisture in the root zone. The water stress experienced by plants can be exacerbated by higher temperatures typically experienced on roofs. For instance, measurements made in Singapore showed that exposed roof surfaces can reach a high of 58°C during daytime, with a corresponding ambient air temperature of 39°C (data not shown). Significant drought periods of eight days or more were experienced in six of twelve months between Jul.2003 and Jun.2004. Drought periods of 10 days or longer as experienced in Feb.2004, can lead to mass dieback of plants on non-irrigated green roofs.

***Green Roofs Are Akin to Water-Limited Agriculture.* –** Instead of harvestable yield at the end of a growing season, the aim of a green roof is to achieve close to 100% coverage with greenery within a defined establishment period, which can subsequently be sustained without further supplemental irrigation. This is especially relevant for places like Singapore where water is a precious resource, and where existing roofs installed with green roofs do not necessarily have convenient watering points for irrigation needs. As highlighted above, non-uniform water supply imposes periods of water deficit in the growing substrate. Green roofs are therefore, akin to water-limited, or rain-fed agriculture where supplemental irrigation is not provided. This imposes a reliance in both instances on the water reservoir held in the substrate. In the case of green roofs, there is a further limitation in that there is no opportunity for ground water recharge of the substrate moisture.

A commonly used identity relating crop yield of a grain crop to water availability in rain-fed agriculture was originally proposed by (Passioura 1977), whereby:

Yield = Cumulative Water Used × Crop Water-Use Efficiency × Harvest Index (1)

Cumulative water used (CWU) is the seasonal amount of water transpired, crop water-use efficiency (WUE) is the (shoot biomass/cumulative water used), and harvest index is the (harvestable plant biomass/shoot biomass). The key feature of this relationship is that the three components are approximately independent of one another. The harvest index is for instance, dependent on the pattern of water supply rather than the total amount used. The water use efficiency of plants was shown to be independent of both the harvest index and water supply, and is more dependent on the class of photosynthetic mechanism employed by the plants, namely C3, C4 or Crassulacean Acid Metabolism (CAM). Such an identity points out that yield can be maximised by optimising one or more of the components.

It is proposed that the same relationship can be applied for green roofs under tropical conditions. However, since green roofs are ornamental, rather than agriculture production systems, yield, and therefore the harvest index are typically not a concern. Therefore, a modified version of the relationship is proposed, whereby

Shoot Biomass = CWU × WUE (2)

In this relationship, WUE is the (shoot biomass/cumulative water used) and CWU is as defined in Equation (1). To increase shoot biomass between the time of planting till complete coverage of the green roofs at maturity, one could then increase CWU and/or WUE.

Water Used By Plants. – In natural ecosystems or agriculture production systems limited by water, plant productivity or yield often increases linearly with evapotranspiration (Passioura, 1983; Clifton-Brown & Lewandowski, 2000; Schenk & Jackson, 2002). It remains to be demonstrated that this also applies to an ornamental system like a green roof, but within limits imposed by the tolerance of the green roof plants for high moisture availability, the same relationship should apply for the reason that growth or yield increases when a limiting factor is alleviated.

Therefore, one strategy to maximise shoot biomass in the green roof system in a rainfed system is to maximise cumulative water used by the plants. This can be achieved by minimising evaporation from the substrate, for instance, by selecting fast-growing species to rapidly cover up exposed substrate, or planting the green roof at a higher density at the time of installation, and by minimising water (and nutrient) competition by weeds. In water-limited agriculture, the potential increase in yield by reducing soil evaporation can be high since as much as 40% of the growing season rainfall is lost through soil evaporation in semi-arid areas (Wallace & Gregory, 2002).

Rapid plant coverage can also aid in minimising the substrate temperature during daytime, which in turn provides more conducive conditions for growth. Data collected on green roofs installed in Singapore showed that when the moisture level of two green roof systems are recharged to levels in excess of their field capacities by rainfall, the system with almost fully exposed substrate experienced a more rapid decrease in soil moisture, compared to the system that is fully covered by plants (Fig. 2). Within three days, soil evaporation had depleted soil moisture in the exposed substrate to about 65% of field capacity, whereas more water was conserved (at 85% of field capacity) in the system well covered by vegetation over the same period. Under the high radiation load experienced in the tropics, substrate temperature in the drier system reached a peak of 45°C, which was up to 10°C higher than the substrate with higher moisture level. Such a high temperature also creates unfavorable conditions for growth. There is not much known about the growth responses of root and shoot to rapid wetting and drying conditions (Passioura, 1983), especially of those occurring in a period of days. However, growing shoot tips are very sensitive to drought stress (Kozlowski et al., 1991) and those that are killed by a sudden onset of drought represent a lost investment of photosynthates by the plants, and necessarily lead to slow growth and increase in biomass.

