Irrigation Scheduling Based on Cumulative Vapour Pressure Deficit to Predict Nursery Tree Water Stress

by

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ABSTRACT

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Ontario tree nurseries are among the heaviest users of irrigation water in the ornamental horticulture sector. Increasing concerns with water conservation, environmental impacts and costs have encouraged the nursery industry to modify its water use, however an effective irrigation management strategy remains elusive. Conventional irrigation scheduling for nursery trees is often based on subjective observations and field experience, which excludes plant water status measurements. Using field-deployable stem psychrometers paired with conventional meteorological measurements, the aim for this thesis was to quantify the relationship between cumulative water potential (CWP) and concurrent cumulative vapour pressure deficit (CVPD) to develop an irrigation scheduling technique which predicts plant water status responses from environmental variables, specifically vapour pressure deficit (VPD). This relationship yielded average slope responses for Thuja occidentalis (L.) of -2.4 MPa*Hrs / kPa*Hrs and for Acer rubrum (L.), -1.5 MPa*Hrs / kPa*Hrs. The CWP/CVPD relationship needs further refinement for irrigation management strategies in a broader selection of nursery trees.
DEDICATION

Dedicated to my parents for being my lifelong supporters and motivators. Thank you for giving me so much love and encouragement since day one.
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LIST OF ABBREVIATIONS SYMBOLS AND NOMENCLATURE

EP – Experimental Plot
CWP – Cumulative Water Potential
WP – Water potential
CVPD – Cumulative Vapour Pressure Deficit
VPD – Vapour Pressure Deficit
COHA – Canadian Ornamental Horticultural Alliance
B&B – Balled and Burlapped
$\text{ET}_0$ – Reference Crop Evapotranspiration Rate
$\text{ET}_c$ – Crop Evapotranspiration Rate
$K_p$ – Pan Coefficient
$E_{\text{pan}}$ – Evaporation Rate from Pan
$R_n$ - Net Radiation at the Crop Surface
$G$ - Soil Heat Flux Density
T - Air Temperature at 2m Height
$u_2$ - Wind Speed at 2m Height
$e_s$ - Saturation Vapour Pressure
$e_a$ - Actual Vapour Pressure
$e_s - e_a$ - Vapour Pressure Deficit
$\Delta$ - Slope Vapour Pressure Curve
$\gamma$ - Psychrometric Constant
SPAC – Soil-Plant-Atmosphere-Continuum
Chapter 1  Introduction and literature review

1.1  Agricultural water use

Water, although plentiful in Canada, is a scarce resource when considering its availability and quality within any given industry or sector (Percy, 2004; Schindler and Donahue, 2006). In Canada, the agriculture industry is the largest consumer of freshwater resources based on statistics reported in 2009 (Bernier, 2010; Government of Canada, 2010). Within the larger context of commercial agriculture, the horticulture sector is comparatively a smaller user of water. However, the consumption is still substantial and is often in direct competition with other industries and domestic demands (Deloitte and Touche, 2009; Loe De et al., 2001) as many horticultural production operations are in close proximity to developed areas. Within the horticulture sector, the nursery industry is the single largest consumer of water (Deloitte and Touche, 2009). Due to the production systems in place, the nursery industry is heavily reliant on irrigation to sustain crop production (Fereres et al., 2003; Ministry of Agriculture and Food and Rural Affairs, 2004a), making the industry very susceptible to water shortages, in terms of quantity or quality.

Irrigation practices that promote sustainable water use are key to improving irrigation efficiency within the horticulture sector. Technologies for promoting effective irrigation management are available to the nursery sector. These technologies generally consist of a computer-controlled scheduling system coupled with a calibrated water delivery system that
attempts to meet the physiological water requirements of the crop (Gladius, 2006). Growers may have difficulty incorporating these systems due to their lack of knowledge on the availability, experience required when using these systems, and their high cost of implementation (Gladius 2006; Bilderback, 2002). If growers invest the time to understand the long-term benefits of effective irrigation, water consumption in field operations can be reduced and allocated to other nursery production beds. These water savings improve the irrigation costs and increase water use efficiency. As the global population continues to grow, the competitive demand for water between energy production, residential use, and the agriculture and food sectors will increase. Effective irrigation and water use will help ensure adequate water supplies for consumers now and in the future (OMAFRA irrigation management, 1994, and OMAFRA irrigation management, 2004).

1.2 Water and the nursery industry

The production of ornamental trees in a typical nursery system requires large quantities of water to support the physiological demands of the plants. Pimentel et al. (2004a, 2004b) estimate that typical agricultural crops (e.g., corn, rice, and soybeans) require 600 to 2000 L of water for each kilogram of dry matter produced in a growing season. Comparatively, nursery crops (shrubs, woody ornamentals, and vines) require approximately 500 L for field-grown crops (i.e., in-ground) and approximately 1500 L for container crops (Bacci et al., 2011).
The Canadian Ornamental Horticulture Alliance (COHA) produced a report assessing the economic and environmental impact of the Canadian horticulture industry. The report estimates that the ornamental horticulture sector uses 190 million m$^3$ of water annually. In comparison to other subsections of the ornamental horticulture sector, 96% of this water use is attributed to nursery operations (Deloitte and Touche, 2009). It should be noted that this does not account for recycling as most nurseries drain the irrigated sectors back to a holding pond.

Overwatering is a significant concern to nursery operators as it increases the cost of production and has more detrimental effects on a crop than under-watering (Jasa, 1973). The cost of production includes the cost of: 1) power to operate irrigation systems, 2) field labour required for maintenance of irrigation infrastructure, and 3) additional amendments (fertilizers and pesticides).

Excessive watering can expose a plant to hypoxic conditions which deprives the root-soil system of oxygen that is required for root respiration. This causes reductions in root growth, stomatal conductance, photosynthesis rates, and chlorophyll content (Hershey 1990; Parent et al., 2008; Huang et al., 1997). Briefly, well-drained soils have sufficient levels of both soil water and air spaces, allowing for water uptake and $O_{2(g)}$ / $CO_{2(g)}$ diffusion. In waterlogged soils, the air is displaced by water leaving little or no air space for the gas exchange necessary for proper root functioning.
The primary issues associated with over irrigation are soil erosion and nutrient runoff, which can lead to degradation of receiving waterways and reduced fertility of the remaining soil (Pimentel, 2000; Forge, 1998; McConkey et al. 2010). The loss of soil fertility forces growers to apply additional nutrients to maintain or improve plant quality. However in combination with inefficient irrigation, this can result in point source pollution events which can lead to eutrophication of local water ways (Juntunen, 2003; Taylor et al. 2006). Nutrient discharges are regulated by several acts/pieces of legislation these include but are not limited to: the Canadian Water Act, (R.S.C., 1985, c. C-11). Nutrient Management Act (S.O. 2002, c. 4), Ontario Clean Water Act (S.O. 2006, c. 22), etc.

There are efforts being made by the nursery industry to conserve water, with approximately 70% of nursery operations adopting some form of water conservation (Deloitte and Touche, 2009). Among the 70% of nurseries adopting water conservation techniques, the most common technologies for improving water conservation are the use of a container system to grow plants, drip irrigation systems and/or capturing/recycling rainwater for irrigation. Overhead irrigation systems are conventionally used, however compared to the drip irrigation system these are inefficient.

1.3 Nursery drip irrigation systems

Typical nursery production systems resort to using overhead irrigation systems, however these systems are inefficient at distributing water (Figure 1.1A). Alternatively, drip irrigation
systems deliver water directly to the soil surface or directly into the root zone of individual plants more effectively by using a network of pumps, valves, pipes, and small diameter tubes that terminate with flow-regulated emitters, misters, or microjets (Irrigation Direct, 2011; OMAFRA 2004). This type of system ensures water is directly applied to the root-soil system of the plant whereas, overhead irrigation systems apply water over a wide area and it is difficult to ensure that water reaches the root-soil system. A comparison is summarized in Table 1.1.

![Figure 1.1](image.png)

**Figure 1.1** - (A) Conventional overhead irrigation practice in which much of the water is applied by simulating rain patterns, and (B) conservation-based drip irrigation in which the irrigation water is applied directly to the root zone of each plant. Photographs courtesy of Rain Bird Corp.
Table 1.1 - Summary of commonly used irrigation systems in nursery crop production systems.

<table>
<thead>
<tr>
<th>Irrigation system:</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Overhead Irrigation | - No drainage problem  
- Uniform irrigation pattern  
- Low maintenance (James, 1993; Beeson and Yeager, 2003). | - Inefficient -- Water loss to air, spaces in between pots and runoff from the sides of the canopy (Beeson and Knox, 1991).  
- Increased fungal or bacterial growth due to water residue on leaves  
- High energy consumption  
- Irrigation can only occur during calm wind periods (Sustainable agriculture initiative platform, 2009)  
- Sprayed fertilizer and pesticides can be washed away from plant canopy during irrigation event in field-grown production |
| Drip Irrigation | - Reduced irrigation costs  
- Water is directly applied to the plant increasing water application efficiency  
- Water evenly distributed around the plant (emitter-type dependent)  
- Emitters can easily be removed and replaced if malfunctioning  
- Leaf foliage is dry; reduced spread of diseases | - High initial investment costs  
- May require multiple drippers per pot  
- Poor placement of emitters (emitter-type dependent) will restrict root growth to one area  
- Emitters can be accidentally removed  
- Emitters can build up precipitate if water quality is not properly maintained causing emitter clogging |
1.4 Conventional tree production systems

A nursery can utilize numerous production systems, the selection of which is governed by several factors. Two common production systems are: 1) container-based where each plant is grown in a dedicated container, or 2) in-ground field production. These systems are discussed below.

1.4.1 Container production system

Container production systems have gained popularity in many nursery operations in the United States (Hodges et al., 2008). Two systems; in-ground and above-ground are commonly employed. The general advantages of either container-grown planting system are summarized in Table 1.2.

Table 1.2 – Advantages and disadvantages of container production systems.

<table>
<thead>
<tr>
<th>Container production systems</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
|                             | • Ease of Transplanting  
|                             | • Lightweight plants for consumers and workers to handle  
|                             | • Reduced harvesting costs (Cregg, 2014, Powell, 1997)  
|                             | • Improved biomass production (Ruter, 1998)  
|                             | • Efficient land area utilization (Arteca, 2006)  
|                             | • Reduced labour costs (harvesting & shipping)  | • Risk of roots being tangled; creates physical barrier for future growth and development of roots  
|                             | | • Restricted soil volumes  
|                             | | • Requires frequent watering and nutrient supplementation (Powell, 1997; Agriculture and Agri-Food Canada, 2003b).  |
1.4.1.1 Container production system – In-ground

In-ground systems or pot-in-pot systems (Figure 1.2) are the traditional methods described by Parkerson (1990). The plantings are constructed by using two similar sized containers referred to as socket containers and production containers. Socket containers are empty containers permanently installed in the ground to structurally support and organize production containers (University of Kentucky, 2013). Production containers containing the potted trees are set into the socket containers. The University of Kentucky has prepared a detailed video describing and illustrating the process of an in-ground system, which can be found at: [https://www.youtube.com/watch?v=wNeBurkznIk](https://www.youtube.com/watch?v=wNeBurkznIk).

In addition to the general advantages of container production, in-ground systems also offer:

- Moderate root zone temperatures when socket containers are surrounded by in-ground soils reducing temperature gradients common in above-ground systems (Young and Bachman, 1996).
- Reduced container evapotranspiration rates due to moderate root zone temperatures (Martin et al., 1999).

Disadvantages of in-ground systems are:

- High initial costs of installing socket containers
- Requires proper subsurface drainage system for water runoff (Miralles et al., 2012)
- Risk of roots growing into the soil underneath socket containers, causing damage (plant and socket) during harvest/moving (Agriculture and Agri-Food Canada, 2003b).
Figure 1.2 - A conventional in-ground (pot-in-pot) container production system at Connon Nurseries C.B.Vanderkruk Holdings Ltd. Production containers (A) are situated into socket containers (C) installed with a drip irrigation system. The drip irrigation system consists of a main dripper line (B) that runs down each row of the production bed. Distributed from the main dripper line is a thinner tube with an emitter (D), controlling the spray pattern and amount of water distributed to the pots. A layer of mulch mixture is spread across the surface to control and maintain water moisture.
1.4.1.2 Container production system – Above-ground

Above-ground systems are similar in layout and infrastructure as in-ground systems with the exception that only the production containers are used and remain on the soil surface (Figure 1.3). The general benefits of container systems outlined previously are maintained in above-ground arrangements with the added benefit of lower initial cost achieved by a reduction in bed preparation requirements (i.e., no need to install sockets). Instead of sockets, a black woven fabric is laid out underneath the containers to protect the roots from weeds and prevent the roots from growing into the soil.

Figure 1.3 - A conventional above-ground container production system. Production containers are placed on black woven fabric that prevents weed establishment and stops the tree roots from growing into the soil. Photograph courtesy of American Nurseryman.
Although less expensive initially, there are several disadvantages associated with above-ground production. During hot summer days, the woven fabric absorbs incident solar radiation and increases the overall temperature of the container and root zone area. These high temperatures lead to increased root stress resulting in reduced plant productivity (Robbins, 2010; Heckathorn, 2013). Above-ground containers are also susceptible to wind blow over that can damage the trees. Staking, reinforcing, and increasing pot size of the trees increases labour and production costs to the nursery (Parish, 2005; Robbins, 2010).

### 1.4.2 Field production systems

Field production systems have alternative production techniques however, the studies in the later chapters were not focused on field grown trees. In summary, two common harvesting techniques are the Balled and Burlapped (B&B) and the Bare-root. Refer to (Dara and Lemer, 2002; Arteca, 2006; Agriculture and Agri-Food Canada, 2003) for further information on B&B and (Dara and Lemer, 2002; Phillips, 2015; Pecknold, 2001) for bare-root systems.

### 1.5 Quantitative irrigation scheduling

Irrigation scheduling encompasses all the information and decisions associated with determining the appropriate time of day, duration of irrigation, and amount of water required to effectively irrigate a crop (Howell and Meron, 2007 and Broner, 2005). Effective irrigation
scheduling is critical to ensure efficient water use and to prevent overwatering (Evans et al., 1996). During periods of water scarcity, effective scheduling is critical in the effort to minimize production losses (Evans et al., 1996). Long-term and short-term factors are considered under effective irrigation scheduling. Irrigation system design and water budgeting based on seasonal water availability are considered long-term factors. Short-term factors relate to how much water is currently required for each crop, and includes time of year and general weather conditions (EPA, 2003).

Scheduling an irrigation event, according to Howell and Meron (2007), can be based on three different predictors: 1) demand estimate systems that estimate, by proxy, the crop water requirements, 2) soil-water status measurements, or 3) plant water status. The most common irrigation scheduling technique currently adopted by growers is the demand-estimate systems due to their ease of use and relative effectiveness.

1.5.1 Crop demand-based system

In a crop demand estimate system, water requirements are traditionally determined by either observation or quantified by estimating evapotranspiration water balance (Jensen et al., 1990; Allen et al., 1998). Scheduling irrigation by observation typically involves observing signs of leaf wilting, leaf discolouration, or total weight of the plant (container-grown only). Quantified scheduling relies on determining or estimating the rate of crop evapotranspiration. To determine the crop evapotranspiration, the reference rate of evapotranspiration (ET₀) must be
initially calculated by the standard Penman-Monteith equation (equation 1.1) or measured using the pan evaporation technique (equation 1.2). The standard Penman-Monteith equation is used for calculating evapotranspiration from a reference grass surface using meteorological measurements. Evapotranspiration estimates are typically calculated in meteorological software packages.

The equation is as follows (Allen et al. 1998):

\[
ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)}
\]  

(1.1)

Where:

- \( ET_o \) - reference evapotranspiration [mm day\(^{-1}\)]
- \( R_n \) - net radiation at the crop surface [MJ m\(^{-2}\) day\(^{-1}\)]
- \( G \) - soil heat flux density [MJ m\(^{-2}\) day\(^{-1}\)]
- \( T \) - air temperature at 2 m height [°C]
- \( u_2 \) - wind speed at 2 m height [m s\(^{-1}\)]
- \( e_s \) - saturation vapour pressure [kPa]
- \( e_a \) - actual vapour pressure [kPa]
- \( e_s - e_a \) - vapour pressure deficit [kPa]
- \( \Delta \) - slope vapour pressure curve [kPa °C\(^{-1}\)]
- \( \gamma \) - psychrometric constant [kPa °C\(^{-1}\)]

Alternatively, the pan evaporation technique is an economical and low maintenance procedure that any nursery operation can adopt to estimate \( ET_o \). The simplest type of pan used to
quantify evaporation rates is a Class-A pan (Figure 1.4), where the pan is filled with water to the maximum volume. After a 24-h period the amount of water lost to evaporation is recorded and the pan is returned to its maximum volume. The Class-A pan is the most practical tool for estimating evapotranspiration rates, if calibrated properly (Pereira et al., 1997), and provides an estimated amount of water a crop requires to minimize water stress. Several studies conducted by Eliades (1988) and Erteck et al. (2006) have demonstrated effective irrigation scheduling for cucumber plants from pan evaporation techniques.

