Keeping nutrients in their place: irrigation management to enhance nutrient retention in container production©

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Irrigation is essential for container production and is typically applied daily during the peak growing season. Under-irrigating plants can result in reduced growth, a longer production period, increased pest pressure on weakened plants, and plant death from desiccation. Since the visible symptoms of under-irrigating are very apparent, irrigators tend to err on the side of applying too much irrigation rather than risk the consequences of under-irrigating. However, there are consequences of over-irrigating that are as deleterious as under-irrigating even though the connection is often unnoticed. Over-irrigation can cause reduced growth, a longer production period, increased pest pressure due to a more favorable environment, and poor plant quality. Over-irrigation in combination with heavy fertilization can cause overly vigorous plants, also reducing plant quality and often resulting in higher pest pressure on the lush growth. Scheduling irrigation to avoid both over- and under-irrigation will improve productivity.

While the problems due to under-irrigating are a result of a lack of adequate water availability for plant uptake, over-irrigation can cause this and other problems. Over-irrigation can cause a lack of water uptake in plants due to anaerobic conditions resulting in loss of proper root function, although this is rare since most container substrates have large pores and drain/aerate quickly. More commonly over-irrigation leaches nutrients from containers thus reducing plant nutrition, delaying flowering and reducing plant growth and quality. If irrigation water has alkalinity issues, as many water sources do, over-irrigating can further exacerbate nutrition problems by increasing substrate pH above the proper range causing some nutrients to be unavailable for plant uptake. Over-irrigation combined with heavy fertilization to counteract high leaching leads to even greater problems. Leached nutrients are not only a waste of money but can result in significant environmental problems that increase the probability of regulatory action. Eutrophication is a proliferation of biological organisms in aquatic systems due to excess nutrients, particularly phosphorus and nitrogen, that can cause serious economic and environmental damage. For example toxic algal blooms have affected the drinking water of nearly half a million people who rely on Lake Erie for their water source off and on over the past decade.

Over-irrigation wastes water, often relatively high quality water. Water is highly undervalued in most areas of the U.S. but that is quickly changing. Although some areas of the U.S. pay a substantial price for irrigation water, the cost of water for most irrigators is the cost to pump it from its source. This is another factor that makes it easy to over-irrigate, however, there are hidden costs to water. Over-irrigation can increase fertilizer costs, although this is often minimal. Most importantly over-irrigation can result in a longer production cycle and all of the costs associated with growing the same crop over a longer period such as more labor, more pesticides, more fertilizer, land costs (fewer crop turns per year), interest, longer return on investment, more water and others.

Some important considerations to keep in mind when implementing leaner irrigation practices are the source water quality (especially soluble salts and alkalinity), substrate properties, and local rainfall patterns. Monitoring of substrate electrical conductivity (EC), for soluble salts, and pH, as an indicator of the effect of water alkalinity, using methods such as the Pour-Thru method (Link 1), should be routine and are essential when using lean irrigation practices. Water with high soluble salts may require periodic leaching if leachate soluble salt levels exceed recommended values of 0.5 to 1.5 dSiemens m^{-1} (mmhos cm^{-1}). If

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leachate soluble salts are consistently high and water does not have high soluble salts it is possible that the fertilizer rate is too high, consider saving some money by backing down on fertilizer rates. Water with high alkalinity will slowly increase the pH of container substrates, possibly above recommended ranges of pH 4.7 to 6.5 depending on the crop and substrate, resulting in the need to apply sulfur compounds or acid-forming fertilizers to reduce pH. In this case irrigating less reduces the problem.

When deciding how much irrigation water to apply, it is important to understand how much water a container can hold. Some terms to know when determining this are:

- Container capacity: the maximum amount of water a container substrate will hold after gravitational drainage.
  - Typically 45-60%
- Unavailable water: water that is tightly bound to the substrate and cannot be extracted by a plant.
  - Typically 25-35%
- Available water: the amount of water that can be extracted by a plant.
  - = Container capacity – Unavailable Water
- Readily available water: the amount of water that can be easily extracted by a plant.
  - Typically 25-35% of available water
- Permanent wilting point: when the plant has extracted all of the available water and is not able to regain turgor.

