Conclusions

The nursery industry in Florida provided input to the process for development of a voluntary incentive–based regulation to address groundwater quality concerns. This process, which relied on industry and regulatory personnel consensus, was different than the traditional process for developing regulations. Even though it was not a novel concept, it was initially awkward or different than past industry regulatory experiences. There were several reasons for the awkwardness that are outside the scope of this discussion, but the nursery industry's participation in the process was important because it resulted in a proactive solution to deal with nitrate contamination of groundwater. Additionally, the experience and confidence gained from the process was important because the nursery industry had to reach a consensus and commit to make changes when a crisis did not exist. It brought to the forefront an urgency of proactiveness and a sense of how one's small involvement can contribute to something that was unachievable alone. This experience will be invaluable as the industry embraces future urban challenges.

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More Plant per Gallon: Getting More Out of Your Water

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ADDITIONAL INDEX WORDS. irrigation efficiency, water application efficiency, irrigation scheduling, irrigation timing, cycled irrigation, container substrate, clay

SUMMARY. Irrigation of container-grown ornamental crops can be very inefficient, using large quantities of water. Much research was conducted in the 1990s to increase water efficiency. This article examined water management, focusing on three areas: water application efficiency (WAE), irrigation scheduling, and substrate amendment. Increases in WAE can be made by focusing on time-averaged application rate and pre-irrigation substrate moisture deficit. Irrigation scheduling is defined as the process of determining how much to apply (irrigation volume) and timing (when to apply). Irrigation volume should be based on the amount of water lost since the last irrigation. Irrigation volume is often expressed in terms of leaching fraction (LF = water leached ÷ water applied). A zero leaching fraction may be possible when using recommended rates of controlled-release fertilizers. With container-grown plant material, irrigation timing refers to what time of day the water is applied, because most container-grown plants require daily irrigation once the root system exploits the substrate volume. Irrigating during the afternoon, in contrast to a predawn application, may increase growth by reducing heat load and minimizing water stress in the later part of the day. Data suggest that both irrigation volume and time of application should be considered when developing a water management plan for container-grown plants. Amending soilless substrates to increase water buffering and reduce irrigation volume has often been discussed. Recent evidence suggests that amending pine bark substrates with clay may reduce irrigation volume required for plant production. Continued research focus on production efficiency needs to be maintained in the 21st century.

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Water management in container-grown plants became a very hot topic in 1988 and has remained so until today (Urbano, 1989). This article will examine water management from the container perspective (i.e., how can we improve water management within the container?). Water management in the container can be broken down into three areas: water application efficiency, irrigation scheduling, and substrate amendment.

Water application efficiency

Water application efficiency (WAE) involves increasing the retention of water applied to the container. WAE is often calculated as:

$$[(\text{water applied} - \text{water leached}) \div \text{water applied}] \times 100$$

There are two factors that have a direct effect on WAE: time-averaged application rate (TAAR) and pre-irrigation substrate moisture deficit (PISMD). WAE tends to increase with decreasing TAAR by allowing time for water to move through the micropore system of container substrate. Currently we decrease the TAAR by using cyclic application, where the daily water allotment is applied in a series of cycles comprised of an irrigation and a resting interval. Cyclic application is time-averaged, which comprises the application rate of the emitter, application duration, and interval between applications (Zur, 1976). Application of water may be delivered at a high rate, but when the interval between applications is taken into account, the TAAR can be quite low. This technique was borrowed from field research conducted in the 1970s (Karmeli and Peri, 1974). El Modeno Gardens (Irvine, Calif.) first reported use of cyclic irrigation in a container-grown nursery (Whitesides, 1989). The facility reduced water use by 30% with cyclic irrigation. This was done before most of the cyclic irrigation research was conducted with containerized plant production in the 1990s. Lamack and Niemiera (1993) and Karam and Niemiera (1994) conducted some of the early cyclic irrigation research with soilless substrate, illustrating its value in increasing WAE.

Cyclic application can improve WAE with both overhead application and microirrigation (Table 1). The reduction in water use (30%) with cyclic irrigation at El Modeno Gardens was

Table 1. Effect of cyclic irrigation on water application efficiency compared to a single irrigation.