Water Use Efficiency. – WUE can be defined at the level of the leaf, at the whole plant level, or at the crop level. At the leaf level, the photosynthetic water use efficiency, defined as the ratio of net carbon gain in photosynthesis to water loss by transpiration, is primarily determined by the type of photosynthetic pathway that the plants uses, namely C3, C4 or CAM. By employing a strategy to fix CO_2 at night when transpirational water loss is kept low, and then releasing the CO_2 at the site of carboxylation during daytime, when the stomata are closed, CAM plants typically achieve photosynthetic WUE that are several fold higher than C3 and C4 plants under comparable conditions (Cushman, 2001). CAM plants also possess morphological adaptations, such as thick cuticles, succulence, low surface-to-volume ratios, and reduced stomatal size and/or density that help to reduce water loss.

Not surprisingly, there is usually a good correlation between photosynthetic WUE and crop WUE (Lambers et al., 1998). With a high photosynthetic WUE and high drought tolerance, CAM plants are therefore ideal plants for green roofs. Smith & Winter (1996) estimated that about 7% of all vascular plants from 33 families exhibit CAM photosynthesis. Currently, the most important family of green roof plants is arguably the Crassulaceae, to which numerous *Sedum* species and cultivars—the mainstay of green roof plants in Europe—belong to.