To calculate how much water a container can hold is pretty straightforward if you know the actual volume (not trade size) of the empty container (usually provided by the manufacturer), the percent moisture at container capacity and the percent unavailable water. The latter two values can be provided by a good substrate supplier or from a substrate analysis by a substrate/soil testing lab. The available water is the difference between these two percentages. It is important to know that as the percent substrate moisture content decreases below container capacity, it becomes more difficult for the plant to take up the remaining water to a point (unavailable water) where the plant can no longer extract moisture. Moisture content closer to container capacity means the plant is more easily able to extract water. Readily available water is somewhere above unavailable water but where depends on plant species and substrate properties. Fortunately, we don't even want to let water get to the end of readily available water. A good target is to irrigate somewhere between 5 and 10% below container capacity.

The amount of irrigation needed to replace available water and for various container sizes for a container substrate with a high container capacity is shown in Table 1. In this example, container capacity is 65% substrate volumetric moisture content (SVMC) and unavailable water is at 25% SVMC making available water of 35%. SVMC is just the volume of water in a substrate divided by the total volume occupied by the substrate (including solids, air and liquids). Rarely do we allow plants to get to the point where all of the available water is depleted, when this happens it is usually the result of applicator error. Obviously irrigating to replace all of the available water is excessive, even the most extravagant irrigator will question irrigating #1 containers with 1.6 acre-inch of water.

Since volumetric water content is based on the percent of the total volume of the container, it is does not matter what the available water content is when determining irrigation rates if we base our calculations on the amount of water depleted (used by the plant or evaporated). For example, when you go from container capacity (65% SVMC in the previous example) to 55% SVMC, 10% SVMC lost, this is calculated as 10% times the total container volume not 10% times the available water. Calculating any % SVMC loss is in relation to the container volume, not the % available water, so it is based on container size, not the substrate. Knowing the % available water is important because it lets you know the maximum amount of water the plant can extract before the permanent wilting point and the maximum amount at the extreme you would ever apply to a container.

Table 1. Determining the maximum amount of irrigation can be applied to replace all available water and 10% depletion below container capacity before leaching occurs based on container size for a substrate with 65% volumetric substrate moisture content (SVMC) at container capacity with 35% available water. Calculations based on 100% land available per acre using overhead irrigation with 100% distribution uniformity. Values will be different for individual plant irrigation (drip or spray stake).

Trade container size[1]	Container diameter (inch)[1]	Container volume (gallon)[1]	Volume 35% available water (gallons container^{-1})[2]	Irrigation to replace 35% available water (acre-in)[3]	Irrigation to replace 35% available water (gallons acre^{-1})[4]	Irrigation to replace 10% (acre-in)[5]	Irrigation to replace 10% (gallons acre^{-1})[4]	Irrigation to replace 5% (acre-in)[6]	Irrigation to replace 5% (gallons acre^{-1})[4]
1	8	1	0.35	1.6	43,676	0.46	12,479	0.23	6,239
3	11	3	1.05	2.6	69,304	0.73	19,801	0.36	9,901
5	11.875	3.7	1.30	2.7	93,343	0.77	20,955	0.39	10,478
7	15	7.5	2.63	3.4	93,176	0.98	26,622	0.49	13,311
10	16.5	10.3	3.61	3.9	105,753	1.11	30,215	0.56	15,108
15	18.375	13.5	4.73	4.1	111,764	1.18	31,933	0.59	15,966

[1]Values obtained from manufacturer web site- varies by manufacturer and container.

[2]Volume available water = container volume × % available water (35%).

[3]Irrigation to replace available water (acre-inch) = gallons available water × 231 (convert gallons to cubic inches) / (πr^2).

[4]Multiply by 27,154 to convert acre-inch to gallons.

[5]Irrigation to replace 10% depletion (acre-inch) = container volume x 10% × 231 / (πr^2).

[6]Irrigation to replace 5% depletion (acre-inch) = container volume x 5% × 231 / (πr^2).

