Chapter

# Measuring Evapotranspiration of Hardy Ornamental Nursery Stock: A Hurdle for Irrigation Management

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## Abstract

Although the land area dedicated to the production of hardy ornamental nursery stock (HONS) is relatively small, the sector places considerable demands on water supplies: production is largely in pots with limited water-holding capacity, and therefore frequent irrigation is essential. It has been shown that accurate scheduling to meet crop demand (rather than over- or under-watering) benefits quality of HONS, as well as reducing water use and run-off of nutrients and pesticides. Deficit irrigation techniques, in which plants are irrigated to replace less than 100% of the water they transpire, can further control growth and may have additional advantages, for example in reducing pests and disease. Deficit irrigation, however, requires precise scheduling to minimise the risk of excessive drying of the substrate. Numerous different species and cultivars, often at different stages in the production cycle, can be grown together on a single nursery, meaning that several different irrigation schedules need to operate at once. One option is to irrigate crops on the basis of their evapotranspiration rates. In other sectors, this entails measurement of weather conditions to calculate the evapotranspiration of a reference crop, which is then multiplied by a crop-specific factor (crop coefficient) to estimate the evapotranspiration of the crop in question. Crop coefficients, however, are not generally known for HONS. Efforts to deal with this issue, as well as alternative methods of estimating evapotranspiration using gravimetric methods or remote sensing, are reviewed in this chapter.

## 1. Introduction

Worldwide, crop production is limited by drought more than by any single other environmental stress [1]. Climate change, which will in general result in increased crop demand for water, will exacerbate this limitation. Dwindling natural resources coupled with consumer concern have led to an increasing requirement for crops to be produced with limited impact on the environment; nonetheless demand for crop products is growing with the increasing global population, and consumers demand high quality and uniformity. Fresh water scarcity is regarded as the single largest water problem worldwide [2, 3], with irrigated agriculture being the single largest component of fresh water withdrawal, accounting for 70% of diverted water and 90% of consumed water globally [3]. The availability of water for irrigation is likely to decrease in the future due to increased competition from other sectors (municipal, tourism, recreation, conservation and industry).

Accurate scheduling of irrigation to meet crop demand is a key factor in maintaining crop productivity without wasting water resources. As irrigation technology improves, more of the water applied as irrigation becomes available to the crop. Crop irrigation requirements, however, change with crop development, soil water availability, and with fluctuating meteorological conditions. For many crops, it is now possible to accurately schedule irrigation to match the loss of water through evapotranspiration from the crop canopy and the soil. For hardy ornamental nursery stock (HONS), however, scheduling of irrigation to match evapotranspiration is rare. Modelling of woody ornamental water use, and subsequent irrigation requirements, has been limited [4]. In this chapter, I discuss why this is the case, describe recent and current research addressing this issue, and highlight future research requirements.

## 2. Water Use in Hardy Ornamental Nursery Stock (HONS) Production

If water productivity is defined as the ratio of yield (measured as biological or economic output) to crop evapotranspiration, then ornamental crops, on account of their high economic value, have high water productivity compared to agronomic crops or even fruit crops. Unfortunately, water productivity even for ornamentals is poor compared to that of municipal or industrial uses [5], and as the availability of water supplies to meet all water needs dwindles, it is likely that water currently being applied in agriculture/horticulture will be diverted to other sectors. Despite relatively high water productivity, and even though, overall, ornamental nurseries occupy relatively small land area compared to agronomic crops, water use in HONS production is of concern because the water use on individual ornamental nurseries is relatively high [6].

There is a trend to shift irrigated acreage from low-value field and row crops to horticultural crops in many water-scarce areas of the United States [5]. Horticultural production there, including nursery stock, is increasingly under scrutiny in terms of water use. This is due to either current or expected future competition for water with urban populations, and concerns regarding run-off [4]. In Florida, overhead irrigation on container nurseries has been restricted since the early 1990s [7]. The availability of water supplies to meet all water needs is particularly problematic in areas where rapid growth and development are occurring. For example in south-east Florida, the nursery stock sector has continued to grow in recent years, with a quadrupling of employment in the sector between 2001 and 2006, and large increases in output as well as area dedicated to nursery production [8]. In Europe, meanwhile, expansion of intensive crop production e.g. in Mediterranean coastal areas is putting increasing pressure on water resources. Climate change scenarios for southern Europe suggest an exacerbation of spring and summer moisture deficits [9], and droughts are already more frequent than 40 years ago [10, 11]. Weather extremes are expected to become more common throughout Europe [10]. In southern and eastern England it is estimated that demand for irrigation water could rise by 20% by 2020. During 2005-2006 there was an 18 month period in southern England when only 75% of normal rainfall was received. One climate change scenario suggests this could become the norm by 2040 [12]. Growers in the UK using mains supplies face rising water costs (mains water prices doubled between 1990 and 2000). Those abstracting water from surface or ground water sources will need to meet tougher legislation in future relating to abstraction permits [13]. The European Union Water Framework Directive (Directive 2000/60/EC) aimed to improve environmental protection through greater control over water quality and usage. As this Directive is increasingly enforced, it will have far reaching implications for the horticultural sector, with an onus being placed on producers to justify water requirements, and to prove efficiency of water use. Thus the extent to which HONS growers will be able to irrigate in future becomes increasingly uncertain.

