Effect of drainage layers on water retention of potting media in containers

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Abstract

Excess water retention in the potting medium is a significant problem for plants grown in containers due to the volume of saturated medium which forms above the drainage hole. Adding a layer of coarse material like gravel or sand at the bottom is a common practise among gardeners with the aim of improving drainage, but some researchers have argued that such layers will raise the saturated area and in fact worsen drainage. Two different depths and four different materials of drainage layer were tested with three different potting media to determine the water retention in the container after saturating and draining freely. For loamless organic media, almost all types of drainage layer reduced overall water retention in the container compared to controls. For loam-based media, most drainage layers had no effect on the overall water retention. Two simple models were also used to estimate the water retention in the media alone, excluding the drainage layer itself. All drainage layers reduced water retention of loamless organic media, according to both models. There was disagreement between the two models applied to loam-based media, and further study is required to determine the most accurate. Both models showed that some drainage layers with smaller particle sizes reduced water retention in loam-based media, but disagreed on the effect of drainage layers with larger particle sizes. Overall, any drainage layer was likely to reduce water retention of any medium, and almost never increased it. Thicker drainage layers were more effective than thinner layers, with the most effective substrate depending on the potting media used. A 60mm layer of coarse sand was the most universally-effective drainage layer with all potting media tested.

Keywords: soil, water-holding capacity, container growing, drainage, potting media

1 Introduction

It is widely recognised that soil in a container behaves differently from soil in the field (Hershey 1990; Landis, 1989; Spomer, 1975). One of the most significant differences is the presence of a saturated volume of soil at the bottom of the container after irrigation and draining, known as a perched water table (Bunt 1988; Goh and Haynes, 1977; Handreck 2002). The depth of this saturated volume is constant for any specific soil, and unaffected by container size and shape. As a result, soil in a shallower container has a greater percentage water-holding capacity (WHC) than the same soil in a deeper container (Bilderback and Fonteno, 1987; Bunt, 1961; Hershey, 1990; Waters et al., 1970). This effect has led to the concept of container capacity, a measure of the total water retained in a specific container filled with specific soil after saturation and drainage (Bunt, 1988; Heiskanen, 1997; Waters et al. 1970).

Adding a layer of rocks or gravel at the bottom of plant pots is a common practise among home gardeners, as well as some researchers (Cavazza et. al. 2005), and is generally intended to reduce this perched water table and improve drainage. However in recent years the recommendation has been disputed, with arguments based on principles of water movement through soil suggesting that a drainage layer will in fact raise the perched water table and worsen drainage overall (Chalker-Scott and Downer, 2019; Evans, 2014). Despite frequent discussion of this practise, there has been little formal research into the effect drainage layers have on the water-holding capacity of soil in containers.

A number of areas of research may be applicable to this subject in part. One of the oldest relevant studies is the tests of water movement through soil interfaces conducted by Hsieh and Gardner (1959). This research demonstrated that when the wetting front encounters an interface between soils of different porosities, it will not advance until the soil behind is nearly saturated. Applying this to the interface between potting medium and drainage substrate in a container suggests that water will not move down into the drainage layer until the medium is almost saturated, and therefore the perched water table in the medium will be raised and the overall aeration reduced.

Recent studies into the capillary break effect have similarly demonstrated that a layer of coarse material acts as a barrier to water movement in field soils (Azevedo and Zornberg, 2013). Khire et al. (2000) also found that more water is stored above a capillary barrier layer when it consists of coarser material than when it consists of finer material. Smesrud and Selker (2001) conducted theoretical analysis which predicted that the effectiveness of a capillary barrier is maximised when the contrast of particle sizes between the soil above and the substrate below is infinite - in other words, when the soil is suspended over a void of air. This would suggest that the perched water table created by soil over any other substrate would be less than that created by soil over air.

Another area of recent relevant research which can be applied to this subject is the construction of green roofs, which are roofs made from a layer of growing medium topped with living plants (Cascone, 2019). This shallow layer of medium is surrounded by an impermeable base and sides, with a small number of drains for excess water to escape through - physical conditions which are similar to a container of soil. In the construction of green roofs a drainage layer of coarse substrate below the growing medium is always considered essential (Berndtsson, 2010; Cascone, 2019). She and Pang (2010) found that water begins to drain out from the soil of the green roof after it has reached field capacity (container capacity), but before it is fully saturated. This result contrasted with predictions that water only escapes at full saturation, showing the need for further research to understand the movement of water through soil in containers with layered contents.

