Title

Approaches to scheduling water allocations to kikuyugrass grown on a water repellent soil in a drying-climate

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Abstract

Water allocation is a principal planning method for managing water supplies to agricultural and horticultural land in drying climates. Regulatory bodies often establish the water allocation amount, but its distribution during the irrigation season is left to the land manager's discretion. We evaluated approaches to best manage water allocations to a warm-season turfgrass [*Pennisetum clandestinum* (Holst. Ex Chiov)] grown on a free-draining sand prone to surface (0–25 mm) soil water repellence in a Mediterranean climate in south-western Australia under 'deficit irrigation', in a two-year field study. The three factorial experiment consisted of three levels for each treatment applied to plots (10 m^2) of kikuyugrass: water allocation (5000, 6250 or 7500 kL ha^{-1} yr^{-1}), irrigation schedule, and soil wetting agent rate (nil, recommended 'label' rate, double recommended 'label' rate), and was replicated three times. The irrigation schedules were based on historical net evaporation at the site, and then refined monthly using in-season net evaporation data or measurements of soil water content. Kikuyugrass growth and color was adequate when irrigated using the current regional water allocation (7500 kL ha^{-1} yr^{-1}) under a low wear situation and to a lesser extent when the water allocation was lowered to 6250 kL ha^{-1} yr^{-1}. Application of a soil wetting agent diminished water repellence and improved kikuyugrass color for 7500 or 6250 kL ha^{-1} yr^{-1} water allocations. Distributing a water allocation based on historical monthly net evaporation rates was a simple and effective scheduling approach to maintain a warm-season turfgrass and a soil wetting agent enhanced turfgrass color.

Keywords: deficit irrigation, evapotranspiration, soil moisture sensor, soil water repellence, soil wetting agent, warm-season turfgrass.

1. Introduction

Ground water resources are expected to decline in many parts of the world due to both non-climatic and climatic drivers (Jiménez Cisneros et al., 2014; OECD, 2012). Turfgrass managers in urban areas are under pressure to maintain high quality sports surfaces despite declining water availability. The importance of well-maintained green spaces for encouraging physical activity and maintaining mental health is well recognized by local communities (Schebella et al., 2014; Townsend and Weerasuriya, 2010). Urban planners are therefore being tasked with retaining and improving public green spaces (Hansmann et al., 2007), which will become increasingly difficult in drying climates.

Water allocation is considered to be a key water planning method for irrigated agriculture lands and public open spaces in various parts of the world (Singh, 2015; Xu and Li, 2015; Young, 2013). Governments and water regulatory authorities often establish the amount of water allocated, however apportioning the annual allocation is generally the decision of the land manager. Furthermore, water planning is an on-going process due to the impacts of climate change and population growth on water supply and demand, requiring adaptive approaches to managing water (Hamstead et al., 2008; Yan et al., 2017). Understanding how to best manage turfgrass on current, and possible lower water allocations, is therefore critical for irrigated public spaces and is increasingly expected by our urban communities.

The effectiveness of a water allocation applied to turfgrass grown in sandy soils is likely to be improved by overcoming the development of soil water repellence. Soil water repellence decreases water use efficiency because irrigation water infiltrates the soil surface unevenly and some can bypass the turfgrass roots (Dekker et al., 2001; Doerr et al., 2000) or some evaporates when temporarily pooled on the soil surface. If left untreated, soil water repellence can lead to localized dry areas and turfgrass death (Dekker et al., 2004). Patchy turfgrass cover in public open space areas is unwelcomed, as it contributes to sports injuries and also encourages weeds. Soil water repellence may also cause over-watering if the manager attempts to prevent wilting of the turfgrass in the affected patches (Cisar et al., 2000). Applying an effective soil wetting agent can prevent or decrease the development of soil water repellence in the field without applying additional water (Barton and Colmer, 2011a; Barton and Colmer, 2011b; Dekker et al., 2019).

South-western Australia has a hot and dry Mediterranean-type climate and rainfall is expected to decline by 40% by the late twenty-first century (Delworth and Zeng, 2014) . Metropolitan areas in the region include substantial amounts of turfgrass (e.g., broad-acre parks and sports fields), predominately on free-draining sands prone to becoming water repellent (McGhie and Posner, 1981; Roper et al., 2015). Local government municipalities are commonly allocated 6750 to 7500 kL ha^{-1} yr^{-1} of groundwater to irrigate public open spaces in the region; however, it is unclear how to most effectively distribute the water allocation during the irrigation season. The overall objective of our two-year field-based experiment was to investigate approaches for best managing current and possible future water allocations to turfgrass grown on sandy soils in public open spaces. Specifically we evaluated i) if a warm-season turfgrass [*Pennisetum clandestinum* (Holst. Ex Chiov)] could be maintained with the current water allocation (7500 kL ha^{-1} yr^{-1}), and the implications of further lowering the allocation on turfgrass quality; ii) if the effectiveness of a water allocation varies with the application of a soil wetting agent and depending on how the irrigation schedule apportions the water allocation. The water volumes applied, at least in the two lowest allocation treatments, would be considered as ‘deficit irrigation’ [irrigation replacements below potential evapotranspiration (ET)].