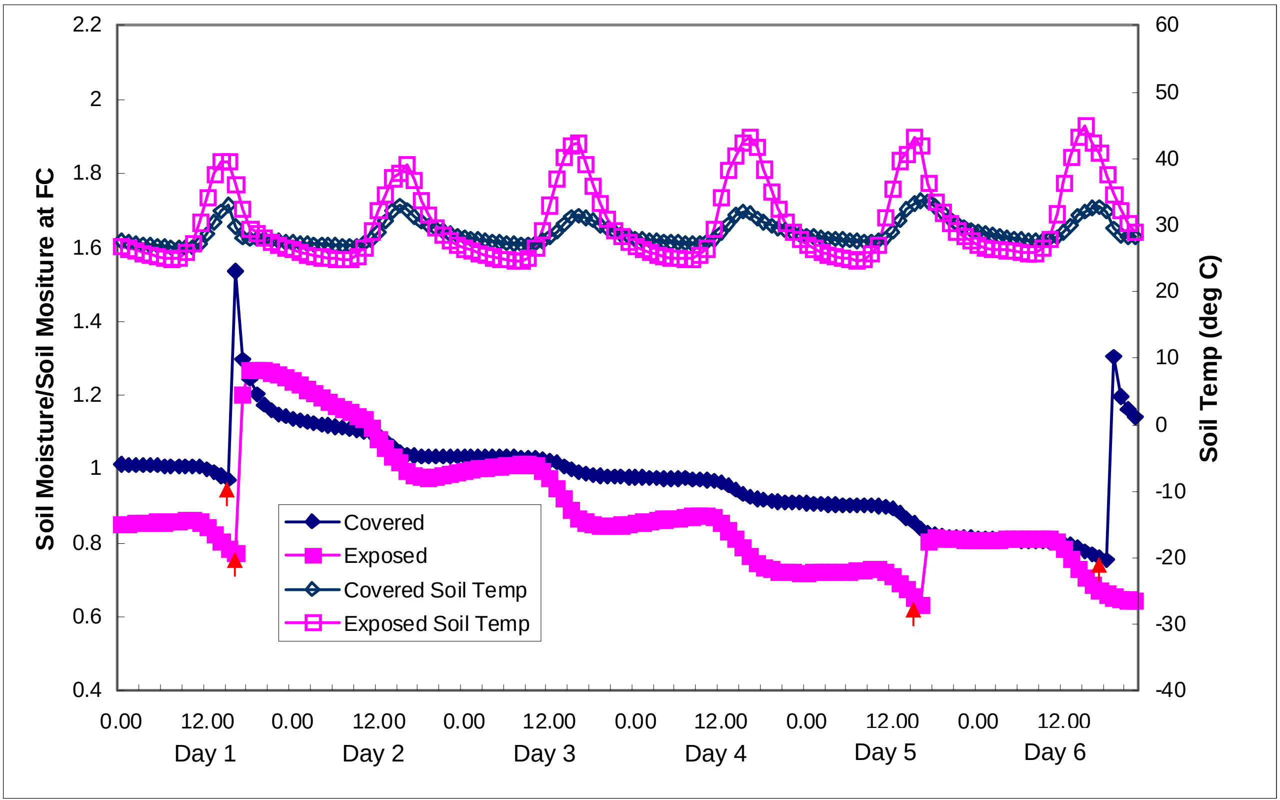

Fig. 2. Ratio of substrate volumetric water content to substrate water content at field capacity (FC), for a green roof substrate that was well-covered by vegetation or exposed, measured over two separate periods. The corresponding soil temperatures measured at about 5 cm beneath the soil surface are shown. The small triangles indicate occurrence of rainfall.

Naturally, maximising shoot biomass is not the only consideration for plant selection, which will also be influenced by client preference, design, and plant availability considerations. There is however, a huge diversity represented in the approximate 18,900 species of CAM plants, which offer practically, unlimited choices of plants for green roofs to meet multiple criteria and needs. Important families for green roofs in the tropics include the Aizoceae, Cactaceae, Commelinaceae, Dracaenaceae, Lamiaceae, Piperaceae and Portulacaceae, which contain important genera of horticultural interest, such as *Aptemia*, *Portulaca*, *Peperomia*, *Tradescantia*, *Plectranthus*, etc. Preliminary tests with two plants native to Singapore, *Cyanotis barbata* (Commelinanceae) and *Sesuvium portulacastrum* (Aizoceae), and other introduced ornamentals such as *Callisia elegans* (Commelinanceae), *Plectranthus australis* (Lamiaceae), *Sanseveria* cultivars (Dracaenaceae), and *Portulaca* cultivars (Portulacaceae) showed good potential for their use as green roof plants. In roofs that are less exposed, tropical epiphytes in the families Asclepiadaceae, Bromeliaceae, Orchidaceae, and Piperaceae would also offer numerous possibilities. The diversity of choices is high as it has been estimated that 57% of all epiphytes in tropical forests are CAM plants (Lüttge, 2004).

CAM plants could also confer two other advantages. This first is the higher tolerance for higher temperatures (Proctor & Tuba, 2002), which are typically experienced in the tropics, especially on rooftops. CAM plants such as *Agave* and some cacti tolerate the highest soil surface temperature for the longest periods compared to other vascular plants (see Lüttge, 2004). The other advantage is that CAM plants such as *Agave* and other desert succulents tend to have a high shoot:root ratio (Graham & Nobel, 1999). Passioura (1983) pointed out an apparent paradox, in that for rainfed agriculture, drought-resistance can be increased by reducing rather than increasing the size of the root system. This is to ensure that the rate of water use can be more effectively buffered to prevent rapid depletion of soil moisture and onset of water stress. In the same manner, as water conservation is important between periods of rain in green roofs, moisture availability can perhaps be prolonged by selecting plants that lack an extensive root system that will rapidly deplete the available moisture in the substrate. Therefore, plants with a lower root:shoot ratio, or higher shoot:root ratio could be preferred for increased tolerance of water-limited conditions.

CONCLUSIONS

Apart from ensuring that the structural and waterproofing integrity of roofs are not compromised, the most critical factor that ensures the long-term performance of green roofs is the selection of suitable plants. Green roofs in the humid tropics also experience periodic drought, largely because of a limited capacity of green roof systems to hold moisture for prolonged use by plants. A biomass yield approach is described to indicate the key components that influence the changes in shoot biomass of green roof plants. Accordingly, shoot biomass can be maximized by increasing one or more of the components.

While the relationship described remains to be validated by research data, it is useful in helping to focus on the components, and hence the physiological and morphological attributes of plants that will likely contribute to a successful green roof. The relationship indicates that plant selection should focus on plants with high photosynthetic WUE, notably CAM plants, which can be selected readily through gas exchange studies or using carbon isotope discrimination. To maximize cumulative water used by plants, substrate evaporation needs to be reduced by management practices, such as planting at higher density, ensuring that green roof coverage is rapid during initial establishment, or by minimizing water and nutrient competition by weeds.

More research is needed to understand the relative importance of each component towards increasing shoot biomass. Since shoot biomass cannot be determined without harvesting the plants, it will also be useful to develop allometric measures, such as leaf area index as surrogate measure of shoot biomass. Leaf area index is particularly suitable as basic measurement unit, as it can be used to correlate green roof provision to environmental benefits such as CO_2 sequestration, temperature reduction absorption of atmospheric pollutants.

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