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RESEARCH ARTICLE

Influence of water storage and plant crop factor on green roof retention and plant drought stress

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Abstract

Green roofs can reduce stormwater runoff with deeper substrates providing greater storage for water retention and evapotranspiration (ET) regenerating storage capacity between rainfall events. In green roof models, ET can be estimated using species-specific plant crop factors (K_c), which characterize water use under non-limiting conditions. We manipulated K_c by altering plant density in a glasshouse experiment under well-watered conditions. We determined K_c of green roof plants growing in pots with different substrate depths (150 mm and 300 mm) and plant densities (0, 1, 2 and 4 plants per pot). We then analyzed the influence of storage and K_c on retention and drought stress using a water-balance model, with a 30-year climate scenario for Melbourne, Australia. We hypothesized that greater planting density and substrate depth would result in proportionally greater ET and therefore higher K_c (glasshouse experiment) and that this would improve retention and reduce drought stress (rainfall simulation). Contrary to our hypotheses, cumulative ET increased by only 38–48% with increased substrate depth and by only 28–38% with increased plant density, despite large increases in plant biomass (67–150%) and growth. K_c values ranged from 1.9–2.2 and 2.7–3.8 for shallower and deeper substrates, respectively. Due to these very high crop factors, our water balance model showed very high annual rainfall retention (97.5%). However, higher K_c and storage only increased rainfall retention by 3–5% and resulted greater drought stress. Plants in deeper substrates experienced 14–29 more days of drought stress, as these plants depleted substrate moisture more efficiently (i.e., had a higher K_c) compared with shallow substrates. These findings suggest that improvements in rainfall retention for green roofs with deeper substrates or higher plant densities are small relative to the increased risk of plant drought stress. The lowest planting density was optimal for improving rainfall retention and reducing plant drought stress.

Introduction

Urbanization results in the creation of impervious surfaces, causing increased stormwater runoff, leading to flooding [1] and degradation of receiving waters [2, 3]. Mitigation of the

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negative impacts of stormwater runoff requires substantial interception and retention of rainfall, through stormwater harvesting or through promotion of evapotranspiration (ET) [4, 5]. Green roofs are an effective approach for improving rainfall retention [6], as rooftops make up a large proportion of impervious surfaces in urban areas and their implementation does not compete with ground-level development for space [7–10]. Hence, green roofs can help compensate for the loss of natural hydrological processes in urban catchments by intercepting, retaining and detaining rainfall [11, 12].

While the potential of green roofs in retaining and detaining stormwater runoff has been demonstrated [13]; stormwater runoff reduction by green roofs is highly variable. It depends on green roof configuration [14, 15], climatic conditions and evaporative demand [16, 17]. Substrate depth, type and plant species selection are considered the most important characteristics of green roof configuration. Substrate depth and type largely determines water storage [18] and shallower substrates can limit both rainfall retention and the amount of water available for plants [19]. While deeper substrates generally provide more water storage for plants and retention [20], this option is not always possible as it is limited by the roof weight-loading capacity, particularly in retrofit situations [21]. Therefore, selecting appropriate substrate depth is a critical aspect of green roofs designed for stormwater control.

While succulent species can survive these stressful periods [22], they have lower rates of water use than non-succulent plants [23], which dry out substrates more quickly between rainfall events [24], regenerating substrate water storage and therefore improving green roof hydrological performance [25, 26]. Shallow green roof substrates are also challenging for plant growth and survival, due to low water availability. In relatively warm and dry climates, green roof plants experience water limitations and may suffer extended drought stress [27, 28]. Survival during extended periods of drought has therefore been a focus of green roof plant selection in most studies, resulting in a prevalence of succulent species, e.g., *Sedum* spp. [27]. These succulent species have internal water storage [22] and lower rates of water use, both of which enhance survival on green roofs [23]. However, plants that dry out substrates more quickly between rainfall events, due to greater rates of ET [24], are more likely to improve green roof hydrological performance but also more likely to encounter drought stress [25, 26, 29]. Therefore, there is a tradeoff between survival and rainfall retention on green roofs [30]. Scarcity of water is a severe environmental constraint to plant productivity, and both the severity and duration of water limitation are critical [31]. Drought-induced damage in plants not only puts them at risk of failure but is also likely to decrease treatment performance [32]. Increased substrate depth has also been shown to promote plant growth and survival [33, 34]. Hence, non-succulent plant species with greater water use may survive for longer without experiencing drought stress when planted in deeper substrates [30, 35]. In a previous study, Zhang et al., (2019) [12] showed that water storage is more important than ET for retention in hot and dry climates, when plants were growing in shallower substrate (100 mm). However, it is not known whether higher water-using species growing in deeper substrates will have greater ET due to access to greater water storage.

In green roof models, plant crop factor (K_c) is a species-specific coefficient and can be used to estimate the daily ET of different plants in response to climatic conditions (reference evapotranspiration (ET_0)) under well-watered conditions. Experimentally, K_c can be manipulated by altering the number of plants established per unit green roof area, i.e., increasing K_c by increasing plant density. This is because K_c is effectively the ratio of ET/ET_0 which will change with both plant species and planting density [14]. The K_c is typically derived under well-watered conditions [36], and an additional stress coefficient, K_s, used to adjust ET for water-deficit conditions. Some green roof studies used a fixed K_c value over the year [14], whereas others showed the K_c changing seasonally [37]; in part reflecting how plants can change according to substrate depth and water availability [38]. Generally, substrate water storage is considered to be more important than ET for determining retention performance of green roofs [12]. However, for long-term retention performance, K_c has been shown to be the most sensitive parameter due to the influence of ET on replenishing water storage capacity after rainfall events [11, 39]. However, plants with higher ET, which also have higher K_c (increasing plant density and green roof cover) are more likely to experience extreme drought stress on green roofs as they will dry substrates out more rapidly after rainfall [25, 40]. Potentially, drought stress could be minimized on green roofs with increased substrate depth and water storage. Therefore, it is important to investigate whether increasing K_c while providing additional substrate water storage can maximize rainfall retention and minimize drought stress.