2. Materials and methods

2.1 Study site and soil

Approaches for effectively utilizing water allocations for a warm-season turfgrass were investigated at the University of Western Australia's (UWA) Turf Research Facility in Perth (31°56′ S, 115°47′ E), which experiences a Mediterranean-type climate. The facility was originally developed in 1996 after clearing the land of native vegetation (Short and Colmer, 2007), and has since supported a series of experiments on turfgrass. In the 24 years (1993–2016) the annual rainfall has averaged 728 mm, with 78% of the rain occurring from late autumn to early spring (May–September), while the mean annual maximum (monthly) temperature and a mean annual minimum (monthly) air temperatures have been 24.7 °C and 12.8 °C, respectively (www.bom.gov.au/climate/data/). The distribution of rainfall, evaporation, mean minimum air temperature and mean maximum air temperature per month during the present study are shown in Fig. 1. A variable-speed travelling irrigator watered turfgrass plots at known application rate with a high coefficient of uniformity (Short and Colmer, 2007). During the present study, the median daily efficiency of discharge [(actual irrigation depth/programmed irrigation depth) x 100)] averaged 97% in 2013/14 and 99% in 2014/15 (data not shown). The irrigator also recorded the volume of water applied to specified turfgrass areas so that we could confirm that plots were irrigated using the specified water allocation treatment. The site also included a weather station (ET107, Campbell Scientific) used to record various climatic parameters, and calculate the daily evaporation, which was used by the irrigator program.

Experimental plots (10 m^2) were planted in September 2011 using a warm-season turfgrass harvested from a local government park. Kikuyugrass [*Pennisetum clandestinum* (Holst. Ex

Chiov)] was selected as it is a warm-season turfgrass (warm-season turfgrasses are widely used throughout various parts of Australia, and kikuyugrass is the dominate turfgrass type managed by local government in metropolitan Perth and many regional areas of Western Australia. The kikuyugrass sourced was greater than 20 years old, included a surface layer (25 mm) of mat with the potential to become water repellent, and was thus more representative of kikuyugrass managed by local government than newly planted kikuyugrass. The two year experiment commenced 1 July 2013, almost two years after planting, which enabled the kikuyugrass to establish and the irrigation schedule to be refined (1 July 2011–30 June 2012; data not shown). The soil at the study site consisted of a deep sand (>1 m; 'Karrakatta Sand', McArthur and Bettenay, 1960) that is classified as a Dystric Xeropsamments (USDA, 1992). In July 2012 the surface soil (0–100 mm) had an average pH of 5.49 (1:5 soil : 0.01 M $CaCl_2$ extract), electrical conductivity of 90 µS cm^{-1} (1:5 soil : water extract), cation exchange capacity of 4.85 cmol (+) kg^{-1} as analyzed using a modified silver thiourea method, a C concentration of 15 mg g^{-1} determined using a CHN analyzer (Elementar Analysensysteme GmbH, Vario Macro), and the mineral component contained 97% sand as measured using a pipette method (Bowman and Hutka, 2002; Rayment and Lyons, 2011).

2.2 Experimental design and approach

The three factorial experiment consisted of three levels for each of the treatments: water allocation, irrigation schedule, and wetting agent rate, and was replicated three times using three blocks. In each block, a split-split plot design was used where the three treatments, water allocation, irrigation schedule, and soil wetting agent rate, were assigned to three main plots, three sub-plots and three sub-sub plots, respectively. The described nesting structure water allocation/irrigation schedule/wetting agent rate provided 27 plots per block, and thus a total of 81 plots for the experiment.

The three water allocations were 5000, 6250 or 7500 kL ha^{-1} per Australian financial year (1 July–30 June). Currently, 6750 to 7500 kL ha^{-1} yr^{-1} is allocated for many public open spaces in metropolitan Perth, which is approximately equivalent to 70% replacement of net evaporation at the present study site during the irrigation season (September –April). Furthermore, State Government laws do not allow water to be applied during the winter months (1 June–31 August). Irrigation mostly occurred from the 1 September to 30 April each year (Fig. 2), and up to five times per week depending on month.