Ruter (1986) found that when a fabric-bottomed container was placed on a column of sand to drain, the perched water table in the medium was completely eliminated. This suggests that water moved more easily from the medium to sand than from the medium into air, and therefore that adding a drainage layer of sand to the bottom of a container may aid drainage. However, the column of sand in this study was many times deeper than the container itself, so this may not predict the behaviour of a thin drainage layer. In addition, the fabric bottom of the container may have an effect on the water movement from the medium to the sand which would not occur if the two materials were in direct contact.

Many of the above studies were conducted on mineral field soils. In contrast, container growing often utilises loamless potting media based on organic materials like peat, coir, and bark, with mineral amendments like perlite and vermiculite. (Boodley and Sheldrake, 1982; Bunt, 1988; Caron et al., 2015; Evans 2014; Goh and Haynes, 1977; Landis, 1989; Waters et al., 1970). These media typically have very different physical properties from loams, including higher total porosity and lower water-holding capacity (Bunt and Adams, 1966; Bunt, 1988). As a result, the water movement through loamless media in containers may not be accurately predicted by applying research conducted on field loams.

Further, researchers have demonstrated that the water movement and other behaviour of soil in containers is highly dependent on the geometry of the container (Spomer, 1975), and can differ greatly from the behaviour of even the same soil in the field (Landis, 1989). Thus, much of the research into the behaviour of water at soil interfaces cannot be applied directly to the situation of container growing because it was conducted in the field or in containers of very different size and shape to those generally used for live plants.

A typical filled plant pot consists of an impermeable container with a small number of holes in the base, full of a single uniform potting medium. When the saturated medium is allowed to drain, the only interface the water passes through is the drainage hole where medium meets air. In contrast, a pot with a drainage layer is a more complex system. First the water passes through the interface between the medium and the drainage substrate, and then it passes through the interface between the drainage substrate and the air under the drainage hole. These multiple interactions make it more difficult to predict the final outcome using only theoretical analysis of individual soil interfaces.

The effect of the volume taken up by the drainage layer is also uncertain. Assuming the same overall container size, a pot with a drainage layer has a smaller volume of potting medium. Therefore, even if the percentage water-holding capacity of the medium is the same in the pot with a drainage layer, the total water retained at container capacity would be reduced. But instead of this reduced water retention being evenly distributed through the volume of the pot (as it would be in a container filled with a more free-draining medium), it is held in alternating layers of saturated and air-filled materials. The effect this would have on growing plants is difficult to determine, and depends on the behaviour of roots growing towards and into the drainage layer. If the roots do not enter the drainage layer, the plant could be considered to be effectively growing in a smaller container with the total water-holding capacity of the medium itself. However, if the roots do enter the drainage layer, they would grow through distinct layers with different moisture and air contents, as well as other physical properties.

This study aimed to determine the effect on water-holding capacity of drainage layers in containers, and compare the effect using different potting media, different drainage substrates, and different layer depths. The intention was to obtain results which could be applied by commercial nurseries and home gardeners in practice, so the conditions were chosen to closely replicate real growing containers. The study did not attempt to determine the effect of drainage layers on growing plants directly. Experiments and theoretical models were used to determine the water-holding capacity of the entire container, and of the medium alone, so that both results could be considered by readers when predicting the effects on plant growth.

2 Materials and methods

Three different types of potting media were used, as follows: JI was a loam-based John Innes No. 1 compost (Bathgate); CV was a mix of 70% coir (Coir Products Coco Peat) and 30% vermiculite (Westland Gro-Sure) by volume; CPB was a mix of 60% coir, 20% perlite (Vitax 2-6mm), and 20% pine bark (Melcourt Propagating Bark 2-7mm) by volume. The two loamless mixes were chosen to represent some of the most common loamless media used by growers according to Bunt (1988). Such media typically contain at least 50% peat or fine bark, with the remainder composed of mineral amendments (such as perlite, vermiculite, or sand), compost, or coarse bark. Coir was chosen as an acceptable alternative to peat in these mixes (Meerow, 1997; Noguera et al., 2000), due to the UK government's intention to reduce or eliminate horticultural use of peat.

Four different drainage substrates were used: gravel (Melcourt Horticultural Gravel 4-10mm), leca (LECA Lightweight Aggregate 4-10mm), grit (LECA Lightweight Aggregate 2-4mm), and sand (Dehner Aquarienkies 1-2mm). This range of substrates was chosen to examine the influence of particle size on drainage effects, as well as to compare the effect of porous substrates with non-porous ones.

Test pots were made from clear plastic containers with a single 10mm hole cut in the centre of the base. The pots had a total capacity of 1,290ml, and were an inverted truncated cone shape with height 175mm, base diameter 86mm, top diameter 118mm, and dry weight of 53g. The base had a slight domed area raised by 4mm relative to the edges. For trials with sand, a piece of fibreglass mesh (16 x 18 mesh count, approximately 1mm spacing) was placed over the drainage hole to prevent the sand escaping. The drainage hole was temporarily sealed with tape before filling.