A start on determining how much irrigation to apply can be made using the same information. A commonly reported irrigation practice is to irrigate #3 containers with 0.75 acre-inch per day during the peak growing season. This ends up being the amount to irrigate when 10% of the water is lost from a #3 container (Table 1). This may seem like a good rate and falls within the above mentioned 5-10% depletion, but this still has not taken plant water use and evaporation into consideration. A better understanding of plant daily water use will allow further refinement in irrigation scheduling.

Scheduling irrigation based on leaching fraction is a practice that has been around for a long time. With leaching fraction we are basically determining how much water was used over a certain period plus a percentage above that to cause a certain amount of leaching. To determine leaching fraction:

1) Just before a normally scheduled irrigation event place 5 to 10 potted plants each into a larger container, such as a bucket, that fits tightly around the pot so that the only water that can enter the bucket has to go through the substrate.
2) Make sure there is a large enough gap between the bottom of the bucket and the pot so that water is not reabsorbed by the substrate through capillary action.
3) Do the same thing except with the same size but empty pot, no plant and no substrate.
4) Run your irrigation system for the normal period.
5) Measure the amount of water collected in each bucket.
6) Average the amount collected in the buckets with plants and the average collected in the buckets without plants, divide the average with plants by the average without plants, multiply by 100 and that is your leaching fraction (Table 2).

Table 2. Leaching fraction is determined by measuring the water leached from container plants and water collected from the same size container without a plant during a normal irrigation period. Average the water collected from the container plants and divide by the average collected without a plant, multiply by 100 to get the leaching fraction.

Container #	1	2	3	4	5	6	7	8	9	10	Avg.
Plant collected (mL)	83	96	98	93	84	91	74	87	72	69	85
Empty collected (mL)	891	866	841	877	804	856	821	902	883	832	857
Leaching fraction (%)	9	12	9	10	8	11	8	10	11	11	10

If the leaching fraction is too high, reduce the time of application and retest at the next irrigation period. Increase the application time if the leaching fraction is too low.

Most recommendations are to target a leaching fraction of 10 to 20%, however, this is based primarily on greenhouse crops. For nursery production, at least in the eastern U.S., leaching fractions should be less than 10%. The reason for the difference is that plants in nursery production periodically receive rain and this will often leach out salts enough to keep EC at acceptable levels, this obviously cannot happen in a greenhouse. Since part of a leaner irrigation program includes monitoring EC regularly, leaching fraction can be increased periodically if EC begins to rise too high and then returned to a lower level. There is no need to continuously leach salts (fertilizers) from nursery crops unless there is a problem with high salts in the irrigation water. Again, if leachate EC is consistently high and the levels of soluble salts in the irrigation water are low, the fertilizer rate may be too high resulting in the need to leach out the fertilizer you paid for. In our research nursery we have been irrigating at zero leaching fraction for years and have not had problems with soluble salts building up even during 2007, which was a very dry summer in Michigan with only 11 inches of rain during our growing period. Nurseries in more arid regions and those with high soluble salts in their irrigation water considering irrigating at low leaching fractions must monitor leachate EC at least monthly to make sure salts are not building up in container substrates.

There are other ways to determine irrigation schedules including evapotranspiration models, plant-based measurements and soil/substrate moisture determination. Evapotranspiration models are based on weather conditions and a crop factor (crop coefficient) to determine how much water is lost through evaporation and transpiration over a period of time. These have been very effective for crop production where there is little diversity in the type of plant grown and crop coefficients can be determined for a limited number of plant species. Unfortunately the great diversity of plants grown at a typical nursery makes it difficult to use evapotranspiration models. Plant-based measurements give a direct indication of the plant water status. These measurements are often tedious and require trained technicians and relatively expensive equipment and are rarely used in production agriculture. Some soil/substrate moisture sensors have been used for decades in field production. Some of them, such as tensiometers, are inexpensive and accurate. Unfortunately tensiometers are not practical for nursery substrates. Sensors using time domain reflectometry or capacitance are becoming common for measuring soil/substrate moisture in commercial nurseries.