While previous studies have focused on how ET affects rainfall retention, few studies have investigated how species-specific K_c changes with substrate water availability, vegetation cover and distribution on green roofs [38, 41]. It is still unknown whether increasing plant density will change the K_c and further how a higher K_c will interact with increasing substrate water storage to 1) increase rainfall retention and 2) impact plant drought stress. Consequently, this may lead to inappropriate green roof design when modelling green roof stormwater performance. Hence, a better understanding of the relative impact of substrate water storage and K_c on overall green roof hydrological performance is required. To do this, we determined whether doubling substrate depth (water storage) or plant density (K_c) would double overall ET under well-watered conditions in a glasshouse experiment. We then used the results of this glasshouse study to parameterize a green roof water balance model and investigate the impacts of water storage and K_c on rainfall retention and plant drought stress in a 30-year climate scenario.

Materials and methods

The first phase was conducted as a glasshouse experiment using *Ficinia nodosa* (Rottb.) Goetgh., Muasya & D.A.Simpson, a grass-like monocot (life-form) in the Cyperaceae family which are planted on Australian green roofs and have a high water-use and drought avoidance strategy [30, 42]. ET was measured to derive K_c under well-watered conditions. Our original plan was to continue measuring ET during a water-deficit phase, however, due to COVID-19 restrictions, the experiment had to be terminated after the well-watered phase. Consequently, in the second phase, ET responses of *Ficinia nodosa* to drought were simulated using an established water balance model [30]. Pre-existing functions describing the drought response of *Ficinia nodosa* [30, 42] were combined with K_c values determined from the well-watered phase, to estimate both the rainfall retention and the incidence of plant drought stress.

Glasshouse experiment

The experiment was a fully randomized block design, with a total of eight treatments, made up of four plant densities (0, 1, 2, or 4 plants per pot) and two substrate depths (150 mm and 300 mm), with five replicates of each treatment (S1 Fig). We used pots constructed with geotextile and substrate layers to simulate a typical green roof structure. Pots were filled by weight with 10 kg and 20 kg with a scoria-based substrate to achieve depths of 150 mm and 300 mm, respectively. Subsamples of substrate were taken during pot-filling to correct weight for moisture content and determine the dry weight of substrate in each pot. The substrate was a blend of 7 mm scoria aggregate (20% v/v), scoria 8 mm minus, which includes fines (60% v/v), and horticultural grade coir (20% v/v). The water holding capacity and the bulk density of the substrate were 46% and 1.26 g cm^{-3}, respectively [24]. Pots differed in size, pots with 150 mm deep substrate were 290 mm x 290 mm x 300 mm, as compared with 290 mm x 290 mm x 400 mm for the 300 mm deep substrate treatments. Although the substrate depths used in this experiment were substantially deeper than studies on extensive green roofs [12, 14, 18–20, 30, 33–35, 43], deeper substrates can be necessary in hotter and drier climates to promote plant growth and survival [28].

Pots were planted with 0, 1, 2 or 4 individuals of *Ficinia nodosa*, supplied as tube-stock (Mansfield's Propagation Nursery, Victoria, Australia) in May 2019 (autumn). Plants were grown outside for a seven-month establishment period and were watered twice a day with an overhead automatic sprinkler irrigation system for 10 minutes in late autumn—early spring (0645 h and 1445 h; May—September 2019) and for 14 minutes in mid spring—summer (0645 h and 1345 h; October 2019—February 2020) to ensure they were well-watered. This meant that the potted plants were representative of an established green roof with fully grown canopy coverage.

The glasshouse experiment was run at the Burnley Campus of The University of Melbourne (-37.828472, 145.020883), Australia. In January 2020 (summer), plants were moved into a glasshouse and for 2 weeks were watered by hand with a hose to pot capacity every 1–3 days to acclimate them to glasshouse conditions. After 2 weeks, for the rest of the experiment, all pots were well-watered by hand every day to exceed pot capacity (until the water was freely draining from pots), for 1 week before and during the measurements of ET.

Reference evapotranspiration. Reference evapotranspiration (ET_0; in mm d^{-1}) represents the depth of water that will be used by a standard grass surface under well-watered conditions and was calculated using the Penman-Monteith equation [36]. A weather station (ATMOS 41, Meter Group Inc. USA) was installed in the glasshouse for measuring air temperature, relative humidity, wind speed and solar radiation. A data logger recorded readings every second and data was averaged to a 15-minute resolution. During the glasshouse experiment, the mean daytime temperature (0600 -1800h) was 20.85 ± 0.2 ˚C (range: 12.8–26.8 ˚C), mean relative humidity was 29.8 ± 1.1% (range: 23.7–37.2%) and mean ET_0 was 1.95 ± 0.04 mm d^{-1} (range: 1.39–2.97 mm d^{-1}).

Evapotranspiration and cumulative evapotranspiration. All pots were placed on scales (Adam CPW, Adam Equipment Australia) and daily ET was determined by mass. Scales for pots with 150 mm deep substrate were calibrated to 15 kg capacity with 5 g resolution, compared with 35 kg capacity and 10 g resolution for pots with 300 mm deep substrate. Pot mass was measured twice per day: 0900 h (morning) and 1700 h (evening). Well-watered pots were re-watered every day following the evening measurement and post-watering pot mass was captured after drainage had finished. ET was determined from the difference in pot mass (allowing runoff overnight), i.e., the change in pot weight each day. Daily evapotranspiration (g d^{-1}) was calculated as:

$$ET = morning\ pot\ mass - evening\ pot\ mass \quad \text{Eq 1}$$

where, *morning pot mass* and *evening pot mass* (in g) represent pot mass at morning and evening each day, respectively. Cumulative ET (g) was determined as the total amount of water lost from each pot during the experiment.

Plant crop factor (K_c). To determine crop factors (K_c) for each treatment under well-watered conditions, daily ET (g d^{-1}) was converted to volume (mm^3 d^{-1}) and then to depth (mm d^{-1}), by dividing the volume by the surface area of the pot (84100 mm^2). Crop factors were then determined from the slope of the relationship between daily ET (mm d^{-1}) and ET_0 (mm d^{-1}).