**Figure 1.4** - A conventional Class-A pan used for pan evaporation measurements. (A) illustration of the typical size of the pan, (B) pan evaporation placed in the field. Illustration was adopted from (A) Allen et al. (1998) and (B) https://en.wikipedia.org/wiki/Pan_evaporation#/media/File:Evaporation_Pan.jpg.
\[ ET_0 = K_p E_{pan} \] (1.2)

\( ET_0 \) – Reference evapotranspiration [mm/day]
\( K_p \) – Pan coefficient [unitless]
\( E_{pan} \) – Evaporation rate from pan [mm/day]

Once the \( ET_0 \) is established by either methods, specific crop coefficients are required to adjust the reference evapotranspiration rate for the crop in question. Several crop coefficients can be found in Allen et al. (1998). When crop coefficients are not available, canopy cover coefficients can serve as a close substitute for crop coefficients (Cahn, 2012).

\[ ET_c = K_c ET_0 \] (1.3)

\( ET_c \) – Crop evapotranspiration rate [mm/day]
\( K_c \) – Crop coefficient [unitless]
\( ET_0 \) – Reference crop evaporation rate [mm/day]

1.5.2 Soil-water status scheduling

The second technique for scheduling irrigation utilizes a soil-water status parameter that describes the characteristics of the soil-water interface (Evans et al. 1996). Measurements of soil-water status can be represented in a variety of forms. Conventionally, the soil-water interface is
expressed volumetrically in m$^3$•m$^{-3}$ or gravimetrically in kg•kg$^{-1}$. To ensure measurements can be compared with other plant water relations, measurements are expressed as pressure (MPa or kPa), or energy per unit weight (Howell and Meron 2007; Hillel, 1998). A wide range of instrumentation is available to aid in measuring soil-water properties; the main ones used are tensiometers and capacitance-based soil moisture sensors.

1.5.2.1 Tensiometer

Tensiometers measure the suction or tension that a plant’s roots must generate in order to pull water from the soil. This tension is a measure of water availability and can be used in irrigation scheduling. Tensiometers are constructed of a partially water filled tube, a vacuum gauge, and a porous ceramic tip that is buried in the soil (Figure 1.5). Under dry soil conditions water is pulled through the ceramic tip and into the soil which increases the suction force in the tensiometer which is registered on the vacuum gauge (Department of Environment and Primary Industries, 2009). In moist soil the partial vacuum in the tensiometer draws moisture from the soil resulting in a decreased the suction force in the tensiometer. The tension is measured in units of pressure (kPa), where 0 kPa indicates soil saturation and optimum plant growth occurs when the tensiometer measures 30 – 40 kPa (Department of Environment and Primary Industries, 2009).
Figure 1.5 - Schematic of a tensiometer. The porous ceramic tip allows water to flow in and out of the tube depending on the water status of the soil. More water is drawn out of the tube under dry soil conditions, this is indicated by a large suction force. Less water is drawn out of the when soil conditions are moist, indicated by a low suction force. Sourced from the Department of Environment and Primary Industries of Melbourne, Victoria. [http://agriculture.vic.gov.au/agriculture/horticulture/vegetables/vegetable-growing-and-management/how-to-use-tensiometers](http://agriculture.vic.gov.au/agriculture/horticulture/vegetables/vegetable-growing-and-management/how-to-use-tensiometers).

1.5.2.2 Capacitance soil-moisture

Capacitance soil-moisture sensors (Figure 1.6) are based on the dielectric constant of the soil, which is understood as the soil’s ability to conduct electricity (Dukes, et al. 2015). As the soil moisture increases, the dielectric constant also increases until a maximum is reached, which is considered field capacity. The advantages of capacitance soil-moisture sensors are the
simplicity of the sensor technology, can be easily deployed in field applications, and the low maintenance. The disadvantages are the high costs associated with the instruments, and heterogeneity in the soil systems which require careful calibrations for accurate measurements (Peters, 2012).

Figure 1.6 - Conventional capacitance sensor used to determine soil moisture content, soil electrical conductivity, and pH. The image presented is an EC-5 soil moisture sensor manufactured by Decagon Devices, Inc. (Pullman, WA, United States). Image obtained from: http://www.decagon.com/en/index.php/products/soils/volumetric-water-content-sensors/ec-5-small-soil-moisture-sensor/?tab=Accessories.
1.5.3 Plant water status scheduling

Plant water status is determined by directly measuring the water potential (WP) of a plant. Water potential is a direct measurement that represents the plant response to all environmental variables that influence the water status of a plant.

Water potential is derived from the concept of chemical potential, where chemical potential is defined as the work required to move or react a substance (Neufeld, 2000). As water is absorbed through the root system, a differential in chemical potential generates the driving force that pulls water through the plant. This is expressed as free energy per mole of water; however, these units are not easily related to pure water (Slayter, 1965). Therefore, WP is derived and expressed in pressure units (MPa). Slayter (1965) has described in detail the derivation from chemical potential to WP.

Water potential is influenced by several factors that change the dynamics of water movement. Factors that decrease WP are (Kramer, and Boyer, 1996):

- Addition of solutes to water solution.
- Addition of porous solids to increase matric force.
- Application of negative pressure or tension in xylem of transpiring plants.

Factors that increase WP are:

- Dilution or removal of solutes
Hydration of matrices
Application of pressure above atmospheric (Turgor)

These factors are summarized into equation 1.4:

$$\Psi_w = \Psi_s + \Psi_p + \Psi_m + \Psi_g$$ (1.4)

Water potential is represented with the Greek symbol $\Psi$ (psi) where subscripts:

- $w$ represents water potential
- $s$ represents solutes
- $p$ represents pressure
- $m$ represents porous matrices
- $g$ represents gravity

The entire plant system is dependent on the WP gradient that is developed across different areas of the plant. Higher WP (close to zero) is found closer to the roots of the plant where water is closest to its purest form. This will progressively decrease negatively towards the upper region of the plant (leaves). This gradient in decreasing WP is the driving force which pulls water throughout the plant. To measure plant WP, two types of sensors are available: 1) the pressure chamber (Scholander, 1965) and, 2) the in situ stem psychrometer (Dixon and Tyree, 1984) (Figure 1.10).
1.5.3.1 Pressure chamber

The pressure chamber is a widely accepted technique for measuring water potential (Jones, 2004). Before a piece of plant tissue (leaves, shoot, and large branches) is excised, the water column found in the xylem is under tension. After the tissue is removed, the tension in the water column is broken causing a strong pull of water into the excised tissue by the potential gradient existing between the plant cells and the xylem. Water potential measurements are taken by placing the plant tissue into a chamber, sealed completely with the edge of the plant exposed (Figure 1.7A). Gas is injected into the chamber until the positive pressures from the gas balances with the negative water potential of the excised tissue. This is representative of the water potential measured before being excised. This particular method requires destructive sampling, is time consuming, and labour-intensive when sampling volumes increase; however, measurements are simple and accurate for the piece of excised tissue.
1.5.3.2 Automated *in situ* stem psychrometer

The alternative method for obtaining WP measurements is the *in situ* stem psychrometer (Figure 1.7B). The sensor is attached directly to an exposed region of the xylem and the internal chamber is sealed from the external environment allowing the chamber vapour phase to come into equilibrium with the plant water status. A Peltier cooling pulse runs through a tiny thermocouple found inside the chamber (Figure 1.8) to generate a psychrometric web bulb to measure the wet bulb depression which is relative to the vapour pressure in the chamber. Through temperature corrections and instrument calibrations, the stem WP is measured (Dixon and Tyree, 1984). Although the sensors are sensitive and require training and experience to operate properly, the instruments provide high temporal resolution, enabling real-time water potential responses to be monitored. The stem psychrometer differs from the pressure chamber.
technique because measurements are automatically collected at programmed intervals without continuously preparing plant samples. Overall it requires less labour compared to the pressure chamber technique since instruments only require one proper installation to collect WP measurements.

Figure 1.8 - The chamber of an automated *in situ* stem psychrometer sealed on to a stem of a plant, which houses two chromel/constantan thermocouples. The C-thermocouple junction is responsible for measuring the wet bulb depression of the chamber air, and the S-thermocouple junction establishes contact with the stem surface to measure the temperature of the evaporating surface of the sample. Initially, the dry bulb temperature (chamber temperature) is taken before a Peltier cooling current is applied to the C-thermocouple. Based on evaporation rate within the chamber, the wet bulb depression is measured and corrected for temperature and calibration coefficients to determine the water potential of the stem.
1.6 Plant physiology and environmental interaction

Plant-water absorption and distribution is essential for plant growth. Several environmental factors such as temperature, humidity, radiation, and soil moisture play an important role in the balance and movement of water within the plant. Water initially absorbed by the roots is pulled upwards into the leaves via transpiration and is lost to the atmosphere. This process is referred as the Soil-Plant-Atmosphere-Continuum (SPAC) (Figure 1.9).

**Figure 1.9** - The Soil-Plant-Atmospheric-Continuum (SPAC) illustrating the movement of water through a plant. The direction of water movement is indicated by the blue lines and
arrows; representing absorption to transpiration within the plant. The direction of organic material transport is indicated by the orange line and arrows; travelling through the phloem. As leaves transpire the water potential of the leaves decreases, thus generating a potential gradient to move water molecules upwards to the leaves. In turn this generates a lower water potential at the base of the plant and moves water from the roots into the xylem. These are a series of potential differences that transport water through the plant. Image modified from [http://guide.makebonsai.com/how-to-water-bonsai](http://guide.makebonsai.com/how-to-water-bonsai).

1.6.1 Water and vapour pressure

As water is pulled through the plant, it takes the form of either liquid water or gaseous water vapour. These two phases of water are fundamental in understanding plant-water relations. Liquid water is continually attempting to establish vapour saturation in the atmosphere through evaporation. As liquid water evaporates into water vapour molecules (gaseous phase) the pressure of the vapour increases. The difference in vapour pressure between the atmosphere and the plants internal water vapour in sub-stomatal cavities acts as a driving force pulling water through the plant (Figure 1.10).
Figure 1.10 – Gas exchange (CO\textsubscript{2}) and water vapour (H\textsubscript{2}O) from the cross-section of a stomate on a leaf. During transpiration, the guard cells of the stomata open to perform CO\textsubscript{2} gas exchange. The CO\textsubscript{2} concentration is different at various locations. The internal, surface, and ambient concentrations are represented by e\textsubscript{i}, e\textsubscript{s}, and e\textsubscript{a}, respectively. In return, gaseous water vapour (H\textsubscript{2}O) escapes from the sub-stomatal cavity into the environment based on a concentration gradient. Image was obtained from the Food and Agriculture Organization of the United Nations (FAO) - http://www.fao.org/docrep/w5183e/w5183e04.jpg
1.6.2 Cohesion theory

In general, the cohesion theory describes the upward movement of water from the roots to evaporating surfaces of the leaves (Figure 1.9). The concentration difference of water vapour found between the environment and the plant is the main cause for water loss via transpiration. On a daily basis, the plant is opening and closing its stomata to capture carbon dioxide molecules for photosynthesis. During the opening phase of the stomata, vapour concentration differences between the leaf and the environment dictate the amount of water transpired to the atmosphere. Because water has high cohesive properties, as water vapour molecules are lost from the stomatal cavities of the leaf to the atmosphere, liquid water is pulled through the water column in the xylem (Kramer and Boyer, 1996). Under dry atmospheric conditions, the leaf-to-air vapour concentration difference is greater and induces a stronger pull that transpires more water from the leaf. In moist atmospheric conditions the concentration difference is less, therefore the magnitude of the pull is less. In addition, as water molecules leave the plant, the leaf water potential decreases creating a differential between the leaf and lower parts of the plant. Water is replenished based on the potential gradient that is generated (Kramer and Boyer, 1996). Figure 1.9 is an illustration of the water movement through a plant.

1.7 Irrigation Scheduling with Current Technology

The issues involved with current nursery water management practices can lead to negative environmental impacts. As previously discussed, overwatering hinders the plants ability
to grow effectively and puts the environment at risk for eutrophication. The decision to irrigate a fixed volume of water on a daily basis, regardless of actual plant requirements, is to ensure that water is never a limiting growth factor. The value a nursery assigns to a tree is largely based on agronomic measurements (e.g., caliper and height); the larger the tree the higher the potential selling price.

A drawback to irrigating nursery crops on a daily basis, aside from inefficient water use, is the preconditioning of the plants to high soil moisture environments. When the crops are sold and transplanted to a new location (recreational space and residential areas), irrigation frequency is significantly reduced and soil moisture is typically lower. These pre-conditioned trees may not be able to respond quickly enough to the relatively dry conditions, leading to poor performance and even loss of the tree.

Despite the research on different irrigation scheduling techniques or water conservation tools, the key to a successful nursery is adapting new technologies that improve water use, nutrient use, and plant quality management. The future of water conservation among nursery operations will be the combined influences of scheduling proper irrigation events, retrofitting irrigation and drainage systems to reduce water waste, and the development of a simple tool that allows growers to easily incorporate demand-based irrigation scheduling into their daily tasks.
1.8 Objectives

Incorporating an effective irrigation schedule protocol was a key component in nursery water conservation. This ensures the plant receives a sufficient amount of moisture at an appropriate time for the plant to grow effectively throughout the growing season. Conventional methods based on subjective observations of plant characteristics, demand-based systems, and soil-water based systems all lack direct measurement of plant-water status to determine the plants need for water. It is understood that all environmental variables contribute to the diurnal response of plant-water status and establishing a relationship between plant-water status and environmental variables can provide a simple method using environmental variables to predict plant-water status. In this study, the environmental demand for moisture will be represented by the vapour pressure deficit (VPD), which is clearly understood to drive evapotranspiration, and the supply of moisture will be represented by irrigation and precipitation events. The main difference from similar studies in the past is that direct measurements of plant water potential in response to these environmental variables were included using *in situ* stem psychrometers. The presented research assessed the effects of irrigation scheduling based on the relationship between cumulative water potential and cumulative VPD.

Each field season discussed in Chapters 2, 3, and 4 was a successive steps in quantifying and modifying conventional irrigation protocols. The 2012 and 2013 field studies were taken as representative measurements of each species under high (2012 field study) and low (2013 field study) stressed conditions (Objective 1). The 2012 field study simulated transplant stress in field-
grown and manually irrigated conditions. The trees were transplanted to a location with poor soil conditions and full sun exposure. In comparison, the 2013 field study trees were grown in containers, irrigated by drip emitters and surrounded by neighbouring trees which provided shaded conditions with cooler temperatures. Despite these differences, the measurements collected from these studies were taken as baseline responses of each species under high and low stressed conditions. After establishing baseline high and low stressed conditions, irrigation scheduling protocols were modified in the 2014 field study. These baseline measurements were used to establish the relationship of cumulative water stress and concurrent cumulative environmental demand to understand how each plant species responds to the environment (Objective 2 and 3). Further modifications were made in the final field study in 2015, which used the relationship between cumulative water stress and cumulative environmental demand to schedule irrigation events based on environmental demand to predict cumulative water stress (Objective 4).

The null hypothesis:

There is no relationship between plant water stress, as expressed by cumulative stem water potential, and environmental demand, as expressed by the cumulative vapour pressure deficit (VPD), in the nursery trees in this study.
The objectives of this study were to:

1. Assess conventional irrigation scheduling protocols by quantifying the range of cumulative water stress and concurrent cumulative environmental demand thresholds using *in situ* stem psychrometers and a conventional weather station (Chapter 2).

2. Evaluate the relationship between cumulative water stress and cumulative vapour pressure deficit in two nursery tree species (Chapter 3).

3. Establish cumulative water stress thresholds, measured with *in situ* stem psychrometers, as an irrigation schedule trigger which is influenced by cumulative environmental demand (Chapter 3).

4. Establish cumulative environmental demand thresholds based on cumulative vapour pressure deficit as an irrigation schedule trigger and confirm the effects on cumulative water potential (Chapter 4).
Chapter 2  Evaluation of conventional irrigation scheduling practices

2.1  Introduction

Irrigation scheduling is the key to success with any irrigation scheduling practice, regardless of the irrigation delivery system. Nursery production systems are likely to schedule irrigation events based on field experience and observation of plant physiology (leaf colour, leaf wilting, soil moisture, and gravimetrically by weight). Although this scheduling technique is easily implemented, it promotes a subjective nature to irrigation management practices and lacks the ability to measure plant water stress quantitatively.

