Turfgrass Water Use and Growth under Low Mowing Heights and Different Nitrogen, Phosphorous, and Drought Conditions

by

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ABSTRACT

TURFGRASS WATER USE AND GROWTH UNDER LOW MOWING HEIGHTS AND DIFFERENT NITROGEN, PHOSPHOROUS, AND DROUGHT CONDITIONS

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Water use of low-cut turfgrass at different heights of cut (HOC) or different fertility levels is not known, and information on turfgrass performance during different water deficit conditions is limited. The effects of HOC (3 vs. 5 mm), nitrogen (N) levels prior to drought (0.8, 4.0, 8.0, and 16 g total N m⁻² for 60 d), phosphorus (P) level (1.1 g total P m⁻² vs. no P), and turfgrass variety (‘L93’ and ‘Penncross’ creeping bentgrasses, annual bluegrass, and ‘SR7200’ velvet bentgrass) under three drought conditions (no drought, periodic drought, and prolonged drought, including a drought recovery phase) on turfgrass growth, net carbon exchange rate (Pn rate), and root parameters were measured through three separate experiments. Real-time water consumption using mini-lysimeter load cell arrays under three drought conditions was also measured. The novel mini-lysimeters were able to detect weight changes of 20.3 cm² pots containing grass at 1-min intervals, and evapotranspiration (ET) differences between treatments at 1-h intervals. The 5 mm HOC resulted in ~8% more water use than the 3 mm HOC for full cover turfgrass with sufficient irrigation. Turfgrass at 5 mm HOC had higher color ratings, Pn rate, and water use efficiency than turfgrass at 3 mm HOC at the beginning phase of drought. Higher HOC resulted in a faster decrease of hourly ET than lower HOC under drought conditions due to greater water consumption and lower water availability. The 8 g m⁻² total N level resulted in better turf performance and more water use than lower N rates. However, 16 g m⁻² total N did not improve turf growth from the 8 g m⁻² total N level. Increasing N rates improved drought tolerance (measured through Pn rate) during drought and post-drought
recovery periods. Turfgrass varieties respond differently to P levels under drought. Low P may improve drought tolerance for ‘Penncross’ creeping bentgrass, whereas high P may lead to better drought tolerance for ‘SR7200’ velvet bentgrass. These findings contribute to the understanding of turfgrass under periodic or prolonged drought conditions and could lead to the use of better predictive models for managing water use by turfgrass manager.
DEDICATION

To my dear husband, Kuo-Hsien Chang, my beautiful children, Emma, George, and Eva, and my strong-minded mother, Lixia Xiao.

This long journey could never have been completed without your unwavering support and unconditional love.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AB</td>
<td>Annual bluegrass</td>
</tr>
<tr>
<td>ABA</td>
<td>Abscisic acid</td>
</tr>
<tr>
<td>Ca</td>
<td>Calcium</td>
</tr>
<tr>
<td>DARC</td>
<td>Day after drought recovery initiated</td>
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<tr>
<td>DARW</td>
<td>Day after the second dry down for the periodic drought treatment</td>
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<tr>
<td>DAT</td>
<td>Day after the start of the experiment</td>
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<td>ET</td>
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<tr>
<td>ET&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Reference ET</td>
</tr>
<tr>
<td>Fe</td>
<td>Iron</td>
</tr>
<tr>
<td>HOC</td>
<td>Height of cut</td>
</tr>
<tr>
<td>K</td>
<td>Potassium</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf area index</td>
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<tr>
<td>Mg</td>
<td>Magnesium</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>P</td>
<td>Phosphorous</td>
</tr>
<tr>
<td>PAR</td>
<td>Photosynthetically active radiation</td>
</tr>
<tr>
<td>Pn rate</td>
<td>Net carbon exchange rate</td>
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<tr>
<td>SRL</td>
<td>Specific root length</td>
</tr>
<tr>
<td>SWC</td>
<td>Soil volumetric water content</td>
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<td>TE</td>
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Chapter 1: Introduction

Turfgrass is used for its environmental and athletic functions, as well as aesthetic value. Healthy and well-maintained turfgrass reduces soil erosion, dust, water and contamination runoff, protects ground water quality, and moderates temperature (Beard, 1973). Well-managed turfgrass is also an excellent carbon sink (Qian et al., 2010, Selhorst and Lal, 2013). Turfgrass landscapes across the United States potentially can store 16.7 Tg of carbon every year if grass clippings are not removed (Milesi et al., 2005). Turfgrass is also valuable in the landscape because it is one of the few ground cover plants that can facilitate play. Moreover, turfgrass is an ideal plant model system for studying canopy level plant response, as a relatively small area is necessary to obtain canopy level information. Therefore, controlled environments such as growth chambers or greenhouses can be utilized conveniently for canopy studies.

Turfgrass areas, including home and commercial lawns, golf courses, and athletic fields, cover an area of about 128,000 km² in the United States. This is three times more than irrigated maize, making turfgrass potentially the largest irrigated crop in the United States, assuming turfgrasses are always irrigated (Milesi et al., 2005), although many home and commercial lawns in humid regions may not require irrigation as rainfall alone is able to meet turfgrass water requirements. As part of the NASA Land Cover Land Use Change Research Program, Milesi et al (2005) used well-maintained turfgrass scenarios (irrigated, fertilized, and regularly mowed) across the US to simulate turfgrass water consumption using ecosystem models, and concluded that if the entire turf surface in the US was irrigated to 80% Evapotranspiration (ET), water consumption would be 900 L per person per day. Although this number might be overestimated if it is in current real-world scenario that many lawns are not irrigated or do not require irrigation especially in wet regions, turfgrass water consumption could increase substantially in the future
as extended hot and dry periods are becoming more and more common partly due to global climate change.

Governments are using different measures to reduce turfgrass water use by limiting either turfgrass surface or irrigation on lawns. For example, the United States Environmental Protection Agency launched a nation-wide program known as Watersense in 2006, which required that turfgrass should not exceed 40% of the landscape area for new homes (EPA, 2006). Moreover, The Watersense program treated water features such as pools as turfgrass, which unfairly treated turfgrass water use equal to any open water body. Many cities in Canada regulate lawn irrigation based on calendar days, which means that homeowners could only irrigate their lawn on a set day of the week in summer (City of Kingston, 2006; City of Vancouver 2019). This calendar-day based regulation is simple for policy makers and homeowners. However, calendar-day based watering policies often ignored or underestimated turfgrass drought tolerance and dormancy mechanisms and may result in residents using more water as homeowners are prone to water on their scheduled day regardless of plant need.

There are three different irrigation programs for turfgrass: 1) Irrigate based on calendar days, which is promoted by policy makers as it is easy to determine and follow; 2) Irrigate when turfgrass starts to turn brown, which should be the way homeowners water their lawn; and 3) Irrigate based on ET (Poro et al. 2017), which should be adopted for golf courses and athletic fields to reduce water use while maintaining physiological functions to tolerate traffic and use. Proper irrigation programs alone are not enough to effectively reduce turfgrass water use. Nutritional levels and cultural management such as mowing height also play important roles in determining turfgrass drought tolerance and water use (Poro et al., 2017). The rest of this chapter therefore explains plant water use, the definition of turfgrass drought tolerance, the plant
physiological responses to drought, and the relationship between turfgrass nutrition, mowing activity, and drought.

1.1 Plant Water Use

Plant water use can be estimated through the calculation of ET, which is the water loss from a vegetated surface through evaporation and transpiration (Allen et al., 2005). Transpiration is the movement of water from soil through the plant and to the atmosphere. Water moves from the soil to the roots, then through the plant, ultimately exiting the plant through aerial organs such as leaves, stems and flowers. Evaporation is the movement of water to the air from soil or plant surfaces without entering the plant. For a well-established turfgrass stand that has full turfgrass cover, soil evaporation is minimal and often negligible (Huang et al., 1998). Water uptake for transpiration accounts for over 98% of water used by turfgrass (Beard, 1973, Hopkins, 1995). Turfgrass ET is affected by climate conditions, turfgrass varieties, management practices, and water availability (Romero and Dukes, 2016). Deficit irrigation can be managed to achieve acceptable turfgrass while using less water (Henry et al., 2005). However, different varieties of turfgrass under different management regimes have different water requirements (Colmer and Barton, 2017). Also, the durations of drought periods, whether periodic or prolonged drought, need to be investigated separately for a better understanding of turfgrass water use under drought.

The most accurate measurement of actual water use by turfgrasses is attained using weighing lysimeters (Kim et al., 2003), but these lysimeters are usually large and difficult to move. This is likely why there are limited water use studies on turfgrass. Studies on turfgrass leaf ET are also limited because turfgrass leaves are small, especially for low height of cut (HOC)
grass, reducing the accuracy of leaf gas exchange water loss measurements. Scaling ET from leaf level to canopy level for water use predictions is also difficult. The study on low HOC turfgrass water use under drought (Chapter 2 of this thesis) was therefore inspired by the lack of tools to investigate turfgrass water use on a small area of turfgrass and in real-time.

When irrigation is sufficient, ET can also be calculated by $ET_a = ET_0 \times K_c$, where $ET_0$ is the reference ET estimated by weather station data, and $K_c$ incorporates crop characteristics (Allen et al., 2005). The $K_c$ for turfgrass should be determined by species, management regimes, and turfgrass quality although it is often assumed to be 1 for all turfgrasses (Allen et al., 1998).

1.2 Turfgrass Mowing

Turfgrass is mowed to maintain its overall health and function. Therefore, turfgrass final yield is unmeasurable and unimportant, whereas crop yield is the primary concern for crop growers. Some turfgrasses are mowed to 3 mm or shorter to provide the desired playability. The frequent removal of clippings for low HOC turfgrass limits root growth and removes nutrients constantly, requiring unique water and nutrient management. Assumptions and results obtained from crop studies may not be applicable to turfgrass at low HOC. For example, Poro et al. (2017) showed creeping bentgrass cut at 3 compared 9 mm resulted in ~10% decrease in actual ET when water was sufficient on. The results are contrary to the assumption that crop ET stabilizes regardless of crop height after reaching full canopy cover (Rogers et al., 2015). The study showed similar results when comparing Kentucky bluegrass and perennial ryegrass each cut at 30 compared to 60 mm. When raising the HOC from 30 to 60 mm, bermudagrass and kikuyugrass ET increased by 27 and 20%, because shorter turfgrass had greater aerodynamic resistance, thus less ET (Biran et al., 1981). St. Augustinegrass ET was 18.5% greater when cut
at 80 mm than at 50 mm (Johns et al., 1983). When under drought condition, Bermudagrass cut at 50 mm resulted in an 11% increase in cumulative ET during the first 15 days of drought, compared with Bermudagrass 20 mm HOC (Zhou et al., 2009). Zhou et al. (2012) also found that raising the HOC from 20 to 50 mm reduced the survival period from 24.3 to 21.4 days after drought for bermudagrasses (Cynodon dactylon L.), the Queensland blue couches (Digitaria didactyla Willd), the seashore paspalums (Paspalum vaginatum Swartz.) and St Augustinegrasses (Stenotaphrum secundatum (Walt.) Kuntze). There has been limited research on the effects of HOC on low-cut turfgrass ET during drought.

In sustainable lawn and gardening maintenance, staying on the higher end of the mowing height range is advocated. Dobbs and Potter (2014) studied tall fescue mowed at 6.4 and 10.2 cm HOC and concluded that high-mowed grass reduced canopy temperatures and the amount of grass-feeding caterpillars, and promoted a robust root system that reduces water and chemical consumption. Tall fescue mowed at a higher HOC (8.8 cm) also resulted in better smooth crabgrass [Digitaria ischaemum (Schreber) Schreber ex Muhlenb.] control, but a larger white clover (Trifolium repens L.) population than 3.2 and 5.5 cm HOC (Dernoeden et al., 1993). On the other hand, mowing is a less expensive and effective way to control weeds mechanically. When a lawn was mowed at 5 cm repeatedly, weeds were reduced by ~30% compared to 10 cm HOC (Butler et al., 2013).

1.3 Definition of Turfgrass Drought Tolerance

Turfgrass that demonstrates better drought tolerance usually has one or more of the following characteristics:
1) Deep Roots. Turfgrass with deeper roots is able to access water at deeper depth when under drought. Therefore, management regimes that encourage deep roots are advocated. For example, mowing grass at the higher end of the desired height range, and promotion of less frequent but deep irrigation (Christians, 2001).

2) Greener Color. Turfgrass that maintains greener color during drought is preferred. Warm-season grasses maintained better color and quality during drought and recovery periods than cool-season grasses, therefore warm-season grasses are usually more drought tolerant than cool-season grasses (Braun et al., 2017).

3) High Photosynthetic Rate During Drought. Drought tolerant turfgrass maintains higher photosynthetic rate under drought. Liu and Huang (2003) determined that creeping bentgrass mowed at 4 mm had higher photosynthesis rate than that mowed at 3 mm when experiencing summer drought stress. Therefore, grass mowed at higher height can withstand drought stress better than lower mowing height.