Each water allocation was distributed using three different irrigation schedules that were determined using the study site's historical weather data ('Budget' schedule), and then further refined using an onsite weather station ('Budget+Net Evaporation') or a soil moisture sensor ('Budget+Sensor'). For the Budget schedule, the monthly water allocation was calculated by multiplying the annual water allocation by the proportion of the annual net evaporation that historically (2005–2012) occurred for that month at the study site (Table 1). For the Budget+Net Evaporation schedule, the monthly water allocation was based on a replacement of net evaporation, which was then adjusted in-season and based on current net evaporation rates. The initial replacement value (i.e., September each year) was determined by dividing the water allocation by the historical annual net evaporation (Table 2). The replacement value was adjusted at the end of each month by calculating the proportion of the remaining water allocation to the remaining historical net evaporation; this enabled scheduling to be adjusted monthly based on the prevailing net evaporation. For the Budget+Sensor schedule, the monthly water allocation was the same as the Budget schedule, however irrigation only occurred when the soil volumetric water content (VWC; 0–100 mm) was expected to be <5%

between irrigation events, as preliminary experimentation for one year had shown turfgrass color did not meet critical turfgrass values below this critical soil VWC (data not shown). The expected soil VWC between irrigation events was determined by measuring soil VWC (0–100 mm) using a portable soil moisture sensor (Hydrosense II, Campbell Scientific) prior to irrigation and estimating total ET until next scheduled irrigation event based on historical monthly ET data. As was the case for the Budget+Net Evaporation schedule, the amount of water allocated to the Budget+Probe schedule was adjusted at the end of each month by calculating the proportion of the remaining water allocation to the remaining historical net evaporation.

A liquid soil wetting agent was applied at three rates: nil (control), at the manufacturer's recommended rate i.e., 'label rate' (1WA; 50 mL per 10 m^2), or double the manufacturer's recommended rate (2WA). We included the 2WA treatment as previous research had shown the effectiveness of soil wetting agents can decrease with increasing soil organic matter content (Barton and Colmer, 2011a).The soil wetting agent was applied three times per year (September, December, February) and contained propylene oxide-ethylene oxide block polymer as the active ingredient. The commercially available soil wetting agent was used by the local turfgrass industry, and was found to be effective in preliminary field studies prior to the current study (data not shown). The wetting agent was diluted in water (50 mL in 10 L of water for the recommended rate; 100 mL in 10 L of water for double the recommended rate) and evenly applied using a watering can before another 10 L of water was applied to each kikuyugrass plot (10 m^2). The 'nil' or '0WA' wetting agent treatments received 20 L of water per plot. After applying the wetting agent treatments, all kikuyugrass plots immediately received at least 5 mm of irrigation depending on the irrigation schedule.

Other agronomic management practices (e.g., fertilizer and mowing regimes) were consistent with the local turfgrass industry. For example, kikuyugrass plots were mown weekly from spring to autumn (September–May) using a cylinder mower at a cutting height of 15 mm, and every two weeks at other times of the year. A soluble granular fertilizer was applied to all kikuyugrass plots (two applications in spring, two in autumn), with each application providing 45 kg N ha^{-1}, 2.8 kg P ha^{-1}, 25 kg K ha^{-1}, 45 kg S ha^{-1}, 2.5 kg Ca ha^{-1}, 1.2 kg Fe ha^{-1}, 1.8 kg Mn ha^{-1}, and 2.2 kg Mg ha^{-1}. The fertilizer was watered in with at least 5 mm of irrigation water.

2.3 Kikuyugrass growth and color

Growth in each kikuyugrass plot was measured using the dry mass of mowing clippings after mowing the plots (cutting height, 15 mm). The mass of the fresh clippings collected from each plot was recorded, and then a weighed sub-sample collected (20–25 g) and dried (60 °C) before calculating the fresh:dry mass ratio. The remaining fresh clippings were redistributed across the surface of the plot immediately after collecting the sub-sample. The dry mass of clippings for each plot was determined after each mowing event and by using the plot fresh mass data and each specific fresh:dry mass ratio.

Kikuyugrass color was quantitatively assessed at the beginning of the experiment, and then every four weeks, using a Chroma Meter (Minolta, CR-410) (e.g., Barton et al., 2006; Landschoot and Mancino, 2000). Kikuyugrass color was determined after dividing each plot into eight subplots (0.56 m^2), with a 0.5 m ‘buffer’ from plot edges, and then further dividing each subplot into nine (0.0625 m^2) sampling squares. On each measurement date, kikuyugrass color was recorded for one randomly selected sampling square per subplot (i.e., eight measurements per plot per sampling date) as described by Barton and Colmer (2011a).

Turfgrass color with a hue angle >97° is considered adequate for kikuyu turfgrass (Barton et al., 2006).

2.4 Soil volumetric water content and water repellence

Soil volumetric water content of the surface soil (25 mm) was measured at the beginning of the experiment, and then every four weeks, using a hand-held moisture sensor (MPM160 Moisture Probe Meter plus MP406 Moisture Probe, ICT International). Measurements were taken immediately after kikuyugrass color was recorded (see section 2.3), and by inserting the moisture probe into the ground and recording the mV output. The moisture sensor was calibrated (i.e., mV converted to soil VWC) by collecting additional soil samples (surface 25 mm) during the study, recording gravimetric water content and bulk density of the samples for calculating soil VWC. The relationship between soil VWC and mV values was determined using a linear regression:

$$\text{Soil VWC (\%)} = 0.0693 \text{ mV output} + 1.2837 \qquad r^2 = 0.80 \qquad (1)$$

The above relationship is consistent with that reported for kikuyugrass where the surface soil had a significant layer of mat (Barton and Colmer, 2011a).