Among the three different types of quantitative irrigation scheduling techniques discussed in section 1.5, it is difficult to determine which is the most effective for plant growth and the simplest for a grower to implement. Some irrigation scheduling techniques require heavy monitoring and expensive instrumentation to properly determine irrigation frequency and amount; however, the benefit of committing to an irrigation schedule based on plant water status has been demonstrated to achieve a 20 – 30% reduction in water use (Neilsen and Neilsen 2002). From section 1.5, demand-based, and soil-water based irrigation scheduling relies on indirect (to the plant) parameter monitoring such as meteorological measurements, soil moisture content, or container weight (Howell and Meron, 1998). On the other hand, plant water status scheduling relies on a direct plant measurement in terms of water potential (MPa) to trigger irrigation. Although demand-based and soil-water scheduling are typically less expensive and requires less
maintenance, they lack a direct measurement of plant water potential (status). Implementing an irrigation schedule based on plant water status could prove to be a more effective technique due to the direct measurement of plant water potential.

This study is part of a larger study which determines the baseline of cumulative water stress for common tree species under drip irrigation systems. The objective of this study was to measure cumulative plant-water potential (MPa*Hrs) of two nursery tree species subjected to conventional nursery irrigation management practices to determine the levels of water stress exhibited by these trees under prevailing environmental conditions. After establishing the cumulative water stress of conventional irrigation practices, the cumulative water stress measurements extracted from a high-stressed transplant study were used to provide a basis for modifying the irrigation schedules for these trees.

2.2 Material and Methods:

2.2.1 Site description

The experimental site was located at Connon Nurseries C.B. Vanderkruk Holdings Ltd. (Waterdown, ON, Canada). Measurements were taken at two separate production beds based on the location of the tree species. Data collection was initiated at production bed I (N 43° 21’ 11.6”, W 79° 54’ 31.8”) on August 2nd 2013 and ran through August 16th 2013 for Red maple – Acer
rubrum (L.) ‘Brandywine’ and Eastern white cedar – Thuja occidentalis (L.) ‘Smaragd’. Data collection was initiated at production bed II (N 43° 21’ 10.2”, W 79° 53’ 42.0”) on August 20th 2013 and ran through September 4th 2013. Each production bed employed an in-ground container system using 38 L (10 gallon) containers. The potting mixture surface was covered with a layer of mulch prepared by Gro-Bark (Ontario) Ltd. (Milton, ON)\(^1\). Water was pumped from a nearby river and stored in a holding pond on nursery property. The nursery used a high pressure drip irrigation system in which each container had a yellow spray stake releasing 0.18 LPM at 30 psi into each container (Netafim, Fresno, CA, USA). In production bed I, each species was assigned to one of two test plots with buffer trees separating the species (Figure 2.1A). The entire experimental plot (EP) was surrounded by two rows of buffer trees to minimize edge effects. Spacing between socket containers was measured to be 0.48 ± 0.2 meters. The trees were placed in close proximity to the power source consisting of a 320-Watt solar panel (Sharp Electronics Corporation, Huntington Beach, CA, USA) connected to a 12-Volt lead-acid car battery (Schumacher Electric Corporation, Mount Prospect, IL, USA). Water potential measurements were initiated on August 2nd 2013 and concluded September 4th 2013 on a total of four different tree species. In situ stem psychrometers and ICT PSY1 data loggers (ICT International Pty., Armidale, NSW, Australia) were attached to each tree species (n=4) to monitor stem water potential (MPa). Due to limited instrumentation, water potential measurements were monitored in two groups of two (species). Stem psychrometers were installed on 8 trees for each species in production bed I. After an approximate 14-day period, sensors were removed, cleaned, and moved to production bed II where they were installed on

\(^1\) Mulch and potting mixtures were provided by the nursery, however it was requested that mixture composition was published and therefore cannot be disclosed.
two new species for the remainder of the measurement period (ending September 4th 2013) (Figure 2.1B).

**Figure 2.1** - Tree arrangements in the field site for production beds I and II of the experiment.

Coloured circles represent production containers monitored by stem psychrometers and grey circles are buffer trees surrounding the experimental trees to mitigate edge effects. (A) Production bed I studied red maple trees represented in red circles, and cedar trees represented by the green circles. (B) Production bed II, tree placement was randomly assigned at this field site where yellow coloured circles represented American aspen - *Populus tremuloides* (Michx.) and orange coloured circles represented Pear tree - *Pyrus calleryana* (Dcne.).
2.2.2 Irrigation management

Irrigation events were scheduled by the nursery field manager at each site. Scheduling was based on meteorological observations and/or physical assessment of the trees during field scouting (leaf colour, leaf wilting, and qualitative soil dryness). The field managers tracked and recorded all irrigation events and provided records at the end of the season. Typical irrigation schedules consisted of a 30 minute irrigation event that was scheduled every other day between 08:30 – 09:30.

2.2.3 Water potential measurements

Water potential responses were measured by *in situ* stem psychrometers paired with PSY1 data logging controllers (ICT international, Armidale, NSW, Australia). For each production bed and all tree species, measurements were collected every 30 minutes. The number of instruments was limited; therefore, the growing season was evenly divided to measure two species continuously at one time. Dividing the growing season into equal sections equated to approximately 14 days for each pair of tree species. After the measurement period of 14 days, instruments were cleaned and installed on the next pair of tree species.

On the stem of each tree, a single edge 0.009 RD razor blade (AccuTec Blades Inc., Verona, VA, United States) was used to scrape away bark and cambium tissue of the tree.
exposing the water conducting tissues on the north side of the tree to reduce large temperature gradients from solar radiation exposure. These installation sites were washed with deionized water and dried with a lint free tissue (KimWipe, Kimberly-Clark Professional, GA, United States). Sensors were installed on the north side of the tree to reduce temperature gradients from incident solar radiation. Fabric batting (Nusso Textiles Ltd.; Toronto, Ontario, Canada) and aluminium foil (Novelis Foil Products; Etobicoke, Ontario, Canada) were used to insulate the instruments from large temperature gradients and to reflect solar radiation (Figure 2.2).

Figure 2.2 – A full stem psychrometer installation on red maple tree. The stem psychrometer is attached to the water conducting tissue of the tree and a vapour seal is applied using silicon grease. Fabric batting and aluminum foil is wrapped around the clamped psychrometer and the signal wires from the psychrometer are attached to a data logger.
Each psychrometer was calibrated in the laboratory in an insulated styrofoam box regulated to 25°C by a temperature controlled water bath. The calibration parameters for each psychrometer were uploaded to the data loggers prior to field deployment. After each measurement the stem psychrometer would run a chamber heating protocol to reduce condensation development within the chamber, which otherwise would interfere with the measurement.

The heating protocol consisted of a heating phase and re-equilibration phase. The heating phase was initialized post-measurement where a resistive heater embedded in the body of the stem psychrometer was turned on for 15 to 90 seconds (based on user settings) to dissipate any condensation. After the heating period had elapsed the heating current was turned off and the psychrometer was allowed to re-equilibrate with the surrounding environment prior to the next measurement. If condensation formed in the chamber or on the thermocouple junctions, then the measurements were confounded as in actuality the sensor was measuring the potential of the condensate solution instead of the plant. Typically this was represented by a zero reading from the instrument.

When water potential measurements were consistently confounded by condensation or measurement sensitivity was reduced, psychrometers were removed from the trees and the chambers were cleaned with a 10 second chloroform wash. If improvements were not seen in water potential measurements, 2M nitric acid was used prior to a second chloroform wash to
return the instrument to working order. A video outlining the installation procedure for the stem psychrometer can be found at http://www.ces.uoguelph.ca/psychrometer_media.shtml.

2.2.4 Meteorological measurements

Meteorological data was collected using a Vantage Pro2 wireless weather station (Davis Instruments Corp., California, USA) (Figure 2.3). Air temperature (°C), wind speed (km·hr⁻¹), precipitation (mm), and relative humidity (%) measurements were collected every 30 minutes throughout the study period. Daytime hours (sunrise to sunset) were based on dates extracted from http://timeanddate.com following the Hamilton, Ontario, Canada location. Only one weather station was available at this time; the weather station was located at the Dundas field site, approximately 10 km away, where the overhead irrigation system was located and was used to approximate weather data for the EP.
2.2.5 Determination and calculation of cumulative water potential thresholds

Spot measurements of water potential have been used to report the predawn and midday water potential (MPa) in numerous studies (Williams and Araujo, 2002; Moriana et al., 2012; Ameglio et al., 1999). Predawn water potential measurements are assumed to represent plant water potentials that are at equilibrium with the soil, thus indicating the soil water available to the plant (Kramer and Boyer, 1996). Midday water potential measurements are indicative of the maximum water stress experienced by the plant over a diurnal cycle. These measurements typically use a pressure chamber at specific times throughout the day. However, plant water stress is cumulative over time and is best represented as an integral of water potential response to
varying soil moisture, radiation, temperature and humidity. Spot measurements of water potential can only describe instantaneous stress, whereas measurements of water potential integrals (MPa*Hrs) can describe the cumulative water potential (stress) over a fixed period.

In general, the daily water potential integral during daytime hours was determined by multiplying the mean water potential by measurement interval (hour(s)) and summed between irrigation events to determine the cumulative water potential integral (MPa*Hrs) for each species. The measurement interval was dependent on the experiment, particularly for this study the measurement interval was 30 minutes per measurement. The daily water potential integral calculation was described in two parts; 1) the daily water potential (DWP) integral described in equation 2.1 ($\Psi_d$) and, 2) the cumulative water potential (CWP) integral ($\Psi_c$) described in equation 2.2. The DWP is the product of water potential (Ψ) and time (t), summed between daylight hours from “sunrise” to “sunset” (n). The CWP integral ($\Psi_c$) is determined by the summation of $\Psi_d$, beginning from the previous watering event (d) until the start of the next irrigation or significant precipitation event (r). Figure 2.5 is a data sample that illustrates the CWP integral calculation.

\[
\Psi_d = \sum_{t=1}^{n} \Psi t 
\] (2.1)

\[
\Psi_c = \sum_{d=1}^{r} \Psi_d 
\] (2.2)
Figure 2.4 – A sample 4-day water potential time course for cedar illustrating the cumulative water potential integral (MPa*Hrs) during daytime hours between irrigation events. The diurnal water potential response is indicated by the green line with vertical error bands representing SEM. The response was smoothed using a loess smoothing algorithm. Grey and white vertical bars indicate night and daytime hours respectively, for Hamilton, Ontario, Canada. Yellow vertical bars indicate a 30 minute scheduled irrigation event.

The average CWP for each species between irrigation events field study were quantified using equations 2.1 and 2.2 and used as a baseline value. Respectively this represented the quantified cumulative stress threshold for each species under high (transplanted conditions) and low stressed conditions (conventional irrigation scheduling).
2.3 Results

2.3.1 Determination of cumulative water potential (CWP) thresholds

Cumulative water potential thresholds for each EP were summarized in Table 2.1. Stem water potential measurements for *Populus tremuloides* and *Pyrus calleryana* were confounded by chamber condensation. Cumulative water potential thresholds could not be determined due to continuous readings of 0 MPa due to condensation buildup. However, CWP data were obtained for cedar and red maple.

Cumulative WP stress thresholds for red maple and cedar were quantified based on two studies to benchmark high and low cumulative stress thresholds, respectively. High stressed thresholds were quantified using the 2012 field study (M. Dixon, personal communication) and low stress conditions were quantified from the 2013 field season as described in this chapter. A mean threshold of -56.08 and -111.14 MPa*Hrs for red maple and cedar, respectively was recorded during repeated high stress and recovery phases throughout the 2012 season (M. Dixon, personal communication). In the second study, the same tree species were irrigated by drip irrigation following the nursery’s irrigation schedule indicated a CWP of -24.55 MPa*Hrs for Red maple and -37.70 MPa*Hrs for cedar between irrigation events. Results are summarized in Table 2.1.
Table 2.1 - Cumulative water potential threshold summary table indicating thresholds (MPa*Hrs) for red maple and cedar. Cumulative stress thresholds were obtained from two studies: 1) High stress control group in 2012 (M. Dixon, personal communication) and 2) a nursery irrigation threshold group from the production bed I in 2013.

<table>
<thead>
<tr>
<th>Species</th>
<th>Mean Cumulative Water Potential (MPa*Hrs)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Irrigation Periods</td>
<td>Stress Threshold (personal communication)</td>
</tr>
<tr>
<td>Red maple</td>
<td>n=2</td>
<td>-56.08 ± 3.88</td>
</tr>
<tr>
<td>Cedar</td>
<td>n=2</td>
<td>-111.15 ± 14.24</td>
</tr>
</tbody>
</table>

2.4 Discussion

To provide quantitative insight into the water stress levels exhibited by red maple and cedar under conventional nursery irrigation scheduling, the CWP values between irrigation events were compared to a previous study. In the previous study (2012), the same tree species were transplanted to a location with poor soil conditions, full sun exposure and irrigation was withheld until a critical water stress threshold was reached (as determined from initiation of stomatal closure or wilting). Although the species used in this study were the same as those in the nursery trial, the production systems were different. In the 2012 field study, plants were transplanted and grown in the field whereas in the 2013 field study plants were grown in field containers and irrigated with drip emitters. Combining these distinct conditions from these two studies, high and mild stress ranges for red maple and cedar were preliminarily quantified.
Despite differences among the experimental procedures, the measurements collected from each study were used as representative responses for each species under high stressed and mild stressed conditions.

Specifically for the conventional nursery irrigation study, the mean CWP of preliminary baseline stress thresholds were affected by several factors such as: irrigation scheduling, production systems, species type, seasonal changes, and stem psychrometer performance. As seen in the data collected during the 2013 season, the study suggested that the irrigation management from the EP rarely allowed plants to accumulate a stress threshold where plants exhibited signs of stress before an irrigation event. A comparison between the results obtained from the high stressed trees in 2012 and the nursery irrigated trees in 2013 indicates that each species must accumulate double the stress levels seen in 2013 to be considered strongly stressed. From these baseline stress thresholds, these two species have been preliminarily tested and the mean high and low stress thresholds have been established. Between these baseline thresholds, a species-specific stress range can be studied with additional testing, as described in the next chapter.
Chapter 3  Modified irrigation scheduling based on preliminary water stress thresholds

3.1 Introduction

Previously quantified CWP thresholds have been established for several ornamental tree species under nursery irrigation management practices. High stress control trees established baseline estimations of CWP for trees under high stress conditions in 2012, while field trials in 2013 established estimations of CWP for trees under mild stressed conditions. These quantified stress levels provided baseline ranges to further investigate and provide a basis to improve current irrigation scheduling protocols.

The baseline estimates of CWP were determined using field-deployed stem psychrometers. These instruments have proven to be valuable research tools in the study of plant water relations and plant-environment interactions. Smart and Barrs (1973) established that 74 – 96% of diurnal variation of water potential can be explained by temperature, radiation, and vapour pressure deficit (VPD). The strong relationship between atmospheric VPD and plant water potential at the whole plant level was chosen as the focus of this study. It was hypothesized that the correlation between these two measurements would provide a means to predict cumulative plant water potential based on the environmental demand for moisture or VPD. Accumulating both measurements of VPD and plant water potential can be used as a guideline to quantify specific levels of stress and stress tolerance. In order to determine a species’ stress tolerance, stress levels
were assigned based on incremental CWP measurements while concurrent CVPD measurements were monitored between irrigation events. The slope response gained from this relationship could allow growers to translate plant stress from easily monitored environmental conditions.

Irrigation stress ranges established in Chapter 2 for two economically important tree species, cedar and red maple, were tested for stress tolerance and the efficacy of using CWP thresholds as an irrigation scheduling protocol. The overall study was to determine the plants’ stress response at incremental stress levels and the strength of the relationship between CWP and CVPD. The objectives of this study were to 1) trigger irrigation events based on predetermined CWP thresholds; 2) relate the CWP values to corresponding CVPD measurements; and, 3) monitor the production effects associated with the modified irrigation scheduling protocols using standard agronomic measurements of each tree species (i.e. caliper and height).

3.2 Materials and Methods

3.2.1 Site description

The study was conducted at Connon Nurseries C.B.Vanderkruk Holdings Ltd. located in Waterdown, Ontario, Canada (N 43° 21’ 24.231”, W 79° 54’34.568”). The experiment ran from June 22nd 2014 to September 9th 2014. Cedar and red maple trees were selected to represent economically important evergreen and deciduous trees, respectively. The container system contained the same potting mixture, mulch mixture, container size, and type of irrigation system
as field site in Chapter 2 (section 2.1.2). However, the yellow spray stake emitters were replaced with PCNL spray stakes of purple grade delivering 0.20 LPM at a controlled pressure of 25 psi (Netafim, Fresno, CA, USA). These spray stakes were deemed superior in maintaining homogeneous water delivery to the containers.