4) Fast Recovery From Drought. Schiavon et al. (2014) concluded that blends or mixtures containing tall fescue have better drought tolerance than perennial ryegrass or Kentucky bluegrass, as they recovered better after 21 days of drought and 30 days of watering post drought.

1.4 Plant Physiological Response to Drought

Stomatal closure is the primary response to drought stress. Photosynthetic rate is decreased due to the increase of leaf temperature (when drought is associated with high air temperature), and lower internal carbon dioxide concentrations (Sullivan and Eastin, 1974). Abscisic acid is the plant hormone involved in plant drought response. When plants are under
drought stress, ABA inhibits leaf growth (Bacon et al., 1998), leads to stomatal closure (Kirkham, 1983, Wilkinson and Davies, 2002), and enhances osmotic adjustment (Kirkham, 1983). Research has shown that application of the plant growth regulators ABA or trinexapac-ethyl (TE) increased plant drought tolerance by conserving water through stomatal closure, lowering shoot growth rate at the beginning of drought and sustaining growth and photosynthesis during prolonged drought periods (McCann and Huang, 2008, Mohammadi et al., 2017). Carbohydrate metabolism also affects drought tolerance. Sucrose accumulation improved turf performance during drought stress, and fructan accumulation was beneficial to rapid growth during a post-drought recovery period for Kentucky bluegrass (Yang et al., 2013).

1.5 Turfgrass Nutrition and Drought

Drought stress causes a change in nutrient partitioning in turfgrass. Nitrogen (N), phosphorous (P), and magnesium (Mg) tissue concentrations decrease, whereas potassium (K), calcium (Ca), and iron (Fe) concentrations increase in tall fescue when under drought (Huang, 2001). Drought stress induces the allocation of N and P more to the roots than to the shoots, and of K more to the shoots than roots (Huang, 2001). Higher N fertilization level increases soybean cell membrane stability and tissue integrity when subjected to drought (Premachandra et al., 1990b). Foliar application of CaCl₂, KH₂PO₄, or NH₄NO₃ resulted in higher shoot growth rate, photosynthesis rate, and photochemical efficiency for creeping bentgrass under heat stress, and heat stress is associated with drought in plant physiological response (Fu and Huang, 2003).

1.6 Summary
Turfgrass is an irreplaceable component in the landscape system because of its aesthetic, athletic, and its environmental functions. Turfgrass water use has been over-estimated by policy-makers and misrepresented by some literature. There is insufficient research on how different management regimes, such as HOC and fertility levels, affect turfgrass drought tolerance. Turfgrass is an ideal plant to study canopy water use because it forms a full cover when the grass is well-established. Turfgrass ET is usually measured by large, in-ground weighing lysimeters which are able to provide an accurate estimate, but these are inconvenient to move around or to allow for maintenance of a controlled environment.

1.7 Research Hypothesis and Objective

Turfgrass water use varies under management regimes including mowing height, N, and P fertilization, all of which also impact the function of turfgrasses that are experiencing different types of drought.

The goal of this research was to investigate how different management regimes, including HOC and nitrogen and phosphorous application levels, impact turfgrass water use and growth under periodic or prolonged drought conditions.

1.7.1 Turfgrass HOC and drought tolerance - Predictions

Turfgrass canopy height has an impact on well-established (full cover) turfgrass ET, photosynthesis rate, and growth under well-watered and drought conditions.

The study in Chapter 2 shows creeping bentgrass performance under two mowing heights (3 and 5 mm) and three water availability treatments (no drought, periodic drought with two
short dry-down periods, and prolonged drought with one long dry-down period). A post-drought recovery period was implemented for all water availabilities.

1.7.2 The method of using an array of load cell weighing lysimeters to measure real-time ET - Predictions

The novel method of using an array of load cell weighing lysimeters will be effective in measuring real-time ET under water sufficient and drought conditions.

Small load cell weighing lysimeters were used in studies in chapters 2 and 3 to monitor real time turfgrass pot weight change at 1-min intervals for turfgrass with different mowing heights and nitrogen levels under different drought conditions.

1.7.3 Turfgrasses with different fertilizer regimes before drought and their performance under drought - Predictions

Improving N fertilization before entering drought conditions would improve low-mowed turfgrass drought tolerance by maintaining green color and/or higher photosynthesis rate during drought and post-drought recovery periods.

The study in chapter 3 adopted four N rates which represented low, medium, high, and very high N levels. A load cell array of weighing lysimeters was also used to monitor real time water use.

1.7.4 Phosphorous levels and cool-season turfgrass varieties - Predictions

Low P fertilization will improve drought tolerance by increasing the root:shoot allocation of available carbon under mowed conditions.
The study in chapter 4 used two P rates and four turfgrass varieties under drought and drought recovery conditions.
Chapter 2: Turfgrass Growth and Evapotranspiration Under Water Deficit at Two Mowing Heights Under Carbon-Limited Conditions

2.1 Introduction

Plant water use is an important part of the global water cycle as transpiration plays a crucial role in linking the global hydrologic cycle between land and atmosphere (Gat, 2010). Evapotranspiration is the combination of evaporation whereby water is vaporized from the soil or plant surface, and transpiration whereby water is vaporized in the intercellular space within the leaf and then lost to the atmosphere predominately through stomata (Allen 1998). Efficient irrigation programs require knowledge of ET because 20% of crops in the world are irrigated and the amount of irrigated crops is increasing (FAO, 2003). Evapotranspiration is affected by environmental factors such as temperature, wind speed, and vapor pressure deficit, as well as plant physiological factors such as developmental stage, stress hardiness, and crop height (Allen, 1998).

Crop ET reaches the maximum when the crop is at full cover and receives sufficient irrigation. Leaf area index (LAI), which is defined as the ratio of one-side leaf surface area to land surface area (Ross, 1981), is the indicator of canopy completeness (Best and Harlan, 1985, Baret, 1995). When the LAI value is greater than 2.7, the ground below a crop is considered to be completely shaded suggesting the crop has reached full cover. In this circumstance, crop canopy ET reaches the maximum regardless of canopy height (Rogers D.H., 2015). Research has shown that irrigated maize crops grew 1.5 m taller from LAI=2.7 (full cover) to the peak LAI of 5 while maintaining the same maximum ET rate (Bergamaschi et al., 2010, Colaizzi et al., 2012). Similarly, sorghum grew 0.3 m taller, cotton 0.5 m taller, and winter wheat 0.5 m taller from LAI = 2.7 to their peak LAIs while maintaining the same ET rate (Colaizzi et al., 2012). Not only
crop height, but also crop density becomes a non-limiting factor when a crop is at full cover if irrigation is sufficient (Rogers D.H., 2015).

Maximum ET is sometimes referred to as reference ET. Turfgrass is usually used as the reference crop to provide a reference ET in a designated region (Allen et al., 1998). This is because healthy and well-established grass is generally regarded as a full cover. Unlike with crops, there is no method to measure LAI to determine that turfgrass reached maximum ET. Allen et al (1998) suggested the following equation to determine LAI for turfgrass: LAI = \(24 \times \text{Plant height (m)}\). However, no research can be found using this equation to estimate LAI or define maximum ET for turfgrass. The inability to relate LAI to turfgrass may be due to the typical destructive measure of LAI being labor intensive for turfgrass and difficult to perform, particularly at low mowing heights (Kopec et al., 1987). Limited effort has been made to estimate grass LAI by using indirect remote sensing techniques (Kopec et al., 1987, Welles, 1990, Przeszlowska et al., 2006, An et al., 2015, Xu and Guo, 2015); but unfortunately, results have been inconsistent due to the complex canopy structure such as leaf angle distribution, and how to include or exclude non-green components (He et al., 2007).

The theory that ET is constant after reaching full cover may not be applicable for turfgrass, as mowing height has been shown to impact water loss from an established turfgrass canopy (Poro et al., 2017). Mowing height studies for close-cut turfgrass are mainly associated with ball roll distance, turf quality, and stress susceptibility (Liu and Huang, 2003, Frank et al., 2004, Horgan, 2012, Kvalbein, 2013). There is limited research on mowing height and water use. However, research has shown that mowing height has a significant effect on water use (Jensen, 1990). Kentucky bluegrass mowed at 5 cm transpires 27% more water than when mowed at 1.3 cm due to the greater leaf surface. However, the lower-cut turf is more susceptible to drought.
when a deficit irrigation program is practiced due to its shallower root system (Kneebone W.R., 1992). Poro et al. (2017) calculated and compared green and fairway height (3.1 and 9.4 mm HOC) creeping bentgrass crop coefficients under well-watered conditions, and concluded that lower HOC resulted in a lower crop coefficient value.

Turfgrass is used as the reference plant to calculate the reference ET ($ET_0$) using weather data in the FAO-56 formula (Allen et al., 2005):

$$ET_0 = \frac{0.408\Delta (R_n - G) + \gamma u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)} \frac{900}{T + 273}$$

Where $ET_0$ is the reference evapotranspiration (mm day$^{-1}$); $R_n$ is the net radiation at the crop surface (MJ m$^{-2}$ day$^{-1}$); $G$ is the soil heat flux density (MJ m$^{-2}$ day$^{-1}$); $T$ is the mean daily air temperature at 2 m height ($^\circ$C); $\gamma$ is the psychrometric constant (kPa °C$^{-1}$) $u_2$ is the wind speed at 2 m height (m s$^{-1}$); $e_s$ is the saturation vapour pressure (kPa); $e_a$ is the actual vapor pressure (kPa). However, the reference plant they used to relate mowed turfgrass is 12 cm-tall alfalfa, which is too tall and not representative of most managed turfgrass. In addition, calculated ET in this model is based on non-limiting water supply, yet turfgrass is able to maintain the same function when under deficit irrigation (Carrow, 1988, Sass, 2006, DaCosta and Huang, 2006). Therefore, the FAO 56 estimation model from Allen (1998) may overestimate turfgrass water needs. In addition, cultural management such as nutrient status and HOC also greatly affect turfgrass water use (Poro et al., 2017). The irrigation policy enacted by regulators for turfgrass using the FAO 56 estimation model may lack a solid basis in response to different turfgrass management scenarios.

The most accurate ET measurements come from using built-in lysimeters in the field. However, these lysimeters are usually very large and importable, limiting the sample size for turfgrass research. Small-scale mini-lysimeters are more feasible, especially in controlled
environments. Also, real-time data-logging techniques are available to estimate real time actual ET.

The objectives of this study were to:

i. investigate whether established turfgrass canopy height impacts water use under different drought conditions,

ii. determine how mowing height influences turfgrass drought tolerance, and

iii. to test the method of using a load cell array for measuring real time turfgrass ET rate.

2.2 Materials and Methods

2.2.1 Plant establishment and growing conditions

‘L93’ Creeping bentgrass (*Agrostis stolonifera*) was seeded in 45-cm tall PVC pipes (5 cm diameter and 5 mm wall thickness) filled with 5 cm gravel at the bottom and 40 cm calcareous sand. The purpose of using this pipe size was to fit it to the 5 cm diameter *Arabidopsis* chamber of a Licor 6400 (LI-COR Inc. Lincoln, Nebraska) used to measure turfgrass canopy photosynthesis (Pn) and transpiration (Tr). Grasses were grown in a greenhouse at the University of Guelph (43.5321° N, 80.2269° W) for 60 d until fully established. During the 60-day establishment period in the greenhouse, liquid fertilizer (20N-8P-20K) was applied every 7 d to a total N of 9 g m\(^{-2}\) for the establishment period. Swirskii-System (a.i. *Amblyseius swirskii*) (Biobest, Belgium NV) was applied every 14 d as a biological control agent for greenhouse thrips (*Heliothrips haemorrhoidalis*). After establishment, the grass was transferred to four growth chambers with 14-h photoperiod from 7 am to 9 pm, a temperature of 22/18 °C (day/night), and photosynthetically active radiation (PAR) of 600 µmol m\(^{-2}\) s\(^{-1}\) for drought treatments. Each chamber contained one replication and all four chambers were set to the same
conditions. Plants were then maintained in growth chambers for 14 d for acclimation. All rootzones were brought to field capacity before drought treatments started. Grasses were maintained at two mowing heights of 3 and 5 mm throughout the experiment by mowing every other day with a clipper (WAHL, Illinois).