We have used both types of sensors to determine SVMC in our research projects. Currently we are using capacitance sensors due to the lower cost. We determine our irrigation schedule daily by measuring the SVMC 30 to 45 minutes following irrigation to determine container capacity, measure again just before the next irrigation period, calculate the difference and use that to determine how much irrigation to apply to replace what was used. This is done through a datalogger/controller so all of these measurements and calculations are done in milliseconds. This type of control is not limited to a small research nursery. Wireless sensor networks have been developed and effectively deployed to use sensors to monitor and control irrigation in commercial nurseries (Link 2). Irrigation can be scheduled to apply the amount used by a crop over a period of time, such as daily as we do in our research nursery, or it can be scheduled to maintain SVMC above a certain set-point. For set-point control, once you know container capacity you can determine the % water depletion to allow (between 5-10%) and use that as the set-point. To determine container capacity, irrigate so that leaching occurs, wait 30 to 45 minutes, record the SVMC at this time as the container capacity. Subtract the % water depletion desired from the container capacity and use that as the low set-point, container capacity will be the high set-point. The system can be programed to turn irrigation on once the low set-point is reached and off just before (it will take some time for the irrigation water to move to the sensor area) the high set-point is reached.

We have done research on scheduling irrigation based on plant water use for many years (Links 3, 4, 5). By knowing the plant daily water use, we can begin to create groupings of plants with similar water use in order to organize them into similar irrigation blocks. A potential grouping based on plant daily (averaged over the season) irrigation requirements for plants grown in #3 containers at our research nursery is shown in Figure 1. Since local and daily climatic conditions will affect water use, the amount of irrigation to apply will vary depending on time of year and location but the relative water use should be similar.

Daily water use for plants grown in #3 containers exceeded 10% SVMC water use (0.73 acre-inch irrigation to replace) for only 1 out of 37 species: *Buddleja davidii* averaged 0.95 acre-inch of water use per day (Figure 1). This was also greater than our control irrigation rate of 0.75 acre-inch, another important reason to know plant water use- you could possibly be under-irrigating. Most plants (25 out of 37) (see Table 3 for list of plants studied) evapotranspired less than 5% SVMC (0.44 acre-inch for a #3 container). Irrigating to replace exactly the amount of water used daily for each crop is impractical but grouping plants with similar water requirements will allow more efficient irrigation scheduling.

Irrigating with low to zero leaching not only reduces the amount of water used for irrigation but reduces the amount of runoff created. In our studies where we've use 0.75 acre-inch as our standard control irrigation rate and zero or deficit irrigation as treatments, depending on species we have been able to reduce the amount of irrigation applied by 30 to

70%, the amount of runoff water generated by 30 to 85% and the amount of nitrate and phosphate in runoff by 30 to 50%. Out of all of the plants we've used, only 3 species had lower growth compared to the control, 4 species had greater growth, and there was no difference for the rest. We did find reduced foliar nutrient levels for several plants irrigated with the control rate compared to the other treatments, indicating that we were leaching fertilizers out of the containers before the plants could acquire them. To attain results as high as this might be difficult for a commercial nursery but substantial reductions in water use, runoff generation and nutrient loss could certainly be attained.