Two rows of 30 trees were arranged parallel to one another with one species assigned to each row. The trees used in the study were surrounded by two rows of buffer trees to mitigate any edge effects. Due to limitations in the irrigation delivery system, treatments were divided in blocks of 10 consecutive trees (Figure 3.1). Water was pumped from a holding pond and distributed throughout the production beds. Water was diverted from the production bed line through a custom two outlet manifold that fed the two irrigation lines, one for each species. The manifold included a flow meter, pressure gauge, and valve switches that allowed monitoring and control of the irrigation flow. For further control, two valve switches were installed after the 10th and 20th tree location, to irrigate specific treatments. The initial group of 10 trees were assigned the mild stress treatment, the next group of 10 trees were moderate stress, and the remaining 10 trees were high stress. The power supply station used the same solar panel and car battery arrangement as the previous year (see section 2.2.1).
**Figure 3.1** - Tree arrangement in the experimental plot for evaluating cumulative water potential thresholds. Water was pumped from the nearby holding pond (reservoir) into one of two irrigation lines, each of which fed a single row of trees (n=30). Cedar trees are represented by the letter T, and Red maple trees are represented by the letter A. Every 10 trees was an assigned stress level. Yellow, blue, and red coloured circles represented containers of mild, moderate, and high stress, respectively. Grey coloured circles represent the buffer row trees; two rows of trees surrounding the experimental plot. Two long pipes were placed on each side of the row with control valves at the beginning of each treatment level and were turned on according to irrigation schedules described below.

### 3.2.2 Modified irrigation management I

Throughout the field trial, trees received water by rain or irrigation. Any significant rain events (rain measurement which accumulated >= 10 mm in a day) or triggered irrigation event were defined as *watering events*. Daily rain measurements that exceeded 10 mm were initially interpreted as a significant rain event that induced a hard reset of CWP thresholds; equivalent to reaching field capacity. Since rain events were random, the 10 mm could be reached within 2 hours or over a period of 18 hours. To establish a rain-buffer range, near the end of the trial, rain measurements were further investigated to validate the effect on plant water status. It was determined that the average time between irrigation events to achieve a significant plant water status response was 75 minutes, any additional time the rain did not have a significant plant
water response. Therefore, the cumulative rain criteria change to include a 75 minute buffer time. It was then decided for the current and future field trials that a continuous rain event which accumulated more than 10 mm of rain with a 75 minute buffer period was sufficient to restore moisture levels back to field capacity on the basis of water potential measurements. If rain was measured after the 75 minute buffer period, the cumulative rain measurement would reset to 0 and the rain event was not considered a hard rest of CWP.

Modified irrigation events were based on lower and upper limit stress ranges covered in Chapter 2. Stress ranges for each species were further developed to form three irrigation regimes of mild, moderate, and high stress. Each scheduled irrigation event had a duration of 30 minutes. Cedar and red maple trees studied in the field site in Section 2.2.1 were selected to study the effects of different irrigation regimes. Thresholds for the modified irrigation treatments are expressed in Table 3.1.

**Table 3.1 - Irrigation scheduling thresholds based on cumulative water potentials for cedar and red maple.**

<table>
<thead>
<tr>
<th>Cumulative Stress Thresholds</th>
<th>Cedar Cumulative Water Potential Threshold (MPa*Hrs)</th>
<th>Red Maple Cumulative Water Potential Threshold (MPa*Hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild Stress</td>
<td>-50</td>
<td>-20</td>
</tr>
<tr>
<td>Moderate Stress</td>
<td>-100</td>
<td>-40</td>
</tr>
<tr>
<td>High Stress</td>
<td>-150</td>
<td>-60</td>
</tr>
</tbody>
</table>

For each stress level, a buffer range (± 15 MPa*Hrs) was subjectively assigned to account for limited access to the field site, since field access was restricted to business days
(Monday to Friday, 07:00 - 16:00). In certain scenarios, plants were unable to receive irrigation due to limited field access which led to exceeded stress thresholds. Therefore, irrigation would occur the next possible field day during times when the field manager was able to turn on pumps and irrigation system.

Three main valve switches were installed in the irrigation system and required specific combination sequences to irrigate specific treatments. Each irrigation line was dependent on the adjacent pipelines for the source of water. As an example, control valve 2 would only receive water if control valve 1 was switched on (Figure 3.2B). Figure 3.2 illustrates all possible combinations that were used to irrigate mild, moderate, and high stress treatments.

**Figure 3.2** - A schematic of control valve (CV) combinations used to irrigation mild, moderate and high stress treatments. Green boxes represent switched on CV, red boxes represent switched off CV, white boxes indicate empty pipelines, blue rectangles represent water-filled pipes irrigating surrounding trees, and blue rectangles with a cross represent water-filled pipes but surrounding trees are not irrigated. Each letter
indicates a specific combination: A) Irrigate mild stress where only CV #1 is active. B) Irrigate mild and moderate stress, where CV#1 and #2 are active. C) Irrigate all stress treatments, where CV #1/2/3 were active. D) Irrigate moderate stress, where CV #1 and 2 are active but drip emitters were plugged in the first block to prevent surrounding trees from being irrigated. E) Irrigate moderate and high stress, where CV #1/2/3 are active but emitters in the first block are plugged to prevent surrounding trees from being irrigated. F) Irrigate high stress, where CV #1/2/3 are active but two blocks of trees are plugged to prevent surrounding trees from being irrigated.

3.2.3 Meteorological measurements

Identical procedures to those covered in 2.2.4 were used for meteorological measurements. The location of the instrument was moved directly on the field site to capture all local meteorological measurements. Changes were made to improve the measurement frequency and “sunrise” to “sunset” timeframes. Briefly, measurements were collected every 15 minutes compared to 30 minutes previously. Solar radiation (W/m²) sensors accurately indicated local sunrise and sunset periods through the field trials rather than using measurements from a secondary service provider. From the radiation sensors, any non-zero radiation measurement was defined as daytime and any zero radiation measurement was defined as nighttime. Maximum and minimum temperatures, and humidity were used to calculate the environmental VPD following procedures outlined by Allen et al. (1998).
3.2.4 Drip emitter calibration

Each spray emitter in the EP (n=60) was gravimetrically measured to determine the total water application per irrigation event. The estimated water applied per 30 minute irrigation was extrapolated from a 10 minute irrigation test. The average water output per 30 minute irrigation was 5.7 ± 0.3 L at 20-30 psi.

3.2.5 Water potential measurements

Water potential measurements for mild and moderate stress treatments were initiated on June 22nd 2014 and high stress measurements were initiated later in the trial on July 23rd due to field and data logging issues. All water potential measurements were stopped on September 8th 2014. Procedures for instrument installation and maintenance were covered in chapter section 2.2.3 and were not altered for this study. Measurement frequency was increased to every 15 minutes for each stem psychrometer installed in order to better capture periods of rapid water potential changes. Each stress treatment was assigned a representative sample of 10 trees. Due to a limited number of stem psychrometers experimental units and arrangement of the irrigation system stem psychrometers were pseudo-replicated. 7 of the 10 trees of each treatment level to randomly be selected for stem psychrometer installation. The remaining trees were still subjected to the same irrigation treatment and used to increase the sample size for agronomic measurements.
There was an insufficient number of PSY1 Dataloggers (ICT International Pty, Armidale, NSW, Australia) to meet statistical significance requirements for the experiment. Therefore, a CR7 Data logger (Campbell Scientific, Logan, Utah, United States) was used as a secondary data logger to ensure sample sizes were statistically relevant. ICT PSY1 data loggers were used on mild and moderate stress treatments, and the CR7 was used on the high stress treatment group due to power distribution limitations.

Wireless telemetry was achieved by connecting a laptop directly to five peripherals:

1) ICT MCC1 communication tower (ICT International Pty Ltd., Armidale, NSW, Australia)
2) Davis wireless weather console (Davis Instruments Corp.; California, USA)
3) CR7 data logger (Campbell Scientific, Logan, Utah, United States)
4) A mobile network connector (Rogers, Toronto, Ontario, Canada)
5) A custom-built mobile switch

This arrangement provided remote access to each data logger and local meteorological data to provide quick access to stem psychrometer and weather data.

### 3.2.6 Agronomic measurements

Tree height and caliper measurements were made prior to and after initiating modified irrigation schedules to estimate the total growth of the trees through the course of the field trials.
Tree heights were measured for cedars, and tree caliper was measured for red maples. The height of the tree was taken as the distance from the top of the socket containers to the apex of the tree (Figure 3.3A). Initial and final measurements of cedar heights were measured on June 10th 2014 and August 29th 2014, respectively. Tree caliper was measured at breast height on the stem of the tree using a CD-4” BS digital caliper (Mitutoyo Corp., Tokyo, Japan) (Figure 3.3B). Initial measurements of red maples were taken on June 12th 2014. A dark marker was used to draw a line at the point of measurement to ensure final measurements were conducted from the same location. Final diameter measurements were taken on September 11th 2014.
Figure 3.3 – (A) Measuring tape stretched to the apex of a cedar tree for height measurements. (B) Tree diameter measurements conducted with a CD-4” BS digital caliper on red maple at breast height on the stem in exactly the same place at both dates.

3.2.7 Statistical Analysis

Statistical analyses were conducted with SAS 9.4 (SAS Institute Inc., Cary, NC, USA) on CWP between significant watering events during daytime hours, slope responses (CVPD plotted against CWP), and agronomic measurements using a mixed model procedure (PROC MIXED). A repeated measures statement found in the mixed model procedure was included to analyze
CWP between watering events throughout the field trials. Cumulative slope responses followed the standard PROC MIXED procedures with no repeated measures statement on the field trial dataset. Agronomic measurements were analyzed by using analysis of variance (ANOVA) to determine significant differences in height and diameter growth throughout the period. All analyses were conducted with a type I error rate of 0.05 with a Tukey-Kramer p-value adjustment.

3.3 Results

Figure 3.4 and 3.5 are a representative sample (8-day period) of data collected to illustrate concurrent measurements of mean water potential and VPD response for cedar and red maples. Water potential response for each stress level were represented by a specific colour; yellow represented mild, green represented moderate, and red represented high stress. As expected, the diurnal patterns of water potential mirrored the concurrent measurements of VPD. A rise in VPD, corresponded to an increasingly negative water potential. As VPD falls, there is a corresponding rise (less negative) in water potential.
Figure 3.4 - A) Time course of concurrent VPD measurements and B) Mean water potential responses comparing incremental stress levels for cedar (n=7) during an eight-day dataset from August 18th 2014 – August 25th 2014. Watering events were manually scheduled irrigation events and did not represent a significant rain event. Full vertical blue bars indicate a significant watering event which affected all treatments, and the partial vertical blue bars only affected the mild treatment. Each treatment level has vertical error bands which are ± SEM. Measurements for plant water status and environmental response were taken every 15 minutes. Mild, moderate, and high stress treatments are represented in yellow, green, and red respectively. Alternating grey and white bars indicate night and daytime hours.
Figure 3.5 - A) Time course of concurrent VPD measurements and B) Mean water potential responses comparing incremental stress levels for red maple (n=7) during an eight-day dataset from August 18th 2014 – August 25th 2014. Watering events were manually scheduled irrigation events and did not represent a significant rain event. Full vertical blue bars indicate a significant watering event which affected all treatments, and the partial vertical blue bars only affected the mild treatment. Each treatment level has vertical error bands which are ± SEM. Water potential response (MPa) with corresponding vapour pressure deficit (kPa) measurements were taken every 15 minutes. Mild, moderate, and high stress treatments are represented in yellow, green, and red respectively. Alternating grey and white bars indicate night and daylight hours.
3.3.1 Irrigation events triggered by cumulative water potential

Figure 3.6 compares the mean CWP measured for each treatment level of cedars. As expected, the mild stress treatment accumulated the largest number of watering periods (27) and a mean CWP of -54.68 ± 9.57 MPa*Hrs. The moderate stress treatment accumulated 21 watering events with a mean CWP of -93.90 ± 10.86 MPa*Hrs. The high stress treatment accumulated 8 watering events with a mean CWP of -154.12 ± 17.59 MPa*Hrs. Compared to the assigned CWP thresholds, the mean CWP fell within range for each assigned stress threshold (Table 3.1). A multiple comparison test indicated significant differences between all treatments (Figure 3.6).

Figure 3.6 - Mean cumulative water potential (MPa*Hrs) measured for cedar for mild, moderate, and high stress treatments. Mild and moderate were initiated June 22th 2014. Due to instrumentation issues, high stress treatments were initiated a month later on July
23rd 2014. Irrigation scheduling of the treatments was completed on – September 6th 2014 for all stress treatments. Vertical error bars are ± SEM with the number of watering events indicated in each bar (“n=”).

Figure 3.7 shows a comparison of mean CWP between stress treatment levels (mild, moderate, and high) for red maple trees. Mild stress treatments were irrigated most frequently with 30 watering events giving a mean CWP of -24.71 ± 4.57 MPa*Hrs. Moderate stress treatments accumulated 26 watering events and a mean CWP of -44.37 ± 4.91 MPa*Hrs. High stress treatments accumulated 9 watering events and a mean CWP of -94.26 ± 8.35 MPa*Hrs. The mean CWP for the high stress treatment exceeded the assigned CWP threshold (Table 3.1). A comparison of stress levels indicated significant differences between mild to moderate stress (p = 0.013), mild to high stress (p < 0.0001), and moderate to high (p < 0.0001).
Figure 3.7 - Mean cumulative water potential (MPa*Hrs) measured for red maple for mild, moderate, and high stress treatments. Mild and moderate stress were initiated June 22th 2014. High stress treatments were initiated a month after on July 23rd 2014 due to instrumentation issues. Irrigation scheduling of the treatments was completed on September 6th 2014. Vertical error bars are ± SEM with the number of watering events indicated by “n=”.

3.3.2 Cumulative water potential and vapour pressure deficit relationship

Figure 3.8 shows the linear relationship between CVPD and CWP for cedar trees under each stress treatment. All linear relationships were combined together which generated a generalized combined slope response to represent each tree species response. Mild, moderate,
high and combined stress exhibited slope responses of -1.6, -2.4, -2.6, and -2.4 MPa*Hrs / kPa*Hrs (CWP/CVPD) respectively. The combined slope encompassed all CVPD measurements and CWP to form a combined slope used to further develop irrigation scheduling protocols. A multilevel comparison of each slope response indicated that mild and moderate stress (p < 0.0001), mild and high stress (p < 0.0001), and moderate and high stress (p = 0.039) were significantly different. A zero slope test indicated that at all treatment levels the CWP and CVPD were significant different (p < 0.0001).

![Figure 3.8](image.png)

**Figure 3.8** - The linear relationship of cumulative vapour pressure deficit (CVPD) and cumulative water potential (CWP) between watering events during daytime hour(s) for cedar at each treatment level. The combined slope response consisted of CVPD and CWP from all treatment levels.
Figure 3.9 illustrates the linear relationship of CVPD and CWP between watering events during daytime hours for red maple trees at each stress level. Mild, moderate, high and combined exhibited slope responses of -0.88, -1.4, -1.7, and -1.5 MPa*Hrs / kPa*Hrs (CWP/CVPD) respectively. The combined slope encompasses all CWP measurements and CVPD to form an overall slope used to further develop future irrigation scheduling protocols. A multilevel comparison of each slope response between stress treatment groups indicated mild to moderate stress (p < 0.0001), mild to high stress (p < 0.0001), and moderate to high stress (p < 0.0001) were significantly different. A zero slope test indicated that at all treatment levels the CWP and CVPD were significant different (p < 0.0001).
Figure 3.9 - The linear relationship between cumulative vapour pressure deficit (CVPD) and cumulative water potential (CWP) between watering events during daytime hour(s) for red maple for each stress treatment level. Mild, moderate, high, and combined slope responses are indicated consecutively along the top of the figure, where the combined slope of CWP and CVPD consisted of data from all treatments levels.

3.3.3 Agronomic measurements and water application

Figure 3.10 illustrates the mean cedar height increments for each treatment level from pre- to post-experiment (June 10th 2014 to August 29th 2014). The largest increase in height was observed in the nursery irrigation protocol (8.86 ± 1.29 cm). Mild, moderate, and high stress treatments showed similar increases in height, 1.41 ± 0.35 cm, 1.15 ± 0.35 cm, and 1.2 ± 0.29
cm, respectively. A multi-group comparison indicated height increases in nursery irrigated trees were significantly different from mild, moderate, and high stress treatments (p < 0.0001). No significant differences were found between mild, moderate, and high stress treatments.

Figure 3.10 - Mean height increments of cedar based on measurements from the start and end of the field trials (June 10th 2014 to August 29th 2014). Nursery irrigated trees were located adjacent to the experimental plot, however irrigation scheduling was based on nursery irrigation protocols. Mild, moderate and high stress treatment groups were monitored from the start to the end of the field trials and irrigated based on predetermined irrigation scheduling triggers.
Agronomic measurements for cedar paired with corresponding water application measurements are summarized in Table 3.2. Nursery irrigated trees had the largest number of irrigation applications totalling 68 events and an application volume of 387.6 ± 23.12 L. Mild, moderate, and high stress treatments were irrigated 18, 11, and 3 times with an application volume of 102.6 ± 6.12, 62.7 ± 3.74, and 17.1 ± 1.02 L respectively. Nursery irrigated trees received 3 times more volume of water compared to the mild stressed trees. Differences between mild, moderate, and high stressed trees showed no significant difference in height increment; however, volume of water applied to a tree showed approximately 40 L difference between treatment levels.