2.2.2 Load cell array establishment

In order to measure real time evapotranspiration, 24 out of the 96 PVC tubes with grass were put on 24 small load cells (Mettler-Toledo, Columbus OH, USA) to record the weight change every minute during the study. A cup container was mounted to the load cell to hold the tube and to collect any leached water and prevent it from evaporating and contributing to weight loss (Picture 2.1). Every four load cells were connected to an electronic signal amplifier (Phidget, Calgary AB, Canada). Each growth chamber was equipped with one PhidgetSBC3 single board computer (Phidget, Calgary AB, Canada) for data processing. Before the drought treatment started, a capacity test was conducted on each tube to determine the field or tube capacity weight. All tubes were watered until drainage and tube weight were recorded at 1, 1.5, 2, 2.5 and 3 h after the watering event. Weight at tube capacity was determined when the drainage stopped and that weight decreased at a steady slow rate due solely to ET. The purpose of the capacity test was to reduce the leaching of water into the cup as much as possible when watering grass tubes on the load cells.
2.2.3 Drought treatments and harvests

Specific drought treatments are listed in Table 2.1. The exact amount of water was added using a syringe to each tube of turfgrass based on the difference of current tube weight and tube capacity weight. Tubes remained in the growth chamber when watering. The 72 tubes not on load cells were used for the destructive harvests of turfgrass verdure and roots, which were conducted at 0 d for both Runs; 13 d in Run 1 and 12 d in Run 2, which was at the end of the first dry-down period for the periodic drought treatment; 22 d in Run 1 and 19 d in Run 2, which was the end of the second dry-down for the periodic drought as well as the prolonged dry-down for the prolonged drought; 28 d in Run 1 and 26 d in Run 2, which was the end of the experiment. For the last harvest, the grass tubes on the load cells were harvested for root and shoot analysis. Grass was trimmed to corresponding heights of 3 and 5 mm before each harvest, to eliminate the factor of different growth rate under different drought treatments impacting verdure parameters.
Table 2.1 Drought treatments for the two runs of the water use experiment in growth chambers.

<table>
<thead>
<tr>
<th>Drought treatment</th>
<th>Treatment Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Run 1</strong></td>
<td></td>
</tr>
<tr>
<td>No drought</td>
<td>Water every other day for 28 days to tube capacity weight as indicated by load cells.</td>
</tr>
<tr>
<td>Periodic</td>
<td>Water withheld for 13 days, re-water one time on 13 days after the start of the experiment (13 DAT) to tube capacity weight, water withheld for another 9 days until 22 DAT, water every other day for 6 days until 28 DAT.</td>
</tr>
<tr>
<td>Prolonged</td>
<td>Water withheld until 22 DAT, water every other day for 6 days until 28 DAT.</td>
</tr>
<tr>
<td><strong>Run 2</strong></td>
<td></td>
</tr>
<tr>
<td>No drought</td>
<td>Water every other day for 26 days to tube capacity weight as indicated by load cells.</td>
</tr>
<tr>
<td>Periodic</td>
<td>Water withheld for 12 days, re-water one time on 12 DAT to tube capacity weight, water withheld for another 7 days until 19 DAT, water every other day for 7 days until 26 DAT.</td>
</tr>
<tr>
<td>Prolonged</td>
<td>Water withheld until 19 DAT, water every other day for 7 days until 26 DAT.</td>
</tr>
</tbody>
</table>

2.2.4 Measurements

Turfgrass color was measured visually on a scale of 1-9 (1-straw brown, 9-dark green).

Volumetric soil water content at 0-10 cm soil depth was measured by using a soil moisture meter.
(HH2, Delta-T Devices Ltd, Cambridge UK) every two days after drought started. Turfgrass evapotranspiration rate was measured by using the load cell array system. The load cell array system recorded grass tube weight at 1-min intervals throughout the study (Graph 2.1) for the 24 grass tubes. Turfgrass canopy net photosynthetic (Pn) rate and transpiration (Tr) rate was measured with a gas exchange system (Licor 6400, LI-COR Inc. Lincoln, Nebraska) equipped with a 5 cm diameter whole plant chamber at a PAR of 1000 mmol m$^{-2}$ s$^{-1}$ and a chamber temperature of 22 °C. Pn and Tr measurements were conducted on the 24 grass tubes on load cells every two days after the start of drought treatments. When taking Pn and Tr measurements, the 24 grass tubes were taken out of the growth chamber one-by-one and returned to the same spot in the growth chamber. Turfgrass verdure and roots were collected and weighed after being oven dried at 80 °C for 72 h. Each root sample was separated into three sections: 0-3, 3-12, >12 cm below the thatch layer for dry weight measurements. Root length (all sections) was determined using WinRHIZO (Regent Instruments Inc., Canada). Instantaneous canopy water use efficiency (WUE) was calculated as Pn/Tr. Specific root length was calculated as root length/root weight (m/g).
Graph 2.1 Turfgrass tube weights for no drought (a and d), periodic drought (b and e), and prolonged drought (c and f) treatments measured at 1-min intervals by the load cell array from the beginning to the end of the study. Red and blue dots represent weights during daytime conditions (lights on) and nighttime conditions (lights off), respectively, for all mowing heights. Run 1 (a, b and c) and Run 2 (d, e and f) represent two independent experiments each with 4 replications.
2.2.5 Statistical analysis

The experimental design was a randomized complete block design with two factors (two mowing heights and three drought treatments) and four replications. Each replication was an independent environment in separate growth chambers. Data were analyzed through mixed effects analysis of variance using PROC MIXED in SAS (SAS Institute, 2002) with date/time as repeated measures. When significant differences were detected (P < 0.05), the least square means were separated using Fisher’s LSD test. Regression analysis for hourly ET data was conducted using the ANCOVA procedure.
2.3 Results

2.3.1 Soil water content

Soil volumetric water content (SWC) measured by TDR for the no drought treatment in the top 10 cm was consistently 30% for the first run and 22% for the second run of the experiment (Figure 2.2 a, b). The periodic drought treatment decreased in SWC content during the dry-down period to 10 and 7% for Run 1 and Run 2, respectively. After the one-time watering event to field capacity at the end of the dry-down period, SWC content returned to 30 and 22%, and then gradually decreased during the second dry-down period back to 10 and 7% at 22 and 19 DAT. During the recovery period, SWC content of the periodic drought treatment remained at 25 and 20% for Run 1 and Run 2, respectively, from 22-28 DAT for Run 1, and 19-26 DAT for Run 2. The prolonged drought treatment decreased SWC content until 13 and 12 DAT to 7% for both runs and then stayed consistently at that level until the watering at the beginning of the recovery period. During the recovery period the SWC content remained at 25% and 20% for Run 1 and Run 2, respectively (Figure 2.2 a, b).
Figure 2.2. Soil water content (a, b), color visual rating (c, d), and photosynthesis rate (e, f) for grasses grown in growth chambers mowed at 3 and 5 mm (pooled) and subjected to three drought treatments. Run 1 and 2 represent two independent experiments each with 4 replications. The dotted vertical line represents a one-time watering event for the periodic drought treatment and the dashed vertical line represents the beginning of the recovery period (watering every other day) for all treatments.
2.3.2 Turfgrass visual color rating

Throughout both runs of the experiment, the no drought treatment remained at a high visual color rating ranging from 7.8 to 8.5 (Figure 2.2 c, d). Grass mowed at 5 mm HOC maintained a higher color rating than grass mowed at 3 mm HOC for 3 and 10 DAT in Run 1, and 10 and 14 DAT in Run 2 (Figure 2.3 a, d).

The periodic drought treatment decreased in color rating to 2.5 at 13 DAT for Run 1 and at 12 DAT for Run 2 during the dry-down period (Figure 2.2 c, d). Color of the turfgrasses dropped below the acceptable level of 6 after 8 and 7 DAT for Run 1 and Run 2, respectively. Color ratings increased from 2.5 and leveled off at 5 and 5.5 for Run 1 and Run 2, respectively, during the second dry-down period. Color ratings for the periodic drought then gradually increased during the recovery period to 6 at the end of the experiment (Figure 2.2 c, d). Grass at 5 mm HOC had higher color rating than grass at 3 mm HOC at 6 and 8 DAT in Run 1, and 3, 5 and 7 DAT in Run 2 (Figure 2.3 b, e). After the one-time watering event, no difference was observed between mowing heights for the second dry-down and drought recovery periods (Figure 2.3 b, e).

Plants exposed to the prolonged drought treatment had a decreased color rating close to 1 before the recovery period for both runs (at 22 and 19 DAT, respectively). Plants in the prolonged drought treatment had the same pattern of decreased color rating as the periodic drought treatment for the beginning of the dry-down period because both treatments experienced the same drought for this period. Color ratings for plants in the prolonged drought treatment then slowly increased to 1.5 and 2 for Run 1 and Run 2, respectively, during the recovery period. Grass mowed at 5 mm had higher color ratings than grass mowed at 3 mm for 6, 8, 10, and 13
DAT in Run 1, and 3, 5 DAT in Run 2 (Figure 2.3 c, f). After 13 DAT in Run 1 and 5 DAT in Run 2, no differences in color ratings were observed between mowing heights.

Grass at 3 mm HOC showed less difference between drought treatment and the no drought treatment than grass at 5 mm HOC at 20, 22, and 24 DAT in Run 1, and 14 DAT in Run 2 when comparing the drought treatments to no drought treatment for color ratings (Figure 2.4 a and c).

For the prolonged drought treatment, grass at 3 mm HOC had better color than grass at 5 mm HOC during the dry-down at 14 and 19 DAT, and at the end of the recovery period in Run 2 (Figure 2.4 d).

Table 2.2 Analysis of Variance for color, photosynthesis, transpiration, water use efficiency, evapotranspiration, and accumulated evapotranspiration of creeping bentgrass.

<table>
<thead>
<tr>
<th>Contrasts</th>
<th>Color</th>
<th>Photosynthesis</th>
<th>Transpiration</th>
<th>WUE</th>
<th>ET</th>
<th>Accumulated ET</th>
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<tr>
<td></td>
<td>Run 1</td>
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<td>Height (H)</td>
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<td>NS</td>
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<td>Drought Treatment (DT)</td>
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<td>Time (T)</td>
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<td>H x T</td>
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<td>DT x T</td>
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<td>Run 2</td>
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<td>Height (H)</td>
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<td>Drought Treatment (DT)</td>
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<td>Time (T)</td>
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<td>NS</td>
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</tr>
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</table>

*, and NS indicate significance at P=0.05, and not significant at P=0.05 level, respectively.
Figure 2.3. Color visual rating for no drought (a, d), periodic drought (b, e), and prolonged drought (c, f) treatments over time throughout the experiment for grasses maintained at 3 and 5 mm HOC grown in growth chambers. Run 1 and 2 represent two independent experiments with 4 replications. The dotted vertical line represents a one-time watering event for the periodic drought treatment and the dashed vertical line represents the beginning of the recovery period (watering every other day) for all treatments. The asterisk denotes statistical significance between mowing heights at a specific measurement date.
Figure 2.4. Difference of color visual rating between periodic drought and no drought treatments (a, c), prolonged drought and no drought (b, d) over time throughout experiment for grasses mowed at 3 and 5 mm grown in growth chambers. Run 1 and 2 represent two independent experiments with 4 replications. The dotted vertical line represents a one-time watering event for the periodic drought treatment and the dashed vertical line represents the beginning of the recovery period (watering every other day) for all treatments. The Asterisk denotes statistical significance between mowing heights at a specific measurement date.

2.3.3 Canopy net photosynthetic rate

The Pn rate of the no drought treatment decreased gradually from 7.5 to 6.5 µmol m$^{-2}$ s$^{-1}$ for Run 1, and from 14.4 to 8.4 µmol m$^{-2}$ s$^{-1}$ for Run 2 from the beginning to the end of the studies (Figure 2.2 e, f) probably due to nutrient deficiency, as no fertilizers were applied after drought treatments started.

For the no drought treatment, grass at 5 mm HOC had 25-30% higher Pn rate than grass at 3 mm HOC throughout the study (Figure 2.5 a, d). Grass at 5 mm HOC maintained higher Pn
rate than grass at 3 mm HOC at 0 and 6 DAT in Run 1, and at 3 DAT in Run 2 (Figure 2.5 b, c) of the periodic drought treatment. Photosynthetic rate dropped down to 3.2 and 5 μmol m$^{-2}$ s$^{-1}$ for Run 1 and Run 2, respectively, at the end of dry-down period. After the one-time watering event, Pn rate then increased to 3.9 and 7.8 μmol m$^{-2}$ s$^{-1}$ for Run 1 and Run 2, respectively, at the end of the second dry-down period. Photosynthetic rate then maintained close to 4 and 6 μmol m$^{-2}$ s$^{-1}$ for Run 1 and Run 2, respectively, during the recovery period. No difference was observed between the two mowing heights during the second dry-down and recovery periods. The prolonged drought treatment had a similar decrease pattern of Pn rate as the periodic drought treatment during the initiated dry-down period because they experienced the same drought for this period. Photosynthetic rate then decreased to close to 0 in both Run1 and Run 2 at the end of the prolonged dry-down period (22 and 21 DAT, respectively) (Figure 2.5 c, f). Photosynthetic rate slightly increased to 1.8 μmol m$^{-2}$ s$^{-1}$ for Run 2 at the end of the recovery period (26 DAT) (Figure 2.5 f). Grass at 5 mm HOC had higher Pn rate than grass at 3 mm HOC until 13 DAT in Run 1, yet this was not observed in Run 2.