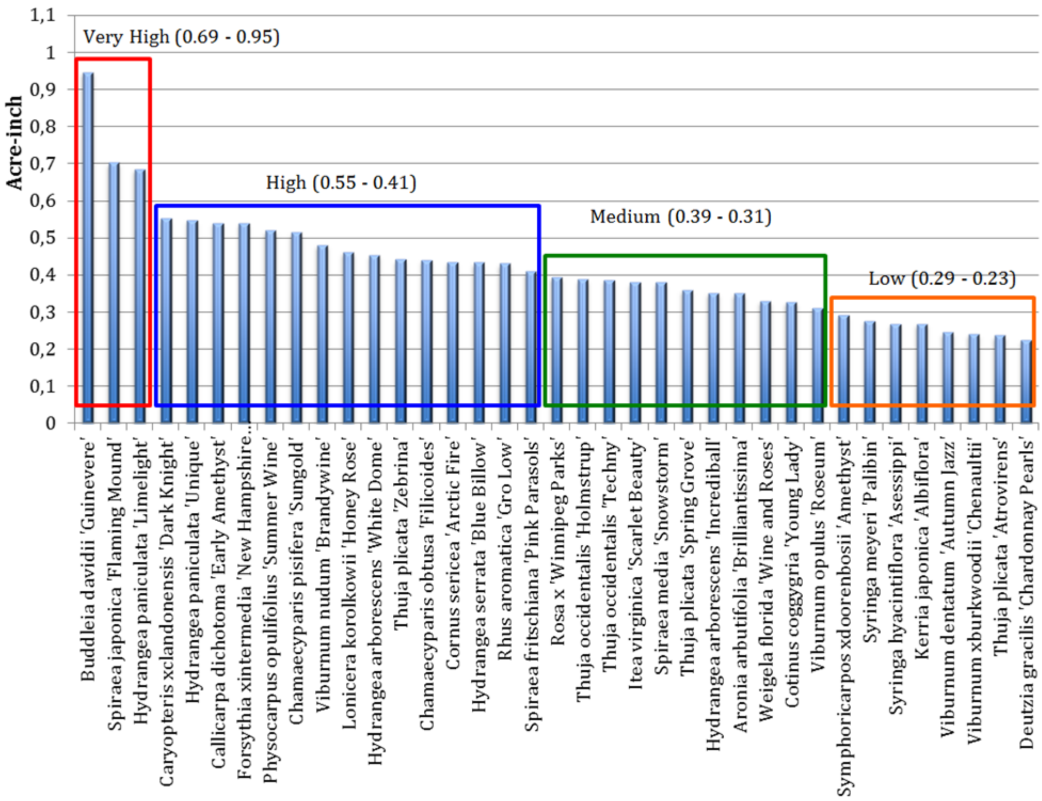

Figure 1. The average plant daily water use in acre-inches averaged over one growing season for 37 taxa of plants. Possible groupings of plants based on relative water use are shown by the different colored boxes. Water use will vary with climatic conditions and location but relative performance of species should be similar.

Water does cost money but the cost per gallon can be negligible to quite expensive depending on where a nursery is located. The cost of water for nurseries in most of the eastern U.S. is the pumping cost. At our research nursery it costs us $0.032 to grow a plant in a #3 container for one season. By reducing our water use by 30 to 70%, as we've shown we can do in our research, we save $0.009 to $0.022 per plant. We can also save approximately $0.005 in fertilizer by reducing leaching. That comes to $0.014 to $0.023 per plant or approximately $150 to $240 per acre. Yes, water itself is cheap, at least the way it is currently valued. However, the cost of improperly using water can be very high, especially for problem crops. Link #6 is to an excellent article that describes how a large commercial nursery saved $1 per square foot of production on a problem crop when they used sensor-based irrigation compared to their normal management practices. When they reduced the amount of water applied they decreased the time it took to produce the crop by an average of 6 months, which reduced all of those associated costs such as labor, fertilizer and pest management. They also reduced losses from the normal range of 10-30% to none. So water may be cheap but not the consequences of misuse.

Table 3. Alphabetical list of plants studied in daily water use experiments shown in Figure 1. Plants were grown in #3 containers in an 85% pine bark to 15% sphagnum peat (by volume) substrate) at the Michigan State University Horticulture Teaching and Research Center in Holt, Michigan.