Table 3.2 - Mean height increment (cm) measurements taken at the start (June 10th 2014) and end of the trial (August 29th 2014) for cedar. The number of irrigation events for each treatment level were counted and used to determine volume of water applied (L) to a single tree based on the drip emitter calibration (5.7 ± 0.34 L/irrigation event) during the field trial from June 22nd 2014 to September 6th 2014.

<table>
<thead>
<tr>
<th>Cumulative Stress Treatments</th>
<th>Agronomic Measurements</th>
<th>Water Application</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Height Growth (cm)</td>
<td>No. of Irrigation Events</td>
</tr>
<tr>
<td>Nursery</td>
<td>8.86 ± 1.29&lt;sup&gt;a&lt;/sup&gt;</td>
<td>68&lt;sup&gt;y&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mild Stress</td>
<td>1.41 ± 0.35&lt;sup&gt;b&lt;/sup&gt;</td>
<td>18</td>
</tr>
<tr>
<td>Moderate Stress</td>
<td>1.15 ± 0.35&lt;sup&gt;b&lt;/sup&gt;</td>
<td>11</td>
</tr>
<tr>
<td>High Stress</td>
<td>1.2 ± 0.29&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3&lt;sup&gt;x&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Drip emitter calibration was measured to be 5.7 ± 0.34 L/irrigation event. Each scheduled irrigation event was set to 30 minutes.

<sup>b</sup> Number was estimated based the nursery irrigation protocol. Irrigation was initiated every day except for rainy periods.

<sup>x</sup> Measurements for high stress treatment did not commence until July 23rd 2014 due to instrumentation connectivity issues.
Figure 3.11 shows the mean red maple caliper increment for each treatment level. Caliper increments were the largest for nursery irrigated trees and the lowest for high stressed treatments. A multiple comparison test of mean caliper measurements showed no difference between nursery versus mild, mild versus moderate, and moderate versus high stressed trees. Mean caliper increment between nursery irrigated trees versus moderate and high stressed trees (p = 0.001, and p < 0.0001, respectively) were significantly different. Mild stressed trees were also significantly different from high stressed trees (p = 0.02).

![Figure 3.11 - The mean caliper increment on red maple from measurements taken pre- and post-experiment (June 12th 2014 – September 11th 2014). Nursery irrigated trees were located within the same EP except irrigation scheduling was based on the nursery irrigation operator. Mild, moderate and high stress treatment groups were monitored from the start to the end of the field trial by predetermined irrigation scheduling triggers.](image-url)
Red maple caliper and water applications (Table 3.3) were used to illustrate the effect of water on tree caliper. Nursery irrigated trees received the largest volume of water with 387.6 ± 23.12 L which translated to the largest mean caliper increment of 3.04 ± 0.19 mm. The high stressed trees received the lowest volume of water with 34.2 ± 2.04 L which corresponded to a caliper increment of 0.95 ± 0.19 mm. Caliper increments from the mild stress were not significantly different from the nursery irrigated trees, however the nursery trees received 3x the number of irrigation events and volume of water.

Table 3.3 - Mean caliper increment (mm) measurements taken pre- (June 12th 2014) and post-experiment (Sept 11th 2014) for red maple. The number of irrigation periods for each treatment level were counted and used to determine the volume of water applied (Liters) to a single tree based on the drip emitter calibration during the field trials from June 22nd 2014 to September 6th 2014.

<table>
<thead>
<tr>
<th>Cumulative Stress Treatments</th>
<th>Agronomic measurements</th>
<th>Water Application</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Caliper Increment (mm)</td>
<td>No. of Irrigation Events</td>
</tr>
<tr>
<td>Nursery</td>
<td>3.04 ± 0.19&lt;sup&gt;a&lt;/sup&gt;</td>
<td>68&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mild Stress</td>
<td>2.09 ± 0.48&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>21</td>
</tr>
<tr>
<td>Moderate Stress</td>
<td>1.32 ± 0.20&lt;sup&gt;b&lt;/sup&gt;</td>
<td>17</td>
</tr>
<tr>
<td>High Stress</td>
<td>0.95 ± 0.19&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>1</sup> Drip emitter calibration was measured to be 5.7 ± 0.34 L/irrigation event. Each scheduled irrigation event was set to 30 minutes.

<sup>2</sup> Number was estimated based the nursery irrigation protocol. Irrigation was initiated every day except for raining periods.

<sup>3</sup> Measurements for high stress treatment did not commence until July 23rd 2014 due to instrumentation connectivity issues.
3.4 Discussion

3.4.1 Mean cumulative water potential measurements

The mean CWPs were used to quantify water stress between irrigation events during daytime hours. Each stress level showed different irrigation frequencies and variation from one irrigation period to another; variability was due to uncontrollable precipitation amounts and durations. Based on the CWPs from each watering event, it was observed that rain events reduced the: 1) ambient environmental demand for moisture and 2) total accumulative water stress (CWP).

Throughout the course of a rain event, the environmental demand for moisture (VPD) was typically reduced (~0 kPa) and as a result WP measurements remained steady (minimal fluctuations in water potential). Figures 3.6 and 3.7 showed that the rate of CWP change was dependent on diurnal fluctuations of stress and recovery in WP. Under stressed periods, the stress integrals increased negatively and increased the rate of cumulative water stress. Likewise, periods of recovery stress integrals increased positively and reduced the rate of cumulative water stress.
In addition to reduced environmental demand for moisture and its effect on CWP, rain events independently prompted a hard reset on CWP (>= 10mm of rain). Despite defining both irrigation and rain as “watering events” the plants responded differently to manually irrigated events compared to resets triggered by rain. In some scenarios affected by rain, CWP measurements were reset to 0 MPa*Hrs in the midst of accumulating stress before the assigned stress limit was reached. It is not certain that the rain threshold of 10 mm was sufficient to equate to a CWP-triggered irrigation event, however diurnal WP response indicated a recovery similar to an irrigation event. A consideration of rain intensity could provide support in estimating the volume of rain required to return plants to field capacity. Therefore, due to this uncertainty the variability of mean CWP measurements was increased.

Although both significant rain and irrigation events were responsible for returning moisture levels of the plants to field capacity, the effects of the method of application (drip emitters versus precipitation) on cumulative stress levels were different. Further investigation is required to determine the impacts of these differences.

3.4.2 Slope response of CWP and CVPD

The slope response was an indication of stress levels exhibited by each treatment of each species in relation to corresponding CVPD in units of MPa*Hrs / kPa*Hrs. The study indicated strong correlation between CVPD and CWP in both species which indicates that these responses may provide growers with the ability to predict water status by simply monitoring and
accumulating VPD with a conventional weather station. Due to the technical skill associated with
the stem psychrometer, the technology transfer is for the growers to use the conventional weather
station to predict the plant water response (confirmed by the stem psychrometer), rather than
deploying the psychrometers themselves. The slope response would need to be defined for
specific production factors such as pot size, substrate and species type.

Different plant species were expected to respond differently to similar environmental
conditions and corresponding water stress. As seen in Figure 3.8 and 3.9 (representative of an
evergreen and deciduous tree) magnitudes for mild, moderate, high, and combined groups
indicated noticeable differences in slope responses. Evergreen species represented by cedar had a
combined slope response (-2.4 MPa*Hrs / kPa*Hrs) which was comparatively more negative
than red maple trees (-1.5 MPa*Hrs / kPa*Hrs). These differences could suggest that the slope
responses were an indication of stress tolerance of a particular species. Cedar expressed a more
negative slope, which allowed the species to withstand a larger threshold of stress and
evaporative demand before requiring water. Therefore to obtain species specific slope responses
would require an effort to establish different irrigation regimes and require additional testing to
validate.

Although differences were seen in slope responses from both species, similar trends were
noted. It was observed that as treatments increased in stress (mild to high stress), the magnitude
of the slope response became increasingly negative. Therefore, depending on the irrigation
frequency and stress threshold desired, the slope response may be different and certainly requires further testing to resolve its reliably.

### 3.4.3 Conclusion

Using CWP thresholds to trigger irrigation events resulted in significant differences between stress levels and CWP was strongly correlated to CVPD measurements. This provides a potential tool for growers to schedule irrigation based on environmental measurements from conventional weather stations and predict and manage corresponding water stress levels in plants. Agronomic measurements for cedar showed no differences among the CWP triggered events, however nursery irrigated trees showed a large height increment with significantly more water applied to the trees. Water applications were significantly different between triggered irrigation events; however, heights did not show significant differences based on this season’s data. Red maples indicated no significant difference between the nursery irrigated trees and mild stress treatment, suggesting that optimal irrigation protocols can be found in this range. The strong relationship between CWP and CVPD indicated these quantities were highly related and showed promise that CVPD can be used to predict CWP.
Chapter 4  Modified irrigation schedules based on cumulative vapour pressure deficit thresholds

4.1  Introduction

The preliminary relationship between CVPD and CWP measured from incremental levels of water stress thresholds showed a strong linear correlation for each species; cedar and red maples based on results reported in previous experiments (Chapters 2 and 3). In the previous chapters, irrigation scheduling were triggered by a set CWP stress level. Incremental stress limits (mild, moderate, and high stress) were assigned to each tree species to help gauge the stress tolerance of each plant species and to provide a wide range of CVPD to CWP responses. Based on these responses, a strong relationship ($R^2 > 0.8$) was established for each species between cumulative plant stress (represented by CWP) and environmental demand for moisture (represented by CVPD). To validate the highly correlated relationship (based on measurements of CWP-triggered irrigation events), irrigation events were now being triggered by CVPD to demonstrate the reliability of the relationship to predict CWP.

The same experimental protocol detailed in Chapter 3 for CWP response was used; however, irrigation scheduling was triggered by CVPD stress thresholds rather than CWP. If slope responses were similar to the responses observed in the 2014 field season, taking into account seasonal environmental variability, then CVPD is likely a promising indicator of CWP in terms of evaluating plant water stress for demand-based irrigation scheduling.
Highly correlated slope responses established for cedar and red maples were -2.4 MPa*Hrs / kPa*Hrs and -1.5 MPa*Hrs / kPa*Hrs, respectively. The slope response can be assigned as coefficients of plant water stress per unit of environmental demand for moisture. To validate the slope response of cedar and red maple trees, corresponding CVPD irrigation regimes (mild, moderate, and high stress) were developed from previously established stress levels (chapter 3). Given the high correlation between CVPD and CWP, stress levels should be reliably predicted by CVPD measurements. The objectives of this study were: 1) establish irrigation regimes based on CVPD triggered irrigation events by using stress limits identical to field season 2014; 2) confirm the relationship between CVPD and CWP; and 3) measure the effects of the irrigation management protocols on conventional agronomic variables (i.e., height and caliper).

4.2 Materials and Methods

4.2.1 Site description

The study was conducted at the same nursery as detailed in chapter 3; Connon Nursery C.B.Vanderkruk Holdings Ltd. located in Waterdown, Ontario, Canada. The field site location was moved to a new production bed (N 43° 21’14.1’, W 79° 53’46.5’) to allow broader and more flexible access to the field site. Attempts were made to use the same tree species and varieties as Chapter 3. The nursery was able to provide sufficient quantities of cedar; however, red maple (Brandywine) was unavailable and was substituted with a closely related variety known as ‘Red
sunset’. Container characteristics such as size, potting mixtures, production systems, and types of irrigation systems remained the same as the previous year (see section 3.1). Solar panels were replaced with grid AC power to provide a continuous supply of electricity to the field-based laptops, data logging controllers and irrigation control systems.

### 4.2.2 Experimental design

The field site is schematically presented in Figure 4.1. It was divided into two sections within the production bed. One section was populated with cedar and the other section with red maple. Trees in each section were arranged in a 3 x 12 grid of socket containers (n=36) which were surrounded by a single row of trees that created a buffer zone to minimize edge effects. Each stress treatment (mild, moderate, and high stress) contained 12 trees that were randomized in each section following a completely randomized design (CRD). With a limited number stem psychrometers, only 7 sensors could be allocated among each stress treatment for each species. A secondary randomization for the 7 sensors within each treatment was applied to mitigate any sensor biases. Agronomic and leachate measurements were collected throughout the field trial to determine the effect from each irrigation regime. All 12 trees were subjected to agronomic measurements. Leachate measurements were conducted only on trees without stem psychrometers due to the risk of disturbing WP measurements on those trees.
Figure 4.1– Tree arrangement on the field site at Connon Nurseries C.B.Vanderkruk Holdings Ltd. Red maples are represented by circles labelled with an “A”, Cedars are represented by circles labelled with a T. Each circle is filled with a colour to represent the stress treatment applied; yellow, blue and red represent mild, moderate and high stress respectively. Experimental trees were surrounded by a single row of
buffer trees (checkered pattern) used to mitigate edge effects. Water pumped from
the holding pond was diverted through a manifold which consisted of a filter, flow
meter, and pressure gauge.

4.2.3 Modified irrigation management II

Rain thresholds for resetting the irrigation schedule, irrigation duration, and
instrumentation remained the same as in Chapter 3. Irrigation scheduling was based on CVPD
thresholds (kPa*Hrs) developed from the slope responses of CVPD and CWP between irrigation
events during daytime hours in field trials 2014. Refer to Table 4.1 for cumulative stress levels
for each species. Drip emitter output calibrations were conducted following the same
methodology outlined in Chapter 3 with both nursery drip emitters (yellow stake 0.18 LPM) and
EP emitters (PCNL purple stake at 0.2 LPM), except the sample size of drip emitters increased
from 10 to 12 emitters. The mean output from each EP drip emitter was 6.00 ± 0.03 L and from
the nursery drip emitters was 9.34 ± 0.31 L per 30 minute irrigation.

Table 4.1 – Summary table outlining measurements obtained from field season 2014 (Chapter 3)
which were used to develop CVPD stress levels to trigger irrigation events in field season 2015.
In field season 2014, irrigation events were triggered by predefined CWP stress levels, outlined
in the third column. These values were related to concurrently calculate CVPD and developed
slope responses for each species (fourth column). Species specific slope responses for cedar and
red maple from field season 2014 (Chapter 3) were further used to determine CVPD stress levels (fifth column) to trigger irrigation events for field season 2015.

<table>
<thead>
<tr>
<th>Tree Species</th>
<th>Stress Treatment Level</th>
<th>Cumulative Water Potential Stress Levels Assigned In 2014 (MPa*Hrs)</th>
<th>Slope Response Determined From Field Season 2014 (MPa<em>Hrs / kPa</em>Hrs)</th>
<th>Corresponding Cumulative VPD Stress Levels Based On CWP From 2014 (kPa*Hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cedar</td>
<td>Mild stress</td>
<td>-50</td>
<td>-2.4</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Moderate stress</td>
<td>-100</td>
<td>-2.4</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>High stress</td>
<td>-150</td>
<td>-2.4</td>
<td>66</td>
</tr>
<tr>
<td>Red maple†</td>
<td>Mild stress</td>
<td>-20</td>
<td>-1.5</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Moderate stress</td>
<td>-40</td>
<td>-1.5</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>High stress</td>
<td>-60</td>
<td>-1.5</td>
<td>42</td>
</tr>
</tbody>
</table>

† Thresholds were based on the ‘Brandywine’ variety, however ‘Red sunset’ was substituted for this field season due to availability issues with ‘Brandywine’ variety.

4.2.4 Meteorological measurements

All meteorological measurements, temporal resolution, and instrument settings remained the same as described in chapter 3 section 3.5.

4.2.5 Water potential measurements
Water potential measurements were collected from June 16th 2015 to September 17th 2015. Installation and maintenance procedures were identical to those outlined in Chapter 3. Midway through the experiment, a dark discolouration started to develop around the area where stem psychrometer were installed on red maple trees (Figure 4.2A). Swab samples were taken and plated on Potato Dextrose Agar (PDA) with 100 mg/l of Streptomycin Sulfate and 50 mg/l of Ampicillin antibiotics. The fungus was identified as *Alternaria alternata*, an opportunistic pathogen. A cleaning procedure was immediately added to the sensor installation and maintenance protocol and applied to all subsequent installations. A 20% diluted bleach solution (Lavo Inc., Montreal, Quebec, Canada) was used to disinfect all tools and installation sites to prevent further contamination by the fungus. Installation sites indicated by the annotated red box were the sites of water conducting tissue exposed over which the stem psychrometers were sealed. While infected installation sites were completely black (Figure 4.2A), after conducting a cleaning procedures and scraping off the contaminated layer, the cleaned installation site improved (Figure 4.2B). Water potential measurements resumed their expected diurnal response for an average 4 to 5 day period however, if installation sites became infected once again, diurnal water potential response showed symptoms of condensation where water potential measured 0 MPa.
Figure 4.2 – (A) *Alternaria alternata* infected installation site, (B) washed and cleaned installation site. The installation site was defined as the water conducting tissue against which the psychrometer chamber was sealed. A and B illustrate the difference between infected and cleaned installation sites on red maple trees. The black ring surrounding the installation site was the initial symptom that the fungus had infected the tree. Black pigment found in panel A was the sign of a tree heavily affected by the fungus, whereas in panel B typical conditions had a lighter brown ring which showed signs of moisture build up around the outside of the psychrometer from a previous rain event or morning dew.
4.2.6 Leachate collection

Leachate samples were collected throughout the field season to determine the volume of leachate (L) from the container after a 30 minute irrigation event. Leachate collection began on July 10th 2015 and continued through September 1st 2015. Measurements on all treatment levels were conducted on the treated trees without installed stem psychrometers (n=5). Trees without stem psychrometers were used for collecting leachate data because any physical disruption, such as that occurring during leachate collection would possibly compromise the psychrometer installation and lead to unnecessary gaps in the monitored data.