Soil water repellence was measured at the beginning of the experiment, and then every four weeks during the irrigation season (September–April), using both a modified molarity of ethanol droplet test (MED; Carter, 2002; King, 1981) and a modified water drop penetration test [WDPT; (Letey, 1969)]. In each plot, four intact soil cores (each core 52 mm in diameter, 25 mm in depth) were collected from the same place soil VWC and kikuyugrass color were determined (see Section 2.3). Samples were only collected from the surface soil so as to assess the impact of soil water repellence on surface water infiltration and the result soil water content. Samples from each plot were combined, air-dried (40 °C) in a custom built drying room for one week, and sieved (<2 mm) before measuring MED and WDPT in 20 °C constant temperature room. The MED test involved applying droplets (40 µL) of ethanol ranging in concentration (0–5.4 M) to each soil sample, and recording the lowest concentration that infiltrated the soil within 10 s. Soil water repellence is ranked as follows: Low ($MED<1.2$), moderate ($1.2<MED<2.4$), severe ($2.4<MED<3.2$), very severe ($MED>3.2$) (King, 1981). The WDPT method involved dispensing a drop (40 µL) of de-ionized water onto each soil sample, and measuring entry time of 600 s or less. Soil samples recording a WDPT >600s were considered ‘severely’ water repellent (Dekker and Jungerius, 1990).

2.5 Statistical analysis

Linear mixed models (LMMs) were used to analyze the data, reflecting the experimental design and the way the measurements were taken, namely accounting for the split-split plot design along with the application of a repeated measures technique. In general, the random components in the fitted models accounted for the design (block) structure and the variance-covariance structure, and fixed terms for the treatment structure. The diagnostic plots of the residuals versus fitted values and the quantiles plots (normal and half-normal) were used to check the adequacy of the distributional assumptions. Cumulative growth was analyzed using a LMM where the random component accounted for the nested plot structure Block/Main Plot/Sub-plot/Sub-sub plot and the fixed component of the model accounted for the treatment structure. The main effects of the treatments (water allocation, irrigation schedule and wetting agent) and their two way and three way interactions defined the latter. Changes in kikuyugrass growth, kikuyugrass color, soil MED and soil VWC over time each year, and each irrigation season (September–April) of each year, were analyzed using repeated measures analysis. The LMM model accounted for possible correlations between the observations made in time on each plot by including a random interaction term of Plot.Day. The assumption was that plots are independent, only the measurements in time (Day) were correlated. In order to account for the latter, we utilized a number of models for the variance-covariance structure of Plot.Day. The final model selection, based on the log-likelihood ratio statistic, the Akaike information criterion and on the adequacy of the distributional assumptions, was two types of models for all responses, 'heterogeneous power model' or 'unstructured model'. All statistical analyses were conducted using R environment (R Core Team, 2018), statistical packages GenStat 18th Edition (VSN International, 2015) and ASReml-R (Butler et al., 2018).

3. Results

3.1 Environmental conditions and irrigation

A total of 670 mm of rain fell in the first year (1 July 2013–30 June 2014), whereas 596 mm of rain fell in the second year of the study (1 July 2014–30 June 2015). Greatest monthly rainfall occurred in July and August each year, before applying the soil wetting agents, while the lowest monthly rainfall was recorded during the summer months (December-February) (Fig. 1). Monthly evaporation ranged from 41 to 213 mm, with the highest loses in January 2014 (Fig. 1). Monthly irrigation amounts increased as summer progressed, and for all irrigation schedule treatments, peaking in December and January before declining (Fig. 2). The monthly minimum average daily air temperature was lowest in July each year, while the monthly maximum average daily air temperature tended to be greatest in February (Fig. 1).

Further inspection of the rainfall and evaporation records shows subtle differences between monthly data between the two study years influenced the distribution of irrigation water. For example, in the 2013/14 irrigation season, above average spring rainfall in September and early October resulted in 14% (i.e., water saving of 139 kL ha^{-1}) and 8% (77 kL ha^{-1}) less water being applied to the ‘Budget+Net Evaporation’ and ‘Budget+Probe’ schedules than the ‘Budget’ schedule with a water allocation of 7500 kL ha^{-1} yr^{-1}, respectively (Fig. 2a). Water saved during the 2013/14 spring was redistributed later in the irrigation season (November–February) when rainfall was less than average (Fig. 2).