Plant biomass and relative growth rate. Plant biomass (g) was not harvested at the end of the experiment due to COVID-19 restrictions. Instead, pot mass was used to estimate plant biomass and relative growth rates during the experiment. Pot masses in the morning of the start and end of the experiment were used as a proxy for the initial and final harvest of the experiment. As all pots were filled with substrate to an exact weight and were watered consistently to pot capacity, initial and final plant biomass (g) for each replicate were calculated as:

$$f_1 = \textit{initial pot mass} - \textit{initial bare control mass} \quad \text{Eq 2}$$

$$f_2 = \textit{final pot mass} - \textit{final bare control mass} \quad \text{Eq 3}$$

where, f_1 and f_2 represents initial and final plant biomass.

Relative growth rate (RGR in g g^{-1} d^{-1}) was calculated as:

$$RGR = \frac{f_2 - f_1}{t_2 - t_1} \quad \text{Eq 4}$$

where, t_2—t_1 represents the time (in days) between the initial and final harvest.

Description of the water balance model

To simulate rainfall retention and plant drought stress, we used a green roof water balance model with a daily time-step, as described in Szota et al., (2017) [30]. This model was originally developed using the same scoria green roof substrate and plant species, *Ficinia nodosa*, as used in our current glasshouse experiment. We used the model to simulate performance of the eight treatments in our experiment. Two depths of scoria green roof substrate (150 mm and 300 mm) were used in combination with K_c values that were determined in the glasshouse experiment for bare pots (0.69 and 0.99, respectively) and pots with 1, 2 or 4 *Ficinia nodosa* plants (K_c ranging from 1.93 to 3.75). The model uses species-specific functions which describe the physiological response of *Ficinia nodosa* to drying scoria substrate, as determined experimentally by Farrell et al., (2017) [42]. Specifically, a function relating stomatal conductance (g_s) to substrate water content is used to penalize the well-watered K_c, to estimate daily ET under water-deficit conditions.

Climatic conditions applied in model simulation. To evaluate rainfall retention and plant drought stress, we ran a 30-year simulation (1985 to 2014) for Melbourne, Australia in the water balance model [30]. A summary of key weather statistics for the simulation is shown in Fig 1.

Summarizing rainfall retention and drought stress from model outputs. Annual rainfall retention was calculated for each year in the 30-year simulation as:

$$Retention = \frac{\sum Rainfall - \sum Runoff}{\sum Rainfall} \times 100 \quad \text{Eq 5}$$

where, *Retention* (in % yr^{-1}) was calculated from total rainfall and runoff each year (both in mm yr^{-1}).

To determine drought stress on each day of the simulation, it was assumed that plants were under drought stress if the depth of water in the substrate at the end of any given day was zero. This is consistent with a previous study where 'zero' depth of water in substrate at the end of the day was used as a critical threshold for determining that plants were drought stressed on that day [30]. We calculated the total number of stress events per year, i.e., the sum of drought stress days for each year (d yr^{-1}) and the maximum stress duration per year, i.e., the longest consecutive period of drought stress days for each year (d yr^{-1}) of the 30-year simulation.

Statistical analysis

For the glasshouse experiment, two-way analysis of variance (ANOVA) and Tukey's post-hoc tests were used to determine significant differences among means for the substrate depth and

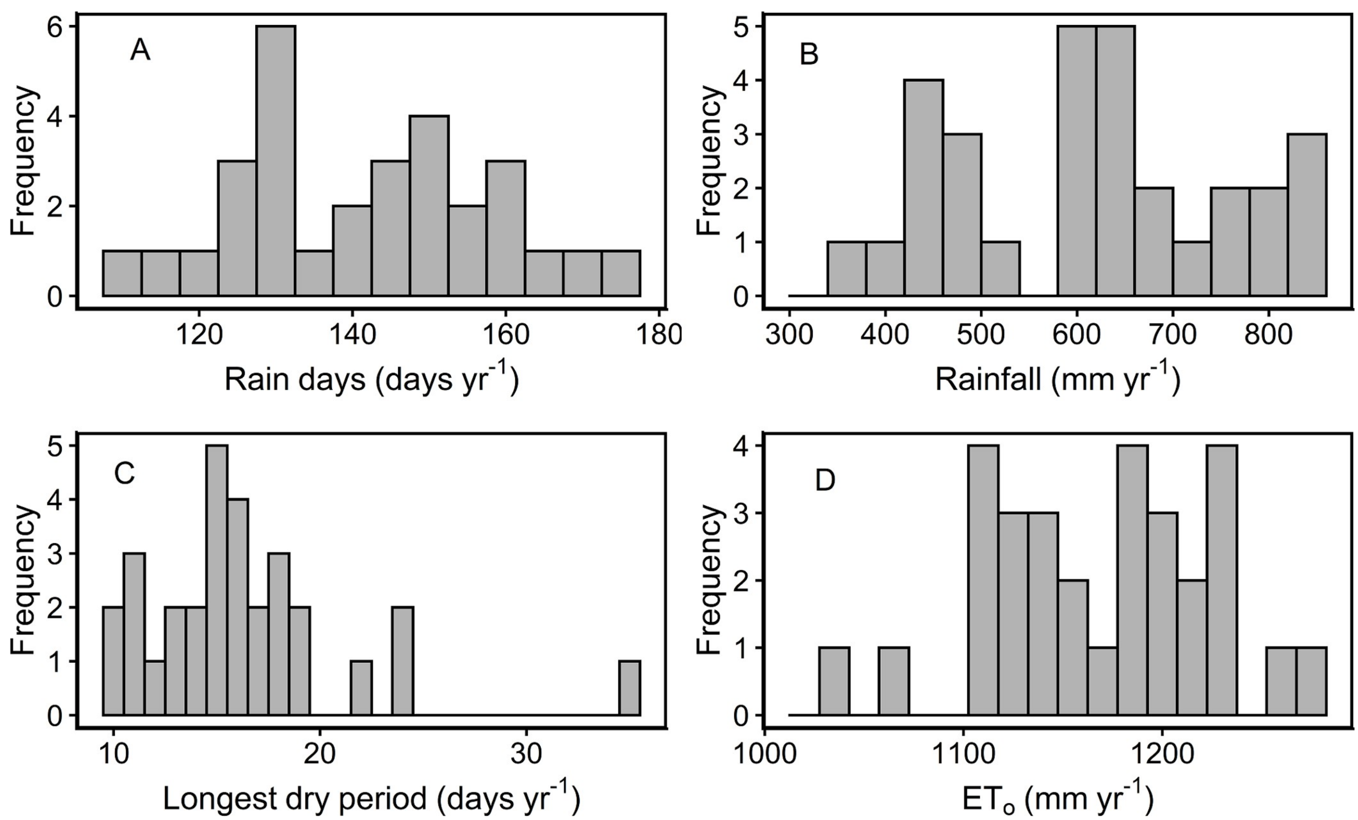

Fig 1. Summary of climate statistics for the 30-year weather scenario (1985–2014). All data were sourced from the Australian Bureau of Meteorology for Olympic Park, Melbourne (station #86071). Key statistics shown include A) number of rain days, B) annual rainfall, C) longest dry period and D) reference evapotranspiration (ET_0).