For both periodic and prolonged drought treatments, grass at 3 mm HOC had closer Pn rate to that of the no drought treatment than grass at 5 mm HOC in both Runs (Figure 2.6 a, b, c and d).
Figure 2.5. Canopy net photosynthetic rate for no drought (a, d), periodic drought (b, e), and prolonged drought (c, f) treatments over time throughout experiment for grasses mowed at 3 and 5 mm grown in growth chambers. Runs 1 and 2 represent two independent experiments with 4 replications. Dotted vertical line represents a one-time watering event for the periodic drought treatment and the dashed vertical line represents the beginning of the recovery period (watering every other day) for all treatments. The asterisk denotes statistical significance between mowing heights at a specific measurement date.
Figure 2.6. Difference of canopy net photosynthetic rate (ΔPn) between periodic drought and no drought treatments (a, c), prolonged drought and no drought (b, d) over time throughout experiment for grasses grown in growth chambers. Run 1 and 2 represent two independent experiments with 4 replications. The dotted vertical line represents a one-time watering event for the periodic drought treatment and the dashed vertical line represents the beginning of the recovery period (watering every other day) for all treatments. The asterisk denotes statistical significance between mowing heights at a specific measurement date.
2.3.4 Canopy transpiration rate measured by gas exchange

For the no drought treatment, grass mowed at 5 mm HOC had higher Tr rate than grass at 3 mm HOC at 6, 24, and 28 DAT in Run 1, and at 19 and 21 DAT in Run 2 (Figure 2.7 a, d) as measured using gas exchange. Grass maintained an average Tr rate of 3.8 and 4.4 mmol m\(^2\) s\(^{-1}\) for Run 1 and Run 2, respectively. For the periodic drought treatment, grass at 5 mm HOC had higher Tr rate than grass at 3 mm HOC at 6 and 8 DAT in Run 1 (Figure 2.7 b). For the prolonged drought, grass at 5 mm HOC had higher Tr rate than grass at 3 mm HOC at 6 and 8 DAT in Run 1, whereas grass at 3 mm HOC had higher Tr rate than grass at 5 mm HOC at 17 DAT in Run 2 (Figure 2.7 c, f).

![Figure 2.7](image)

Figure 2.7. Canopy transpiration rate measured by gas exchange for no drought (a, d), periodic drought (b, e), and prolonged drought (c, f) treatments over time throughout experiment for grasses grown in growth chambers mowed at 3 and 5 mm. Runs 1 and 2 represent two independent experiments with 4 replications. The dotted vertical line represents a one-time watering event for the periodic drought treatment and the dashed vertical line represents the beginning of the recovery period (watering every other day) for all treatments. The asterisk denotes statistical significance between mowing heights at a specific measurement date.
2.3.5 Instantaneous Water Use Efficiency

For the no drought treatment, grass at 5 mm HOC had 23-30% higher water use efficiency (WUE) than grass at 3 mm HOC throughout the study for both Runs (Figure 2.8 a, b). For the periodic drought treatment, no significant difference was observed between the two mowing heights except for 0 and 3DAT in Run 2, where grass at 5 mm HOC had higher WUE than grass at 3 mm HOC. For the prolonged drought, grass at 5 mm HOC had higher WUE than grass at 3 mm HOC only at 3 DAT in Run 1 (Figure 2.8 c).

Figure 2.8. Instantaneous water use efficiency for no drought (a, d), periodic drought (b, e), and prolonged drought (c, f) treatments over time throughout experiment for grasses mowed at 3 and 5 mm grown in growth chambers. Runs 1 and 2 represent two independent experiments with 4 replications. The dotted vertical line represents a one-time watering event for the periodic drought treatment and the dashed vertical line represents the beginning of the recovery period (watering every other day) for all treatments. The asterisk denotes statistical significance between mowing heights at a specific measurement date.
2.3.6 Evapotranspiration

Mowing height did not result in a significant difference between turfgrass daytime and nighttime ET when observed at 1 h intervals (Appendices 2.1-2.4). However, daily ET did differ in some cases between mowing heights (Figure 2.9). In Run 1, the ET rate for the no drought treatment consistently averaged 4.9 mm d\(^{-1}\) for grass maintained at 3 mm HOC, and 5.2 mm d\(^{-1}\) for grass maintained at 5 mm HOC throughout the experiment (Figure 2.9 a). In Run 2, grass at 5 mm HOC maintained average ET of 6.4 mm d\(^{-1}\) while grass at 3 mm HOC had an average of 5.9 mm d\(^{-1}\) (Figure 2.9 d). Grass at 5 mm HOC had higher daily ET at 6, 9, and 14 DAT than grass at 3 mm for the no drought treatment in Run 2 (Figure 2.9 d). For the periodic drought treatment, ET decreased to 2.7 and 2.1 mm d\(^{-1}\) for grasses at 3 and 5 mm HOC, respectively, in Run 1, and to 2.25 and 3 mm d\(^{-1}\) for grasses at 3 and 5 mm HOC, respectively, in Run 2 at the end of the first dry-down period. It then increased to around 4 mm d\(^{-1}\) for grasses at both HOC in both Runs after the recovery period (Figure 2.9 b, e). However, no significant difference was revealed between the mowing heights. ET for the prolonged drought treatment dropped to almost 0 and 1 in Run 1 and Run 2, respectively, at the end of prolonged drought (Figure 2.9 c, f). ET then increased to 2 and 3 mm d\(^{-1}\) for Run 1 and Run 2, respectively, at the end of the recovery period. Grass at 5 mm HOC had a higher ET rate than grass at 3 mm HOC at 2 DAT in Run 2 (Figure 2.9 f).
Figure 2.9. Evapotranspiration for no drought (a, d), periodic drought (b, e), and prolonged drought (c, f) treatments over time throughout experiment for grasses mowed at 3 and 5 mm grown in growth chambers. Runs 1 and 2 represent two independent experiments with 4 replications. The dotted vertical line represents a one-time watering event for the periodic drought treatment and the dashed vertical line represents the beginning of the recovery period (watering every other day) for all treatments. The asterisk denotes statistical significance between mowing heights at a specific measurement date.

2.3.7 Accumulated evapotranspiration

Grass at 5 mm HOC had a higher accumulated ET than grass at 3 mm HOC from 17 DAT to the end of the study in Run 2 for the no drought treatment (Figure 2.10 d). However, no difference in accumulated ET was observed between HOC in Run 1 (Figure 2.10 a).
Figure 2.10. Accumulated evapotranspiration for no drought (a, d), periodic drought (b, e), and prolonged drought (c, f) treatments over time throughout experiment for grasses grown in growth chambers mowed at 3 and 5 mm. Runs 1 and 2 represent two independent experiments with 4 replications. The dotted vertical dotted line represents a one-time watering event for the periodic drought treatment and the dashed vertical line represents the beginning of the recovery period (watering every other day) for all treatments. The asterisk denotes statistical significance between mowing heights at a specific measurement date.

2.3.8 Verdure dry weight

Maintained HOC affected verdure dry weight at all harvest dates (Table 2.3), with grass at 5 mm HOC having 19-33% more dried verdure weight than grass at 3 mm HOC (data not shown) except for the periodic and prolonged drought treatments at 8 day after recovery initiated (DARC) in Run 2 (Figure 2.11).
Table 2.3 ANOVA of verdure dry weight before drought (0 DAT), at the end of first dry-down (13 DAT), at the end of second dry-down (7 DARW), and at the end of recovery (8 DARC).

<table>
<thead>
<tr>
<th></th>
<th>DF</th>
<th>0 DAT</th>
<th>13 DAT</th>
<th>7 DARW</th>
<th>8DARC</th>
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<td><strong>Run 1</strong></td>
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<td><strong>Height (H)</strong></td>
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<td><strong>DT x H</strong></td>
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<td>NS</td>
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<tr>
<td><strong>Run 2</strong></td>
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<td><strong>Drought trt</strong></td>
<td>2</td>
<td>NS</td>
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<td><strong>(DT)</strong></td>
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<td><strong>DT x H</strong></td>
<td>2</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>*</td>
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</tbody>
</table>

NS and * mean nonsignificant or significant at P=0.05.

Figure 2.11. Verdure dry weight for grasses grown in growth chambers mowed at 3 and 5 mm under no drought, periodic drought, and prolonged drought conditions at the end of study (8 DARC). Run 1 and 2 represent two independent experiments with 4 replications. The asterisk denotes statistical significance between mowing heights for the drought treatment.
2.3.9 Root total length

Grass at 5 mm HOC had longer root length than grass at 3 mm HOC, regardless of drought treatments at the end of recovery (8 DARC) for data pooled for both runs (Figure 2.12). When mowing heights were combined, drought treatment affected root length in Run 2. The no drought treatment had the longest roots at the end of second dry-down (7 DARW) and the end of recovery (8 DARW). Prolonged drought treatment had the shortest root length at the end of recovery (Figure 2.13).

Figure 2.12. Mowing height main effect on root total length per 0.002 m² ground area before drought (0 DAT), at the end of first dry-down (13 DAT), at the end of second dry-down for the periodic drought treatment (7 DARW), and at the end of recovery (8 DARC) for Run 1 and Run 2 pooled together. Asterisk represents statistical significance between mowing heights for the date of measurement.
2.1 Figure 2.1. Drought treatment main effect on root total length per 0.002 m$^2$ ground area before drought (0 DAT), at the end of first dry-down (13 DAT), at the end of second dry-down for the periodic drought treatment (7 DARW), and at the end of recovery (8 DARC) in run 2. Letters indicate significant difference among drought treatment for the date of measurement.

2.3.10 Specific root length

The no drought treatment had the lowest specific root length at the end of recovery (Figure 2.14). Grass that experienced drought and post drought recovery had higher specific root lengths than the no drought treatments.

2.1 Figure 2.14. Drought treatment main effect on specific root length before drought (0 DAT), at the end of first dry-down (13 DAT), at the end of second dry-down for the periodic drought treatment (7 DARW), and at the end of recovery (8 DARC) for run 1 and run 2 pooled together. Letters indicate significant difference among drought treatment for the date of measurement.
2.3.11 Root dry weight

Mowing height affected root dry weight for all sampling dates except for 0 DAT in Run 2 (Table 2.4). Grass at 5 mm HOC had a higher amount of root dry weight than grass at 3 mm HOC for all sections and all sampling dates when a difference was detected (data not shown). The no drought treatment resulted in more roots especially at >12 cm depth than the two drought treatments (periodic and prolonged).

Table 2.4. ANOVA of root dry weight at 0-3 cm, 3-12 cm, >12 cm, and total weight of all sections before drought (0 DAT), at the end of first dry-down (13 DAT), at the end of second dry-down for the periodic drought treatment (7 DARW), and at the end of recovery (8 DARC) for run 1 and run 2.

<table>
<thead>
<tr>
<th></th>
<th>Run 1</th>
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<tr>
<td></td>
<td>0-3 cm</td>
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<td>NS NS NS NS</td>
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<tr>
<td>Drought trt (DT)</td>
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<td>Drought trt (DT)</td>
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NS and * mean nonsignificant or significant at $P=0.05$. 

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2.4 Discussion

When water was sufficient, grass at 5 mm HOC had higher color ratings, photosynthesis, evapotranspiration, and transpiration rate, as well as WUE than grass at 3 mm HOC. Other studies also reported that higher mowing heights increase turfgrass quality and photosynthesis rate, but had no effect on color when compared with lower mowing heights (Salaiz et al., 1995, Liu and Huang, 2003). Taller grasses maintained at 25, 35, and 45 mm HOC under well-watered conditions showed no quality difference amongst mowing heights (Elansary and Yessoufou, 2015). Liu and Huang (2003) reported that grass at a lower mowing height of 3 mm had a higher transpiration rate than grass at 4 mm HOC potentially due to the higher canopy temperature associated with the 3-mm mowing height in summer months. However, the current chamber study presented here shows the opposite relationship under well-watered conditions as turfgrass in the growth chamber did not expose to extreme temperatures. Poro et al. (2017) concluded that grass mowed at 3.1 mm uses less water than grass mowed at 9.4 mm, and recommended different crop coefficients of 0.9 and 1.0, respectively, to be used in the FAO-56 estimation model to calculate ET. The results for this experiment are similar to those of Poro et al. (2016) in that grass at higher HOC uses more water than grass at lower HOC, when irrigation is sufficient.

During drought and post-drought recovery, grass color, photosynthesis rate, ET rate, as well as WUE were not able to return to the level before drought. Shahba et al. (2014) and Yu et al. (2015) saw similar lack of recovery on seashore paspalum cultivars and Kentucky bluegrass experiencing 20 d drought and 7 d recovery. This may due to the decreased ability to regulate osmotic water movement due to the reduced accumulation of sugars, proline, and glycine betaine during drought (Yu et al., 2015). This work showed grass at 5 mm HOC maintained greener
color as well as higher photosynthesis rate than grass at 3 mm HOC during dry-down, which has previously been reported with fairway height grasses (Shahba et al., 2014).

At the beginning of the dry-down period, grass at higher mowing height was more drought tolerant than grass at lower mowing height, as evidenced by higher color rating, photosynthesis rate, and WUE. As drought continued, the effect of mowing height disappeared for all of the parameters as the drought became the driving factor affecting the health of the turfgrass. There were also few differences between mowing heights for the post-drought recovery period in all physiological measurements, showing that mowing height (3 and 5 mm) is not the limiting factor in drought recovery.