3.2 Kikuyugrass growth

Average weekly growth varied (13–783 kg DM ha^{-1}) seasonally each year for all treatments with the lowest growth rates typically occurring in winter (June–August) and peaking in late summer/early autumn (February–April) (Fig. 3). The influence of water allocation on weekly growth rates was apparent during the irrigation period (October–May), with growth decreasing with decreasing water allocation (P<0.001). Applying a wetting agent at the recommended rate benefited weekly kikuyugrass growth for all water allocations during the 2013/14 irrigation period (P<0.001), but had a variable effect during the 2014/15 irrigation period depending on the water allocation (P=0.001); doubling the wetting agent application rate did not necessarily further increase growth in either year. The effect of water allocation on weekly growth was only influenced by scheduling during the 2014/2015 irrigation period (P=0.018; data not shown), but the response was inconsistent. For example, for the 7500 kL ha^{-1} yr^{-1} and 6250 kL ha^{-1} yr^{-1} water allocations the Budget schedule gave the greatest growth, whereas for the 5000 kL ha^{-1} yr^{-1} the Budget+Net Evaporation schedule produced greater growth than the other irrigation schedules.

Cumulative kikuyugrass growth after two years (i.e., total clipping DM) varied depending on water allocation (P=0.005) and wetting agent (P<0.001) with a weak interaction between the two treatments (P=0.073). Overall, cumulative growth was greater for the 7500 kL ha^{-1} yr^{-1} allocation (14,126 kg DM ha^{-1}) than the two lower water allocations (10,027 kg DM ha^{-1}, 6250 kL ha^{-1} yr^{-1}; 8,151 kg DM ha^{-1}, 5000 kL ha^{-1} yr^{-1}); with no difference in cumulative growth between 6250 or 5000 kL ha^{-1} yr^{-1} (P<0.05). Applying a wetting agent increased cumulative growth (12,213 kg DM ha^{-1}, WA; 11,896 kg DM ha^{-1}, 2WA) relative to not applying a wetting agent (8,195 kg DM ha^{-1}, 0WA) (P<0.05), however there was no advantage in doubling the wetting agent application rate to cumulative growth (P>0.05).

3.3 Kikuyugrass color

Greatest color (i.e. highest hue angle) was measured during winter and early spring, while lowest color (i.e. least hue angle) was observed during summer and early autumn for all treatments (Fig. 4, Supplementary Fig.1, Supplementary Fig. 2). ‘Scalping’ of the kikuyugrass during high growth lowered color from mid-April to mid-May 2014 for three single plots: 7500 kL ha^{-1} yr^{-1}, Budget, 2WA; 7500 kL ha^{-1} yr^{-1}, Budget+ET, 1WA; 7500 kL ha^{-1} yr^{-1}, Budget+Probe, 1WA; and for all plots in June 2015. Kikuyugrass color during the irrigation season was greatly influenced by the water allocation in both years (P≤0.009), with kikuyugrass color decreasing as the water allocation was lowered. Applying a wetting agent increased the kikuyugrass color for all water allocation treatments on average during the 2013/2014 irrigation season (P<0.001), but appeared to only positively influence the 7500 kL ha^{-1} yr^{-1} during the 2014/2015 irrigation season. Kikuyugrass color during the 2013/2014 irrigation season was also influenced by irrigation schedule (P=0.001), with the Budget+ET irrigation schedule tending to provide greater kikuyugrass color than the other irrigation schedules irrespective of water allocation (compare Supplementary Fig.1 compare Fig. 4 and Supplementary Fig. 2). However in the 2014/2015 irrigation season, the effect of irrigation schedule on kikuyugrass color was not consistent and varied depending on water allocation (P=0.025). Kikuyugrass color only met local industry minimum requirement (a hue angle >97°; Barton et al., 2009a) throughout the irrigation season for the plots which received a water allocation of 7500 kL ha^{-1} yr^{-1} plus a wetting agent.

3.4 Soil water repellence

Soil water repellence was rated as either 'severe' (MED>2.3–3.5 M) or 'very severe' (MED >3.5 M; Carter, 2002) throughout the year for treatments not receiving a wetting agent, and irrespective of the water allocation or irrigation schedule (Fig. 5, Supplementary Fig. 3, Supplementary Fig. 4). All wetting agent treatments were at least severely water repellent (MED>2.3 M) before applying soil wetting agent treatments in early spring (September), which decreased to 'moderate' (MED>1.1–2.3 M) following the recommended wetting agent application, or 'low' (MED>0–1.1 M) when the wetting agent application rate was doubled. The extent that the wetting agent treatment decreased water repellence depended on the water allocation and irrigation schedule ($P\leq0.017$) (compare Fig. 5 with Supplementary Fig. 3 and Supplementary Fig. 4), and the time of the year that the wetting agent was applied. For example applying twice the recommended wetting agent application decreased MED on average by 2 M following the spring application (September), but by only 1 M following early summer application (December), or resulted in no change (February, in 2015 only). Furthermore, soil water repellence tended to increase during the periods between wetting agent applications.

Soil water repellence measured using WDPT confirmed MED observations. Overall, and during the course of the 2 year study, a large proportion (97–100%) of soil samples were classed as severely water repellent (WDPT >600s; Dekker and Jungerius, 1990) in the absence of a wetting agent (Table 2). Applying a wetting agent at the recommended application rate decreased the proportion of soil samples classed as severely water repellent to at least 40%, while doubling the recommended application decreased the proportion to at least 20% (Table 3).