Ornamental production involves considerable applications of nutrients and pesticides [14]. Most HONS production systems rely on overhead irrigation with containers being placed on a non-water retentive, freely draining, 100 mm deep, gravel base. Some systems incorporate a break between the underlying soil and the growing medium, by use of either a polyethylene or woven polypropylene membrane. The use of such a break may restrict downwards drainage, which would increase the likelihood of water, containing contaminants, leaving the gravel beds through the central drainage pipe normally installed at their base. Harris et al. [14] found that concentrations of nitrate and phosphorus in water draining from nursery stock beds considerably exceeded the EU limit for drinking water and represented a considerable eutrophication potential; concentrations of pesticides were also considerably higher than the EU Drinking Water Directive (1980) limit. Avoidance of the pollution associated with excess run-off is likely to be as much an incentive for accurate irrigation scheduling as is reducing water wastage. Customers, particularly the major retailers, are putting pressure on growers to improve environmental responsibility [13].

A distinction should be made between HONS growing in the field and HONS growing in containers. In many parts of the United States, much of tree production has shifted from in-ground to above-ground container production [15], since transport of container-grown trees is less expensive due to the lower mass of bark-based growth media compared to soil. HONS growing in the field have access to a far larger volume of soil than those grown in containers. Excess irrigation applied to containers will run through the base of the container and is therefore wasted. Less frequent irrigation is generally required for field production because the soil can hold more water.

Despite increasing application of precision irrigation in many agricultural sectors, irrigation in most woody ornamental nurseries has changed little since the 1960s [4]. Irrigation in the majority of small Mediterranean intensive container plant production units is controlled by simple timers, set by the growers who rely on their own experience rather than a scientific assessment of crop water needs [16]. Technological advances, however, mean that more accurate delivery of irrigation water is now possible compared to in the past. Therefore the limitation in future for irrigation scheduling is a lack of information regarding water requirements for HONS. While water requirements of food crops have been relatively well quantified, there has been little quantification of the requirements of ornamental plants [17].

## 3. Advantages of Irrigation Scheduling for HONS

Irrigation scheduling to meet crop demand, rather than over- or under-irrigation, has clear advantages in terms of crop quality and management. Excessive vegetation leads to pest and disease problems, and non-uniform irrigation leads to non-uniform plant size and quality, and hence time has to be spent manually grading and picking out plants to meet orders for top-quality crops. Accidental under-watering can lead to crop losses. Even where under-irrigation is less severe, remedying the problem requires time to be spent hand-watering. Grant et al. [18] recently showed that irrigation scheduling in combination with uniform overhead irrigation improved plant quality and reduced water use in comparison with use of an irrigation timer (with no adjustment to meet changing water demand) and a sprinkler system with poor uniformity of irrigation output. Irrigating Florida royal palm on the basis of soil tensiometric readings led to water savings of 75% to 96%, compared to the nursery grower’s irrigation regime, without reductions in palm size [8]. Capillary rise from groundwater, however, contributed to water availability, so these results would not necessarily be found elsewhere. Nonetheless, it is interesting to note that economic savings of 16 to 22% were calculated for the tensiometer-scheduled irrigation regimes, compared to the control – with the benefits outweighing the cost of installation and maintenance of tensiometers in the second or third year of production [8].

Knowledge of evapotranspiration of HONS is not only of benefit to irrigation scheduling, but also for landscape architects to choose the most suitable shrubs and trees for particular landscapes, such as low water-use landscapes [19]. Where residential areas are irrigated, lack of information on the evapotranspiration of the species used again becomes a problem: over-irrigation of residential landscapes has been noted in the US, Spain [20, 21], and Abu Dhabi (C. J. Atkinson, pers. comm.).

## 4. Deficit Irrigation: Application to HONS

Deficit irrigation is the application of water at a rate and volume lower than the evapotranspiration rate [5]. It can be applied either as sustained deficit irrigation i.e. by systematically applying water at a constant fraction of potential evapotranspiration through the season, or as regulated deficit irrigation, in which case water deficits are imposed only at certain crop developmental stages. Deficit irrigation strategies have emerged as a means to save water in horticulture by imposing a (usually mild) drought stress with little or no reduction in yield or quality [22].

Since growth control of many HONS crops requires substantial labour investments, the possibility of reducing these costs via irrigation scheduling to control growth is appealing to many growers [23]. Grant et al. [23] showed that deficit irrigation of selected HONS crops could be used to control growth. Encouragingly for application on nurseries, these results were consistent whether precision drip irrigation or overhead irrigation was applied (albeit in a polythene tunnel – the impact of wind and rainfall on crops grown outdoors is an extra complication that needs further investigation). Cameron et al. [24] showed that controlled water stress can substitute for pruning as a means of manipulating growth and improving quality of Rhododendron ‘Hoppy’ at point of sale. For a range of HONS, deficit irrigation removed the need for mid-season pruning in order to obtain compact, well-branched plants [25].

Irrigation and nutrition on the nursery can impact on the growth and resistance to stress of woody perennials once they are planted [26]. Cameron et al. [27] showed that deficit irrigation enhanced the capacity of *Forsythia* to cope with later drought. Controlled drought may lead to an accumulation of carbohydrate reserves in the plants that, together with an increased root to shoot biomass ratio, could promote more rapid establishment of ornamental plants in the garden [25]. Application of deficit irrigation of *Cornus alba* ‘Elegantissima’ on the nursery also had beneficial effects later when the compost was allowed to dry, in a test of ‘shelf-life’: insufficient irrigation is often applied to HONS in garden centres [28]. With oleander seedlings, the combined effect of deficit irrigation and low atmospheric humidity during production hugely reduced the rate of mortality after transplant compared with full irrigation and relatively high relative humidity. Acclimation during exposure to deficit irrigation and low humidity was associated with smaller plant size and leaf area, and shorter, thicker, denser and less ramified roots [29]. These plants also showed osmotic adjustment and more efficient stomatal regulation. Such hardening of HONS during the nursery stage is likely to become increasingly important for revegetation and landscaping, particularly in dry regions. Deficit irrigation is already the most commonly used pre-conditioning technique to produce high quality seedlings for use in semi-arid environments [30]. The aim in this case is to confer on the seedlings the ability to withstand transplanting shock, establish rapidly, and resume growth under xero-gardening or semi-arid landscaping conditions [30]. Root to shoot ratio has been shown to increase in some HNS crops during deficit-irrigation on the nursery, as reviewed by Franco et al. [30], which may be expected to be particularly beneficial in re-establishment in dry soils.