Crop plants, such as corn, wheat, and sorghum, are assumed to have the same level of water use regardless of crop height after a closed canopy is established (Rogers et al., 2015). In turfgrass, this study reveals higher-cut grass uses more water than lower-cut grass when water is sufficient. Field crops and a frequently mowed turfgrass respond differently in terms of water use.

The effect of mowing height outweighs the impact of drought, periodic or prolonged, in terms of verdure and root parameters as seen by grass at 5 mm HOC having more verdure dry weight, root dry weight at all depths, and longer root length than grass at 3 mm HOC whether or not under drought. Similar verdure weight across drought treatments but not mowing heights imply that turf density was not impacted by drought but was related to mowing height for turfgrass cut at 3 mm.

Regardless of mowing height, turfgrass under drought had less root length and higher specific root length than turfgrass under well-watered conditions. Specific root length is generally negatively correlated to average root diameters (Eissenstat, 1992). Smaller diameter
roots have the ability to access more water and nutrients even in non-favorable conditions, and thus can enhance drought tolerance (Eissenstat and Caldwell, 1989, Eissenstat, 1992). On the contrary, larger diameter roots have the potential to penetrate into deeper soil and develop more lateral roots, and therefore prove to be more drought avoidant (Torbert and Pederson, 1990, Huang et al., 1997). In the present study, mowing height was not correlated to the development of smaller or larger-diameter roots. However, drought reduces root length and resulted in higher specific root length (smaller diameter roots), which is consistent with what Huang (2001) and Huang (1997) reported on the characteristics of several grass species and cultivars with different drought tolerance.

The innovative load cell array was able to capture tube weight change at 1-min intervals and differences in ET at 1-h intervals. Future research may use larger grass pots to better detect differences in ET with the load cells.

### 2.5 Conclusion

When irrigation is not limited, turfgrass mowed at higher HOC (5 mm) performed better than turfgrass mowed at lower HOC (3 mm) in terms of visual color, Pn, Tr, and ET rates. Under conditions of frequent mowing, turfgrass canopy ET is different from crops that are only harvested at the end of the season. When irrigation is limited, turfgrass at higher HOC showed better drought tolerance as it remained green longer during drought than turfgrass at lower HOC. However, turfgrass at lower HOC recovered better after prolonged drought than turfgrass at higher HOC. The mini-lysimeter load cell array was able to measure pot weight change at 1-min intervals and detect ET change at 1-h intervals for turfgrass with different mowing heights.
Chapter 3: Nitrogen Effects on Creeping Bentgrass Growth and Water Use During Drought and Post-drought Recovery

3.1 Introduction

Nitrogen (N) fertilization plays an important role in plant carbon allocation to shoots and roots and sufficient levels of N promote the growth of both. When N becomes limited, however, root growth rate increases and shoot growth rate decreases but if N is deficient for a prolonged period, root growth becomes inhibited as well (vanderWerf and Nagel, 1996). Under temporary N deficiency increased root growth and decreased shoot growth results in a higher root to total biomass weight ratio, and this is mediated by cytokinin and sucrose (vanderWerf and Nagel, 1996, Yang et al., 2013, Chang et al., 2016). Nitrogen deprivation decreases cytokinin production and concentrations, as well as its transport rate from roots to shoots. Root and shoot cells respond differently to nitrogen rates in terms of sucrose concentration and turgor pressure gradients to favor more carbohydrates exported to the roots (vanderWerf and Nagel, 1996, Forde, 2002, Werner et al., 2010, Wang and Ruan, 2016). Previous studies observed that fertilization with CaCl₂, KH₂PO₄, or NH₄NO₃ improved creeping bentgrass heat tolerance as shown by sustaining photosynthetic activities at higher temperatures, and the mechanism of heat tolerance was related to the inhibition of lipid peroxidation and limiting the effects of reactive oxygen species (Fu and Huang, 2003).

Turfgrasses maintained at a low height of cut are growing under carbon-limited conditions but unlike edible crops, yield is not a concern in turfgrass. Instead, emphasis is placed on quality and playability of the turfgrass stand. The benefits of proper management and nutrient application for crops cannot be measured in turfgrass as yield responses are unimportant and are difficult to measure. Also, in crops increased water use efficiency can result in lower yields as shown by the reduced stomatal conductance during drought for durum wheat cultivars, leading to
yield losses (Rizza et al., 2012). Reducing stomatal conductance could be beneficial for turfgrass where yield is not a concern, resulting in more drought tolerant turfgrass when it is during the early phase of drought (McCann and Huang, 2008).

Nitrogen fertilization is recommended for golf course putting greens at the rate of 146-244 kg N ha⁻¹ yr⁻¹, depending on soil type, desired growth rate, and length of the growing season (Christians, 2001). Proper N fertilization promotes root and shoot growth and recovery from damage and stress (Beard, 1973). Higher N fertilization than required may have negative effects on turfgrass growth, although there is limited evidence to define the amount of nitrogen that becomes excessive for turfgrass. Christians et al. (1979) studied seven N application rates of 6, 24, 54, 96, 150, 216, 294 ppm for a 10 week period on creeping bentgrass that was mowed at 1 cm. Creeping bentgrass had maximum clipping dry weight and highest quality ratings when N was applied at 96 ppm. Clipping dry weight was reduced by around 50% of its maximum at the N rate of 294 ppm. Quality rating also decreased from the maximum of 7 to 5 when N was applied at the highest rate of 294 ppm. In another study, a lower N fertilization rate was reported to maintain a slower top growth rate, which may be desirable in saving labor costs on golf courses, and to increase root density and root depth (Schlossberg and Karnok, 2001).

Nitrogen fertilization and irrigation work together in managing water consumption and maintaining acceptable turfgrass quality. Candogen et al. (2015) concluded that although decreases in irrigation and N fertilization cause a decline in color, quality and clipping yield, acceptable turfgrass color and quality can be maintained when doubling monthly N rate from 25 to 50 kg N ha⁻¹ and reducing the need of water from 763 to 571 mm for the season (May to September) for perennial ryegrass in a sub-humid climate. When water is sufficient, lower N rates result in lower turfgrass ET (Ebdon et al., 1999, Barton et al., 2009, J. Poro et al., 2017).
However, turfgrass does not need 100% ET replacement irrigation to maintain color and quality (Fu et al., 2004, DaCosta and Huang, 2006). Moreover, turfgrass exposed to moderate drought may alter carbon allocation, resulting in deeper roots and slower shoot growth rate (Qian and Fry, 1996). Higher N levels in soybean and maize resulted in higher cell membrane stability and leaf tissue integrity when under drought (Premachandra et al., 1990b, Premachandra et al., 1990a). N fertilization increases osmotic regulation under water deficit conditions, and increases plant drought resistance (Ackerson, 1985). Chang et al. (2016) concluded that both cytokinin and N increase creeping bentgrass color, quality and antioxidant metabolism under drought. However, there is a lack of research on how turfgrass with different N fertilization levels uses water under drought, and how turfgrasses responds morphologically and physiologically during post-drought recovery.

Turfgrass mowed at low HOC grows under carbon-limited conditions due to limited photosynthetic rates (Poro et al., 2017, Colmer and Barton, 2017). As such, the effects of N on low-mowed turfgrass growth and water use under drought and post-drought recovery require more investigation. Objectives of this research are to determine how turfgrass color, photosynthesis, transpiration, and water use change with different nitrogen fertilization during dry-down and post-drought recovery periods.
3.2 Materials and Methods

3.2.1 Plant establishment and growing conditions

‘Tyee’ creeping bentgrass (*Agrostis stolonifera*) was seeded into 45 cm tall tubes made from PVC pipes (51 mm diameter and 5 mm thick) filled with 5 cm of gravel at the bottom and 40 cm of calcareous sand. Grasses were grown in a greenhouse at the University of Guelph (43.5321° N, 80.2269° W) for 60 d until fully established. Liquid fertilizer (20N-8P-20K) was applied every 14 d providing a total of 4.4 g N m\(^{-2}\) for the grow-in period. All tubes were flushed with deionized water before different rates of N were applied for the 60-day treatment period described below. Plants were then transferred to growth chambers under a 14-h photo period, a temperature of 22/18 ºC (day/night), and photosynthetically active radiation (PAR) of 600 µmol m\(^{-2}\) s\(^{-1}\) for three drought treatments. Four growth chambers were used with one chamber for each replication. Grasses were acclimated for 14 d and all rootzones were brought to tube capacity as described in Chapter 2 before drought treatments. Grasses were trimmed every other day to a height of 3.5 mm.

3.2.2 Nitrogen and Drought Treatments

In the first run (Run 1), three N treatments, applied as NH\(_4\)NO\(_3\) containing 35% N, were 0.1 (low), 0.5 (medium), and 1.0 (high) g N m\(^{-2}\) wk\(^{-1}\) with a total N of 0.8, 4.0, and 8.0 g N m\(^{-2}\), respectively. Nitrogen treatments were applied for 60 d prior to subjecting the plants to drought treatments. A very high N rate of 2 g N m\(^{-2}\) wk\(^{-1}\) with a total N of 16 g N m\(^{-2}\) was added in Run 2. Fertilizer 0N-52P-34K was applied at the rate of 0.5 g P m\(^{-2}\) wk\(^{-1}\) to provide sufficient P and K for the plants during the 60 d treatment period. The three drought treatments are shown in Table 3.1. In Run 1 there were a total of 3 drought treatments x 3 N rates x 4 harvests x 4 replications =
144 grass tubes. In Run 2, there were 3 drought treatments x 4 N rates x 4 harvests x 4 replications = 192 grass tubes (Picture 3.1).

Table 3.1 Drought treatments in Run 1 and Run 2 for an N fertilization rate experiment conducted in growth chambers.

<table>
<thead>
<tr>
<th>Drought treatment</th>
<th>Run 1</th>
<th>Run 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No drought</td>
<td>Water every other day for 21 days to tube capacity weight as indicated by load cells.</td>
<td>Water every other day for 28 days to tube capacity weight as indicated by load cells.</td>
</tr>
<tr>
<td>Periodic</td>
<td>Water withheld for 8 days, rewater one time on 8th day after the start of the experiment (8 DAT) to tube capacity weight, water withheld for another 7 days until 15 DAT, water every other day for 6 days until 21 DAT.</td>
<td>Water withheld for 10 days, rewater one time on 10 DAT to tube capacity weight, water withheld for another 7 days until 17 DAT, water every other day for 11 days until 28 DAT.</td>
</tr>
<tr>
<td>Prolonged</td>
<td>Water withheld until 15 DAT, water every other day for 6 days until 21 DAT.</td>
<td>Water withheld until 17 DAT, water every other day for 11 days until 28 DAT.</td>
</tr>
</tbody>
</table>
Picture 3.1. Grass grown in 45 cm tall PVC pipes (51 mm diameter and 5 mm thick) with different N rate treatments before moving to specific growth chambers for drought treatments.

3.2.3 Measurements

Turfgrass color and soil volumetric water content (SWC) were measured as described in Chapter 2. Evapotranspiration was measured by calculating the difference of tube weights before and after 24 hr at 0 d, 10 d, 17 d, and 24 d after drought started in Run 1. In Run 2, a load cell array was used to measure real-time water use by weight (method described in detail in Chapter 2) (Figure 3.1). Turfgrass canopy net Pn rate was measured with a gas exchange system (Licor 6400, LI-COR Inc. Lincoln, Nebraska) equipped with a 50 mm diameter whole plant chamber at a PAR of 1000 \( \mu \text{mol m}^{-2} \text{s}^{-1} \) and a chamber air temperature of 22 °C. Root and verdure parameters were measured at each of the four harvests as described in Chapter 2.
Figure 3.1 Run 2 turfgrass tube weight change for no drought (a), periodic drought (b), and prolonged drought (c) treatments measured at 1 min intervals by the load cell array from the beginning to the end of the study. Red and blue dots represent day and night, respectively. Values shown are across all four N rates.
3.2.4 Statistical analysis

The experimental design was a randomized complete block design with two factors (three N fertilization rates and three drought treatments) and four replications. Each replication was an independent environment in a separate growth chamber. Data were analyzed through mixed effects analysis of variance using PROC MIXED in SAS (SAS Institute, 2002) with date as the repeated measure. Tukey’s HSD test was used to detect significant differences among treatments (P < 0.05). Regression analysis was conducted using the ANCOVA procedure.

3.3 Results

3.3.1 Visual Color Rating

The low N rate had lower color ratings than the higher N rates for the no drought treatment in both Run 1 and Run 2 throughout the experiment (Figure 3.2 a, d), for the periodic drought treatment in Run 1 (Figure 3.2 b) throughout the experiment, and before 8 DAT for the prolonged drought in Run 1 (Figure 3.2 c).