For each potting medium, trials were conducted with a layer of each drainage substrate to depths of 30mm and 60mm (giving a total of 24 combinations). Control trials were also conducted without drainage substrate with the pot filled with media to the top, to 30mm from the top, and to 60mm from the top. In addition, trials were conducted of all the 30mm and 60mm drainage layers with no media. Ten replications were conducted for each condition, with the exception of two conditions (CV-leca-30mm and sand-60mm) which each had one invalid trial for a total of nine results.

Each potting medium was air-dried to a uniform moisture level before each condition (determined by weighing a fixed volume of medium until it reached a specified mass). All the containers were then filled with equal masses of medium (as recommended in the procedure Bilderback (2009) gives for measuring soil porosity in the nursery) to within 5g precision. Each filled container was irrigated from above using a watering can with a rose until the water level reached the top of the pot (or to the specified height for the tests involving pots filled to below the top). Finally the drainage hole was unsealed and the container allowed to drain suspended on a grate. Once drainage ended (which took between one minute and three hours, depending on the condition), the pot was weighed a final time with its wetted contents. The mass of the empty container was subtracted from the measurements to determine the initial dry mass (m_i) and drained mass (m_d) of the contents alone.

The saturating and draining process caused all the potting media to compact. The compacted depth was measured from one representative sample for each medium with each depth of drainage substrate, and the final compacted volume calculated (v). None of the drainage substrate layers compacted measurably, so their final volume was taken as equal to the initial volume.

The water-holding capacity ($WHC = (m_d - m_i)/v$) was then calculated for each trial. ANOVA post-hoc Tukey tests were used to determine the significance of differences between the means of different conditions. Different potting media were not compared directly to each other, because their compacted volumes and initial moisture levels were not standardised for this study.

Two simple models were created to estimate the WHC of the medium itself in containers with drainage layers. In both models, the initial mass of the medium in each trial was calculated using the initial mass of the full container and the initial mass of the corresponding drainage layer, $m_{i(med)} = m_{i(full)} - m_{i(drn)}$.

Model A was intended to estimate the highest possible WHC for the medium itself. The model was based on the assumption that the drainage layer held the same amount of water after draining when in a container filled with medium as when in a container alone. Thus, the drained mass of the medium in each trial was calculated by subtracting the drained mass of the drainage layer from that of the full container, $m_{d(med)} = m_{d(full)} - m_{d(drn)}$.

Model B was intended to estimate the lowest posible WHC for the medium itself. The model was based on the assumption that the drainage layer remained fully saturated with water after draining when in a container filled with medium. Thus, the drained mass of the medium in each trial was calculated by subtracting the saturated mass of the drainage layer from the drained mass of the full container, $m_{d(med)} = m_{d(full)} - m_{s(drn)}$.

The combination of these two models provided a range of possible values for WHC of the medium alone in each condition, to use as a basis for comparison against the control condition using the same depth of medium.

This enabled the volume and depth of the drainage layer itself to be eliminated as a factor, and the effect of the drainage layer on the medium above it to be considered in isolation.

3 Results

3.1 Coir-perlite-bark medium

The CPB mix showed the least compaction, with the effective volume of mix in a full pot decreasing from 1,290ml to 1,133ml. The control container filled to 30mm from the top compacted from 1,030ml to 838ml, and the container filled to 60mm from the top compacted from 780ml to 672ml.The WHC of the controls increased as the depth of medium decreased.

The results of the CPB drainage layer trials are presented in Fig. 1. Compared to the control, every container with a drainage layer had a lower overall WHC ($p < 0.001$). There were significant differences between many of the drainage layer conditions, with the 30mm grit condition having the highest WHC and 60mm leca the lowest. Analysing only according to the drainage substrate, all had lower overall WHC than the control ($p < 0.001$). Leca had significantly lower WHC than gravel ($p < 0.05$) and grit ($p < 0.001$). Combining all substrates, both 30mm and 60mm drainage layer conditions had lower overall WHC than the control ($p < 0.001$) with no significant difference between them.