Beeson [31] suggested that deficit irrigation does not reduce irrigation requirements for HONS since restricting daily evapotranspiration via deficit irrigation prolongs production times. While this may be true of HONS in large containers, such as studied by Beeson [31], it will not always apply to HONS in smaller containers (2 or 3 L). While for some HONS, full irrigation may be required to ensure the crop reaches the height specified by sale, for others excessive height would make the plants too tall for the trolleys used in transport. Thus deficit irrigation can save water, and in addition reduce leaching of nutrients and pesticides to the environment. As a result of reduced wastage, nutrient and pesticide costs can also be reduced using deficit irrigation.

There are incentives to use deficit irrigation with HONS, but it is essential that its use does not lead to non-uniformity of crop growth or quality, or to increased need for hand-watering e.g. at the edge of nursery stock beds. Moreover, the line between controlling growth and reducing plant size to unacceptable levels must not be crossed. For example, 25% crop evapotranspiration was found to be too severe for *Lonicera periclymenum* ‘Graham Thomas’ [23]. Irrigating with 60% of control (full) irrigation reduced water consumption while maintaining plant quality in potted geranium [32], but a more severe deficit (40% of the control) had deleterious consequences for plant quality: numbers of flowers were reduced. Seventy percent of control irrigation had a mild effect on height, total dry mass, and leaf area of pot-grown carnations [33], while all these variables were severely reduced under 35% of control irrigation, and, more importantly, flower quality was reduced under this treatment. Cameron et al. [24, 25] showed that not only the degree of water-limitation but the timing of that water-limitation impacts on plant growth in container crops. This was also found to be the case with field-grown ornamentals [34]. Where the most important feature of an ornamental plant is the flower(s), e.g. in the case of carnations, then water deficit may be safely applied during the vegetative phase without risking any deleterious effect on flower quality [33]. Thus, deficit irrigation requires accurate scheduling. Hence, where deficit irrigation is applied, information on evapotranspiration of HONS is even more important than is the case where full irrigation is scheduled.

Fereres et al. [5] pointed out that deficit irrigation techniques will only be taken up by horticultural growers if benefits are demonstrated e.g. in terms of reduced consumptive use of water or irrigation requirements and in terms of grower profits. Thus understanding of evapotranspiration of HONS is necessary not only to improve scheduling of deficit irrigation, but to calculate the benefits associated with its use.

## 5. Approaches for Scheduling Irrigation of HONS

Irrigation requirement on nurseries is commonly determined by simply judging by eye, lifting up containers, or setting a timer to apply the same amount of water daily. Scientific irrigation scheduling, on the other hand, is based on 1) soil water availability, 2) evapotranspirational demand i.e. meteorological conditions and a model of transpirational response to those conditions, or 3) direct measurement of plant water use.

One approach to scheduling irrigation of HONS is therefore to monitor soil moisture content or soil water potential. Gravimetry (weighing soil samples, drying them, and weighing them again) is the only direct means to determine how much water is in the soil. All other techniques rely on indirect methods to measure other properties of the soil that vary with water content [35]. Soil moisture deficit is an indicator of the moisture status of the soil, and for field crops is generally seen as a key measure in irrigation scheduling [12]. When water is lost from the soil by evaporation and transpiration, water content is reduced and a soil moisture deficit develops, lowering soil moisture content below field capacity. These processes tend to extract water from the larger soil pores first, because it is held less tightly by the soil. As these processes continue, only the tightly retained water remains. If soil is allowed to dry beyond a critical soil moisture deficit, the rate of water uptake decreases and plant growth is compromised. It is important to note that the amount of irrigation that should be applied at any one time is limited both by the current soil moisture deficit and the infiltration rate of the soil i.e. irrigation should not be applied at a faster rate than can be accepted by the soil. Irrigating with more water than the soil can accept can lead to erosion, as well as causing drainage and run-off problems [12]. To some extent, the same principles can be applied to growing media in containers. Hence soil moisture content can be used for irrigation scheduling of HONS, whether the crops are grown in the field or in containers. Migliaccio et al. [8], for example, reported on use of automated irrigation on a Florida nursery based on soil tensiometers. Charlesworth [35] thoroughly reviewed all the soil moisture sensors available in Australia. Although that report was aimed at producers of field crops, many of these sensors are relevant to container producers too. Many sensors, including soil moisture sensors, are now able to link with a variety of measurement systems. This means that several instruments can be integrated on the same data logger [35]. Alternatively, a soil moisture sensor can be linked directly to an irrigation solenoid valve to switch irrigation on and off at certain thresholds [18, 23]. Suitable thresholds, however, are not always easy to determine, and will be greatly influenced by the structure and composition of growing media. Most proprietary growing media include wetters to aid water dissipation [13].