Ten to fifteen minutes before a scheduled irrigation event, a catchment system was prepared for water collection (Figure 4.3). The trees without stem psychrometers were removed from their sockets and the socket was lined with a black plastic bag (Figure 4.3A). The production container was then suspended approximately 20 cm above the socket container using wood risers (Figure 4.3B), allowing sufficient space for the free flow of drainage into the lined socket container. After the catchment system was prepared, a 30 minute irrigation event was initiated. Following the irrigation, an additional 10 minutes elapsed to allow for complete drainage before the socket liner was removed and the plastic bag was weighed (Mettler-Toledo, OH, United States).
4.2.7 Agronomic measurements

Cedar height and red maple caliper were the agronomic measurements taken monthly to determine the effect of different irrigation regimes on growth rates. Tree height and caliper measurements (Figure 4.4) followed the same procedures outlined in Chapter 3 – section 3.6. Tree caliper measurements were taken 30 cm from the root ball following nursery standards. A dark line was made to indicate the location of caliper measurements, to ensure subsequent measurements were measured at the same location.
Figure 4.4 – A digital caliper measuring diameter of a red maple tree at 30 cm from the root ball of the tree.
4.2.8 Cumulative vapour pressure deficit determination

Every 15 minutes, meteorological measurements were collected (solar radiation, humidity, and temperature) to calculate daily VPD values based on Allen et al. (1998). Daily and cumulative calculations for VPD followed equations (2.1) and (2.2), see Chapter 2 – section 2.7 for further details. In terms of rain, cumulative rain events that exceeded 10 mm of rain per day were treated as a hard reset on CVPD measurements.

4.2.9 Statistical Analysis

Statistical analysis was conducted using SAS 9.4 (SAS Institute Inc., Cary, NC, USA) to determine differences between stress treatments of each species. The analysis focused on comparing stress treatments for: (1) mean CWP between irrigation events, (2) CVPD and CWP slope response, (3) slope comparisons on cumulative growth from each agronomic measurements for each tree species during growth periods. The growth period of the field trials extended from June 16th 2015 – September 7th 2015, and was separated into three growth periods to determine monthly differences which may occur during the growth season. Growth period 1 was designated from June 16th 2015 to July 15th 2015, growth period 2 was designated from July 16th 2015 to August 16th 2015, and growth period 3 was designated from August 17th 2015 to September 7th 2015. Each analysis utilized SAS’s PROC MIXED with repeated measures, which followed a type I error rate of 0.05 and used Tukey-Kramer multiple comparison p-value adjustments.
4.3 Results

Figures 4.5 and 4.6 show a 7-day sample of mean diurnal water potential and corresponding VPD measurements for cedar and red maple, respectively. Irrigation events throughout the field season were triggered by CVPD stress levels indicated on Table 4.1. Coloured vertical columns indicate a scheduled irrigation event for each stress treatment where yellow columns were mild stress, green columns were moderate stress, and red columns were high stress treatments that received a 30 minute irrigation. After completing an irrigation event, water potential rose indicating recovery from the imposed water stress. These plots were used to illustrate the frequency of each irrigation event and the effect on water potential. As expected, a rise in VPD corresponded to a fall in water potential. Stress responses in each treatment showed distinct separation during the drying phase. Of necessity, irrigation events were not synchronized because they were all scheduled to irrigate based on the CVPD thresholds.
Figure 4.5 - A 7-day sample dataset representing the time course of mean diurnal water potential response (MPa) and concurrent vapour pressure deficit (kPa) with measurements taken every 15 minute intervals for cedar trees. Data collected for each treatment group (n=7) were smoothed via a loess smoothing algorithm. Daily rhythms of plant stress (increasingly negative water potential) and recovery (decreasingly negative water potential) response of trees are fully represented, with the time course before and after irrigation events based on CVPD. Scheduled irrigation events are represented by colour coordinated vertical bars for each treatment level; yellow represents mild stress, green represents moderate stress, and red represents high stress. Alternating grey and white vertical bars indicate night and daytime hours measured by a solar radiation sensor built onto the Davis wireless weather station. For each treatment level, vertical error bands are ± SEM.
Figure 4.6 - A 7-day sample dataset representing the time course of mean diurnal water potential response (MPa) and concurrent vapour pressure deficit (kPa) with measurements taken every 15 minute intervals for red maple trees. The data of each treatment group (n=7) were smoothed using a loess smoothing algorithm. The time course of daily plant stress (increasingly negative water potential) and recovery (decreasingly negative water potential) response of trees is fully represented, with scheduled irrigation events based on CVPD. Scheduled irrigation events are represented by colour coordinated vertical bars for each treatment level; yellow represents mild stress, green represents moderate stress, and red represents high stress. Alternating grey and white vertical bars indicate night and daytime hours measured by a solar radiation sensor built onto the Davis wireless weather station. For each treatment level, vertical error bands are ± SEM.
4.3.1 Cumulative water potential under stress thresholds

Figure 4.7 shows the mean CWP between watering events, during daytime hours, throughout the growing season (June 16th 2015 to September 7th 2015) for cedar. The mild stress treatment received the largest number of watering events (45) with a mean CWP of -25.1 ± 2.09 MPa*Hrs. The moderate stress group was watered 24 times with a mean CWP of -69.71 ± 5.48 MPa*Hrs. The high stress group was watered the fewest times with 18 events and a mean CWP of -109.35 ± 15.48 MPa*Hrs. A multiple comparison test between stress treatment groups indicated significant differences between all treatments: mild versus moderate stress (p < 0.0001), mild versus high stress (p < 0.0001), and moderate versus high stress treatments (p = 0.0011).
Figure 4.7 - Mean cumulative water potential (MPa*Hrs) before a scheduled irrigation event for each stress treatment level for cedar trees between June 16th 2015 - September 14th 2015. Scheduled irrigation events were based on CVPD thresholds summarized in Table 4.1, each CVPD corresponded with water potential measurements accumulated during daytime hours between irrigation events. Vertical error bars are ± SEM, with the number of significant watering events (rain ≥ 10 mm or a scheduled irrigation event) for each treatment level indicated in each bar.

Figure 4.8 shows the mean CWP of each growth period (1, 2, and 3) at each stress level for cedar. In each bar, the number of watering events is indicated during each period. A trend was observed in all treatments in which growth period 2 received the highest frequency of watering events, however the mean CWP was the lowest when compared to growth periods 1 and 3. In contrast, growth period 3 accumulated the largest stress but received the fewest
watering events based on CVPD stress limits. Multiple comparison testing between growth periods within each treatment indicated growth period 1 versus growth period 2 and 3 were not significantly different. Growth period 2 versus 3 were significantly different (p = 0.0027) in the mild treatment. In the moderate stress treatment, the mean CWP did not differ across all growth periods. In the high stress treatment, growth period 1 versus 3 and growth period 2 versus 3 (both p < 0.0001) were significantly different; however, growth period 1 versus 2 were not significantly different.

Figure 4.8 - Scheduled irrigation events were evenly divided into three separate one-month periods for cedars during June 16th 2015 - September 7th 2015; dates for growth periods can be found in section 4.2.10. The mean CWP measurements and number of significant watering events were considered in the assessment of seasonal differences. Vertical error bars are ± SEM. For mild stress treatments no significant differences were found for growth periods 1 versus growth periods 2 and 3.
Figure 4.9 details the mean CWP of each treatment level between watering events throughout the growing season (June 16th 2015 - September 7th 2015) for red maple. The mild stress treatment had the largest number of watering events at 67, with a mean CWP of -8.85 ± 0.6 MPa*Hrs. The moderate stress treatment was watered 37 times, with a mean CWP of -24.16 ± 2.29 MPa*Hrs. The high stress treatment was watered the least with 28 events resulting in a mean CWP of -42.13 ± 4.81 MPa*Hrs. A multiple comparison test detected differences between mild versus moderate stress (p < 0.0001), mild versus high stress (p < 0.0001), and moderate versus high stress (p < 0.0001).

**Figure 4.9** - Mean cumulative water potential (MPa*Hrs) for each stress treatment level between June 16th 2015 to September 7th 2015 for red maple. Vertical error bars are ± SEM. Significant watering events were scheduled based on CVPD thresholds summarized in Table 4.1 and significant rain events.
Figure 4.10 shows the mean CWP between treatments during three growth periods throughout the field season for red maple. The number of irrigation events is indicated in each bar. Similar trends for growth period 2 and 3 were observed as for cedar. Multilevel comparison tests showed that growth period 1 versus 2 and 3 (p = 0.0095 and p = 0.0106, respectively) were significantly different within the mild treatment. Within the moderate treatment growth period 1 versus 2 were significantly different (p = 0.0255). High stress treatments between growth period 1 versus 2 were significantly different (p = 0.0207).

**Figure 4.10** - Mean CWP measurements triggered by CVPD thresholds were evenly divided into three growth periods for red maple trees. Vertical error bars are ± SEM and the number of significant watering events is indicated in each bar.
4.3.2 Cumulative water potential vs. cumulative VPD slope response

Figure 4.11 indicates the slope response for mild, moderate, high, and combined stress for cedar over all three growth periods. The slope response is a measure of the plant's stress response (CWP) to evaporative demand (CVPD) between irrigation events. The mild, moderate, high, and combined slope responses were -1.2, -1.8, -2.1, and -2 MPa*Hrs / kPa*Hrs, respectively. A slope comparison between each treatment group indicated that mild versus moderate stress (p = 0.0099), and mild versus high stress (p < 0.0001) were significantly different. Moderate versus high stress indicated no significant difference. Linear regression tests for all slopes indicated that CWP and CVPD were significantly different (p < 0.0001).
Figure 4.11 - Relationship between CWP and CVPD between irrigation events during daytime hours for each treatment level and the combined relationship for cedar.

Figure 4.12 shows the monthly slope response for cedar within mild, moderate, high, and combined treatment groups for each growth period. The slope responses within mild stress treatments were -1.1, -1.1, -1.7 MPa*Hrs / kPa*Hrs for growth period 1, 2, and 3, respectively. Slope responses within moderate stress treatments were -1.8, -1.6, and -2.2 MPa*Hrs / kPa*Hrs for growth period 1, 2, and 3. Slope responses for the high stress treatment were -1.7, -1.9, and -3.2 MPa*Hrs / kPa*Hrs. The combined slope responses for growth period 1, 2, and 3 were -1.7, -1.9, -3 MPa*Hrs / kPa*Hrs, respectively. Differences were found within stress treatments. In the mild treatment, the slope response for growth period 1 versus 3, and 2 versus 3 showed significant differences (p = 0.0026 and p = 0.0049, respectively). Slope responses for the moderate stress treatment were only significantly different between growth period 2 versus 3 (p
Slope responses for high stress groups were significantly different between growth period 1 versus 2 and 2 versus 3 (p < 0.0001). Linear regression tests for all slopes of each treatment and growth period combination indicated that CWP and CVPD were significantly different (p < 0.0001).

**Figure 4.12** - Relationship between CWP and CVPD for cedar between irrigation events during daytime hours.

Figure 4.13 illustrates the slope responses between CVPD and CWP between irrigation events for red maple over all three growth periods. Each slope response measured the plant’s stress response for mild, moderate, high, and combined stress conditions. The slope responses were -0.65, -0.93, -1.2, and -1.2 MPa*Hrs / kPa*Hrs, respectively. All treatment comparisons,
mild versus moderate ($p = 0.0441$), mild versus high ($p < 0.0001$), and moderate versus high ($p = 0.0036$) stress were significantly different. Linear regression tests for all slopes indicated that CWP and CVPD were significantly different ($p < 0.0001$).

**Figure 4.13** - Relationship between CWP and CVPD for red maple between irrigation events during daytime hours.

Figure 4.14 shows the seasonal changes in the slope response for each stress treatment level for red maple. Mild stress treatments exhibited slope responses of -0.65, -0.47, and -0.83, respectively over the 3 seasonal growth periods. Moderate stress treatments exhibited slope responses of -1.2, -0.62, and -0.92, respectively. High stress treatments exhibited slope responses of -1.5, -0.95, and -1.2, respectively. The combined slope of each growth period was -1.4, -0.88,
and -1.2, respectively. Multilevel comparison tests of slope responses between growth periods indicated that the mild stress treatment was only significantly different between growth periods 2 and 3 (p = 0.0017). For moderate stress and high stress treatments, growth periods 1 and 2 exhibited significant differences (p = 0.0005, p = 0.004 respectively). Linear regression tests for all slopes from each treatment and growth period indicated that response and explanatory variables were significantly different (p < 0.0001)

**Figure 4.14** - Relationship between CWP and CVPD for red maple between irrigation events during daytime hours for each growth period over the season.

### 4.3.3 Agronomic measurements
Figure 4.15 shows the mean cumulative height increments for cedar during three different growth periods (June to July, July to August, and August to September). The total height increments from June to September for nursery irrigated trees, mild, moderate, and high stress trees were 14.06 ± 1.34 cm, 10.70 ± 1.65 cm, 7.66 ± 1.48 cm, and 3.71 ± 0.53 cm, respectively. Based on the multilevel slope comparison, nursery irrigated trees versus mild, moderate, and high stress (p = 0.0476, p = 0.0005, p < 0.0001, respectively) were significantly different. Mild versus high stress (p < 0.0001) and moderate versus high stress (p < 0.0001) were also significantly different. No significant difference was found between mild and moderate stress.

Figure 4.15 – Slope analysis of cumulative height increments measured monthly for nursery, mild, moderate, and high stress treatments between June 16th 2015 to September 7th 2015 for cedar trees. Vertical error bars are ± SEM.
Figure 4.16 shows the mean cumulative caliper increment for three growth periods (June to July, July to August, and August to September) for red maple. The total caliper increments through the growing season for nursery irrigated, mild, moderate, and high stress treatments were 3.53 ± 0.32, 4.15 ± 0.53, 3.00 ± 0.43, and 1.61 ± 0.21 mm. A multiple slope comparison test indicated nursery irrigated versus high stress (p = 0.0005), mild versus moderate (p = 0.0302), moderate versus high stress (p = 0.02), and mild versus high stress (p < 0.0001) were significantly different. Nursery irrigated versus mild stress, mild versus moderate stress, and nursery irrigated versus moderate groups were not significantly different.

**Figure 4.16** – Slope analysis of cumulative caliper increments measured monthly nursery, mild, moderate, and high stress treatments between June 16th 2015 to September 7th 2015 for red maple trees. Vertical error bars are ± SEM.
4.3.4 Water application and leachate

Table 4.2 shows the mean leachate measurements from the field season. Leachate collections for the nursery treatment were conducted on October 23rd 2015 (post field trial), however during the test on nursery irrigated trees, only one production bed with 1 row of emitters was actively irrigating. This allowed pressure to build up in active emitters which may have affected the leachate for the nursery treatment. The flow exceeded earlier emitter calibrations conducted at the start of the field trials. As stress levels increased, the volume of the leachate also increased in both species. Cedars produced a mean leachate volume of 13.25 ± 0.95, 3.98 ± 0.15, 4.41 ± 0.10, and 4.71 ± 0.91 L for nursery irrigated, mild, moderate, and high stress treatments, respectively. Red maple results were 12.96 ± 0.99, 2.41 ± 0.93, 2.86 ± 0.11, and 3.03 ± 0.17 L for nursery irrigated, mild, moderate, and high stress treatments, respectively. Species differences were observed with a greater amount of leachate recovered from cedar compared to red maple. A multilevel comparison test showed significant differences for nursery irrigated treatments versus mild, moderate and high stress treatments (p < 0.0001). The mild stress versus moderate and high stress treatments for cedar (p < 0.035 and p < 0.0001, respectively) and red maple (p < 0.047 and p < 0.0004, respectively) were significantly different.
Table 4.2 – Volume of leachate collected after a VPD triggered irrigation event for cedar and red maple trees during the field season from July 10th 2015 to September 1st 2015. Generally multiple irrigation system were active through the field trials. Direct comparisons between nursery irrigated treatment with mild, moderate, and high stress treatments could not be compared.

<table>
<thead>
<tr>
<th>Cumulative VPD threshold stress treatments</th>
<th>Mean (n=20) leachate collected after a VPD triggered irrigation event (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cedar</td>
</tr>
<tr>
<td>Nursery treatment(^z)</td>
<td>13.25 ± 0.95</td>
</tr>
<tr>
<td>Mild stress treatment</td>
<td>3.98 ± 0.15(^a)</td>
</tr>
<tr>
<td>Moderate stress treatment</td>
<td>4.41 ± 0.10(^b)</td>
</tr>
<tr>
<td>High stress treatment</td>
<td>4.71 ± 0.91(^b)</td>
</tr>
</tbody>
</table>

\(^z\) Leachate collection for this treatment was conducted post field trial on October 23\(^{rd}\) 2015.