Method of application	Substrate[z]	Percent increase over single application	Author(s)
Overhead	3 PB : 1 P	34	Fare et al., 1994
Overhead	PB	5 to 10	Karam and Niemiera, 1994
Spray stake	8 PB : 1 S	27	Groves et al., 1998
Spray stake	PB	11 to 17	Lamack and Niemiera, 1993
Spray stake	8 PB : 1 S	27	Ruter, 1998
Spray stake	8 PB : 1 S	38	Tyler et al., 1996a

[z]P = peat; PB = pine bark; S = sand.

similar to the average increase (24%) in WAE reported with spray stakes compared to a single application. In much of our discussion, however, we have lost sight that TAAR is the critical factor. Cyclic irrigation is the vehicle used to decrease the TAAR.

The fact that TAAR is more critical than the volume or number of cycles is illustrated by the following. The TAAR appears to be independent of water volume and number of cycles, as 2.5 mL·min^{-1} (0.08 fl oz/min) TAAR resulted in the same WAE whether applied at 50 mL (1.7 fl oz) per 20 min, 100 mL (3.4 fl oz) per 40 min, or 150 mL (5.1 fl oz) per 60 min (Lamack and Niemiera, 1993). Similarly, a TAAR of 6.5 mL·min^{-1} (0.22 fl oz/min) resulted in the same WAE whether applied in three or four cycles (Ruter, 1998). Tyler et al. (1996a) also reported that WAE did not increase whether irrigation water was applied in two, four, or six cycles. Thus, as few as two cycles may be adequate to increase WAE with the appropriate TAAR.

Lamack and Niemiera (1993), working with a pine bark substrate in a greenhouse, found a linear relationship between TAAR and WAE. As TAAR decreased from 7.5 mL·min^{-1} (0.25 fl oz/min) to 0.9 mL·min^{-1} (0.03 fl oz/min), WAE increased from 62% to 86%. In contrast, Tyler et al. (1996a), working with a 8 pine bark : 1 sand (by volume) substrate on an outdoor gravel pad, did not improve WAE with TAAR ranging from 13.6 mL·min^{-1} (0.46 fl oz/min) to 2.9 mL·min^{-1} (0.10 fl oz/min). Cyclic irrigation, however, did improve WAE by 24% compared to a single application. Regardless, TAAR has merit in formulating irrigation regimens for soilless substrate. Based on reported research, a TAAR <10 mL·min^{-1} (0.3 fl oz/min) should significantly increase WAE compared to a single application.

Pre-irrigation substrate moisture deficit

Common sense would suggest that a substrate with a high moisture deficit would have a relatively high proportion of unfilled micropores and hence a high matric potential leading to increasing the WAE. Indeed, there is some data to support an increase in WAE with increasing moisture deficit. With overhead irrigation, as percent container capacity (CC) decreased from 89% to 79%, WAE increased from 42% to 71% in a pine bark substrate (Karam and Niemiera, 1994). With spray stakes, however, WAE decreased as percent CC decreased (Lamack and Niemiera, 1993). Beeson and Haydu (1995) cautioned that WAE may decrease if pine bark is allowed to become too dry due to hydropholic conditions that develop in pine bark–based substrate at low moisture. Bark at low moisture content has hydrophobic properties that result in channeling during irrigation. This implies that simply refraining from irrigating until the substrate is dry may not increase WAE. Furthermore, Tyler et al. (1996b), working with a 3.8-L (4 qt) container with an 8 pine bark : 1 sand (by volume) substrate, reported that macropore flow of irrigation water through the substrate occurred when irrigation was applied when daily water loss from the substrate was <450 mL (15.2 fl oz) (79% CC). Thus, it appears that there is a minimum and a maximum PISMD for maximizing WAE.

Maximum growth of photinia (*Photinia fraseri*) was obtained when the plants were irrigated when the substrate reached 75% available water (AW) (Welsh and Zajicek, 1993). Growth decreased 15% when irrigated at 50% AW. Growth dropped rapidly if irrigation was withheld until the substrate reached < 50% AW. Growth of 'Gutbier V-14 Glory' poinsettia (*Euphorbia pulcherrima*) was reduced when the irrigation was withheld until the substrate reached 40% AW (53% CC) compared to daily irrigation (Morvant et al., 1998). Kiehl et al. (1992) and Lieth and Burger (1989) grew mums (*Chrysanthemum ×morifolium*) with moisture levels ranging from 35% to 80% CC compared to plants receiving daily irrigation. At the lowest moisture deficit (35% CC), top dry weight was reduced 22%. Plants grown at an 80% CC were not different from plants irrigated daily. Unfortunately, the moisture level within the substrate irrigated daily was not measured. This data does not support Biernbaum's (1992) recommendation that most plants should be watered when percent AW reaches 30% to 40%. In a pine bark substrate this would be in the range of 39% to 42% CC (T. Bilderback, personal communication). This recommendation was made, however, concerning greenhouse crops in a peat-based substrate.