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plant density treatments. Linear regression analysis was used to describe the strength (adjusted R^2) and significance (P-value) of the relationship between ET and ET_0 for each treatment. The slope of the relationship is equivalent to the K_c for each treatment.

For the model simulation, rainfall retention and plant drought stress means were calculated for each metric for each treatment using two-way analysis of variance (ANOVA) and Tukey's post-hoc test. All analyses used the R software, version 4.1.0. [44].

Results

Cumulative evapotranspiration in the glasshouse experiment

Substrate depth and planting density significantly influenced cumulative ET ($P<0.001$), but the interaction between the two factors was not significant ($P = 0.08$; Fig 2). Cumulative ET was 38–48% higher for plants growing in the deeper substrate, compared with plants growing in the shallower substrate. In both substrate depths, planted treatments had significantly greater cumulative ET than bare treatments, with pots with no plants using only 19–22% of water used by single plants. However, increasing plant density from one to two plants did not significantly increase cumulative ET, regardless of substrate depth. Pots with four plants showed 30% and 40% greater cumulative ET compared with pots with a single plant for shallower and deeper substrates, respectively.

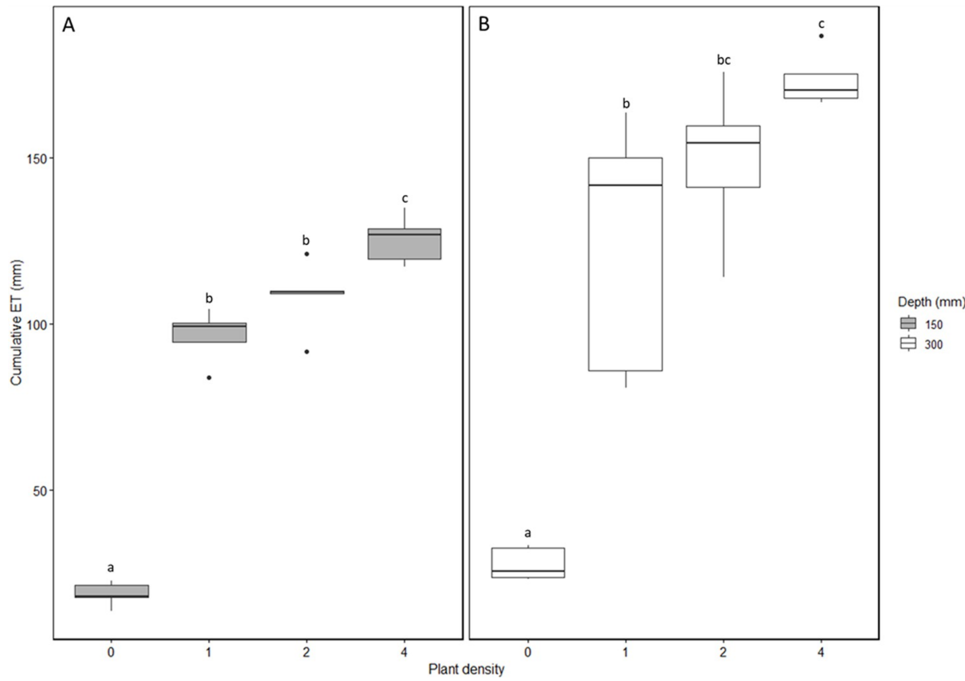

Fig 2. The effect of all treatments on cumulative ET. Cumulative ET for all plant density treatments (0, 1, 2 and 4 plants per pot) growing in two different substrate depths A) 150 mm and B) 300 mm, in the glasshouse experiment. Different letters denote significant differences among means within each of the two different substrate depths (all P values are given in results; two-way ANOVA; n = 5; Tukey post-hoc test).

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Plant biomass, relative growth rate and cumulative ET per unit biomass in the glasshouse experiment

For plant biomass, only plant density had a significant effect ($P<0.001$; Fig 3A), with no significant difference between the two substrate depths ($P = 0.31$) and no interaction between the two factors ($P = 0.99$). Increasing plant density from one to two plants increased biomass by 64 and 71% in shallower and deeper substrates, respectively.

Relative growth rate (RGR) was only affected by plant density ($P<0.001$; Fig 3B), with no significant difference between the two substrate depths ($P = 0.32$), and no interaction between the two factors ($P = 0.99$). There was 63% and 72% higher growth rate in pots with two plants than in pots with a single plant, in shallower and deeper substrate, respectively. However, pots with four plants showed 1.4 to 1.6 times greater growth rate than pots with a single plant.

When cumulative ET was adjusted for plant biomass, there were only weakly significant differences in cumulative ET per unit biomass among plant density treatments ($P = 0.05$; Fig 3C). There were no significant differences between the two substrate depths ($P = 0.11$) and no significant interaction between the two factors ($P = 0.31$). In shallower substrates, increasing plant density from one to two plants decreased cumulative ET per unit biomass by 41–66%, while pots with four plants showed 53–75% lower cumulative ET per unit biomass than pots with a single plant, in shallower and deeper substrate, respectively.