Particularly where plants are grown in the field, soil moisture content can be very variable [e.g. 36]. This also occurs for container plants under overhead irrigation [18 and Figure 1], which is commonly used on HONS nurseries – in the UK, 94% of nurseries use overhead sprinkler irrigation [13]; the percentage in the US is lower (60%), but is still high in some areas such as Florida, where it is 78% [37]. Where moisture content of soil or growing media is variable, many sensors would be required to obtain representative information on soil water availability over a crop. In addition, this approach could be very costly where several crops are grown at once, with different rates of water use. In this situation, many tensiometers (or other substrate moisture sensors) would be required to track water availability for all species/cultivars: Migliaccio et al.’s [8] study, for example, relates to only one crop. Automating irrigation on the basis of soil moisture content measurement is thus possible where single or few crops are produced on one nursery, as often occurs for example in Germany or the Netherlands. Where several different crops are grown at once, however, as is the norm in UK production, installation and maintenance of numerous sensors would probably be impractical. Indeed Briercliffe et al. [13] found that few growers were using equipment to measure compost moisture content, largely because they did not see how such equipment could improve their irrigation management. Another problem occurs where very large containers are in use: the position of the sensor in the pot is crucial, as plants will not be able to take up water from much of the pot until the root system is well developed. Beeson [38] found that canopies of *Viburnum odoratissimum* in 11 L containers were half their marketable size before a root system had expanded sufficiently to take up water near the bottom of the container.



Figure 1.Spatial variation in substrate moisture content (%) in 3 L pots of three HONS crops (*Cistus creticus*, *Potentilla fruticosa* ‘Tangerine’, and *Spiraea nipponica* ‘Snowmound’) in 100% peat growing media under relatively uniform overhead irrigation on an outdoors gravel bed (10 m × 5 m). The pattern varies between three consecutive months.

## 6. Methods for Monitoring Evapotranspiration of HONS

An alternative to irrigation on the basis of soil water availability is to irrigate on the basis of crop evapotranspiration. This can be either measured directly or modelled. Three different approaches are highlighted below.

### 6.1. Lysimeters

Lysimeters can be used to measure actual evapotranspiration from a plant plus the soil in a container. Drainage lysimeters allow calculation of evapotranspiration by monitoring excess water removed by drainage and subtracting this from a known volume of water applied to the soil surface. Weighing lysimeters, on the other hand, allow direct measurement of evapotranspiration as a change in mass [39]. Weighing woody plants in containers of up to 19 L has been used to calculate periodic water use in a range of studies [e.g. 40, 41]. Owen et al. [42] connected top-loading balances to a data logger on a nursery to automate assessment of evapotranspiration. Beeson [43] and Cáceres et al. [44] however have shown that if the weighed plants are in a different microenvironment to the ‘typical’ nursery plants e.g. as a result of being elevated above the other plants on a nursery bed, then their evapotranspiration will not be representative of the other plants – as a result of different exposure to radiation and wind. A completely automated system for determining daily evapotranspiration and then applying replacement irrigation was developed at the University of Florida for a range of plant sizes [39]. The practicalities of this system have been published in detail [36].

### 6.2. Meteorological

The most common practice for estimating crop evapotranspiration of agricultural and horticultural crops is to multiply a crop coefficient (Kc) by an estimate of reference evapotranspiration (ETo) [45]. The Kc often varies with time to reflect changes in actual evapotranspiration (ETA) relative to ETo.

The crop coefficient considers all characteristics of the crop that are different to those of the reference crop. ETo is calculated using available climatic data and usually represents a clipped, cool-season grass. The Penman-Monteith equation takes into account the energy balance and aerodynamic and bulk stomatal resistances of an extensive vegetation surface to estimate evapotranspiration. Applied to the evapotranspiration of a reference crop, it takes the form:



where *R*n is net radiation, *G* is soil heat flux, *ρ* is air density, *c*p is specific heat of air at constant temperature, *e*a is average saturation vapour pressure, *e*d is saturation vapour pressure at dew point, *r*a is aerodynamic resistance to vapour and sensible heat flux, Δ is the slope of the saturation vapour pressure-temperature curve, *γ* is the psychrometric constant, and *r*c is the bulk stomatal resistance of the vegetation [46].

*r*a can be estimated as



where *z*a is the height of the anemometer used to measure wind speed, *u*a; *d* is zero plane displacement height of the vegetation, *z*om is roughness height of the vegetation, *z*t is the height of the temperature and humidity sensor, and *k* is von Karman’s constant for turbulent diffusion (0.41).

*r*c can be calculated as a function of individual leaf stomatal resistance per area of leaf and the total leaf area of the plant:



where *r*l is stomatal resistance of a single leaf, taken as 100 s m−1 for grass, and LAI is leaf area index, defined as the area of leaves per unit area of ground surface: 24 × mean grass height is suitable for clipped grass [46].

Many commercially available meteorological stations are pre-programmed to calculate ETo on a daily basis. From the above equations, and where a crop coefficient, Kc, can be defined as ETA/ETo, it is evident that Kc is not actually constant from day to day, but may vary with solar radiation, wind speed, air temperature and humidity. In practice, therefore, Kc values which are mean values over several dates are used, and these mean values change slowly and uniformly with time [45]. Kc values can be established by monitoring ETo and ETA in the field, and as a result Kc values exist for many field crops – with different Kc values for different stages of their cycle.

The adaptation of the Penman-Monteith equation for use as a grass reference in combination with Kc is considered the most reliable approach to estimating evapotranspiration requirements for planning and management [45]. Variations on the Penman-Monteith model exist but generally all provide sufficiently similar values of ETo to meet the precision required for irrigation scheduling [4]. The most current international standard is the UN-FAO 56 model [47]. An alternative to the Penman-Monteith equation, which is more sensitive to wind speed, called the CIMIS equation [48], may be more appropriate for HONS [16]. However, even using this equation to estimate reference evapotranspiration, Schuch and Burger [40] suggested the reference may not be suitable for container crops during periods of high winds.