Plant	Water use group
Aronia arbutifolia 'Brilliantissima'	Medium
Buddleia davidii 'Guinevere'	Very high
Callicarpa dichotoma 'Early Amethyst'	High
Caryopteris × clandonensis 'Dark Knight'	High
Chamaecyparis obtusa 'Filicoides'	High
Chamaecyparis pisifera 'Sungold'	High
Cornus sericea 'Farrow' (Arctic Fire® red twig dogwood)	High
Cotinus coggygria 'Young Lady'	Medium
Deutzia gracilis 'Duncan' (Chardonnay Pearls® deutzia)	Low
Forsythia × *intermedia* 'New Hampshire Gold'	High
Hydrangea arborescens 'Abetwo' (Incrediball® smooth hydrangea)	Medium
Hydrangea arborescens 'Dardom' (White Dome® hydrangea)	High
Hydrangea macrophylla subsp. serrata 'Blue Billow'	High
Hydrangea paniculata 'Limelight'	Very high
Hydrangea paniculata 'Unique'	High
Itea virginica 'Morton' (Scarlet Beauty™ Virginia sweetspire)	Medium
Kerria japonica 'Albiflora'	Low
Lonicera korolkowii	High
Physocarpus opulifolius 'Seward' (Summer Wine® ninebark)	High
Rhus aromatic 'Gro-Low'	High
Rosa 'Winnipeg Parks'	Medium
Spiraea fritschiana 'Wilma' (Pink Parasols® spirea)	High
Spiraea japonica 'Flaming Mound'	Very high
Spiraea media 'Darsnorm' (Snow Storm™ spirea)	Medium
Symphoricarpos × *doorenbosii* 'Kordes' (Amethyst™ coral berry)	Low
Syringa meyeri 'Palibin'	Low
Syringa × hyacinthiflora 'Asessippi'	Low
Thuja occidentalis 'Holmstrup'	Medium
Thuja occidentalis 'Techny'	Medium
Thuja plicata 'Atrovirens'	Low
Thuja plicata 'Grovepli' (Spring Grove® arborvitae)	Medium
Thuja plicata 'Zebrina'	High
Viburnum × burkwoodii 'Chenaultii'	Low
Viburnum dentatum 'Ralph Senior' (Autumn Jazz® arrowwood viburnum)	Low
Viburnum nudum 'Bulk' (Brandywine™ withered viburnum)	High
Viburnum opulus 'Roseum'	Medium
Weigela florida 'Alexandra' (Wine and Roses® weigela)	Medium

In summary, when scheduling is done properly it can result in more efficient water use, nutrients retained where they are available for plant uptake, reduced problems with alkaline water, reduced plant losses, improved plant growth and quality, shortened production cycle, less runoff generated and less off-site movement of water and nutrients. Below are a list of links referred to in the article along with a few more that should be of interest to anyone wanting to improve their irrigation and water management practices.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the many years of support from Spring Meadow

Nursery, Inc., Renewed Earth LLC, Harrell's Fertilizer, USDA NIFA Hatch Project MICL 02473, USDA SCRI Clean WateR^3 – Reduce, Remediate, Recycle Grant Number 2014-51181-22372, MSU Project GREEEN, Michigan Department of Agriculture and Rural Development. I would also like to thank my former graduate students Aaron Warsaw and Nicholas Pershey, much of whose research contributed to this article.

Additional reading

http://msue.anr.msu.edu/uploads/235/67987/resources/6-4FactSheetTemplateOverhead_Sprinkler. pdf

http://msue.anr.msu.edu/uploads/files/6-28FactSheet_WaterApplicationTOM.pdf

https://content.ces.ncsu.edu/using-the-pourthru-procedure-for-checking-ec-and-ph-for-nursery-crops

https://www.researchgate.net/publication/228506613_Water_Conservation_Growth_and_Water_Use_Efficiency_of_Container-grown_Woody_Ornamentals_Irrigated_Based_on_Daily_Water_Use

https://www.researchgate.net/publication/231520634_Container-grown_Ornamental_Plant_Growth_and_Water_Runoff_Nutrient_Content_and_Volume_Under_Four_Irrigation_Treatments

https://www.researchgate.net/publication/259674301_Implementation_of_Wireless_Sensor_Networks_for_Irrigation_Control_in_Three_Container_Nurseries

https://www.researchgate.net/publication/283703373_Irrigating_Based_on_Daily_Water_Use_Reduces_Nursery_Runoff_Volume_and_Nutrient_Load_Without_Reducing_Growth_of_Four_Conifers

http://www.nurserymag.com/article/nm0612-precision-irrigation-benefits/

http://www.watereducationalliance.org/