Plant crop factor (K_c)

The relationships between ET and ET_0 were significant for all treatments (all $P<0.001$; Fig 4), but slightly weaker in the shallower substrate ($R^2 = 0.26–0.49$) compared with the deeper substrate ($R^2 = 0.35–0.61$). Values of K_c increased with increasing planting densities from 1.93 to

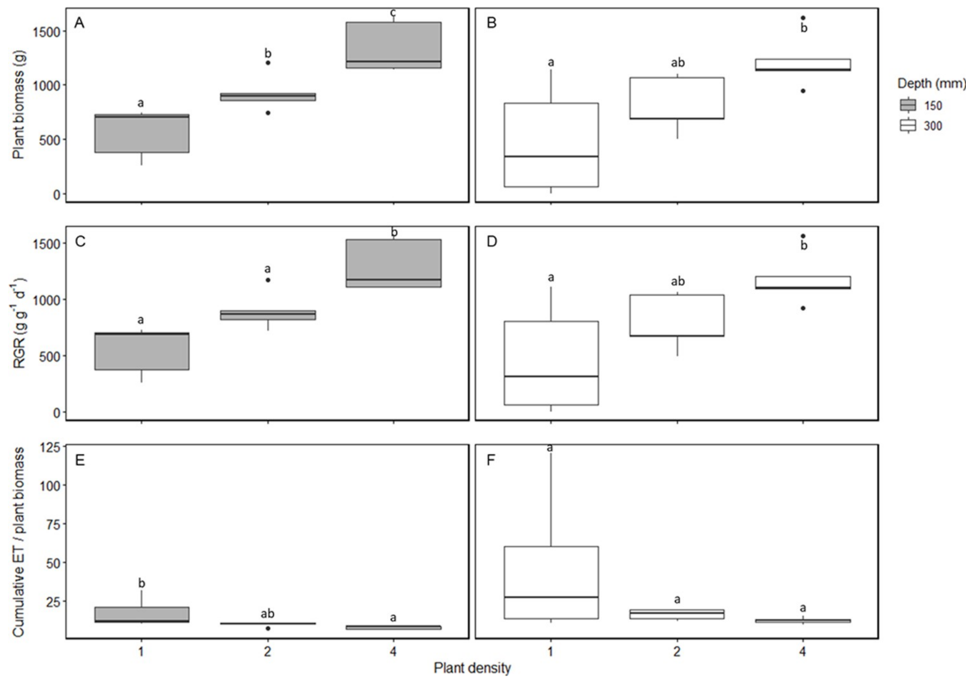

Fig 3. The effect of all treatments on biomass, relative growth rate and ratio of cumulative ET per unit biomass. (A & B) Final plant biomass, (C & D) Relative growth rate (RGR) and (E & F) the ratio of cumulative ET per unit plant biomass, for all plant density treatments (0, 1, 2 and 4 plants per pot) growing in two different substrate depths: 150 mm and 300 mm, in a glasshouse experiment. Different letters denote significant differences among means within each of the two different substrate depths (all P values are given in results; two-way ANOVA; n = 5; Tukey post-hoc test).

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2.20 for shallower substrates and 2.68 to 3.75 for deeper substrates. The bare (0 plants per pot) had a K_c of 0.69 for the shallower substrate and 0.99 for deeper substrate.

Rainfall retention and plant drought stress in the model simulation

For rainfall retention, substrate depth had only weak significance (P = 0.05; Fig 5), while plant density had no significant effect (P = 0.35) and there was no significant interaction between the two factors (P = 0.40). There was only 13.7% greater retention in bare (0 plants per pot) substrates when substrate depth increased from 150 mm to 300 mm. Although not significant, planted 150 mm deep substrates (1, 2 and 4 plants per pot) had 11% more rainfall retention than bare (0 plants per pot) substrates.

The total number of stress events was significantly influenced by substrate depth and plant density and there was a significant interaction between the two factors (all $P<0.001$; Fig 6A). The total number of stress events in the deeper substrate was 30 days more than those in the shallower substrate. Although statistically significant, increasing plant density from one to two plants resulted in only 3 days more stress events in the shallower substrates, whereas in deeper substrate there were 14 more stress event days. Pots with four plants showed 4 days and 15 days of greater total drought stress events than pots with a single plant, in shallower and deeper substrates, respectively.

The maximum stress duration was significantly affected by substrate depth ($P<0.001$; Fig 6B) and there was no significant effect of plant density (P = 0.10) and no significant interaction between the two factors (P = 0.50). Deeper substrates had four days greater maximum stress duration than the shallower substrate.

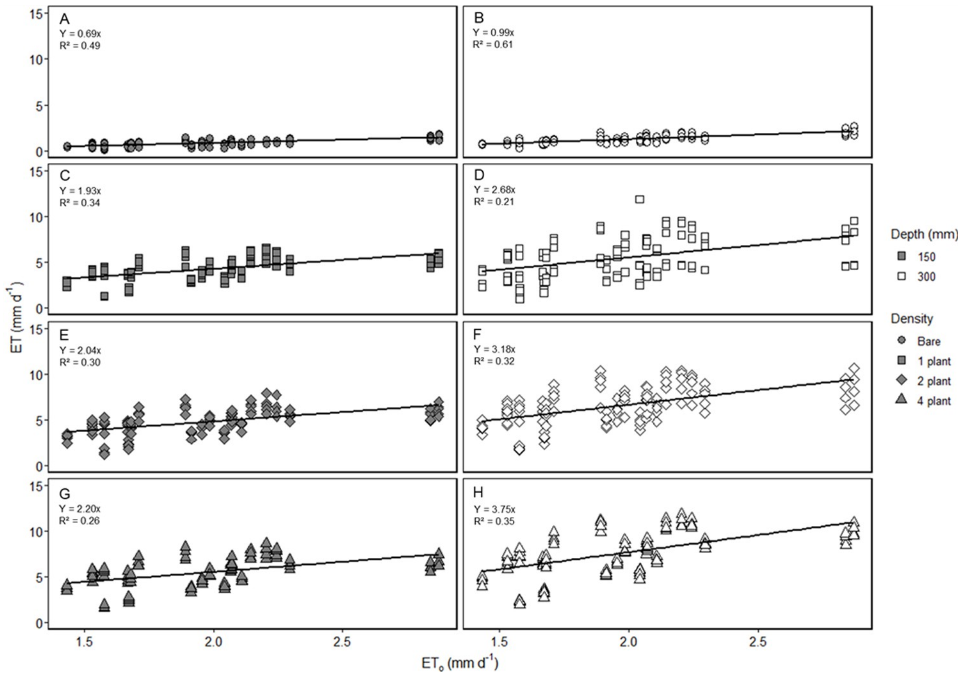

Fig 4. Relationships between measured evapotranspiration (ET) and reference evapotranspiration (ET_0) for well-watered plants. Symbols indicate four different planting density treatments (0, 1, 2 and 4 plants per pot) growing in two different substrate depths: 150 mm and 300 mm, in a glasshouse experiment. The equation is equivalent to the crop factor (K_c) for all treatments. R^2 values were derived from linear regression models (all $P < 0.001$).