* *Estimation of reference evapotranspiration for ornamental nursery crops*

Automated weather stations computing ETo are available in many agricultural regions and on some farms, and are mainly used for the evaluation of average daily water consumption of field crops. Automated weather stations have not generally been used to compute ETo for the purpose of scheduling irrigation of HONS, even though much nursery irrigation is centrally controlled using electric valves, and therefore daily adjustment of irrigation quantities to allow for daily changes in ETo should be fairly easy to implement [7]. However, while for field crops daily ETo is usually sufficient, for plants in containers, with limited water holding capacity, several irrigation events may be needed in a day. Therefore hourly reference evapotranspiration may be more useful [16], depending on the level of accuracy required. Another limitation to the use of weather stations to compute ETo is that it is often inconvenient to measure a full set of meteorological data on nurseries, and standard meteorological stations do not provide information relating to conditions inside plastic tunnels or greenhouses. For these reasons, it may be more appropriate to use small portable evaporimeters. A method to derive an electrical signal from a simple leaf-model evaporimeter was described by Harrison-Murray [49, 50]. It has now been developed into a practical device known as an ‘Evaposensor’ that is available commercially (Skye Instruments, Powys, UK). The Evaposensor consists of two leaf-like probes, one of which is kept wet by a wick. The temperature difference between these two artificial leaves is approximately proportional to the rate of evaporation from the wet leaf [50], providing certain assumptions are met. To estimate potential evapotranspiration the temperature difference signal from the Evaposensor is integrated over time using a data logger such as the dedicated ‘EvapoMeter’ (Skye Instruments, Powys, UK) to produce a value in ‘degree hours’ (Wet Leaf Depression Sum, Ws), where one degree hour (1°C h) equates to a temperature difference of 1°C over 1 h. Use of the Evaposensor was validated against Penman-Monteith estimates of potential evapotranspiration by Atkinson et al. [51], and further verified by Grant et al. [18]. It has been used successfully for scheduling irrigation of ornamental crops, and routinely for estimating evapotranspiration in several research projects [52, 53]. This required determination of crop calibration factors (*F*c) to enable ETA to be derived from the Evaposensor output by the equation

ETA = *F*c × Ws.

Crop calibration factors can be determined gravimetrically for container plants (Figure 2). The Evaposensor is portable, can be logged continuously, requires minimal maintenance, and is suitable for any environment. It has recently been used on several commercial nurseries to estimate evapotranspiration [54, 55] and Evaposensor-based systems for automatic scheduling of irrigation are now available (Figure 3). Some values of ETA/*W*s for different HONS crops, all potted up from liners to 2 L pots in April 2007 and placed on a Mypex bed in a closed polythene tunnel, serve to show to variability of evapotranspiration rates in HONS (Table 1), even when grown under the same conditions.

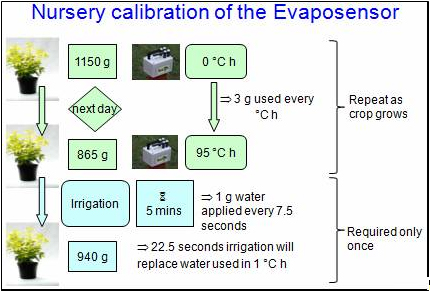


Figure 2.Schematic diagram of how an Evaposensor (Skye, Powys, Wales, UK) can be used, along with weighing of container plants, to schedule irrigation on the nursery. Example pot weights (g) and Evaposensor readings (°C h) are provided.

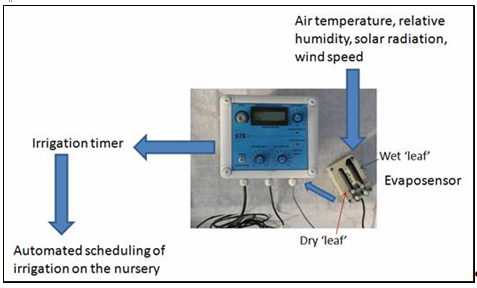


Figure 3. Scheme for automation of irrigation using an Evaposensor to determine the rate of evaporation from a wet leaf, connected via an interface to an irrigation timer. The interface used here is designed and produced by Electronic and Technical Services Ltd. (Wallasey, Wirral, UK).

Table 1. Evapotranspiration per Wet Leaf Depression Sum (ETA/*W*s)   
of a range of HONS grown in a polythene tunnel at different stages   
in their development. Experimental details are provided in [60]

|  |  |  |
| --- | --- | --- |
| Crop | Stage | ETA/*W*s  [mL (°C h)−1] |
| *Ceanothus thyrsiflorus* ‘Autumn Blue’ | 1 month after potting-up | 0.69 |
| *Ceanothus thyrsiflorus* ‘Autumn Blue’ | 3 months after potting-up | 1.73 |
| *Ceanothus thyrsiflorus* ‘Autumn Blue’ | 4 months after potting-up | 2.31 |
| *Choisya ternata* | 3 months after potting-up | 3.38 |
| *Choisya ternata* | 4 months after potting-up | 3.78 |
| *Griselinia littoralis* | 3 months after potting-up | 0.78 |
| *Physocarpus opulifolius* ‘Dart’s Gold’ | 1 month after potting-up | 1.05 |
| *Physocarpus opulifolius* ‘Dart’s Gold’ | 3 months after potting-up | 2.81 |
| *Physocarpus opulifolius* ‘Dart’s Gold’ | 4 months after potting-up | 3.29 |

* *Crop coefficients for HONS*

Crop coefficients have now been estimated for a wide range of horticultural crops, including strawberry, beans, onion, and lettuce [56]. It is more complicated to estimate Kc for tree crops, given that crop cover (the proportion of the land that is covered in the crop’s leaves, as opposed to bare soil) is always partial, and the relationship between cover and Kc does not seem to be consistent across different tree species (peaches, olives, almond etc.). Nonetheless, Allen and Pereira [57] have added guides for tree crops to Kc tables, estimating Kc as a function of ground cover and crop height. Unfortunately, Kc values are rarely known for ornamental crops [16], on account of the vast numbers of species and cultivars in production [4]. Hence, a major difficulty arises in estimating ETA for HONS. For container-grown ornamentals, this could be dealt with by weighing pots after irrigation and then a day later, to establish ETA. If ETo is determined simultaneously, then a Kc value can be calculated. The problem is that Kc changes over time, and frequent gravimetric measurement of large numbers of species and cultivars at different growing stages is impractical.