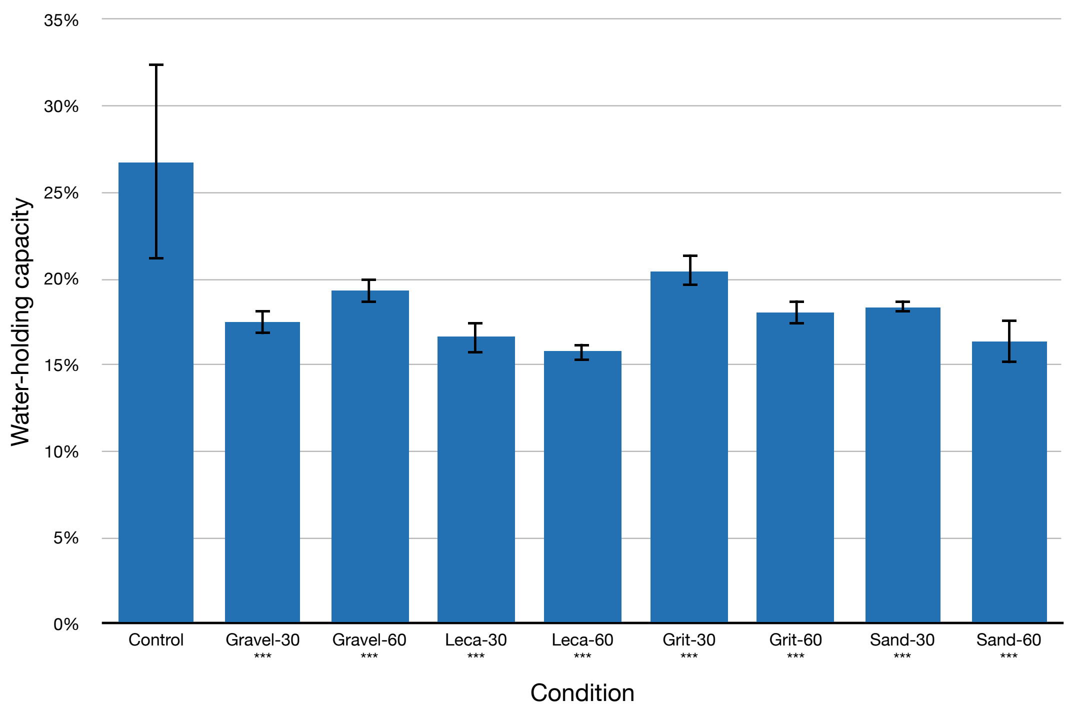

Figure 1: Mean and standard deviation water-holding capacity (WHC) of the entire container of CPB medium with different drainage layers. Asterisks mark conditions which were significantly different from the control (*** $p < 0.001$).

The modeled WHC of the medium itself in the drainage layer conditions is presented in Fig. 2 (30mm drainage layers) and Fig. 3 (60mm drainage layers), compared with the control containers with the same initial medium depth. With both drainage layer depths, both the modeled WHC values were lower than the control values for every condition.

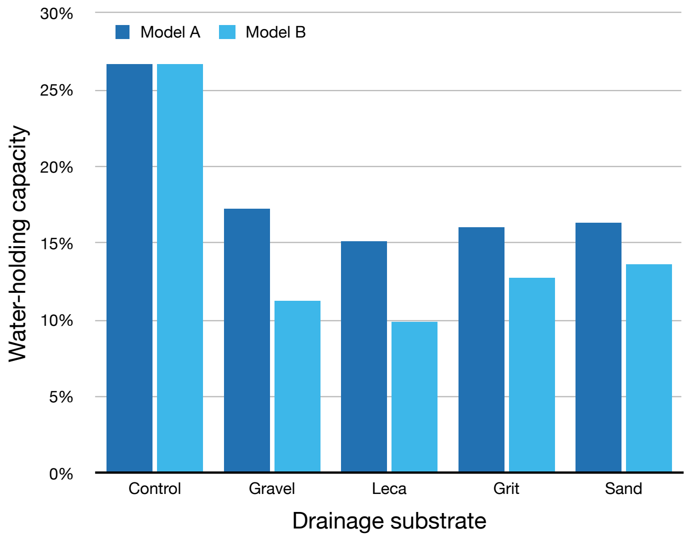

Figure 2: Estimated mean water-holding capacity (WHC) of the CPB medium alone with different 30mm drainage layers, according to models A and B.

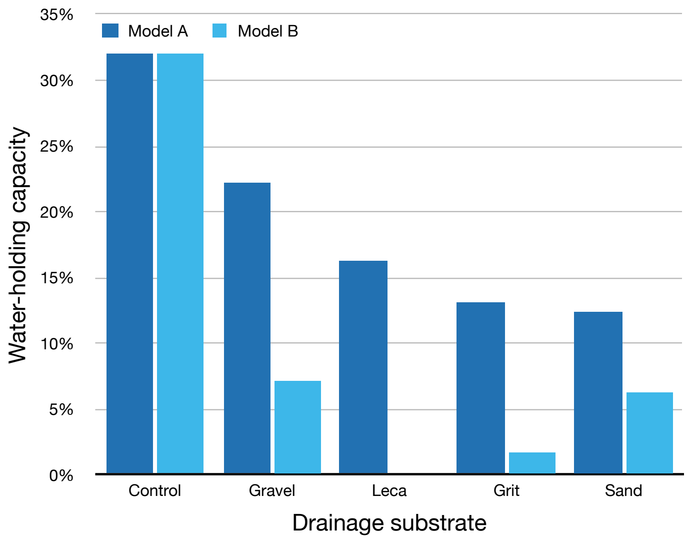

Figure 3: Estimated mean water-holding capacity (WHC) of the CPB medium alone with different 60mm drainage layers, according to models A and B.