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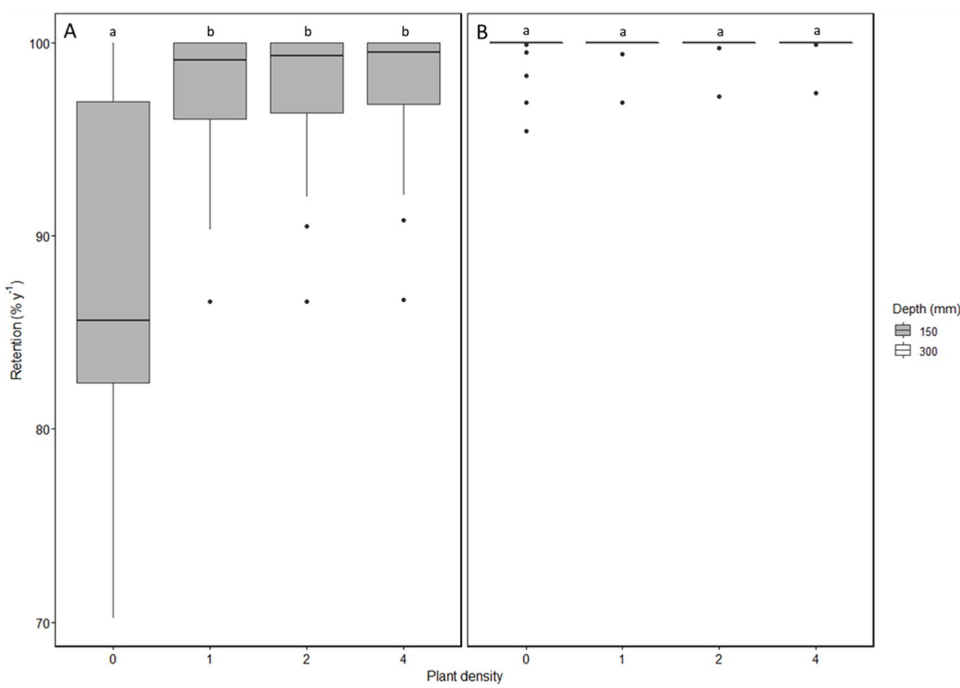

Fig 5. The effect of all treatments on retention. Percentage retention for the simulated 30-year Melbourne weather scenario (1984–2014) for all plant density treatments (0, 1, 2 and 4 plants per pot) growing in two different substrate depths: A) 150 mm and B) 300 mm, in a glasshouse experiment. Different letters denote significant differences among means across each of the two different substrate depths (all P values are given in results; two-way ANOVA; n = 5; Tukey post-hoc test).

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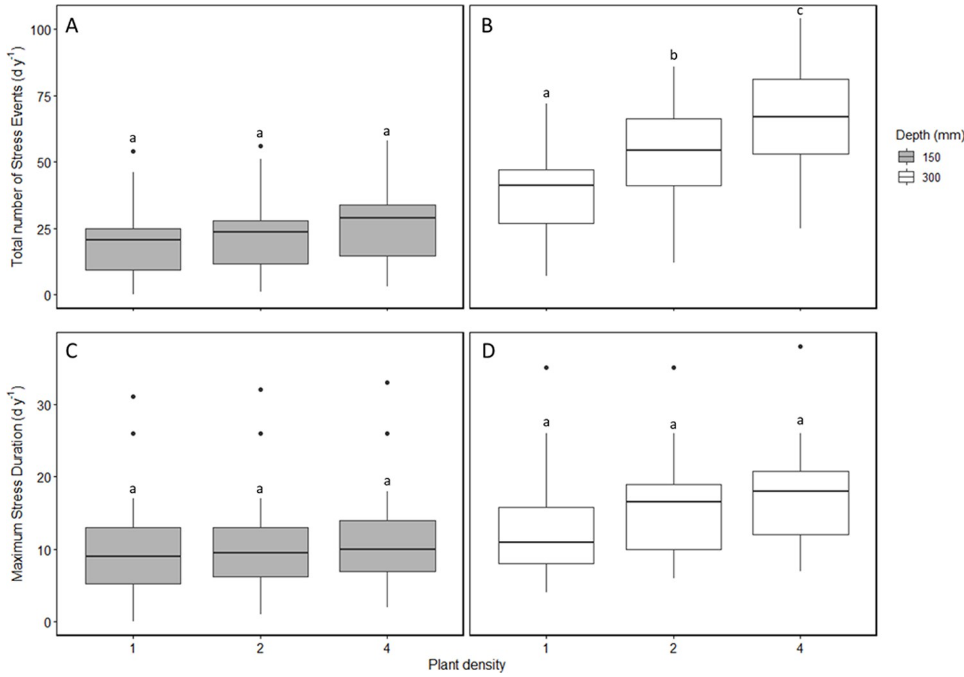

Fig 6. The effect of all treatments on total stress and maximum stress. (A & B) Total number of stress events and (C & D) Maximum stress duration, for a simulated 30-year Melbourne weather scenario (1984–2014) for all plant density treatments (0, 1, 2 and 4 plants per pot) growing in two different substrate depths: 150 mm and 300 mm, in a glasshouse experiment. Different letters denote significant differences among means within each of the two different substrate depths (all P values are given in results; two-way ANOVA; n = 5; Tukey post-hoc test).