3.5 Soil volumetric water content

Greatest soil VWC was observed in winter (e.g., 55 % VWC) and early spring while lowest VWC was reported in summer and early autumn (e.g., 15% VWC; Fig. 6, Supplementary Fig. 5, Supplementary Fig. 6). The upper soil VWC values reported for the surface 25 mm are not surprising when the low soil bulk density (0.80 g cm^{-3}) and presence of an organic mat layer is taken into account. Soil VWC was greatly influenced by the water allocation during the irrigation season (P<0.001). Applying a wetting agent further increased soil VWC each year and by varying amounts depending on the water allocation treatments ($P \leq 0.008$), with the effect most marked increase for the 7500 kL ha^{-1} yr^{-1} and 6250 kL ha^{-1} yr^{-1} treatments during the summer months ($P \leq 0.002$). Doubling the application of the wetting agent did not necessarily increase soil VWC in comparison to the recommended application rate (e.g., Fig. 6). The effect of water allocation on summer soil VWC was only influenced by irrigation scheduling in 2014/2015 (P<0.001), however the findings were not consistent. For example, the Budget+Net Evaporation schedule tended to have the greater soil VWC on average than the Budget+Probe schedule for the 7500 kL ha^{-1} yr^{-1} and 5000 kL ha^{-1} yr^{-1} water allocations (compare Supplementary Fig. 5 and Supplementary Fig. 6), however there were not differences in soil VWC between these two irrigation schedules for the 6250 kL ha^{-1} yr^{-1} water allocation.

4. Discussion

Kikuyugrass can be maintained on a water allocation as long as the amount applied meets the water requirements of the plant in the environment of interest. In the present study, applying 7500 kL ha^{-1} yr^{-1} maintained the color and growth of a warm-season turfgrass in a Mediterranean climate under low 'wear' conditions, and when water was distributed from early spring to late autumn using an irrigation system with a high distribution of uniformity. A water allocation of 7500 kL ha^{-1} yr^{-1} is approximately equivalent to 70% replacement of net evaporation at the study site, which previous research has demonstrated is sufficient for maintaining kikuyugrass in the region (Barton et al., 2009b; Short and Colmer, 2007). Further lowering the water allocation to 6250 kL ha^{-1} yr^{-1} would be expected to decrease kikuyugrass color and growth below industry standards even if a soil wetting agent is applied; particularly during 'dry' summers such as in 2014/15. A water allocation of 5000 kL ha^{-1} yr^{-1} is not expected to result in acceptable kikuyugrass color during summer in the present study environment. The water allocation required to maintain warm-season grasses in other regions will differ from the present study as turfgrass irrigation requirements varies depending on a number of factors including turfgrass type, agronomic management, and climate (Kopp and Jiang, 2013). A review of warm-season turfgrass reported water use values ranging from 52 to 94% replacement of net evaporation, from four climates, and under deficient irrigation (Colmer and Barton, 2017). We recommend an initial water allocation for turfgrass be based on the known site-specific water requirement of a turfgrass.

There are a number of approaches available for distributing a water allocation to turfgrass during the irrigation season. The three approaches investigated in the present study in a Mediterranean climate evaluated various options for irrigation scheduling that required different levels of resources. Distributing water each month based on historical monthly evaporation and rainfall data (‘Budget’ schedule) proved to be a simple and effective approach to maintaining kikuyugrass when the water allocation was sufficient. Refining the ‘Budget’ scheduling by utilizing daily net evaporation values or soil moisture measurements saved water that was redistributed to later in the irrigation season (2013/14), improving kikuyugrass quality for the Budget+ET irrigation schedule in comparison to the other irrigation schedules, but requires additional equipment and time of personnel. Similarly, Pathan *et al* (2007) demonstrated informing irrigation scheduling using a matric suction soil water sensors decreased the irrigation volume by 27% and maintained warm-season turfgrass quality during summer relative to simply regulating the number of watering days. Although various technologies have been developed to assist with water scheduling so as improve turfgrass water use efficiency (e.g., McCready and Dukes, 2011; Pathan et al., 2007; Schiavon et al., 2014), their relative effectiveness at distributing a water allocations to turfgrass does not appear to have been previously reported.