Irrigation scheduling

Irrigation scheduling is defined as the process of determining how much water to apply (irrigation volume) and timing (when to apply). Irrigation volume is often expressed in terms of leaching fraction (LF = water leached ÷ water applied). The question is how much leaching do we need to maximize growth of nursery crops? Or do we need leaching at all? The perceived need for leaching may be based on floriculture research, where very high rates of liquid fertilization are applied with every irrigation in an enclosed structure (no rainfall). Ku and Hershey (1992) reported top dry weight of 'Yours Truly' geranium (*Pelargonium ×hortorum*) was reduced by 26% when grown with 0 and 0.1 LF compared to 0.2 to 0.4 LF. EC levels reached 6 dS·m^{-1} in the 0.1 LF, which the researchers speculated reduced growth. They stated, however, that at 0 and 0.1 LF, water did not appear to be a limiting factor. In the 0 LF, enough water was added to return the substrate to 100% CC. In contrast, growth of 'Gutbier V-14 Glory' poinsettia was unaffected from 0 to 0.4 LF (Ku and Hershey, 1991). Electrical conductivity ranged from 6 (0.4 LF) to 15 dS·m^{-1} (0.1 LF) when fertigated with 300 mg·m^{-1} (ppm) N. They speculated that water was not limiting at 0 LF and that poinsettia was a very salt tolerant plant. These studies used liquid fertilization, while much of the nursery industry utilizes controlled-release fertilizers (CRFs) (Fain et. al., 2000). With CRFs and typical rainfall (eastern U.S.) will we experience high EC with no additional leaching in a nursery?

One of the earliest studies to examine the effect of 0 LF combined with CRFs on plant performance was conducted by Poole and Conover (1982). They reported that leaching of containers was unnecessary for foliage crops fertilized properly. Haver and Schuch (1996) grew 'Illusion' and 'Blazon' new guinea impatiens (*Impatiens* sp. hybrids) in a greenhouse with two moisture levels (69% to 92% CC, and 43% to 58% CC) and three rates of a CRF (0.5x, 1x, and 1.5x; x = recommended rate). There was no leaching. With 43% to 58% CC, EC levels at the 1x and 1.5x rates limited plant growth. However, when the moisture level was maintained between 69% and 92% CC, EC levels did not limit growth regardless of rate of fertilization. This suggests that by maintaining adequate CC in combination with recommended rates of CRF, EC levels may not be a detriment to plant growth. Little research, however, has examined how CRFs respond to low LFs in a nursery production environment. Results from Groves et al. (1998) and Tyler et al. (1996b) suggested that with CRFs at typical rates combined with low LF, EC levels may not reach damaging levels. These studies were conducted on an outdoor gravel surface, so some leaching occurred with rainfall.

Zero LF does not imply simply reducing irrigation volume. If low volumes of water are applied to eliminate leaching without regard to maintaining adequate water in the container, then reduction in growth will occur. Schuch et al. (1995) applied set volumes of water [240 $mL \cdot d^{-1}$ (8.1 fl oz/d) or 120 $mL \cdot d^{-1}$ (4.1 fl oz/day)] to six cultivars of poinsettias growing in a peat-based substrate. The low irrigation volume reduced all growth parameters in all cultivars by 36% to 41%. Even with 0 LF, the substrate must be returned close to CC or reductions in growth will occur. If EC levels are not a concern, then we can concentrate on providing enough water to avoid water stress with minimal leaching. More research is needed before this can be claimed with confidence.

A giant leap in water efficiency could be made by choosing to apply irrigation volume based on water needed to replace the moisture deficit within the container in lieu of applying a set volume or run time. Is this easy? No. Is it painful in terms of time and effort? Yes.