3.2 Coir-vermiculite medium

The CV mix showed intermediate compaction, with the effective volume of mix in a full pot decreasing from 1,290ml to 1062ml. The control container filled to 30mm from the top compacted from 1,030ml to 816ml, and the container filled to 60mm from the top compacted from 780ml to 615ml. The WHC of the controls increased as the depth of medium decreased.

The results of the CV trials are presented in Fig. 4. Compared to the control, the gravel-30mm, grit-30mm, and leca-30mm drainage layer conditions did not have significantly different overall WHC. The grit-60mm ($p < 0.01$), gravel-60mm, leca-60mm, sand-60mm, and sand-30mm conditions ($p < 0.001$) all had lower WHC than the control. There were significant differences between many of the drainage layer conditions, with the 30mm grit condition having the highest WHC and 60mm gravel the lowest. Analysing only according to the drainage substrate, conditions with grit did not have significantly different overall WHC, while leca ($p < 0.05$), gravel ($p < 0.01$), and sand ($p < 0.001$) all had lower WHC than the control. Sand had the lowest WHC, and was significantly different ($p < 0.001$) from grit which had the highest WHC. Combining all substrates, 60mm layers had lower overall WHC ($p < 0.001$). 30mm layers were not significantly different from the control, but were significantly higher that 60mm layers ($p < 0.001$).

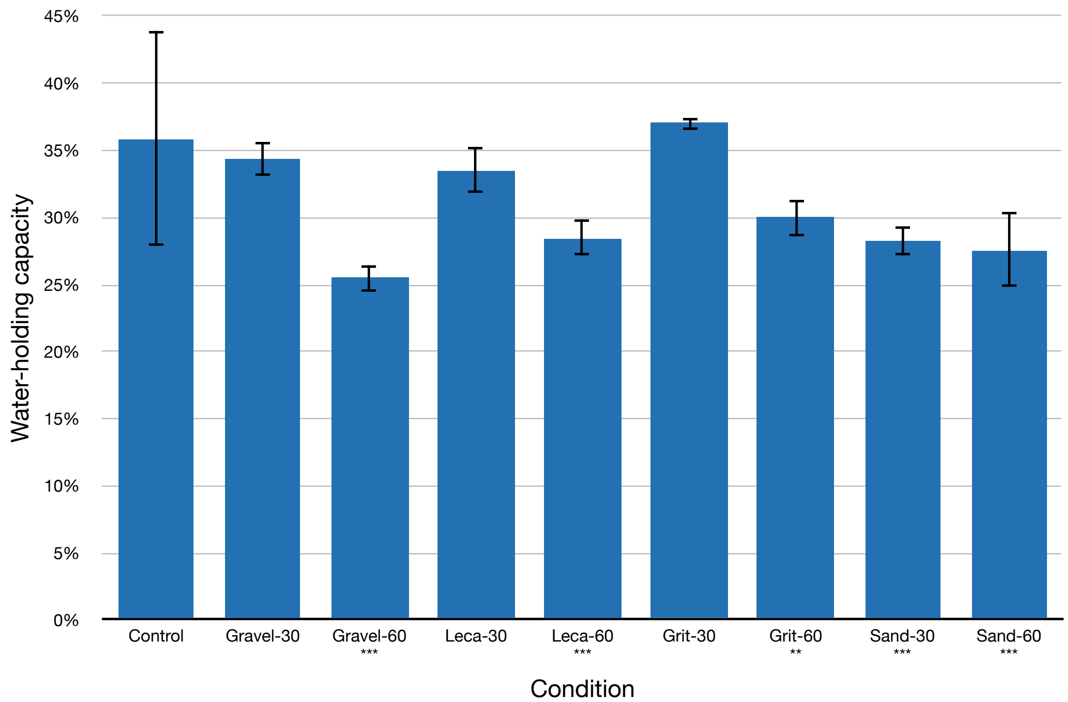

Figure 4: Mean and standard deviation water-holding capacity (WHC) of the entire container of CV medium with different drainage layers. Asterisks mark conditions which were significantly different from the control (** $p < 0.01$, *** $p < 0.001$).