The very high N rate treatment led to the fastest decrease in color rating by 10 DAT (first dry-down) for the periodic drought treatment in Run 2, and plants showed no difference when compared to those in the low N rate treatment during 10-17 DAT in Run 2 (second dry-down for the periodic drought) (Figure 3.2 e). Plants treated with the very high N rate then recovered to the same level of color as those in the medium and high N rate treatments from 21 DAT (recovery period).

No difference among N rates was revealed after 13 DAT in run 1 and 5 DAT in Run 2 for the prolonged drought treatment (Figure 3.2 c and f).
Table 3.2 Analysis of Variance for color, photosynthesis, transpiration, and water use efficiency of creeping bentgrass.

<table>
<thead>
<tr>
<th>Contrasts</th>
<th>Color</th>
<th>Photosynthesis</th>
<th>Transpiration</th>
<th>WUE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Run 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pr&gt;F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drought Treatment (DT)</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>NS</td>
</tr>
<tr>
<td>Nitrogen level (N)</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>N x DT</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Time (T)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DT x T</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>NS</td>
</tr>
<tr>
<td>N x T</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>DT x N x T</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Run 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pr&gt;F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drought Treatment (DT)</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Nitrogen level (N)</td>
<td>NS</td>
<td>*</td>
<td>NS</td>
<td>*</td>
</tr>
<tr>
<td>N x DT</td>
<td>*</td>
<td>*</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Time (T)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DT x T</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>N x T</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>DT x N x T</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

*, and NS indicate significance at P=0.05, and not significant at P=0.05 level, respectively.
Figure 3.2 Turfgrass color visual rating on a scale of 1-9 (1-straw yellow, 9-dark green) for the three drought treatments (no drought, periodic drought, and prolonged drought) across dates in Run 1 and Run 2. Bars represent HSD values for N rates for each date. The dotted vertical line indicates the one-time watering event for the periodic drought (b and e), and the dashed vertical line indicates the beginning of recovery for all treatments.

3.3.2 Canopy photosynthetic rate

Higher N rates resulted in higher canopy Pn rate across all dates for the no drought treatment in both Run 1 and Run 2 (Figure 3.3 a, d), and periodic drought in Run 1 (Figure 3.3 b). No difference was revealed between the very high and high N rates for all the drought treatments in Run 2. The medium N rate did not result in higher Pn rates than low N rate in Run 2 (Figure 3.3 e). The very high and high N rates resulted in higher Pn rates than medium and low N rates throughout the experiment for periodic and prolonged droughts in Run 2, except that the high N rate had no difference with medium and low N rates at 14 DAT and later dates for the prolonged drought in Run 2.
Figure 3.3 Canopy photosynthetic rate for the three drought treatments (no drought, periodic drought, and prolonged drought) across dates in Run 1 and Run 2. Bars represent HSD values for N rates for each date. The dotted vertical line indicates the one-time watering event for the periodic drought (b and e), and the dashed vertical line indicates the beginning of recovery for all treatments.

3.3.3 Canopy transpiration rate measured by gas exchange

The low N rate resulted in the lowest Tr rate for the no drought and periodic drought treatments for all dates, and at 2 and 6 DAT for the prolonged drought treatment in Run 1 (Figure 3.4 a, b, and c). The high N rate had the highest Tr rate at 6, 8, and 13 DAT for the periodic drought treatment in Run 1. However, differences among N rates were not observed in Run 2 (Figure 3.4 d, e and f). Tr rate decreases as water supply decreases, and recovers as water becomes available.
3.3.4 Instantaneous water use efficiency

Higher N rate resulted in higher instantaneous water use efficiency (WUE) for all dates throughout the experiment for the no drought and periodic drought treatments, and before 13 DAT for the prolonged drought in Run 1 (Figure 3.5 a, b and c). The very high and high N rates had higher WUE than medium and low N rates for the no drought and periodic drought treatments in Run 2, and for the prolonged drought treatment before 14 DAT (Figure 3.5 d, e and f). The medium N rate did not result in higher WUE than the low N rate for the no drought treatment in Run 2. The very high N rate did not result in higher WUE than the high N rate in Run 2.
3.3.5 Evapotranspiration

The load cell array was able to detect hourly ET change for daytime and nighttime. However, no significant difference among N fertilization treatments was revealed (Appendices 3.1 and 3.2). The four crucial dates: the beginning of dry-down, the end of first dry-down for the periodic drought treatment, the end of the prolonged dry-down for the prolonged drought treatment, and end of the recovery period, were picked and analyzed over a 24-hr period to compare to Run 1 and Run 2 because the load cells were not available for Run 1 (Figure 3.6). In Run 2, the very high N rate had higher ET rate than the low N rate but was not different compared with medium and high N rates at 0, 10, and 17 DAT for the no drought treatment. For the periodic drought treatment, the high N rate had higher ET rate than the low N rate at 15 and 21 DAT in Run 1. In Run 2, the very high N rate had higher ET rate than the low N rate at 0
DAT. Drought decreased ET rate regardless of N rates (Figure 3.7 b and c). When irrigation resumed, ET increased correspondingly. Grass experiencing periodic drought was able to resume ET rate to a higher level than grass experiencing prolonged drought. However, neither were able to resume back to the level before drought during the time frame in this experiment (21 and 28 days).

Figure 3.6 Canopy evapotranspiration measured gravimetrically for the three drought treatments (no drought, periodic drought, and prolonged drought) for each harvest date (Beginning of dry-down, end of dry-down, end of second dry-down for periodic drought treatment, end of recovery) in Run 1 and Run 2. Bars on each data point represent standard error mean. Different letters indicate significant difference among N treatments for the measurement date.
Figure 3.7 Evapotranspiration for the three drought treatments (no drought, periodic drought, and prolonged drought) across dates in Run 2. Bars on each data point represent standard error mean. The dotted vertical dotted line indicates the one-time watering event for the periodic drought (b), and the dashed vertical line indicates the beginning of recovery for all treatments.
3.3.6 Verdure dry weight

The high N rate had larger verdure dry weight than the low N rate at 8 DAT for the no drought treatment, at 15 and 21 DAT for the periodic drought treatment, and at 15 DAT for the prolonged drought treatment (Figure 3.8 a, b and c). The low N rate had the lowest verdure dry weight for all drought treatments across all harvest dates. Differences among the very high, high and medium N rates were not observed.

Figure 3.8 Verdure dry weight for the three drought treatments (no drought, periodic drought, and prolonged drought) for each harvest date (Beginning of dry-down, end of dry-down, end of second dry-down for periodic drought treatment, end of recovery) in Run 1 and Run 2. Bars represent HSD values for N rates for each date.
### 3.3.7 Root length

In Run 1, the low N rate had the shortest root length for all drought treatments. The medium N rate had longer total root length than the high and low N rates at 21 DAT for the no drought treatment in Run 1 (Figure 3.9 a). In Run 2, where grass was grown at a higher density, it generated almost double the amount of root length as in Run 1. The very high N rate had the highest values in root total length at 0 and 10 DAT for the no drought treatment, and at 17 DAT for the periodic drought treatment. The medium N rate had the highest root length values at the end of prolonged drought treatment.

![Figure 3.9](image-url)  
**Figure 3.9** Root length for the three drought treatments (no drought, periodic drought, and prolonged drought) per 0.002 m² ground area for each harvest date (Beginning of dry-down, end of dry-down, end of second dry-down for periodic drought treatment, end of recovery) in Run 1 and Run 2. Bars represent HSD values for N rates for each date.
3.3.8 Specific root length

Few differences were observed in specific root length amongst N rates (Figure 3.10). The very high N rate resulted in the highest values of specific root length at 17 DAT for the periodic drought treatment in Run 2. The medium N rate had the highest values at 21 DAT for no drought in Run 1, and at 28 DAT for prolonged drought in Run 2.

Figure 3.10 Specific root length for the three drought treatments (no drought, periodic drought, and prolonged drought) for each harvest date (Beginning of dry-down, end of dry-down, end of second dry-down for periodic drought treatment, end of recovery) in Run 1 and Run 2. Bars represent HSD values for N rates for each date. The asterisk indicates significant difference for a specific measurement date.
3.3.9 Root dry weight

The low N rate had the lowest root weight at 15 DAT in Run 1, and at 17 DAT in Run 2 for the no drought treatment. The very high and medium N rates had the highest root weight at 17 DAT for the no drought treatment, and at 17 DAT for the periodic drought treatment in Run 2. No difference were revealed between the high and medium N rate treatments in both Runs.

Figure 3.11 Root dry weight for the three drought treatments (no drought, periodic drought, and prolonged drought) for each harvest date (Beginning of dry-down, end of dry-down, end of second dry-down for periodic drought treatment, end of recovery) in run 1 and run 2. Bars represent HSD values for N rates for a specific date.
3.4 Discussion

The higher Pn rate, verdure dry weight, and root dry weight (all indicative of denser grass) observed in Run 2 over Run 1 prior to the drought treatments may have been due to better establishment as a result of overseeding in Run 2.

Under carbon limited (low HOC) and water-sufficient conditions, higher N rates led to higher color visual ratings, photosynthesis rate, and instantaneous water use efficiency than lower N rates. The very high N rate (16 g m\(^{-2}\) total N) did not improve color rating or photosynthesis rate compared to the high N rate (8 g m\(^{-2}\) total N). The present study did not demonstrate a decline in color, photosynthesis rate, or verdure dry weight for the very high N rate (four times the medium rate) with sufficient water, in contrast to what was reported by Christians et al. (1979) that their very high N rate (294 ppm), which was three times their medium rate (96 ppm), resulted in turfgrass quality decline. The present research results agree with Porro et al. (2017) who reported that a higher N rate resulted in higher WUE for creeping bentgrass and Kentucky bluegrass. Nitrogen is largely involved in the photosynthetic system and is allocated to the three components, Rubisco, electron carriers and other Calvin cycle enzymes, and light-harvesting complex (Westbeek et al., 1999). Higher N application level would result in a larger portion of N being allocated to photosynthetic system, which therefore would decrease leaf intercellular CO\(_2\). Stomatal conductance would therefore increase and facilitates CO\(_2\) uptake for higher Pn rate (Schulze et al., 1994, Farquhar et al., 2012). Although the results of the present research showed that the very high N rate (16 g m\(^{-2}\) total N) had significantly higher ET than the low N rate(0.8 g m\(^{-2}\) total N), the medium and high N rates were not different from the low or very high N rates. The research results showed that N rate needs to be increased dramatically in order to increase turfgrass water use at low HOC when irrigation is sufficient. Turfgrass color
and photosynthesis rate decreased over time regardless of N rates for the no drought treatment, because of the gradual depletion of nutrients during the course of the experiment and as extra nutrition could not be added during the drought period. Nutrients are vital to maintain plant health when there is no water stress. Increasing rate from 0.8 to 8 g m\(^{-2}\) total N led to an increase in verdure dry weight. However, this was not the case when total N was increased from 8 to 16 g m\(^{-2}\) total N. Verdure dry matter production did not respond to N fertilization above double the recommended amount. Insufficient N fertilization has adverse effects on grass shoot and root mass, but may not constrain roots from growing deeper. Lower root mass but deeper roots is in line with previous research on a native ryegrass (Schuurman and Knot, 1973) and on ‘TifEagle’ Bermudagrass (Tucker et al., 2006) when N is limited.

Under carbon-limited conditions for low mowing heights, increasing N rate enhanced turfgrass drought tolerance in terms of the increased Pn rate during drought and post-drought recovery. The length of the first dry-down period was increased from 8 to 10 d in Run 2, and more difference in Pn was revealed among the N rates. Plants in the high and very high N rate treatments had higher WUE than those in the low and medium N rates during drought and post-drought recovery periods for the periodic drought treatment. However, for the recovery period after prolonged drought, only the very high N rate had higher WUE. Nitrogen rates did not have a significant effect on turfgrass ET during drought and post-drought recovery periods. These results were similar to those of Liu et al. (2013) in their research on a medium-sized deciduous tree, black locust, that N fertilization did not enhance WUE under severe drought. Improving N rates encourages shoot growth more than root growth during the drought recovery period. Maintaining sufficient but not excessive N is vital to maintaining healthy roots and restraining top growth.
3.5 Conclusion

When irrigation was not limited, turfgrass with higher N rates (up to 8 g total N m\(^{-2}\)) showed better performance than turfgrass at lower rates of total N. However, when the N rate was further increased to 16 g total N m\(^{-2}\), it did not further improve the performance, and the low N rate (0.8 g total N m\(^{-2}\)) did not constrain roots from growing deeper. Increasing N rates did not result in increased ET rates except that the very high N rate (16 g total N m\(^{-2}\)) had higher ET rates than the low N rate (0.8 g total N m\(^{-2}\)). When irrigation is limited, increasing N rate improved turfgrass Pn and shoot growth, but not color or root growth under drought and post-drought recovery. Turfgrass applied with higher N rates showed better WUE under periodic drought, but not prolonged drought.
4.1 Introduction

Phosphorus is an important structural constituent and bridge molecule in phospholipid membranes and other bio-chemicals within a plant. Phosphorus (P) plays an important role in forming high-energy bonds for storing and transferring energy in plants. Phosphorus is also a key element involved in photosynthesis, for example as a constitutive of 3-PGA, the first stable product of photosynthesis (Hopkins, 1995).