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Discussion

Effect of increasing plant density and substrate depth on evapotranspiration

We hypothesized that doubling plant density would double ET due to a proportional increase in K_c [30, 45]. However, doubling plant density from one to two plants per pot increased ET by only 12–20%. When plant density was quadrupled, there was only a 30–40% increase in ET relative to that of a single plant. The observed range in daily ET in our study (0.8–7.5 mm d^{-1}) is very high as compared with other green roof studies. However, these studies mainly used shallower substrates planted with succulent species, which have generally lower ET rates due to their conservative water use. For example, Voyde et al., (2010) [46] observed daily rates of 2.19–2.21 mm d^{-1} and Sherrard et al., (2012) [47] found average daily ET rates of 0.52–1.24 mm d^{-1}. Since, the species used in our study had very high rates of ET, up to 7.5 mm d^{-1}, which is similar to ET recorded for the same species in biofiltration studies [48, 49]. This shows that the high ET rates in our study are very much due to the selection of a higher water-using species in deeper substrates and under well-watered conditions. However, as increasing plant density did not proportionally increase ET in our glasshouse experiment, this suggests limitations in the gains in overall water use for densely planted green roofs.

Plant biomass and relative growth rates increased by approximately 70% when planting density increased from one to two plants, regardless of substrate depth. This is consistent with Schmid et al., (2008) [50], who found that greater biomass and productivity would retain more water and show higher ET. Although the increase in ET for our plants was related to increases in biomass, there were proportionally lower gains in ET with increasing plant density, which may suggest that ET at higher plant densities was limited by plants shading themselves, neighboring plants, and/or substrate surfaces. Although plants were well-watered in our glasshouse study when crop factors were derived, and therefore experienced no drought stress. On green roofs, shading has also been shown to reduce plant drought stress [51] and ET [52–54]. This is further supported by ET per unit biomass, which significantly decreased with increasing plant density, indicating that a single plant was more efficient at using water.

In planted pots, we observed a 28–38% increase in ET from the 150 mm to 300 mm deep substrates. This increase in ET was proportionally less than the increase in substrate depth and is consistent with other green roof studies [40, 55, 56]. For example, Buccola et al., (2011) [55] found only a 36% increase in hydrological performance when almost tripling substrate depth from 50 to 140 mm. Further, as Soulis et al., (2017) [56] showed that doubling substrate depth (80 to 160 mm) only increased plant water use when plants were able to dry out substrates and significantly replenish green roof storage between rainfall events. Hence, doubling substrate storage is unlikely to double ET where water is not limiting [57, 58], which was the case in our experiment as plants were well-watered each day to determine their K_c. The effect of well-watered conditions on reducing ET is also reflected in the minimal increase in ET for bare unplanted pots, where increasing substrate depth from 150 mm to 300 mm only increased cumulative ET by 9 mm during our study period. As plant biomass was the same for both substrate depths when planted with the same number of plants, this suggests that plants in deeper substrates were unable to access more water at depth. The scoria-based substrate had a water holding capacity of ~50%, and therefore in 150 mm deep substrate, nearly 75 mm of water was available for daily ET. However, the maximum daily ET observed in 150 mm deep substrate was 5.5 mm d^{-1} at the highest density (4 plants per pot), suggesting that ~70 mm of water remained unused. Since our plants were fully grown with full canopy cover at the start of the glasshouse experiment, they should have had maximum ability to extract water from the pots [27, 30, 54, 59]. Plants in deeper substrates may have had lower allocation to roots and this may also have reduced their water use. However, we were unable to partition root and shoot biomass or measure root depth. Plants were not stressed during this experiment as they were kept well-watered. Under water-deficit conditions, we expect that plants in deeper substrates would show greater ET, due to greater available storage, than plants in shallower substrate. However, under well-watered conditions and regardless of the mechanism, additional storage achieved through increasing substrate depth only marginally increased ET.

In our study unplanted substrates had 78–81% lower ET than planted substrates. These results are lower than the results found in literature [12, 37, 60, 61], and are likely due to our experimental conditions. For example, a previous study in green roof modules showed that unplanted modules had 93% of the ET of modules planted with similar high water-using species [12]. However, plant coverage in our study was far greater (i.e., leaves extended well outside the pot area) than this previous module study, and this is likely to have caused greater ET in planted versus bare substrate. It is plausible that the lower ET of bare substrates was reduced by the pot sidewalls causing shading or reducing air flow across the surface. However, the greater ET in our planted substrates is more likely due higher canopy cover [62] and high water-using species [63]. Hence, coverage with high water-using plants will considerably increase ET rates as compared to unplanted green roofs, suggesting that green roofs should be planted to maximize plant coverage to ensure greater plant water use and in turn greater replenishment of substrate water storage between rainfall events.

Effects of increasing substrate depth and plant density on rainfall retention

Rainfall retention was very high for all substrate depths and plant densities ($> 95\%$) in our 30-year water balance simulation. Rainfall retention increased from 95 to 99.5% when substrate depth increased from 150 to 300 mm and increasing plant density increased rainfall retention from 97 to 100%. Such an outcome is likely to reduce runoff to near pre-development levels in many parts of the world [4]. However, the rainfall retention in our study is higher than most other studies which range between 5 and 80% [11, 14, 15, 30, 46, 64–67], although these studies were investigated under different climatic conditions.

We investigated the effect of climate on rainfall retention by comparing 'dry' (2009) and 'wet' (2011) rainfall years, based on an analysis of the long-term 30-year (1985–2014) rainfall data (see S2 Fig) in Melbourne. The total annual retention was 452 mm (2009) and 750 mm (2011), suggesting a ~10% decrease in retention in the dry rainfall year relative to the wet rainfall year. Small rainfall events (< 5 mm) were common, representing 76% and 72% of all events observed in these dry and wet years, respectively. Such events typically produce no runoff [11, 25, 26, 40, 45, 60]. For these events, rainfall is likely intercepted by plants and evaporated [57, 68, 69], resulting in smaller rainfall events being retained [70]. Therefore, in our study, the large number of small rainfall events likely minimized differences in retention among planting treatments. This is consistent with the results of Zhang et al. 2019 [12] who showed that storage and ET did not affect retention for small rainfall events (~5–10 mm) in a green roof module experiment in Melbourne with similar plant species. For the large and infrequent rainfall events in our simulated study, ET was small relative to the total rainfall depth (> 45–82 mm) [25], which may also have reduced the effect of substrate depth or plant density on retention performance and has also been observed in other studies [11, 25, 40, 45, 60]. Therefore, in our study increased substrate water storage and plant density had minimal effect but there was high rainfall retention across all treatments, likely due to the high water-using plant species [24].