The impacts of lowering a water allocation to turfgrass grown in soils prone to soil water repellence can be partly mitigated by applying an effective soil wetting agent. For example in the present study, applying a soil wetting agent improved the quality (i.e. color) of kikuyugrass grown in sandy soil with a water repellent surface (0–25 mm) and receiving a 7500 kL ha^{-1} yr^{-1} water allocation. Applying a soil wetting agent alleviated water repellence, increased soil water content and thus increased kikuyugrass color. The extent to which applying a soil wetting agent improves turfgrass quality under deficit irrigation is expected to vary. In the present study region (present study; Barton and Colmer, 2011a; Barton and Colmer, 2011b), and in some regions of the USA, applying a soil wetting agent benefited the quality of warm-season turfgrasses grown under deficit irrigation (Alvarez et al., 2016; Serena et al., 2018); whereas in the southern USA, two warm-season turfgrasses grown under deficit irrigation did not benefit from the application of a wetting agent (Schiavon et al., 2014). The present study also demonstrates simply alleviating water repellence may not necessarily benefit turfgrass if the irrigation volume is too low to maintain acceptable turfgrass color and growth (e.g., 5000 kL ha^{-1} yr^{-1}). Overall, we would expect applying a soil wetting agent will benefit turfgrass quality when grown on a water-repellent soil, when the water allocation and water quality are sufficient, and if the water is applied uniformly.

As particular climates continue to dry in some parts of the world, further research and technological developments would benefit turfgrass management under restricted water supplies. Firstly, ‘wear’ (or ‘traffic stress’, see Murphy and Ebdon, 2013) was not applied to the turfgrass in the present study, however local antidotal evidence from turfgrass managers indicates turfgrass water needs will rise with increasing ‘wear’ and in situations where rapid turfgrass growth is needed to ‘repair’ the turfgrass surface. This is also true for other studies investigating turfgrass water requirement (Colmer and Barton, 2017), and currently limits our ability to determine and assess strategies for managing water allocations for turfgrass under ‘high wear’ situations, such as high use recreational sports grounds. Secondly, the development of soil water repellence is likely to increase as the availability of irrigation water declines as maintaining high soil water contents is known to prevent the development of soil water repellence (Cisar et al., 2000; Müller and Deurer, 2011). Soil water repellence is not a static property, and the timing and development of soil water repellence can vary during and between years; yet its transient nature is not fully understood (Müller and Deurer, 2011). Developing non-invasive techniques for early detection of soil water repellence (Kim et al., 2014; Lewis et al., 2008) before plant symptoms develop, and better understanding the conditions whereby soil water repellence occurs in turfgrass are therefore needed for maintaining turfgrass in drying climates.

5. Conclusions

Kikuyugrass can be maintained on a water allocation if the amount meets minimum turfgrass water requirements. A water allocation of 7500 kL ha^{-1} yr^{-1} maintained the color and growth of a warm-season turfgrass in a Mediterranean climate under low ‘wear’ conditions, and when distributed from early spring to late autumn using an irrigation system with a high distribution of uniformity. Applying less than 7500 kL ha^{-1} yr^{-1} lowered kikuyugrass growth and meant color did not meet industry requirements. Applying a wetting agent to soil prone to water repellence improved the color and growth of kikuyugrass receiving a water allocation 7500 kL ha^{-1} yr^{-1} and partly mitigated the impact of lowering the water allocation to 6250 kL ha^{-1} yr^{-1}. However, simply alleviating water repellence will not benefit kikuyugrass if the irrigation volume is too low to maintain kikuyugrass. Refining the scheduling approach by taking into account daily net evaporation values saved water early in the irrigation season in the first year of study, enabling water redistribution to later in the season and to the benefit of kikuyugrass growth. Finally, we recommend further research investigate the water requirements of turfgrass under ‘high wear’ situations, plus develop non-invasive techniques for early detection of soil water repellence in turfgrass.

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TABLES

Table 1.

Historical evaporation, proportion of total evaporation and water allocations[a] for the 'budget' irrigation schedule for each water allocation treatment by month during the irrigation season, at the study site in Perth, Australia.

Month	Historical net evaporation[b]		Proportion of total evaporation[c]	7500 kL ha^{-1} water allocation[d]		6250 kL ha^{-1} water allocation[d]		5000 kL ha^{-1} water allocation[d]	
	(mm mo^{-1})	(kL ha^{-1})	(%)	(mm mo^{-1})	(kL ha^{-1})	(mm mo^{-1})	(kL ha^{-1})	(mm mo^{-1})	(kL ha^{-1})
Sept.	39	390	4	30	300	25	250	20	200
Oct.	113	1130	11	82	825	69	688	55	550
Nov.	151	1510	14	105	1050	88	875	70	700
Dec.	182	1820	17	128	1275	106	1062	85	850
Jan.	202	2020	19	142	1425	119	1188	95	950
Feb.	173	1730	16	120	1200	100	1000	80	800
Mar.	149	1490	14	105	1050	88	875	70	700
Apr.	57	570	5	38	375	31	312	25	250

[a] Monthly water allocation calculated by multiplying the annual water allocation by the proportion of the total net evaporation during the irrigation period (Sept. to Apr.) that has historically (2005–2012) been recorded for that month at the study site.

[b] Based on data collected from the UWA Turf Research Facility (2005–2012) in Perth, Western Australia (31°56′ S, 115°47′ E).

[c] Total historical net evaporation is the sum of monthly historical net evaporation during irrigation months of Sept. to Apr. (i.e., 1067 mm or 10670 kL ha^{-1}).