A worthy goal would be 0 LF; however, maintaining adequate water with 0 LF is very difficult to achieve. Because WAE is always less than 100%, some leaching occurs when attempting to replace 100% of the water lost from the container. For example, when replacing a deficit of 600 mL (20.3 fl oz) in a pine bark substrate, the first 300 mL (10.1 fl oz) were applied with an WAE of 100%; the fourth 100 mL (3.4 fl oz) had an WAE of 96%; the fifth 100 mL had an WAE of 89%; and the sixth 100 mL had an WAE of 84% (Lamack and Niemiera, 1993). As the moisture deficit within the container is decreased, it becomes more difficult to maintain 100% WAE. Most researchers that were attempting to maintain 0 LF stated that any leachate that occurred was collected and returned to the container. If it is difficult for a researcher to maintain 0 LF, then how much more difficult would it be for a grower? If enough water is applied to replace the moisture deficit, then we will have some leaching. However, it appears to be possible to successfully grow plants at a very low LF.

Current best management practices for determining irrigation volume state that it should be based on the amount of water lost since the last irrigation (Yeager et al., 1997). Right now, the easiest way to determine the container moisture deficit may be by weighing the container. The difference in weight from CC describes the volume (milliliters or fluid ounces) of water needed to return the container to 100% CC. As technology improves, less labor intensive methods may be available to determine water lost to evapotranspiration.

Irrigation timing

Irrigation timing for field-grown agronomic crops has been studied extensively (Hill and Allen, 1996; Wanjura et al., 1995). Irrigation timing for field soil refers to when the soil reaches a known moisture deficit; then water is applied. Thereafter it may be days or weeks before it is applied again. With container-grown plant material, however, our discussion of irrigation timing will refer to what time of day, because most container-grown plants require daily irrigation after the root system exploits the entire substrate. Once roots have exploited the container, it appears that water becomes limiting if applied only in early morning (Beeson, 1992; Ruter, 1998; Warren and Bilderback, 2002)

Irrigation applied at 1200, 1500, and 1800 HR resulted in 63% greater total plant dry weight compared to plants irrigated at 0300, 0500, and 0700 HR (Warren and Bilderback, 2002). Reduced substrate temperature from 1800 to 2200 HR and increased rates of photosynthesis accounted for the increase in growth. Irrigation applied at 1200, 1500, and 1800 HR also had higher water utilization efficiency [WUE = irrigation volume retained in substrate ÷ total plant dry mass (liters of water required to produce 1 g plant dry mass)] requiring 0.45 L (15.2 fl oz) per gram of plant dry weight compared to 0.55 L (18.6 fl oz) per g of plant dry mass for early morning application. This is an increase of 22%. Keever and Cobb (1985) also reported that irrigation during the day (1300 HR or split application at 1000 and 1500 HR) reduced substrate and canopy temperature, which they proposed enhanced top and root growth of *Rhododendron* x 'Hershey's Red' compared to irrigation at 2000 HR.

Beeson (1992), working with four woody ornamentals, also reported increased growth when irrigation was applied during the day in contrast to predawn (0600 HR) irrigation. He attributed the increased growth to lower daily accumulated water stress. Similarly, microirrigation with either two cycles applied at 0500 and 1300 HR or three cycles applied at 0500, 1100, and 1500 HR increased growth of red maple (*Acer rubrum*), winged elm (*Ulmus alata*), live oak (*Quercus virginiana*), and crape myrtle (*Lagerstroemia indica*) compared to a single early morning cycle (Beeson and Haydu, 1995). They stated that growth increases were due to prevention or reduction of substrate moisture stress. Ruter (1998) also reported that microirrigation applied with three cycles at 0800, 1200, and 1600 HR or four cycles at 0800, 1100, 1300, and 1600 HR increased shoot dry weight of 'Okame' cherry (*Prunus ×incamp*) by 40% compared to a single cycle at 0800 HR. These data suggest that plants are reaching substrate moisture levels during the day that induce water stress. Unfortunately, none of these studies determined water content of the substrate during the day. In addition, water application reducing substrate temperatures will also reduce temperature stress. Thus, irrigating during the day may increase growth by reducing heat load and minimizing water stress in the later part of the day. Both irrigation volume and time of application should be considered when developing a water management plan.