Tables 4.3 and 4.4 summarize the number of irrigation events, total volume applied, and percent of leachate for nursery irrigated, mild, moderate, and high stressed conditions for each species. Nursery leachate measurements were not collected prior to a nursery scheduled irrigation event. The nursery did not have a set schedule in regards to how much and when each group of trees were irrigated. Measurements were collected on October 23\(^{rd}\) 2015, however due to significant differences in weather and operational conditions (weather and irrigation lines), values measured from Table 4.2 were recorded but not used to calculate the % leachate since numbers exceeded the average nursery irrigation output.
Among the scheduled irrigation events, mild stress treatments were irrigated most frequently, but showed the lowest % of leachate during the trials. When increasing the level of stress towards high stressed conditions, irrigation frequency decreased, however % leachate increased. As the soil-root interface of the plant dried with increasing water stress, the ability for the roots to absorb and soil to retain water was apparently reduced. The downward movement of water is dependent on gravity. During the drying period of the soil on hot summer days, the soil probably became highly porous. When water was applied by irrigation or rain, the water was infiltrated quickly allowing leachate volumes to be larger in dry soil conditions than moist soil conditions.

Table 4.3 – Summary table of the total number of triggered irrigation events, mean values per tree of volume of water applied (L), volume of water runoff (L), and percentage of water runoff for cedar trees on mild (22 kPa*Hrs), moderate (44 kPa*Hrs), and high (66 kPa*Hrs) CVPD threshold stress for a field season from June 16th 2015 to September 7th 2015. Leachate data for nursery irrigated trees were not reported because the leachate collected exceeded the original emitter calibration possibly due to varying pressures in the lines or some other source of variability.

<table>
<thead>
<tr>
<th>Cumulative VPD threshold stress treatments</th>
<th>No. of triggered irrigation events</th>
<th>Total volume of water applied in growing season (L)(^z)</th>
<th>Total volume of water leachate in growing season (L)(^y)</th>
<th>% of water leachate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nursery treatment</td>
<td>86</td>
<td>803 ± 26.66</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mild stress treatment</td>
<td>43</td>
<td>258 ± 15.48</td>
<td>171.27 ± 6.66</td>
<td>66 %</td>
</tr>
<tr>
<td>Moderate stress treatment</td>
<td>22</td>
<td>132 ± 7.92</td>
<td>97.08 ± 2.20</td>
<td>74 %</td>
</tr>
<tr>
<td>High stress treatment</td>
<td>15</td>
<td>90 ± 3.96</td>
<td>70.74 ± 1.00</td>
<td>79 %</td>
</tr>
</tbody>
</table>

\(^z\) Drippers were calibrated to apply 6.00 ± 0.06 L of water per 30-minute irrigation for mild, moderate, and high stress treatments. Drippers from nursery treatment were calibrated to apply 9.34 ± 0.31 L of water per 30-minute irrigation.
Average runoff measurements for each treatment were based on collected mass of runoff which were converted into liters assuming the density of water to be 1kg/L.

Table 4.4 – A summary table of the total number of triggered irrigation events, mean volume of water applied (L), volume of water runoff (L), and percentage of water runoff per tree for red maple trees on mild (14 kPa*Hrs), moderate (28 kPa*Hrs), and high (42 kPa*Hrs) cumulative VPD threshold stress for a field season from June 16th 2015 to September 7th 2015. Leachate data for nursery irrigated trees were not determined because the leachate collected exceeded the original emitter calibration possibly due to varying pressures in the lines or some other source of variability.

<table>
<thead>
<tr>
<th>Cumulative VPD threshold stress treatments</th>
<th>No. of triggered irrigation events</th>
<th>Total volume of water applied in growing season (L)(^z)</th>
<th>Total volume of water leachate in growing season (L)(^y)</th>
<th>% of water leachate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nursery treatment</td>
<td>86</td>
<td>803 ± 26.66</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mild stress treatment</td>
<td>67</td>
<td>402 ± 4.02</td>
<td>161.80 ± 6.23</td>
<td>40 %</td>
</tr>
<tr>
<td>Moderate stress treatment</td>
<td>35</td>
<td>210 ± 2.10</td>
<td>100.38 ± 3.88</td>
<td>48 %</td>
</tr>
<tr>
<td>High stress treatment</td>
<td>25</td>
<td>150 ± 1.50</td>
<td>75.77 ± 4.40</td>
<td>50 %</td>
</tr>
</tbody>
</table>

\(^z\) Drippers were calibrated to apply 6.00 ± 0.06 L of water per 30-minute irrigation for mild, moderate, and high stress treatments. Drippers from nursery treatment were calibrated to apply 9.34 ± 0.31 L of water per 30-minute irrigation.

\(^y\) Average runoff measurements of each treatment were based on collected mass of runoff which were converted into liters assuming the density of water.

4.4 Discussion

Continuous monitoring of CVPD triggered irrigation events with corresponding CWP measurements of two common nursery tree species has demonstrated the possibility of
scheduling irrigation events based on environmental conditions as a surrogate measurement to predict water potential response. The species specific slope responses can be further refined to meet the needs of the nursery industry. Introducing growers to this quantitative approach allows the development of different irrigation regimes that consider species specific plant water requirements instead of subjectively scheduled irrigation events.

### 4.4.1 Cumulative water potential irrigation stress

Cumulative water stress measurements between irrigation events triggered by CVPD were summarized in Figure 4.7 and 4.9. The mean CWP measurements for each treatment corresponded with CVPD measurements for each stress level. The mild stress treatment had the greatest number of irrigation events and high stress treatment had the least. In terms of mean CWP, the target values based on 2014 field season were -50, -100, and -150 MPa*Hrs / kPa*Hrs for cedar and -20, -40, and -60 MPa*Hrs / kPa*Hrs, in red maple for mild, moderate, and high stress treatments, respectively. Although the frequency of triggered irrigation events was as expected, the mean CWP did not accumulate to the level expected based on data from the 2014 field season. Thresholds of CWP exhibited by the 3 irrigation treatments in 2015 for cedar were -25.1 ± 2.09, -69.71 ± 5.48, and -109.35 ± 15.48 MPa*Hrs and for red maples were -8.85 ± 0.6, -24.16 ± 2.29, and -42.13 ± 4.81 MPa*Hrs for mild, moderate, and high stress treatments, respectively for each species. This difference compared to the 2014 season was likely attributed to seasonal environmental variability. It was clear that CVPD triggered irrigation events were
prone to these seasonal changes which tended to modify the CWP responses in the trees for the 2015 season.

Figures 4.8 and Figure 4.10 demonstrated that for each species, the mean CWP of each growth period was not consistent for all stress treatments. Seasonal changes had an effect throughout the field trial and were contributing factors which caused fluctuations in the mean CWP. The general trend seen in both species was: (1) in growth period 2 cumulative stress (CWP) was lower with an increased irrigation frequency, (2) in growth period 3 cumulative stress (CWP) was higher with a decreased irrigation frequency, all of which were compared to other growth periods.

Environmental conditions which controlled the rate of CVPD impacted the way irrigation events were scheduled. These changes in the environment promoted the differences observed between CWP measured in the 2015 field trial in each growth period for each species. In each growth period, the rate that VPD was accumulated varied through the season. In growth period 2 (July to August), VPD measured a maximum of 1.4 kPa and rose to 1.9 kPa towards the end of the growth period (obtained from field weather station). This demonstrated that the temperature was increasing and humidity levels were lowering which translated into higher VPD conditions. Under these conditions, the rate of cumulative environmental demand for moisture (CVPD) responded more aggressively, allowing assigned stress limits to be reached more frequently. In growth period 3 (August to September), the initial VPD measured 1.9 kPa and towards the end of the growth period measurements of VPD dropped to 1.0 kPa (obtained from field weather
station). This demonstrated that temperatures decreased and atmospheric conditions became moist as the period progressed, and these conditions favoured lower VPD. These conditions reduced the rate of CVPD, requiring more time to reach assigned stress limits. The additional time required to reach CVPD thresholds resulted in more time a plant must spend under water stressed conditions and as a result the CWP values endured by the plants were larger later in the season. Some consideration of total incoming solar energy may provide some additional corrections of the relationship between CWP and CVPD and make it more reproducible under varying seasonal conditions.

Sensor maintenance and proper scheduling of irrigation events were contributing factors that confounded reliable measurements of expected stress levels as well. Sensors were continuously monitored to limit the number of confounding measurements caused by condensation and contaminated thermocouple junctions. During psychrometer maintenance and cleaning procedures, some WP data were not obtained. These did not affect the sample size since there were enough psychrometers to have a statistically significant sample size. Scheduled irrigation events were manually triggered for each stress level, but there were times when remote access to each irrigation valve was hindered due to poor connectivity therefore some irrigation events were delayed beyond the assigned stress limits. Although the majority of irrigation events were triggered at proper stress limits, the lack of automation increased the variability at each stress limit by sometimes allowing more time for WP and VPD to accumulate.
To further improve irrigation treatment application, controllers must be able to automatically integrate and calculate cumulative environmental demand for moisture to trigger irrigation events in real-time.

4.4.2 Slope response

As seen in the previous chapter, the established relationship between CVPD and CWP, represented by the slope response, was an indication of cumulative plant stress in relation to cumulative environmental demand for moisture. This response was strongly correlated ($R^2 > 0.8$) in field season 2014, however the slope response obtained from 2015 field trials exhibited a poorer correlation ($R^2 > 0.65$ in most cases) even though irrigation events were strictly controlled.

Slope responses from the 2015 field trial were determined for each stress treatment as well as for the combination of all treatments (combined). For both tree species, the general trend indicated that the magnitude in slope response increased as stress level increased (Figures 4.11 and 4.13). In terms of the combined slope response, the magnitude was less than the slope response in 2014 field trials. Differences may be due to stricter controls over scheduling irrigation events in real time in 2015.
The combined slope response illustrated in Figures 4.11 and 4.13 provides growers with a guideline that shows the relationship between cumulative evaporative demand (CVPD) and cumulative plant stress (CWP) for each species. Quantitatively, a list of these slope responses could indicate tree species that can tolerate a larger range of stress (high slope response seen in cedars) and other tree species that may require frequent irrigation events to meet their water requirements (low stress response seen in red maple). A species with a steeper slope response (more negative) can withstand larger levels of environmental demand (CVPD); translating to high levels of cumulative water stress (CWP). On the other hand, a species showing a more shallow slope response (more positive), accumulates lower levels of environmental demand; translating to low levels of cumulative water stress.

Accumulating plant water stress and understanding how plants deal with stress between irrigation periods is a major challenge when establishing the relationship between CVPD and CWP. The application of these slope responses can provide growers with some predictive power for determining cumulative plant stress, however it requires refinement to determine the optimal level for plant growth. Specific targets have not been determined but in terms of optimal growth and to achieve efficient and effective irrigation, this study suggested that the desired stress can be found between conventional nursery irrigation protocols and the assigned mild stress treatment.

### 4.4.3 Seasonal changes
Scheduling irrigation events triggered by CVPD was dependent on environmental conditions. Due to variations observed between and within seasons, seasonal environmental variations can change how irrigation events were triggered. From sections 4.4.1 and 4.4.2, growth periods 2 and 3 exhibited the largest changes based on the mean CWP measured by stem psychrometers and the month to month slope response from each growth period. During these growth periods the environment began to transition from warm summer temperatures to cooler autumn temperatures. These types of changes affected the CVPD measured and the interpretation of results.

Strictly using CVPD as the only predictor of plant water stress may not provide growers with the best estimation of plant water stress. Although the field trials were focused on the relationship between CVPD and CWP there are other factors that can be considered to improve the predictive reliability of scheduling irrigation events. Environmental conditions will differ throughout each growing season (year to year) and will not remain consistent. Other factors such as solar radiation could be included to improve the capacity to predict plant responses in terms of CWP from measurements of cumulative environmental demand for moisture (CVPD), using the weather station as the main instrument. A few horticultural management variables to consider to enhance the predictability of plant-environment interactions for the management of irrigation include: irrigation duration, applied volume of irrigation, substrate type, pot size and age of the tree or extent of root growth.
4.4.4 Conclusion

Correlated slope responses between CWP and CVPD for cedar and red maples from the 2014 field season were used to schedule irrigation events based on CVPD at incremental stress levels during the 2015 field season. Phenological variation and other factors reduced the accuracy of CVPD to predict cumulative plant stress (measured by CWP). Under the conditions of this study, it cannot be assumed that the slope response of each species will remain constant; seasonal variation and other variables mentioned above will influence how much and how quickly plants accumulate stress. Agronomic and water application measurements confirmed the differences in species response to the amount of water applied. While cedars responded well to greater water availability at all stress levels tested, red maples showed no appreciable growth gains when given more water than the mild stress level. Species specific slope responses overall provided a strong guideline to indicate the target irrigation thresholds for each species.
Chapter 5  General Discussion

With increasing demands from several sectors (energy, residential, and agriculture and food), access to existing water resources has become increasingly more competitive. The nursery industry represents the largest consumer of water resources in the ornamental horticulture sector due to its heavy reliance on irrigation to produce trees (Deloitte and Touche, 2009). Subjective irrigation scheduling protocols preclude growers from allowing their production trees to exhibit any level of stress and conditions plants to receive a large amount of water on a daily basis. The success rate for transplanting trees is probably reduced because trees are not given an opportunity to adapt to stress. Providing growers with a quantifiable approach to predicting plant water stress using a surrogate measurement of environmental demand for moisture (CVPD) can help reduce the subjective nature of irrigation scheduling and encourage growers to improve their subjective scheduling. Irrigation events can be scheduled by relying on a calculated plant response rather than visual cues which may not fully reflect the plants’ response to water management. Irrigation protocols based on quantified variables could change how nurseries manage their water resources, with a focus on irrigation efficiency and effectiveness.

In the preceding chapters, the assessment of species specific slope responses between CWP and the environmental demand for moisture expressed as CVPD were used to demonstrate a quantified approach to scheduling irrigation events. Water potential and concurrent meteorological measurements were collected on two common nursery tree species to establish the range of accumulated stress under varying conditions. The measured responses demonstrated
that each species had distinct stress responses (Chapter 2). Further evaluation of these species specific stress responses was conducted in the following field study in 2014 (Chapter 3) by irrigating trees based on CWP and assigned incremental levels of stress (mild, moderate, and high stress). It was then proposed that, due to the strong correlation between CVPD and CWP for each species, it may be possible to use CVPD to predict CWP (Chapter 3). The ability to use this slope response to predict plant water status from measured environmental conditions will provide growers with a tool to more effectively and efficiently schedule irrigation events. In the following field study in 2015 (Chapter 4), irrigation events which were previously scheduled by CWP stress limits were scheduled on corresponding CVPD to determine the predictive capacity of the CVPD-CWP relationship. The relationship between CVPD and CWP can be used to fine tune irrigation management strategies in nursery trees without significant losses in productivity and quality with consideration of seasonal variability and species responses.

5.1 Effect on price based on agronomic measurements and water applications

Pricing of a tree is generally based on three factors: agronomic measurements, water applications, and market supply and demand. Among these three factors, agronomic measurements (caliper or height) were the simplest cost indicator to validate the effectiveness of each modified irrigation regime for each tree species. Results demonstrating plant productivity from varying levels of water reductions are not enough to persuade growers to adopt an effective irrigation management practice. Potential profits and/or losses from water reductions must be
demonstrated alongside plant productivity to show growers the effectiveness of each method when compared to their current practices in order to improve their usage of water resources. Data from field trials 2014 (Chapter 3) and 2015 (Chapter 4) is used to provide, a summary of plant productivity and its effects on pricing and water applications was demonstrated for each tree species.

5.1.1 The effect of agronomic measurements on tree pricing

According to pricing information provided by the nursery, a typical cedar tree can be purchased for $43 - $339 based on tree heights between 110 cm - 275 cm. In order for the tree to be priced, the minimum height of the tree must be 110 cm. To estimate the cost of each tree, a linear relationship was established from these numbers as:

\[ \text{Selling price} = 1.79 \times \text{Height measurement} - 154.33 \]  

(5.1)

This linear relationship (Equation 5.1) indicates for each centimeter increase in height (beginning from 110 cm) of a cedar tree, the price increases by $1.79. The intercept of the relationship shows a negative cost to the selling price because of the associated costs in time, labour, and resources required to grow a cedar tree until it has reached a minimum height of 110 cm.
Pricing for a red maple tree averages $156 - $524 starting at a base caliper measurement of 30 mm and increasing to 80 mm. Interpolating these values as a linear relationship (Equation 5.2) the standard equation would equate to:

\[
\text{Selling price} = 7.36 \times \text{Caliper measurement} - 64.80 \quad (5.2)
\]

A minimum caliper measurement of 30 mm must be reached in order for a tree to be considered marketable. Based on the linear regression, a 1 mm increase in caliper would approximately adjust the selling price by $7.36. The intercept of the relationship shows a negative cost to the selling price because of the associated costs in time, labour, and resources required to grow a red maple tree until it has reached a minimum caliper of 30 cm.