The modeled WHC of the medium itself in the drainage layer conditions is presented in Fig. 5 (30mm drainage layers) and Fig. 6 (60mm drainage layers), compared with the control containers with the same initial medium depth. With both drainage layer depths, all the modeled WHC values were lower than the control values, with the 60mm drainage layers showing the greatest difference.

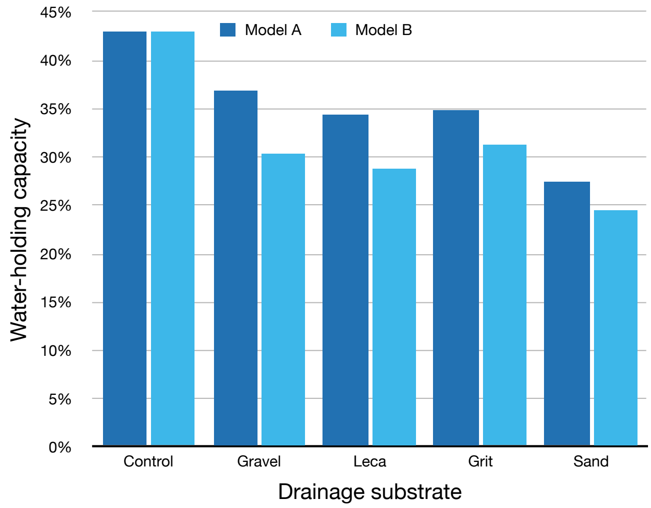

Figure 5: Estimated mean water-holding capacity (WHC) of the CV medium alone with different 30mm drainage layers, according to models A and B.

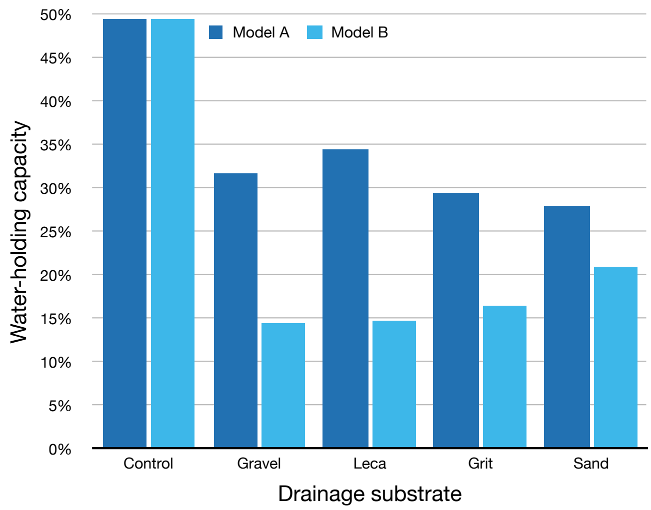

Figure 6: Estimated mean water-holding capacity (WHC) of the CV medium alone with different 60mm drainage layers, according to models A and B.

3.3 John Innes medium

The JI mix showed the most compaction, with the effective volume of mix in a full pot decreasing from 1,290ml to 925ml. The control container filled to 30mm from the top compacted from 1,030ml to 800ml, and the container filled to 60mm from the top compacted from 780ml to 590ml. The WHC of the controls was lowest for the full pot and highest for the pot filled to 60mm from the top.

The results of the JI trials are presented in Fig. 7. Compared to the control, the leca-30mm drainage layer condition had higher overall WHC ($p < 0.05$), the sand-60mm drainage layer condition had lower overall WHC ($p < 0.01$), and all other conditions were not significantly different. Analysing only according to drainage substrate, sand had lower overall WHC ($p < 0.05$), and other substrates were not significantly different. Sand had the lowest overall WHC, and was significantly different from all other substrates, while leca had the highest WHC. Combining all substrates, neither 30mm or 60mm drainage layers had significantly different overall WHC from the control.