Phosphorus concentration often limits plant growth in soil and is one of the primary nutrients that requires fertilization to meet crop needs. However, P fertilization to turfgrass is limited for the following reasons: 1) fertilizers applied to mature turfgrass usually have low P analysis for financial and environmental reasons; 2) phosphorus application is regulated by government as it contributes to eutrophication; 3) there were concerns over annual bluegrass (poa annua) invasion into creeping bentgrass caused by sufficient P fertilization (Hull, 1997, Turner, 1992). Phosphorus recommendations stated it should be maintained at modest levels to enhance stress tolerance, drought recovery, and water use efficiency (Hull, 1997) with little evidence of what constitutes proper levels.

Deficiency of phosphorus delays allocation of biomass to plant leaves or stems, resulting in less yield for crops. Wheat that was deficient in phosphorus displayed slow leaf emergence from the main stem (Rodriguez et al., 1999). Grain filling was increased by 10%, and grain yield 6%, for corn with P fertilization compared with low P (Liu et al., 2011). Jupp and Newman (1987) found that drought and rewetting stopped perennial ryegrass (Lolium perenne) P uptake, probably due to P unavailability in the drying soil, and determined that the control of the uptake
reduction was located in the root. However, application of phosphate before a drought event has a major effect on reducing drought-induced leaf necrosis in the turfgrass *Agrostis castellana* (Lawson, 1999). Lyons et al. (2008) concluded that low P fertilization resulted in greater turfgrass root-to-shoot ratios in un-mowed creeping bentgrass. High P rates during drought could be detrimental to kentucky bluegrass and sufficient P fertilization was needed for fast recovery after drought (Pellett and Roberts, 1963). When irrigation is sufficient, higher P rates resulted in more shoot and root mass but lower root-to-shoot ratios compared with lower P rates, indicating that more biomass and energy is allocated to root rather than shoot when P fertilization was limited (Lyons et al., 2008). Turfgrass with low P also had deeper roots than that with high P rate indicating that low P could be beneficial to turfgrass in terms of better drought tolerance (Lyons et al., 2008).

Turfgrass species possess different ability to withstand and recover from drought. Kentucky bluegrass (*Poa Pratensis*) had better drought tolerance in terms of higher photosynthetic rate and lower electrolyte leakage, and faster recovery from drought than perennial ryegrass (*Lolium perenne*) because of higher cell wall elasticity and cell membrane stability (Chai et al., 2010). Velvet bentgrass (*Agrostis. canina L.*) demonstrated less drought injury in terms of higher quality rating, photosynthetic rate, and daily evapotranspiration (ET) rate during drought than creeping bentgrass (DaCosta and Huang, 2006). Bermudagrass (*Cynodon dactylon*), bahiagrass (*Paspalum notatum*), and buffalograss (*Buchloe dactyloides*) displayed better drought resistance in terms of less leaf firing and faster shoot recovery rate than seashore paspalum (*Paspalum vaginatum*), zoysiagrass (*Zoysia japonica*), and centipedegrass (*Eremochloa ophiuroides*) (Severmutlu et al., 2011). Limited research could be found to determine the combined effect of P fertilization and drought on turfgrass species and cultivars.
with differing drought stress tolerance. The objective of this study was to determine the effects of P fertilization on four cool-season turfgrass varieties under drought and post-drought recovery conditions.

4.2 Materials and Methods

4.2.1 Plant establishment and treatment

Four turfgrass varieties, ‘Penncross’ and ‘L93’ creeping bentgrass (*Agrostis stolonifera*), ‘SR7200’ velvet bentgrass, and annual bluegrass were established in flat trays in a greenhouse at the University of Guelph (43.5321° N, 80.2269° W) for 60 d. During the 60 d establishment period, liquid fertilizer (20N-8P-20K) was applied every 7 d with a total N of 9 g m$^{-2}$. Grasses were then cut and transferred to 40 cm tall and 7.6 cm diameter PVC tubes, with 30 cm of rooting zone mix (80/20 sand/peat) over a 10-cm layer of gravel. Holes were drilled on the side of the PVC tubes for soil moisture measurement at 5, 10, 15, 20 and 25 cm from the top of the tube. Turfgrass was mowed at 5 cm throughout the study. The study was first run in 2008 and repeated in 2013.

Two nutrient solutions, a full Hoagland solution (Hoagland and Arnon, 1950) providing all necessary nutrient elements (P treatment), and a modified Hoagland solution which contained no phosphorus but all other necessary nutrient elements (no P treatment), were applied at the rate of 0.5 g N m$^{-2}$ wk$^{-1}$, with a total N of 8 g m$^{-2}$ for 120 d in Run 1 and 90 d in Run 2. A total P of 1.1 g m$^{-2}$ was applied for the P treatment before drought started. Drought was then initiated for 21 d in Run 1 and 25 d in Run 2. There was a no drought control treatment that was irrigated with de-ionized water every 2-3 d. After the dry-down period, nutrient solutions were resumed for 30 d in Run 1 and 25 d in Run 2, which was the drought recovery period. De-ionized water
was used to irrigate the grass throughout the experiment when nutrients were not being applied to prevent from adding phosphorus to the no P treatment. The timeline of the P and drought treatment schedule is specified in Table 4.1.
Table 4.1 Phosphorous and drought treatment schedule for a fertilization and drought trial in the greenhouse.

<table>
<thead>
<tr>
<th></th>
<th>Before drought</th>
<th>Drought</th>
<th>After drought</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Duration-Run 1</strong></td>
<td>120 d</td>
<td>0-21 d</td>
<td>22-51 d</td>
</tr>
<tr>
<td><strong>Duration-Run 2</strong></td>
<td>90 d</td>
<td>0-25 d</td>
<td>26-50 d</td>
</tr>
<tr>
<td><strong>Treatment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Full strength Hoagland solution (P treatment)</td>
<td>- No drought: Irrigation with de-ionized water every 2-3 d</td>
<td>- Full strength Hoagland solution (P treatment)</td>
</tr>
<tr>
<td></td>
<td>- Modified full strength Hoagland solution without P (No P treatment)</td>
<td>- Drought</td>
<td>- Modified full strength Hoagland solution without P (No P treatment)</td>
</tr>
<tr>
<td></td>
<td>- Irrigation with de-ionized water</td>
<td></td>
<td>- Irrigation with de-ionized water</td>
</tr>
</tbody>
</table>
4.2.2 Measurements

Turfgrass visual color was measured on a scale of 1-9 (1-straw brown, 9-dark green). Chlorophyll data was collected using a FieldScout CM 1000 chlorophyll meter (Spectrum Technologies Inc., Aurora, IL). Volumetric soil water content (SWC) was measured horizontally at 5, 10, 15, 20, and 25 cm from the top of the tube by using a soil moisture meter (HH2, Delta-T Devices Ltd, Cambridge UK) inserted into the holes on the sides of the PVC tubes. These measurements were conducted every week after establishment. The measurement of SWC in different soil depth is an estimation of water uptake and possibly root density at different depth in the soil column. At the end of the experiment, turfgrass verdure and root samples were collected and oven-dried at 70°C for 72 h. Each root sample was separated into three sections: 0-3, 3-12, >12 cm below the thatch layer for dry weight measurements. Root length (all sections) were determined using WinRHIZO (Regent Instruments Inc., Canada).

4.2.3 Statistical analysis

The experiment was a Randomized Complete Block Design with 4 replications. Data were analyzed through mixed effects analysis of variance using PROC MIXED in SAS 9.2 (SAS Institute, 2002). Analysis of Variance was used to determine significant effects. When significant differences were detected (P < 0.05), the least square means were separated using the Tukey’s HSD test.
4.3 Results

4.3.1 Visual color rating

Phosphorous fertilization did not impact turfgrass visual color ratings whether under no drought or drought conditions for L93, AB, and SR7200, except for SR7200 at 18 days after drought (DAT) at the end of dry-down, where the no P treatment had higher color rating than the P treatment (Figure 4.1 d). When under drought, the no P treatment had higher color ratings than the P treatment for Penncross at 36, 40, and 48 DAT (drought recovery period) in Run 1, and at 18 DAT (end of dry-down) in Run 2 (Figure 4.1 b and f). The no P treatment showed a slower color decline during dry-down and a faster color recovery during the recovery period for the drought treatment (Figure 4.1 a-h). Penncross without P treatment had a color rating of 6.3 at the end of the recovery period, which is close to the starting color rating of 7 in Run 1 (Figure 4.1 b).
Table 4.2 Analysis of variance for visual color of turfgrass for each measurement date.

<table>
<thead>
<tr>
<th>Effects</th>
<th>DF</th>
<th>4 DAT</th>
<th>9 DAT</th>
<th>14 DAT</th>
<th>18 DAT</th>
<th>21 DAT</th>
<th>1 DAW</th>
<th>5 DAW</th>
<th>9 DAW</th>
<th>13 DAW</th>
<th>16 DAW</th>
<th>20 DAW</th>
<th>24 DAW</th>
<th>28 DAW</th>
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<tbody>
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<td>Species(S)</td>
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<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
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<td>NS</td>
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<td>NS</td>
</tr>
<tr>
<td>S x F</td>
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<td>*</td>
<td>NS</td>
<td>*</td>
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Run 2

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*, and NS indicate significance at P=0.05, and not significant at P=0.05 level, respectively. DAT stands for days after drought, and DAW stands for days after re-watering.
Figure 4.1 Turfgrass color visual rating on a scale of 1-9 (1-straw yellow, 9-dark green) for the four turfgrass varieties (‘L93’ (a and e) and ‘Penncross’ (b and f) creeping bentgrass, annual bluegrass (c and g), and ‘SR7200’ velvet bentgrass (d and h)) across days after drought treatment in Run 1 and Run 2. Bars represent HSD values for treatment comparisons for each date. Vertical dotted lines indicate the end of drought treatment and the beginning of recovery period for all treatments.
4.3.2 Soil water content for the upper 15 cm rootzone for the drought treatment

With P fertilization, AB resulted in higher SWC than L93 at 14 and 16 DAT in Run 1 for the dry-down period (Table 4.3). AB had higher SWC than Penncross at 11 DAT in Run 2. No difference between P treatments or among turfgrass varieties was revealed for the recovery period in both Run 1 and Run 2. Soil water content returned to the same level as before drought at 9 days after re-watering (DARW) and 12 DARW in Run 1 and Run 2, respectively. No difference was revealed between P and no P treatments for each turfgrass variety.
Table 4.3 Soil water content for the upper 15 cm rootzone below turfgrass verdure for the four turfgrass varieties (‘L93’ and ‘Penncross’ creeping bentgrasses, annual bluegrass (AB), and ‘SR7200’ velvet bentgrass) and two phosphorus treatment (P and no P) across days after drought treatment (DAT) and days after re-watering (DARW) in Run 1 and Run 2.

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4.3.3 Soil water content for the 15-25 cm rootzone for the drought treatment

P application resulted in higher SWC than no P treatment for AB at 16 DAT in Run 1 (Table 4.4). With P fertilization, AB resulted in higher SWC than L93 at 7, 11, 14 and 16 DAT in Run 1, and at 6 and 11 DAT in Run 2 for the dry-down period (Table 4.4). AB had higher SWC than Penncross at 14 and 16 DAT in Run 1, and 6 and 11 DAT in Run 2. SR 7200 had higher SWC than L93 at 11 and 14 DAT in Run 1. SR 7200 resulted in higher SWC than Penncross at 12 DARW in Run 2. Without P fertilization, AB and SR7200 resulted in higher SWC than L93 at 16 DAT in Run 1. L93 had the lowest SWC compared with other varieties at 11 DAT in Run 2. Soil water content returned to the same level as before drought at 9 DARW and 12 DARW in Run 1 and Run 2, respectively.
Table 4.4 Soil water content for the 15-25 cm rootzone below turfgrass verdure for the four turfgrass varieties (‘L93’ and ‘Penncross’ creeping bentgrasses, annual bluegrass (AB), and ‘SR7200’ velvet bentgrass) and two phosphorus treatment (P and no P) across days after drought treatment (DAT) and days after re-watering (DARW) in Run 1 and Run 2.

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4.3.4 Root dry weight at 0-3, 3-12, and >12 cm

At 0-3 cm depth, turfgrasses with P treatment had higher or equal value of root dry weight than that with no P treatment for L93, Penncross, and AB for both no drought and drought treatments in both Run 1 and Run 2 (Figure 4.2 a and d). For SR7200, no P treatment had larger or equal root dry weight compared with P treatment when grass is irrigated (Figure 4.2 a and d). At 3-12 cm depth, less difference was revealed between P and no P treatments, except that no P had larger root weight than P treatment for SR7200 after drought and drought recover (Figure 4.2 b). At >12 cm depth, no P treatment had larger root dry weight than P treatment for SR7200 after both drought and irrigated conditions in Run 1 (Figure 4.2 c). Overall, P treatment with sufficient irrigation resulted in the largest root dry weight at all depths. When under drought, difference between P and no P treatment became less significant, with the exception for SR7200, that no P treatment resulted in larger root dry weight than P treatment at 3-12 and >12 cm depths.