**5.1.2 Field trial comparison**

In the 2014 field trial (Chapter 3), water application measurements for the high stress treatment were initiated later in the field trial. Although the high stressed measurements were included in Table 5.1 and 5.2, they were not explicitly discussed or compared with the other treatments due to varying start times. In the 2015 field trial (Chapter 4), all stress treatments were initiated together and compared.

**5.1.2.1 Cedar species**
The nursery irrigated cedar trees received the highest irrigation and grew the tallest trees, however these trees also were the largest consumers of water resources. Table 5.1 provides a comparison between stress treatments for cedar based on plant productivity (agronomic measurements), estimated selling price, and water savings.

**Table 5.1** - Percentage reduction of mean height, selling price, and water and total water application measurements for nursery rate, mild, moderate, and high stressed treatments of a single cedar tree compared to measurements of nursery irrigated trees in field seasons 2014 and 2015. Nursery irrigated trees represent no reduction in height growth, maximum potential selling price, and maximum water application and were used as a baseline to make comparisons with mild, moderate, and high stress treatments.

<table>
<thead>
<tr>
<th>Stress Treatment</th>
<th>Change in Mean Height Measurements (%)</th>
<th>Change in Selling Price (%)</th>
<th>Total Water Application (L)</th>
<th>Change in Water Application Compared to Nursery Irrigated Trees (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nursery</td>
<td>0.00&lt;sup&gt;a&lt;/sup&gt; 0.00&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.00 0.00</td>
<td>388 803</td>
<td>0.00 0.00</td>
</tr>
<tr>
<td>Mild</td>
<td>-6.27&lt;sup&gt;b&lt;/sup&gt; -23.90&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-22.82 -8.87</td>
<td>103 256</td>
<td>-73.53 -68.12</td>
</tr>
<tr>
<td>Moderate</td>
<td>-6.49&lt;sup&gt;b&lt;/sup&gt; -45.52&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-23.62 -16.91</td>
<td>63 132</td>
<td>-83.82 -83.56</td>
</tr>
<tr>
<td>High</td>
<td>-6.44&lt;sup&gt;b&lt;/sup&gt; -73.61&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-23.78 -27.35</td>
<td>17 90</td>
<td>-95.46 -88.79</td>
</tr>
</tbody>
</table>

In both field trials, cedar were influenced by the volume of water applied. Nursery irrigated trees received the largest volume of water, which resulted in the largest height increment during both field trials. The differential height reductions, on a percentage basis,
translated to a direct price reduction affected by height. In the 2014 field trial, the selling price was reduced by slightly less than 24% among all stress treatments, while the 2015 field trial showed an increase in price reductions based on the stress level factor. The reduction in price was offset by substantial water savings of 73% and 68% from each field trial, respectively. These water savings have direct economic benefits in the form of reduced resource inputs per tree; however, under limited water supplies the real benefit may come from the greater overall production capacity.

A grower may consider reducing ~70% of water applications to obtain agronomic results seen in the mild stress treatment. Although the selling price of the tree was reduced by ~9% in the mild stress, the water savings to improve water efficiency (68%) in other production beds can offset these reductions. Moderate and high stress treatments showed water reductions of >80%. Although water applications were significantly reduced, the quality of the tree may reach levels which are unacceptable in plant quality.

Water reductions in a production operation can improve water use efficiency by reallocating water resources to other plants that require more water resources. However, the cost of water reductions generates reduced tree growth leading to reduced per tree profits. Although the selling price of a tree was estimated to decrease by ~25%, water resources saved were 73% and 68% from each field trial. These savings could be effectively managed and allocated to other or expanded production systems to offset the reduced selling price of the trees.
5.1.2.2 Red maple species

Red maple species responded differently to the reduction of water compared to cedar. In Table 5.2, plant productivity, estimated selling price, and water saving factors were compared in both field trials (2014 and 2015). Although the caliper reduction showed no statistically significant differences between the nursery treatment and the mild stress treatment, the caliper on the mild stress treatment in 2014 was reduced (2.85% less), whereas in 2015 it grew slightly larger (2.5% more) than the nursery treatment. The selling price only changed by ± ~4% for mild stress conditions. More significant price reductions was only realized in the higher stress treatments when price was reduced by less than 7-9% in both trials. The reduction in plant productivity was offset by a water use reduction, starting as low as 50%. In some cases, the 2015 field trial showed that a water reduction did not affect the plant negatively. Instead it showed a slight caliper increase, and as a direct result increased the selling price of the tree.

A grower could consider a 50% water savings and show no significant change in quality as demonstrated in 2015 in Table 5.2. Further water savings in the moderate stress treatment (~74%) would be advised due to a slight price reduction of ~2% while providing plant conditioning benefits to improve overall quality. High stress treatments provided the largest water savings, however the quality of the plants was unacceptable to a nursery grower. It is not certain how different plant varieties interact and utilize different levels of water reductions for overall growth. However, results indicated that water reductions seen in all stress treatments reduced the price in red maple trees, while the mild stress condition improved the price with the
‘Red sunset’ variety and showed a smaller reduction in price for moderate and high stressed conditions. A balance between optimizing growth while maintaining effective water use, although not strictly determined, would appear to fall somewhere between current nursery practices and the moderate stress treatment.

Table 5.2 - Percentage reduction of mean caliper, selling price, and water application; and absolute water application measurements for nursery, mild, moderate, and high stressed treatments of a single red maple tree compared to measurements of nursery irrigated trees in field season 2014 and 2015. The tree varieties used in the 2014 and 2015 field trials were different; ‘Brandywine’ was used in 2014, and ‘Red sunset’ was used in 2015. Nursery irrigated trees represented no reduction in caliper growth, maximum potential selling price, and maximum water application and were used as a baseline for stress treatments.

<table>
<thead>
<tr>
<th>Stress Treatment</th>
<th>Change in Mean Caliper Measurements (%)</th>
<th>Change in Selling Price (%)</th>
<th>Total Water Application (L)</th>
<th>Change in Water Application Compared to Nursery Irrigated Trees (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nursery</td>
<td>0.00a</td>
<td>0.00a</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Mild</td>
<td>-2.85ab</td>
<td>+17.56ab</td>
<td>-3.88</td>
<td>+2.51</td>
</tr>
<tr>
<td>Moderate</td>
<td>-5.18b</td>
<td>-15.01b</td>
<td>-7.06</td>
<td>-2.14</td>
</tr>
<tr>
<td>High</td>
<td>-6.60b</td>
<td>-54.39c</td>
<td>-9.00</td>
<td>-7.76</td>
</tr>
</tbody>
</table>
5.1.3 Reduction benefits

Improving irrigation efficiency requires that growers balance water use reduction and selling price (plant productivity). If the grower reduces the amount of water applied to the crop, the growth rate may be reduced which directly influences the selling price of the tree. Based on agronomic and water application data collected during this field trial, acceptable water reductions appear to be species specific.

Agronomic measurements in cedars indicated that tree growth responded well when irrigated frequently. However, continuously irrigating cedars to reach a higher selling price may condition the plant to high moisture conditions. As the trees are transplanted to a permanent location with lower moisture conditions, transplant shock and reduced water availability could seriously hinder plant productivity and even survival. Reducing the volume applied a few seasons prior to transplanting may allow the plants to ‘harden off’ to improve survivability. The issue of conditioning plants using irrigation management strategies requires more attention and will be the subject of ongoing work in this field. Similarly in red maple, the balance between caliper measurements and the reductions seen in price and water applied suggests that optimal caliper growth, water reductions, and selling price can be found between conventional nursery practices and the mild stress treatment.

As an example of the potential water savings (using 2014 water application data), 1 hectare (10,000 m²) of land has a holding capacity of 62500 x 10 gallon (38 L) containers. If
each tree was irrigated with the conventional irrigation protocol, each tree would receive 388 L which would equate to 24,225,000 L per hectare. Irrigating the same trees with the water reductions of the mild treatment, the nursery would have applied 7,509,750 L and saved 16,715,250 L. With the additional water savings the nursery could essentially reallocate these resources to other tree products or reduce the amount of water resources they were using. This would be particularly important in situations where there was a significant cost to obtaining irrigation water.

5.2 Future research

Baseline testing demonstrated that the magnitude of the slope responses was species dependent. However, as demonstrated in Chapter 4, the slope responses of each species changed based on environmental conditions and time of the season. Throughout the growing season, atmospheric conditions varied between periods of dryness and wetness which determined the rate that VPD accumulated. Dry atmospheric conditions translated to rapid VPD increases while moist atmospheric conditions resulted in a slower accumulation of the VPD integral. Thus, the next phase of this research should be directed at validating these seasonal effects on the slope response of cedar and red maple species and how they affect the prediction of CWP. Further research can be focused on establishing slope response for a number of species, as it is clear that each species will have a different slope responses. Finally, if the slope responses do indicate a dynamic yet predictable relationship, it would be a relatively simple task to develop an automated irrigation control system based on CVPD, possibly normalized for incoming
radiation. This would allow growers to respond to the environmental issues regarding management of irrigation while providing effective use of water resources.

The work presented in this thesis was focused on quantifying plant water stress in relation to environmental demand to allow fine tuning of a more efficient and effective irrigation schedule in nursery applications. Although the findings were preliminary, the work showed that irrigation scheduling can rely on conventional weather stations to predict plant water stress with some modest degree of accuracy. There is no doubt that technological advancements and education are key components to developing water reduction programs in the nursery industry. These initial trials will serve as baseline from which to develop a protocol which all nurseries can use.
Literature cited


Appendix A – Extended Abstract

Irrigation Scheduling Based on Cumulative Vapour Pressure Deficit to Predict Nursery Tree Water Stress

Newton Tran

University of Guelph, 2015

Advisor: Professor M.A. Dixon

Ontario tree nurseries are among the heaviest users of irrigation water in the ornamental horticulture sector. Increasing concerns with water conservation, environmental impacts and costs have encouraged the nursery industry to modify its water use, however an effective and efficient irrigation management strategy remains elusive. Conventional irrigation scheduling for nursery trees is often based on subjective observations and field experience, which excludes plant water status measurements. Using field-deployable stem psychrometers paired with conventional meteorological measurements, the aim for this thesis was to quantify the relationship between cumulative water potential (CWP) and concurrent cumulative vapour pressure deficit (CVPD) to develop an irrigation scheduling technique which predicts plant water status responses from environmental variables, specifically vapour pressure deficit (VPD). Using the combined slope responses for *Thuja occidentalis* (-2.4 MPa*Hrs / kPa*Hrs) and *Acer rubrum* (-1.5 MPa*Hrs / kPa*Hrs) the CWP/CVPD relationship needs refinement for irrigation management strategies in the nursery trees.
Nursery tree species (*Thuja occidentalis* and *Acer rubrum*) exhibited ranges of CWP under variable stressed conditions in the 2013 field trial. The CWP for high to mild stress limit ranges was quantified as $-111.15 \pm 14.24$ to $-55.37 \pm 16.30$ MPa*Hrs for *Thuja occidentalis* and $-56.08 \pm 3.88$ to $-24.55 \pm 10.45$ MPa*Hrs for *Acer rubrum*, respectively.

In the 2014 field trial, treatments were assigned as multiples of the mild stress limit from the 2013 field trial to establish a modified irrigation schedule (triggered by CWP). Treatments consisted of a: mild (1x), moderate (2x), and high stress (3x) limit for each species. The slope responses for *Thuja occidentalis* were $-1.6$, $-2.4$, $-2.6$, and $-2.4$ MPa*Hrs / kPa*Hrs for mild, moderate, high, and combined responses, respectively. The slope responses for *Acer rubrum* were $-0.88$, $-1.4$, $-1.7$ and $-1.5$ MPa*Hrs / kPa*Hrs for mild, moderate, high, and combined responses.

In the final field trial (2015), previously established combined slope responses for each species were used to define a modified irrigation schedule of similar stress limits were tested. Irrigation scheduling was triggered by CVPD rather than CWP stress limits. The slope responses for *Thuja occidentalis* were $-1.2$, $-1.8$, $-2.1$ MPa*Hrs / kPa*Hrs for mild, moderate, high and $-2$ MPa*Hrs / kPa*Hrs for the combined responses. The slope responses for *Acer rubrum* were $-0.65$, $-0.93$, $-1.2$ for mild, moderate, high, and $-1.2$ MPa*Hrs / kPa*Hrs for combined stress. It was found that slope responses were not static but changed based on environmental conditions and the time of the season. The relationship between CVPD and CWP can be used to fine tune
irrigation management strategies in the nursery trees without significant losses in plant productivity and quality due to consideration to seasonal variability and species response.
Appendix B – Data filtration for stem psychrometers

Introduction:

The automated stem psychrometer was a major asset in collecting water potential measurements for all field trials from 2012-2015. The sensor provided the highest temporal resolution for water relations data (measurement interval ranging between 10 minutes to 2 hours) compared to pressure chambers. However, the validity of the measurements can be heavily influenced by the installation and maintenance of the sensor.

In the field, water potential data were collected by either an ICT International PSY1 datalogger (Armidale, NSW, Australia) or a CR7 (Campbell Scientific, Logan, Utah) datalogger to make the best use of available data-logging techniques and thus ensure that sample sizes for each stress treatment level were statistically relevant. Raw data for psychrometric measurements (dry-bulb temperature, wet-bulb temperature, chamber temperature, etc.) were collected by both data loggers; however, calculation protocols were handled differently. The ICT dataloggers incorporated psychrometer-specific calibration coefficients and automatically calculated the corrected water potential within the instrument firmware. Comparatively, the CR7 datalogger only collected the raw psychrometric measurements and the corrected water potential was calculated off line, using psychrometer specific calibration coefficients and correction factors.
The raw water potential measurements can be “noisy” depending on the species the psychrometers are measuring, the physical environment under which the instrument is deployed and the length of time the psychrometer have been installed. Measurement artefacts such as chamber condensation, poor thermocouple positioning, and dirty or broken thermocouples affected water potential measurements. These artefacts were easily identified by inspecting the water potential time courses. Once identified they were removed from the final dataset. Standard filtering protocols were developed to help remove or correct these artefacts to provide a less distorted water potential response. Data filtration techniques were applied daily to field trials in 2015 to ensure data was filtered correctly each day. Data collected from 2012-2014 followed filtration techniques after the field season was completed. Positive measurements, extreme (high or low) water potentials that were inconsistent with neighbouring values, sensor reinstallation, and replicate comparisons were all considered.

**Positive measurements:**

Positive water potential measurements were handled differently based on the datalogger to which the psychrometer was attached. The ICT data logging firmware automatically replaced positive measurements with a zero for the majority of water potential measurements that approached 0 MPa. However, there were certain instances where the combination of:

1. Wet-bulb depression (µV)
2. Chamber temperature (°C)
3. Δ Temperature (°C)
4. Slope and intercept calibration coefficients
resulted in a slightly positive water potential which was not zeroed by the firmware. On the other hand, the CR7 was not programmed to detect positive water potential measurements automatically. These measurements were zeroed manually using a spreadsheet or computer script. Positive water potential measurements are theoretically impossible, even under rare conditions (O’Leary, 1970). In these experiments the incidence of positive readings was invariably overnight when plant water status was closest to zero and the resolution and accuracy of the instrument was challenged. Therefore, any positive measurements recorded were zeroed based on this justification.

**Extremely high or low measurements:**

Extremely high and low water potentials were easily identified in the dataset because measurements exceed the measurement range of the sensor (0 MPa to -10 MPa). These extreme readings occurred when stem psychrometers were physically detached from the dataloggers or installation site during the measurement phase. Broken thermocouples also cause extreme values as the system was unable to establish a measurement protocol reliably (i.e. Peltier cooling current, chamber temperature measurement, detection of temperature difference between the chamber and the sample). The thermocouples of each psychrometer were routinely inspected, cleaned and repositioned during the field season to ensure accurate plant water status readings and limit the number of spurious readings that required further evaluation.

**Sensor reinstallations:**
After inspecting positive and extreme measurements, sensor reinstallations were considered as part of the filtration and data validation process. Sensor reinstallations required a 90 minute equilibration period before water potential measurements were used for data analysis. It was empirically determined that 90 minutes was sufficient time for a newly installed stem psychrometer to return to equilibrium with the plant and surrounding environment. Data collected during the 90 minute equilibration period were removed following inspection of the data and notes made throughout the field season.

Throughout the 2015 field season, a log was maintained to keep records of sensor removal times, sensor re-installation times, reasons for sensor removal, and sensor replacement. These procedures were only practiced during the 2015 field season, having developed the approach after experience in the previous field season. A sensor maintenance log from field season 2014 was maintained but not to the degree of detail in 2015.