Beeson [4] reviewed early attempts to establish Kc for selected HONS. Irmak [58] developed models based on weeks after transplanting, growth index, cumulative reference evapotranspiration, or fraction of thermal units (a measure of cumulative temperature during the growth of the crop) for estimation of Kc for use with *Viburnum odoratissimum* at different stages of its development. The equations developed were, however, season-specific. Additionally, fraction of thermal units requires knowledge of the total thermal units accumulated from transplanting until physiological maturity, so can only be applied to estimation of Kc retrospectively. The growth index used required previous investigation of growth as a function of days after planting for the crop in question, so cannot be applied to crops for which this is unknown. The relationship between Kc and weeks after transplanting is unlikely to be consistent across environments or years. Devitt et al. [19] found strong relationships between average yearly evapotranspiration and total leaf area, canopy volume, and tree height for oak grown in a range of container sizes, and found that trunk diameter correlated with average yearly evapotranspiration for willow and mesquite. They also found that monthly evapotranspiration could be predicted by a combination of a growth variable, the month of the year, and monthly ETo. This, however, would not allow ‘real-time’ adjustment of irrigation in crops that require frequent watering, as monthly ETo would need to be determined before the required irrigation for the preceding month could be calculated. Schuch and Burger [40] developed regression equations for 12 ornamental species that described evapotranspiration as a function of canopy height and month of the year, suggesting that once water requirements were known, similar species could be grouped together. The equations were very different for different species, and there was no attempt to determine a method for deciding which equation would be most likely to suit any species that had not been studied. The inclusion of month of the year in the equations also means they are likely to be specific to the region where the work was undertaken [4].

Progress towards real-time establishment of Kc was made by Stanley and Harbaugh [59], who used multiple regression analysis of evaporative demand and canopy height and width to develop an equation predicting the water requirements of *Poinsettia*; application of the prediction resulted in water savings compared to standard commercial application of a fixed daily rate of irrigation. Beeson [6] suggested that projected canopy area or percentage canopy closure could be used to calculate calibration coefficients for use with ETo. A model to irrigate *Ligustrum japonica* was developed based on the previous day’s ETo and a ‘water needs index’ [7]. This index was derived from percentage canopy closure, calculated by expressing the square of the average canopy width as a percentage of the allocated plant area, and was updated every three weeks. The model functioned well without the need for adjustment through different seasons. It represents a substantial improvement on earlier work [40], since elaborate mathematical transformations are not required to account for multi-year production [7]. The same authors found that for *Acer rubrum* ‘Florida Flame’, as plants were potted into progressively larger containers over four years, ETA was linearly correlated with ETo multiplied either by trunk cross-sectional area or projected canopy area [15]. Bacci et al. [16] attempted to combine both meteorological and soil water potential data to determine Kc for 2-year old *Hypericum hidcote* in containers.

They used a soil-specific tensiometeric curve to derive the mass of water in pots from tensiometer data, so as to estimate actual hourly evapotranspiration. This estimate was strongly and significantly correlated with hourly actual evapotranspiration measured using precision balances. In parallel, they used meteorological data to calculate reference evapotranspiration, allowing calculation of crop coefficients using either the tensiometric or precision balance method. Their work, however, only relates to one particular crop species at one particular production stage.

Although these studies have provided useful information for specific crops (e.g. see http://www.mrec.ifas.ufl.edu/rcb/TreeWater/), real progress in dealing with the vast numbers of HONS crops in production will only occur with the development of generic crop coefficients for a range of different HONS. Recent work on ‘crop calibration factors’ indicates that plant height and percentage cover could be sufficient to model water requirements of a wide range of very different nursery stock [60]. Plant height can be easily and rapidly measured on the nursery. Percentage cover can be rapidly estimated visually (this was validated using estimation of percentage cover based on analysis in Photoshop (Adobe Systems Incorporated) of digital images and/or based on interception of photosynthetically active radiation). A model was developed from data obtained on 12 species/cultivars over a year. Each plant was grown in a 2 L black polyethylene pot in a 100% sphagnum peat (medium grade) substrate, with 1.5 kg m−3 limestone and 6 kg m−3 CRF (Osmocote Plus [15 + 9 + 11 + 2MgO + trace elements]) incorporated at the time of potting up. Pots were placed in groups of six on a woven polypropylene ground cloth (MyPex) bed in a closed polytunnel.

With the exception of *Lonicera*, which were trimmed as required to prevent excessive growth beyond the top of the supporting canes, plants were not pruned during the first four months of the experiment so as to allow development of differences between crops and over time in leaf area and cover. They were then pruned and allowed to grow prior to the final set of measurements two months later. Plant height and cover was estimated monthly, and evapotranspiration measured at the same time, gravimetrically, along with Wet Leaf Depression Sum (*W*s – see above), measured using the Evaposensor. This allowed derivation of a generic equation (across all crops) describing evapotranspiration per Wet Leaf Depression Sum as a function of plant height and cover. The following year, *Buddleia* ‘Lochinch’, *Cornus alba* ‘Gouchaultii’ and *Griselinia littoralis* ‘Variegata’ were grown in a similar manner, in order to validate the equation. ETA per Ws of these three crops compared favourably with that predicted from plant height and percentage cover (Figure 4). Although in that work the crop calibration factors were determined for use in conjunction with *W*s (Figure 5 shows how this system can be applied on the nursery), the same principles can be applied to modelling Kc to use in conjunction with ETo.