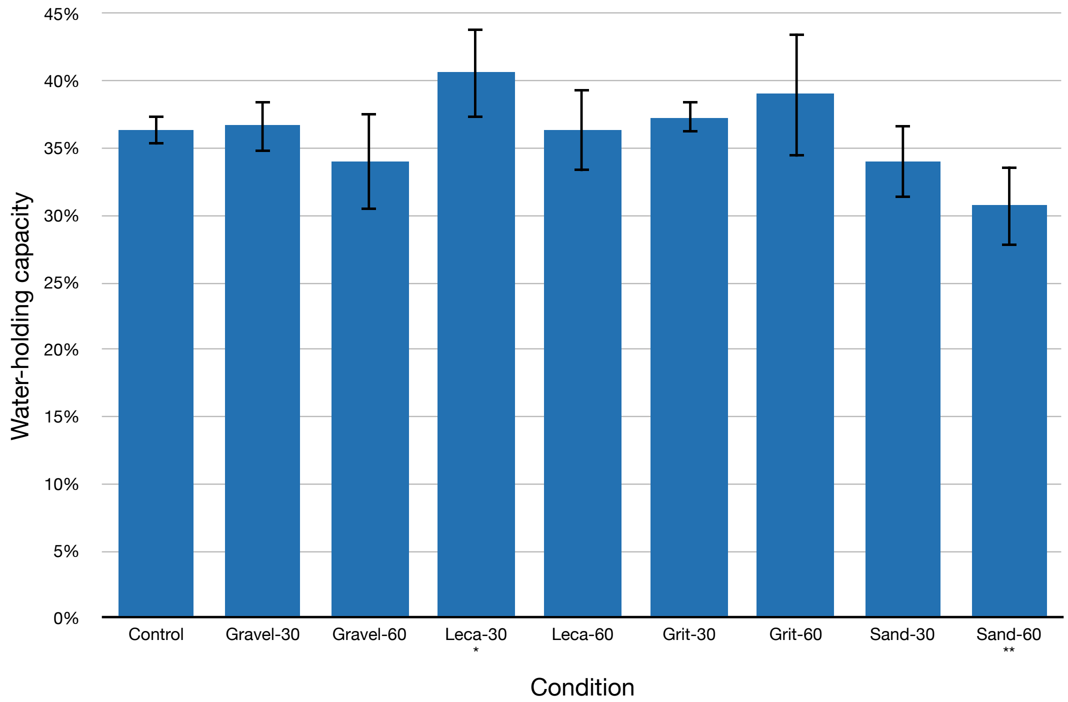

Figure 7: Mean and standard deviation water-holding capacity (WHC) of the entire container of JI medium with different drainage layers. Asterisks mark conditions which were significantly different from the control (* $p < 0.05$, ** $p < 0.01$).

The modeled WHC of the medium itself in the drainage layer conditions is presented in Fig. 8 (30mm drainage layers) and Fig. 9 (60mm drainage layers), compared with the control containers with the same initial medium depth. For 30mm drainage layers, grit and sand had lower WHC than the control according to both models, while gravel and leca had modeled WHC values both above and below the control. For 60mm drainage layers, sand had lower WHC than the control according to both models, while all other substrates had modeled WHC values both above and below the control.

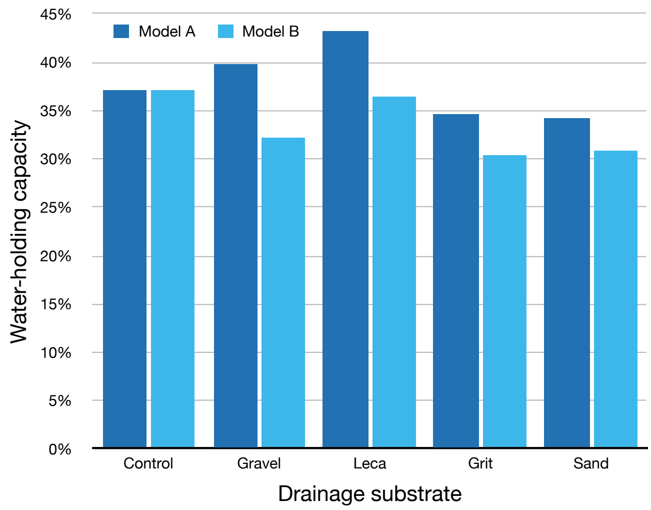

Figure 8: Estimated mean water-holding capacity (WHC) of the JI medium alone with different 30mm drainage layers, according to models A and B.

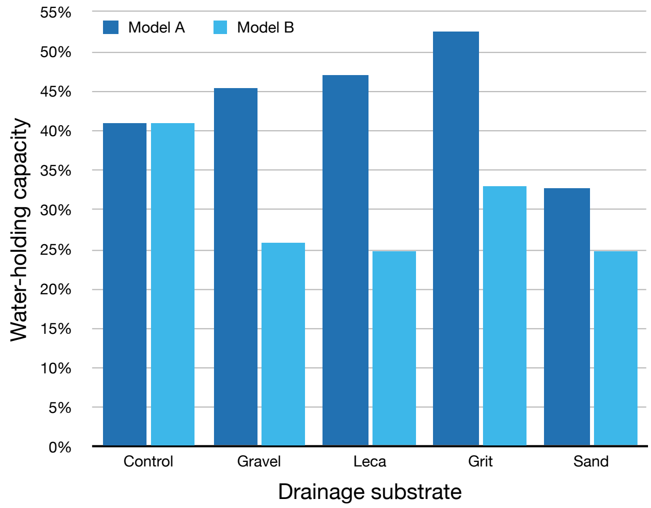

Figure 9: Estimated mean water-holding capacity (WHC) of the JI medium alone with different 60mm drainage layers, according to models A and B.