Substrate amendment

The value of adding clay to soilless substrates has been debated since 1964 (Wildon and O'Rourke, 1964). Even though amending pine bark substrates with clay would appear to have many potential benefits, there was little empirical evidence to definitively answer this question (Ingram and Joiner, 1980; Laiche and Nash, 1990; Warren and Bilderback, 1992). To date the most detailed study for clay-amended pine bark has been conducted with arcillite by Warren and Bilderback (1992). They reported that CC, AW, and bulk density increased with increasing rate of arcillite-amended pine bark, whereas arcillite did not affect total porosity and unavailable water.

Unfortunately, "clay" is often used generically to describe soils that have high water and nutrient holding capacity. Clays, like soils, are not the same due to differences in physical and chemical properties as a result of handling, source, and packaging. The effectiveness of clay should differ with type (1:1 vs. 2:2), handling (temperature pretreatment, particle size), and source or location mined (chemical composition). The type of clay and heat treatment (pasteurized or calcined) are important factors affecting water holding capacity and available water content, thus determining water buffering capacity. Therefore, it is misleading to simply talk about "clay" soils, because they differ in their ability to improve the water and nutrient capacity of a soilless substrate. Recent research with clay-amended peat in the Netherlands indicated that clay particle size and heat treatment (calcined or pasteurized) may affect how effective clay will be in increasing water and nutrient buffering of soilless substrates (H. Verhagen, personal communication). In addition, data from Owen et al. (2003) suggest particle size and heat treatment are important in determining the effectiveness of clay in a pine bark substrate. Owen et al. (2003) reported that clay- (8% by volume, calcined 2:1 with a particle size of 24/48 mesh size) amended pine bark substrate reduced mean daily irrigation volume applied per container by 18% compared to an 8 pine bark:1 sand substrate (by volume). This resulted in a decreased mean daily water application of ~0.4 $L \cdot d^{-1}$ (13.5 fl oz/d). When extrapolated over a growing season [May through September (153 d)], this is equivalent to 935,360 L per growing hectare (100,000 gal per growing acre) of water savings. Thus, it appears that clay may play a role in water management in pine bark substrates. For growers to continue increasing water management efficiency will require reducing TAAR, reducing leaching fraction towards zero, applying irrigation at the appropriate time of day, and possibly amending the substrate.

More research is needed in the following areas: 1) irrigation applied with a known TAAR along with the pre-irrigation substrate deficit; 2) determining if we can grow plants with zero LF with recommended rates of CRF in a nursery; and 3) improvements in determining water loss from the container due to evapotranspiration.

Even though in this article we did not discuss the interdependence of water and nutrient management, there are also critical research needs to be conducted in this area. Do we need to adjust rates of CRF application as we approach 0 LF? How efficient do we need to be before we can reduce rates of CRF without losing crop growth? Much progress was made in the 1990s in increasing nursery production efficiency. Continued focus on production efficiency needs to be maintained in the 21st century.

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Modeling Irrigation Requirements for Landscape Ornamentals

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ADDITIONAL INDEX WORDS. **nursery production, irrigation scheduling, woody ornamentals, water requirements**

SUMMARY. **In many sectors of agriculture, precision irrigation, applying only what water is needed for a given small area, has become a familiar term. Irrigation in most woody ornamental nurseries, though, has changed little since the 1960s. In many areas of the U.S., irrigation volumes required for nursery production have come under scrutiny due to projected, or real, competition for water with urban populations, or concerns over nursery runoff. Modeling of woody ornamental water use, and subsequent irrigation requirements, has been limited and focused mostly on trees. Previous research for modeling of non-tree water use is reviewed as an introduction to current efforts to develop models for precision irrigation of woody ornamentals. Pitfalls and limitations in current modeling efforts, along with suggestions for standardizing future research is emphasized. The latest model derived from recent research is presented.**

What is modeling? Modeling is the development of a mathematical description that imitates or emulates an entity based on data, postulates, and inferences (Merriam-Webster, 1991). In the case of irrigation modeling, it is estimating how much water should be applied in the upcoming irrigation event, based on conditions that have occurred since the crop was last irrigated. Fortunately, modeling of irrigation requirements has been studied intensively since early 1940s in agronomic crops (Thornth-

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