Figure 4. Actual evapotranspiration (ETA) per Wet Leaf Depression Sum (*W*s) of three HONS crops compared to that predicted from plant height and percentage cover – based on a model established for a wider range of crops the previous year. Different shading indicates different months. The dotted line represents 1:1. Growing conditions are described in the text.

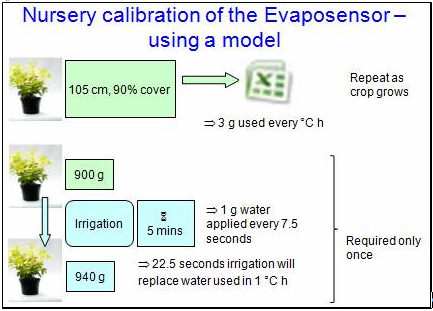


Figure 5. Schematic diagram of how an Evaposensor can be used, along with a model of crop specific factors, to schedule irrigation on the nursery. An example average plant height (cm) and percentage cover and example pot weights (g) before and after irrigation are provided.

* *Difficulties with Kc for HONS*

Other than a shortage of research on development of Kc for HONS, there are other issues that make coefficients for these crops more complicated than for many agronomic crops. Kc for isolated stands of vegetation are often significantly greater than those for large, continuous expanses due to advection of heat and vapour deficit into small vegetative stands and increased *r*a of small stands. This leads to the average *R*n captured by a small stand or single row of trees or shrubs being greater than that estimated per unit ground area using the above Penman-Monteith equation, and the *r*a and amount of air in contact with leaves is increased. For ornamental production, this situation of non-uniform vegetation arises frequently, resulting in far higher Kc than occur for example for cereal crops [45].

Bacci et al. [16] found that hourly Kc values showed high variability between consecutive days, indicating that plant water use in some ornamental species may not respond to changes in environmental conditions in the same way as a reference crop. Grant et al. [23] also found considerable daily variability in *F*c for those crops that used relatively large quantities of water.

One problem with the research on Kc for HONS to date is that the same standard reference calculations have not been used – some studies use the ASCE 2000 equations and a grass reference [see 4], others use CIMIS [16], and recent work has used a portable evaporimeter rather than a grass or alfalfa reference crop [60]. Although the latter approach has been validated against the traditional ETo approach, and Grant et al. [23] provided Figures for converting models predicting *F*c to models predicting Kc, there have been small discrepancies in the exact relationship between Kc and *F*c in separate experiments [18, 51, 61]. The relationship between Evaposensor output and ETo therefore needs to be further tested under a wide range of environments.

Even where Kc values are known, if different crops are on the same nursery stock beds and irrigated with overhead irrigation, the question remains – for which crop do you schedule irrigation [18]? If calibration coefficients can be established for different crop types, these could be used to determine which crops are placed together, minimising the risk of over- or under-watering some crops, independent of the method of scheduling irrigation. However, since differences between species also occur in uptake of water, due to funnelling of water or the canopy throwing water away from the pot, grouping crops according to water use alone may not be sufficient to ensure efficient irrigation of all crops on a bed.

### 6.3. Remote Sensing

Remote sensing provides an alternative means of estimating evapotranspiration [62]. This approach utilizes plant canopy energy budget models, which allow calculation of evapotranspiration from plant canopy temperature along with meteorological data. Aerial or satellite imaging allows temperature of large areas of plant canopies to be captured at once. In these cases, hyperspectral imaging is often also used in order to distinguish crop cover from soil. This approach has not yet been applied with HONS, although it is clear that canopy temperature on HONS beds is a useful indicator at least of relative evapotranspiration ([23] and Figure 6).