Effect of increasing substrate depth and plant density on drought stress

While increased water storage was expected to reduce plant drought stress in our model simulation, as shown in other studies [35, 71], this was not the case in our study. The higher crop factors which were derived from high planting density treatments in the glasshouse, resulted in faster depletion of the substrate water storage in the model simulation and therefore greater drought stress. This is consistent with a study in Sheffield, UK which showed that although quadrupling plant water use (K_c from 0.5 to 2.0) doubled annual retention, it also resulted in an almost 4-fold increase in drought (>8 days) plants experienced on a green roof planted with *Sedum* species [45]. From our model, plants in deeper substrates experienced 14–29 more days of drought stress. This was surprising as plants in deeper substrates in the glasshouse only had a slightly higher K_c than in shallower substrates. The total number of stress events for plants in the deeper substrate also increased with higher planting density. In contrast, increasing plant density had a negligible impact on the total number of stress events in shallower substrate. Therefore, our study suggests that there is no advantage in increasing substrate depth beyond 150 mm for green roofs, particularly in Melbourne's current climate as this does not significantly reduce plant drought stress. This substrate depth has also been suggested as optimal in Melbourne's climate to minimize cost and weight loading [12]. However, our results are specific to the scoria-based green roof substrate and plant species with similar crop factors. If substrates with lower water holding capacity were used, much deeper substrates may be needed to avoid drought stress under the same conditions when planted with *Ficinia nodosa*. It is also likely that under a changing climate with hotter and drier conditions, irrigation may be necessary to reduce drought stress and ensure plant survival [28, 72].

Effect of plant crop factor on rainfall retention and drought stress

In our study, K_c was manipulated by increasing plant density. The glasshouse results showed plants in the deeper substrate had higher K_c values compared with the shallower substrate at the same planting density. Even unplanted substrates had higher K_c values of 0.69 and 0.99 in shallower and deeper substrate, respectively. For a single plant, the K_c values were 1.93 (150 mm depth) and 2.68 (300 mm depth), and are very high when compared to *Sedum* based green roofs [14, 37, 47, 56, 58]. Higher K_c values for *Ficinia nodosa* in our study (calculated as the ratio of ET/ET_0) relative to *Sedum* species are likely due to greater plant size, coverage [12] and water use Szota et al., (2017) [30]. However, the K_c values of *Ficinia nodosa* in our study are also much higher than those reported in the Szota et al., (2017) [30] pot-based study under well-watered condition (K_c = 1.67). As the plants in our experiment were fully established the plants had bigger canopies than the pot surface area, which may have overestimated the daily ET rates, resulting in higher K_c values. On a green roof this may mean that these plants would have lower K_c values than estimated from pots with a confined area [36].

The high K_c very likely explains the observed maximum overall annual retention predicted in our model. With higher K_c values plants depleted the deeper substrate quickly due to higher ET rates, resulting in greater retention. The maximum retention with high K_c (> = 1) relates to a study in Sheffield, UK which showed that an increase in K_c from 0.5 to 2.0 would approximately double annual retention, with the side-effect of almost four-fold increase in the number of drought periods [45]. Hence, plant survival becomes an important attribute in improving the ecohydrological performance on a green roof. The K_c is typically the most sensitive parameter in green roof water balance models [14, 25, 37] and several studies recommend development of accurate K_c values as a research priority [37, 47]. We suggest that plants with high K_c value should be planted to ensure maximum coverage (growth), without necessarily increasing plant density. Increasing substrate depth which can increase cost and weight loading is also not required; particularly where future climate predictions indicate a reduction in rainfall.

Conclusion

Contrary to our hypothesis, doubling substrate depth and plant density did not double overall water use (ET), despite increases in both plant biomass and productivity. The shading effect of mature plants likely limited evaporative demand under well-watered glasshouse conditions. In the model simulation, higher $K_{c,}$ and storage only increased rainfall retention by 3–5% and resulted in greater plant drought stress. Unplanted bare substrates had lower ET than planted treatments, indicating the benefits of planted green roofs. However, the plants were under favorable glasshouse conditions, where water was not limiting, showing limited increase in ET with increasing substrate depth and plant density. Future research should investigate ET and drought stress for different substrates and plant species under realistic rooftop condition, especially under a combination of high heat, light and wind conditions. How plant water use and drought stress respond under real world conditions could be used to validate our water balance model [37]. Further, temporal aspects of plant growth and recovery of ET following periods of drought, which were not quantified in our study, would further improve our understanding of the water balance of green roofs. In our model simulation, using a 30-year climate scenario for Melbourne, rainfall retention was very high, and plants experienced greater drought stress in deeper substrates due to higher water use (i.e., a higher K_c). Our results suggest that the use of a single plant (1 plant per 0.08 m^2) in shallower substrate (150 mm) was optimal for rainfall retention and minimized plant drought stress. Although the water-deficit phase has only been simulated in our study, it would be interesting to repeat the glasshouse experiment under water-deficit conditions to see if plant response to drying substrates is similar to the modelled scenario. These results also highlight the importance of determining rainfall retention using ET derived from fully-grown plants. The method of deriving crop factor is important to green roof model performance and requires further investigation.

Supporting information

S1 Fig. Eight experimental treatments. The left-side shows two "water storage' treatments (150 mm & 300 mm deep substrates). The right-side shows plant species *Ficinia nodosa* used for four 'plant density' treatments (0, 1, 2, or 4 plants per pot). There are five replicates for each treatment.
(TIF)

S2 Fig. Model components for a dry year (2009) and a wet year (2011) for the 30-year Melbourne weather scenario (1985–2014) evaluating the effect of plant density and substrate depth on rainfall retention. The left-side shows the model outcome for *Ficinia nodosa* planted with a single plant (1 plant) or four (4 plant) plants in the shallower green roof substrate (150 mm depth). The right-side shows the model outcome for *Ficinia nodosa* planted with a single plant (1 plant) or four (4 plant) plants in deeper substrate (300 mm depth). The red line shows substrate water storage at the end of each day (mm), the blue line shows ET (mm d^{-1}), and grey bars show the amount of rainfall (mm).
(TIF)

S1 Dataset.
(XLSX)

S2 Dataset.
(XLSX)

S3 Dataset.
(XLSX)

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