Figure 4.2. Root dry weight (mg) at 0-3 cm (a and d), 3-12 cm (b and e), and >12 cm (c and f) for the four turfgrass varieties (‘L93’, ‘Penncross’ creeping bentgrass, AB annual bluegrass, and ‘SR7200’ velvet bentgrass) and the two phosphorus treatment (P and no P) at the end of the experiment in Run 1 and Run 2. Bars on each data point represent standard errors. Different letters indicate significant difference among treatments for the variety.
4.3.5 Root total dry weight

For the no drought treatment, P treatment resulted in larger or equal root dry weight than no P treatment for L93, Penncross, and AB, whereas no P treatment had more root dry weight than P treatment for SR7200 (Figure 4.3 a and b). For the drought treatment, no difference between P and no P treatments was revealed except that no P resulted in larger root dry weight for SR7200 in Run 1 (Figure 4.3 a).

![Figure 4.3](image-url)

Figure 4.3 Root total dry weight (mg) for the four turfgrass varieties (‘L93’, ‘Penncross’ creeping bentgrass, AB annual blugrass, and ‘SR7200’ velvet bentgrass) and the two phosphorus treatments (P and no P) at the end of the experiment in Run 1 and Run 2. Bars on each data point represent standard errors. Different letters indicate significant difference among treatments for the variety.
4.3.6 Root total length

For the no drought treatment, the no P treatment had longer or equal root total length than the P treatment for all turfgrass varieties (Figure 4.4 a and b). For the drought treatment, less difference was revealed between P and no P treatments, except that no P had longer total root length than P treatment for Penncross and AB in Run 1 (Figure 4.4 a), and P treatment had longer root total length than no P treatment for SR7200 in both Run 1 and Run 2 (Figure 4.4 a and b).

Figure 4.4 Root total length (cm) per 0.0045 m² ground area for the four turfgrass varieties (‘L93’, ‘Penncross’ creeping bentgrass, AB annual blugrass, and ‘SR7200’ velvet bentgrass) and the two phosphorus treatments (P and no P) at the end of the experiment in Run 1 and Run 2. Bars on each data point represent standard errors. Different letters indicate significant difference among treatments for the variety.
4.3.7 Specific root length

For the no drought treatment, no P treatment had higher or same specific root length (SRL) than P treatment for L93, Penncross, and AB in both Run 1 and Run 2 (Figure 4.5 a and b). For the drought treatment, there was no difference between P and no P treatments except for SR7200 in run 1. Phosphorus treatment had larger SRL than no P treatment for SR7200 regardless of drought treatment (Figure 4.10 a and b).

Figure 4.5 Specific root length (m/g) for the four turfgrass varieties (‘L93’, ‘Penncross’ creeping bentgrass, AB annual blugrass, and ‘SR7200’ velvet bentgrass) and the two phosphorus treatment (P and no P) at the end of the experiment in Run 1 and Run 2. Bars on each data point represent standard errors. Different letters indicate significant difference among treatments for the variety.
4.4 Discussion

The four turfgrass varieties used in the study have different characteristics. ‘L93’ is a relatively newer creeping bentgrass variety whereas ‘Penncross’ is an older creeping bentgrass variety. AB is often considered a weed in creeping bentgrass stand, and ‘SR7200’ is known for its low input, slow growing, as well as stress tolerance capacity. In terms of deeper roots, L93 > Penncross > SR7200 > AB regardless of P treatment, which indicates the order of drought avoidance by maintaining deep roots. However, AB had high SRL values, which is also an indicator of drought tolerance but, in this case, it showed that that roots of AB were thinner than other varieties and stayed at the upper part of the soil profile. High SRL indicates smaller and thinner roots, which is a beneficial trait for water and nutrient acquisition (Ostonen et al., 2007). However, Zobel et al. (2007) pointed out that it is not known to what extent plants would benefit from increased SRL in terms of water and nutrient uptake. Trubat et al. (2012) also determined that root hydraulic conductance decreases with increased SRL. We need not forget that a root system has multiple functions. Coarse or thicker roots (low SRL values), on the other hand, provide anchorage and transport channels, and are equally important for a healthy plant (Eissenstat et al., 2000). Plant size largely affects root morphology in terms of the distribution of coarse or fine roots (Ryser and Eek, 2000). For low-mowed turfgrass, the increased fine roots (high SRL) is preferred as turfgrass is a small plant and limited anchorage is required.

When under drought, turfgrass with low P fertilization demonstrated less drought injury in terms of slower visual color decline during dry-down, and better drought tolerance in terms of faster visual color recovery during post-drought recovery compared with high P fertilization. However, P rate effect was not significant in the final root dry weight or root total length after the drought and post-drought recovery periods, which means that P fertilization had no
measurable effect on turfgrass root parameters after a drought. High P fertilization increased specific root length for SR7200 velvet bentgrass, which means that thinner but longer roots were produced in response to P. This is regarded as an acquisitive trait for higher water and nutrient uptake after drought is relieved (de Vries et al., 2016). Therefore, high P fertilization resulted in better drought tolerance than low P in terms of better drought recovery possibility for SR7200. However, this recovery ability was not observed in visual color rating for SR7200.

L93 and Penncross creeping bentgrasses had the fastest soil water content decline during dry-down and lower soil water content in deeper soil (20 and 25 cm) compared to AB and SR7200, indicating that a greater amount and deeper roots were produced for L93 and Penncross, which is reflected in the root mass measurements. Under high P fertilization Penncross may have more root mass than low P treatment at 10 and 15 cm depths based on lower soil water content for high P than low P treatment at these depths. However, when looking at the root weight for 3-12 and >12 cm, there was no significant difference between high and low P fertilization for Penncross during dry-down. Therefore, Penncross with high P fertilization used water faster than low P treatment with the same amount of root mass. In this case, low P fertilization actually preserved water better or had better water use efficiency than high P treatment with the same root mass when under drought, thus resulting in better plant drought tolerance. This conclusion is in contrast with Payne et al (1992) that increasing soil P levels increased water use efficiency under water-stressed condition for pearl millet (Pennisetum glaucum (L.)). Payne et al (1992), calculated WUE as the ratio of grain dry matter to cumulative transpiration. Turfgrasses are not typically filling grain with phosphorus and color and recovery from wear are the important growth characteristics. Low P increased Penncross drought tolerance over high P during drought
as shown by a slower color decline for the low P treatment and that low P fertilization preserved more water than high P treatment.

When water is sufficient, high P treatment resulted in larger root dry weight than low P treatment, which agrees with Lyons et al (2008) which showed greater root mass in high P grasses but lower root-to-shoot ratios without mowing. However, high P showed lower SRL values than low P treatment for some varieties.

4.5 Conclusion

Different turfgrass species and varieties responded differently to P rates under drought. Unfortunately, conclusions from this study are difficult to state because the second round results were not consistent with the results from the first round. Despite the differences between different runs of the experiment some general conclusions are still able possible. L93 produced the largest amount of root mass and deeper roots but the smallest SRL values indicating bigger roots that can penetrate deep in the soil and better drought resistance. Low P fertilization improves turfgrass drought tolerance for slower color decline, and more soil water content during drought for Penncross. High P fertilization may improve SR7200 drought tolerance, although it was not revealed in visual color recovery.
5. Overall Conclusion

When water is sufficient, grass mowed at 5 mm HOC had higher color ratings, Pn, Tr, and ET rates, and WUE than grass mowed at 3 mm HOC, indicating that the higher the turfgrass canopy height, the higher the canopy ET rate. Therefore, under frequently mowed conditions, turfgrass canopy ET responds differently to height conditions than crop canopy ET after full canopy cover without mowing. The higher HOC stayed greener during drought periods and recovered faster after watering. Lower mowing height resulted in better recovery after prolonged drought maybe due to larger root to shoot ratio. However, specific root length, which is a parameter of drought tolerance, appears to not be related to mowing height, but to drought condition itself.

A novel load cell array was able to measure tube weight change at 1-min intervals and ET change at 1-h interval for turfgrasses with different mowing heights and N levels. The load cell array was able to detect ET difference between mowing heights and N rates, as well as differences in ET for daytime and nighttime using regression analysis. Future research may use larger grass pots to detect significant ET differences using the load cells.

When water is sufficient, higher N rate resulted in better turf performance, however, increasing the N level to 16 g m\(^{-2}\) total N did not further improve turf performance. Increasing N fertilization improved turfgrass drought tolerance because of increased Pn rate during drought and post-drought recovery periods. Maintaining sufficient N but not excessive N is vital to maintain healthy roots and control top growth.

Different turfgrass species and varieties responded differently to P rates under drought. Higher P fertilization resulted in better drought tolerance than low P for SR7200 in terms of
higher values of specific root length. Low P fertilization improves turfgrass drought tolerance because of slower color decline, and more soil water content during drought for Penncross.
6. References


City of Kingston (2006), A By-law to Provide for The Regulation of Water Supply for The City of Kingston.


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Appendix 2.1 Run 1 day time (lights on) turfgrass ET change (mm/h) for no drought (a), periodic drought (b), and prolonged drought (c) treatments measured at 1 h intervals by the load cell array from the beginning to the end of the study with 4 replications. Red and blue dots represent 3 mm and 5 mm HOC, respectively. Red and blue solid lines represent the regression analysis and the collective trend of the data points for 3 and 5 mm HOC, respectively.
Appendix 2.2 Run 2 day time (lights on) turfgrass ET change (mm/h) for no drought (a), periodic drought (b), and prolonged drought (c) treatments measured at 1 h intervals by the load cell array from the beginning to the end of the study with 4 replications. Red and blue dots represent 3 mm and 5 mm HOC, respectively. Red and blue solid lines represent the regression analysis and the collective trend of the data points for 3 and 5 mm HOC, respectively.
Appendix 2.3 Run 1 night time (lights off) turfgrass ET change (mm/h) for no drought (a), periodic drought (b), and prolonged drought (c) treatments measured at 1 h intervals by the load cell array from the beginning to the end of the study with 4 replications. Red and blue dots represent 3 mm and 5 mm HOC, respectively. Red and blue solid lines represent the regression analysis and the collective trend of the data points for 3 and 5 mm HOC, respectively.
Appendix 2.4 Run 2 night time (lights off) turfgrass ET change (mm/h) for no drought (a), periodic drought (b), and prolonged drought (c) treatments measured at 1 h interval by the load cell array from the beginning to the end of the study with 4 replications. Red and blue dots represent 3 mm and 5 mm HOC, respectively. Red and blue solid lines represent the regression analysis and the collective trend of the data points for 3 and 5 mm HOC, respectively.
Appendix 3.1 Run 2 day time (lights on) turfgrass ET change (mm/h) for no drought (a), periodic drought (b), and prolonged drought (c) treatments measured at 1 h interval by the load cell array from the beginning to the end of the study with 4 replications. Green, blue, red and purple dots represent low (0.8 g N m\(^{-2}\)), medium (4 g N m\(^{-2}\)), high (8 g N m\(^{-2}\)), and very high N (16 g N m\(^{-2}\)) rates, respectively. Green, blue, red and purple solid lines represent the regression analysis and the collective trend of the data points for low, medium, high, and very high N rates, respectively.
Appendix 3.2 Run 2 night time (lights off) turfgrass ET change (mm/h) for no drought (a), periodic drought (b), and prolonged drought (c) treatments measured at 1 h interval by the load cell array from the beginning to the end of the study with 4 replications. Green, blue, red and purple dots represent low (0.8 g N m\(^{-2}\)), medium (4 g N m\(^{-2}\)), high (8 g N m\(^{-2}\)), and very high N (16 g N m\(^{-2}\)) rates, respectively. Green, blue, red and purple solid lines represent the regression analysis and the collective trend of the data points for low, medium, high, and very high N rates, respectively.
Appendix 5 An interesting observation during the mowing height experiment in Chapter 2:

When conducting the mowing height study in the growth chamber, it was noticed that Pn rate was largely impacted by mowing within 30 min following the mowing event. In the following graph, turfgrass was clipped from 5 to 3 mm. Pn rate dropped from 13.2 to 1.4 µmol m⁻² s⁻¹ in 3 min. Pn rate was then measured every 2 min for a period of 30 min, and was gradually increased to 7.3 µmol m⁻² s⁻¹ at 35 min after the mowing event. Pn rate was then climbed to 8.2 µmol m⁻² s⁻¹ at 2.5 h after the mowing event. We did not continue this interesting observation to be a separate experiment due to equipment constraints. However, the implication of this observation is that frequently mowed turfgrass, such as putting greens on golf courses that are mowed daily, is subject to drastically reduced and disrupted photosynthesis activities right after mowing, and it may take at least 30 min to recover to its desired Pn rate. The disruption in photosynthesis may have accumulated effect on turfgrass health and stress tolerance.