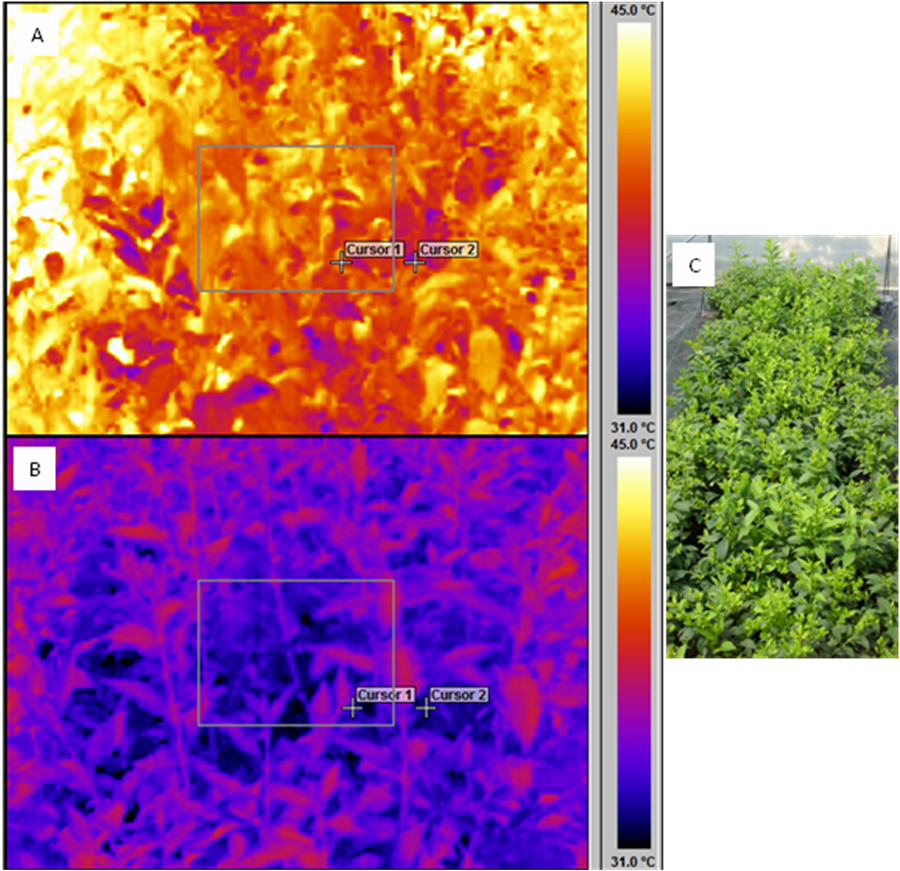


Figure 6. Thermal images (A, B) of sections of bays of *Forsythia* × *intermedia* ‘Weekend’ nursery stock (a typical bay is shown in C), showing higher temperature where plants were irrigated to meet 50% of ETA (A) compared to where plants were irrigated to replace all water lost in evapotranspiration (B).

### 6.4. Alternatives

One advantage of a remote sensing approach such as thermal imaging is that it is the plants, rather than the soil or environment, that are monitored, and therefore the plant response to its environment is detected, rather than inferred. The same can be said of other plant-based scheduling techniques. For woody plants, the extent of daily trunk shrinkage between the time of minimum and maximum stress is sometimes used as an indicator of plant water status [e.g. 63]. In order to establish a reference (no stress) baseline, some such studies have established the relationship between maximum trunk shrinkage and ETo. The approach could presumably be reversed, using maximum trunk shrinkage as an indicator of ETA. Recently, Miralles-Crespo et al. [64] indicated that dendrometers to measure trunk diameter fluctuations can be a useful means of monitoring ornamental plant water status. Whether this approach can be extrapolated to measurement of ETA needs further research. Of course, monitoring evapotranspiration is not the only possible means of irrigation scheduling, but alternative approaches fall outside the scope of this review.

## 7. Comparison of Techniques for Scheduling Irrigation of HONS

In some cases monitoring evapotranspiration appears to deliver improved irrigation scheduling compared to use of soil moisture sensing. Grant et al. [23] found that attempts to impose a mild deficit irrigation treatment (70% ETA) successfully reduced biomass (the aim being to control growth) when irrigation was scheduled according to estimates of evapotranspiration, but not when irrigation was triggered to turn on and off at selected soil moisture contents.

On the other hand, imposition of a deficit to match 70% crop evapotranspiration on the basis of estimating ETA was not completely straightforward. Initially a few fully irrigated plants were weighed to gravimetrically determine crop factors, but later in the season growth reductions in the deficit irrigated plants meant that 70% of the water use of fully irrigated plants would in fact have corresponded to 100% of the water use of the smaller plants in the deficit treatment. To continue imposing deficit irrigation, the crop factor therefore had to be adjusted; this was largely based on trial and error. A model of evapotranspiration based on plant size would remove this problem.

The above comparisons of two different techniques, however, are perhaps unfair, in that at this stage simply irrigating HONS to match ETA is a big step forward, and scheduling of deficit irrigation should be seen as a further challenge. In fact, for field crops it is now accepted that ‘stress’ can be taken into account in the estimation of ETA, using an appropriate ‘water stress coefficient’ (Ks) [47]. Ks can be calculated based on knowledge of the total available soil water in the root zone, and the water shortage relative to field capacity. This approach has not yet been explored for ornamentals – not even those grown in the field – but merits attention.

A combination of different approaches may also be used to support irrigation decisions [e.g. 16].

## 8. Future Improvements for Monitoring Evapotranspiration of HONS

Unfortunately, shortcomings in monitoring evapotranspiration of HONS are not the only limitations to optimal irrigation scheduling on the nursery. Where overhead irrigation is used, wind can have a major impact on the rate of supply of water to containers – which means that rates of irrigation based on estimates of water entering containers on still days may under-irrigate on windy days – or under-irrigate part of the crop and over-irrigate other parts. However, in a ‘smart’ irrigation system, irrigation control could be adjusted to meet such day-to-day variability. Hence it seems that if horticulturalists and biologists/environmental scientists can provide a blueprint for monitoring evapotranspiration of HONS, the remaining issues are technological – and in the rapidly developing technology sector, such issues should soon be surmountable. Interestingly, a UK report [13] found that HONS growers would like their staff to be better trained and would welcome the use of equipment to put more ‘science’ into irrigation decision making. The will to change exists, the technology is possible – and so the onus is on the scientific community to provide the information to allow progress in irrigation management in the HONS sector.

One issue for scientists working in this area is the fragmented, national or even regional structure of funding, which does not aid integration of research. This is unfortunate given the effort required to obtain Kc for large numbers of different species and growing systems. Another issue is that research funding is not continuous.

Future improvements for monitoring evapotranspiration of HONS require improved communication between all involved. Specifically, interested parties need to agree on shared objectives. It is likely that concern over water resources will lead to increased efforts to improve the efficiency of irrigation scheduling for HONS. Such efforts should build on past work while expanding to include more crops and environments.

## Conclusion

The major remaining hurdle for improving water management in the HONS sector is a lack of information on crop water requirements. Efforts to model HONS crop evapotranspiration over the last 15 years are serving to address this issue, but progress has been slow and as yet no truly generic system for predicting evapotranspiration of widely differing types of HONS crops exists. Increasing concern over dwindling water resources and awareness of the economic advantages of good irrigation scheduling mean this should be a priority.

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