4 Discussion

The results show that adding a layer of coarse substrate below potting media will usually improve drainage of the container overall, sometimes have no effect, and is very unlikely to reduce drainage. This supports the recommendation of adding drainage layers among home gardeners, and contradicts previous theoretical predictions that such layers have a negative effect (Chalker-Scott and Downer, 2019; Evans, 2014).

The addition of drainage layers made a greater improvement to drainage when the potting media was coarser and more porous. This may be due to the similarity in pore size improving the capillary movement of water through the interface between different materials (Smesrud and Selker, 2001). This explanation is also supported by the fact that the loam-based John Innes media had the most improvement in drainage when using a substrate of 1-2mm sand, the smallest particle size which can therefore be assumed to have a pore size closest to the JI medium itself.

Thicker layers of drainage substrate tended to improve drainage more than thinner layers. This could be due to the perched water table of the drainage substrate itself making up a smaller proportion of the volume of the deeper layer. There was no apparent difference in drainage effects between porous and non-porous drainage substrates of the same particle size (leca and gravel). This may be because leca is slow to absorb water, and holds onto water at high tensions (Spomer, 1998). Thus, the leca in the drainage layer would not absorb significant quantities of water in the short time the container is saturated before drainage, and would therefore behave similarly to non-porous gravel of the same particle size.

For a very coarse loamless medium such as the CPB mix, the results show that any drainage substrate of any depth can be used to good effect to improve drainage. For a finer loamless medium such as the CV mix, a 60mm drainage layer is recommended, but any substrate is effective. For a loam-based medium such as John Innes, a 60mm layer of coarse sand is recommended for the best improvement to drainage.

The two different models for WHC of the potting medium alone were intended to provide the widest possible range of values, as a starting point for analysis. From visual examination (Fig. A.1), the drainage layers in containers with loamless potting media seemed to have approximately the same perched water table depth as when alone. Thus, for the CV and CPB media, the predictions of model A are likely to be most accurate for the WHC of the medium alone. For these media both models showed that all drainage layers reduce WHC, so the choice of model for analysis does not significantly change the conclusions.

In contrast, the drainage layers in containers with JI medium seemed to remain almost completely saturated after drainage (Fig. A.2). Thus, for JI medium the predictions of model B are likely to be most accurate for the WHC of the medium alone. The predictions of model B showed that all substrates decreased WHC, whereas model A showed a decrease for some substrates and an increase for others. Thus if model B is considered to be more accurate, it can be concluded that all drainage layers reduce WHC in the medium iself, whereas only some drainage layers reduced WHC in the container as a whole. More detailed study is required to confirm these predictions and validate the models.

When considering the effect of drainage layers on growing plants, it must be remembered that such a container has much more complex contents than a container of pure potting medium. There are two different materials in layers, and each layer has an air-filled volume at the top and a water-saturated volume at the bottom, giving a stratified effect in the pot. Further study is required to determine whether the roots of a growing plant remain in the main volume of potting medium or grow down into the drainage substrate. If roots do not enter the drainage substrate, then the more relevant conclusions are from the modelled results for WHC of the potting medium alone, and the container should be considered to have a reduced effective volume compared to the same container filled with pure medium. Whereas if roots do enter the drainage substrate, then the more relevant conclusions are from the WHC of the container as a whole, and further study is also required to determine how plants are affected by the alternating layers of air and water throughout the container.

5 Conclusions

Adding drainage layers had almost universally either beneficial or neutral effects on drainage of potting media. Coarser organic media showed the greatest improvement in drainage and fine loam-based media the least. Thicker drainage layers had the most effect for all potting media, but the most effective drainage substrate to use was dependent on the specific medium.

Warnings about the raised perched water table and increased water retention should be considered inaccurate, as the present study shows that such warnings may not consider the full complexities of water behaviour involved. Instead, drainage layers can be considered a potentially useful tool for growers and home gardeners to reduce the water retention of a given potting medium. A 60mm layer of coarse sand was the most universally-effective drainage layer with all potting media tested and therefore the best single recommendation for growers.

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Appendix

Figure A.1: Comparison of CPB medium with 60mm layer of grit (left) to CPB medium alone to a depth of 60mm below the top (right). In the left image, the perched water table in the medium is completely eliminated, and the low perched water table in the grit is visible.

Figure A.2: Comparison of JI medium with 60mm layer of grit (left) to JI medium alone to a depth of 60mm below the top (right). In the left image, the grit layer appears to be completely saturated after drainage.