[d] Multiply water allocation by proportion of total net evaporation for that month e.g., 4% of the water allocation is applied in September, which is 300 kL ha^{-1} (or 30 mm) if the annual water allocation is 7500 kL ha^{-1}.

Table 2.

Proportion of net evaporation replaced in the first month (September) of each irrigation season at the study site in Perth, Australia. The replacement value for the ‘Budget+Net Evaporation’ and ‘Budget+Sensor’ irrigation schedules in the following months determined at the end of each month by calculating the proportion of the remaining water allocation to the remaining historical net evaporation.

Water allocation ($kL\ ha^{-1}\ yr^{-1}$)	Total historical net evaporation[a] ($kL\ ha^{-1}$)	Initial replacement of net evaporation (%)
7500	10670	70
6250	10670	59
5000	10670	47

[a] Calculated using historical monthly data collected from the UWA Turf Research Facility in Perth, Western Australia (2005–2012; Table 1).

Table 3. Effect of irrigation and wetting agent treatments on the proportion of water drop penetration test (WDPT) values recorded as 'severely' water repellent (WDPT > 600s) from 20 sampling dates during a two year study[a] in Perth, Australia. Values are means (and standard errors) of three replicates.

Water allocation ($kL\ ha^{-1}\ yr^{-1}$)	Irrigation schedule[b]	Wetting agent rate[c]	Proportion (%)
7500	Budget	0WA	98 (1.7)
		1WA	23 (6.0)
		2WA	3 (1.7)
7500	Budget+Net Evaporation	0WA	97 (3.3)
		1WA	25 (5.8)
		2WA	12 (4.4)
7500	Budget+Sensor	0WA	100 (0)
		1WA	32 (4.4)
		2WA	10 (2.9)
6250	Budget	0WA	100 (0)
		1WA	25 (7.6)
		2WA	15 (2.9)
6250	Budget+Net Evaporation	0WA	100 (0)
		1WA	40 (2.9)
		2WA	15 (5.0)
6250	Budget+Sensor	0WA	97 (3.3)
		1WA	32 (6.0)
		2WA	15 (2.9)
5000	Budget	0WA	98 (1.7)
		1WA	38 (12)
		2WA	13 (4.4)
5000	Budget+Net Evaporation	0WA	100 (0.0)
		1WA	20 (2.9)
		2WA	13 (4.4)
5000	Budget+Sensor	0WA	100 (0.0)
		1WA	30 (2.9)
		2WA	20 (2.9)

[a] Soil water repellence measured at the beginning of the experiment, and then every four weeks during the irrigation season (September–April) using a modified water drop penetration test [WDPT; (Letey, 1969)]. In each plot (81), four intact soil cores (each core 52 mm in diameter, 25 mm in depth) were collected and combined for determining WDPT. A total of 20 samples were analyzed over time per treatment plot. Soil samples recording a WDPT >600s were considered ‘severely’ water repellent (Dekker and Jungerius, 1990).

[b]‘Budget’ irrigation schedule: water allocation for each month was calculated by multiplying the annual water allocation by the proportion of the annual net evaporation that historically occurred in that month; ‘Budget+Net Evaporation’ irrigation schedule: initial replacement value was the proportion of the water allocation to the net evaporation (historical, as in the ‘Budget’ schedule) at the start of the irrigation season, but irrigations were based on actual net evaporation for the current season and the allocation remaining was recalculated at the end of each month; ‘Budget+Sensor’ irrigation schedule: monthly water allocation calculate as for the Budget schedule, however irrigation only proceeded if the soil water content was below a critical value.

[c]Wetting agent applied at either nil rate (0WA), manufacturer’s recommended ‘label’ rate (1WA) or double manufacturer’s recommended ‘label’ rate (2WA).

FIGURE CAPTIONS

Fig. 1 Monthly distributions of rainfall, evaporation, average daily maximum air temperature, and average minimum air temperature in 2013/14 (a) and 2014/15 (b) at the UWA Turf Research Facility, Perth, Australia.

Fig. 2. Monthly irrigation water distribution for three irrigation schedule approaches for a water allocation of 7500 kL ha^{-1} yr^{-1} (a), 6250 kL ha-1 yr^{-1} (b), and 5000 kL ha^{-1} yr^{-1} (c) at the UWA Turf Research Facility, Perth, Australia. In the ‘Budget’ irrigation schedule the water allocation for each month was calculated by multiplying the annual water allocation by the proportion of the annual net evaporation that historically occurred in that month. In the ‘Budget+Net Evaporation’ irrigation schedule the initial replacement value was the proportion of the water allocation to the net evaporation (historical, as in the ‘Budget’ schedule) at the start of the irrigation season, but irrigations were based on actual net evaporation for the current season and the allocation remaining was recalculated at the end of each month enabling re-budgeting for remaining months in the current season and with continued adjustments based on prevailing net evaporation. The ‘Budget+Sensor’ irrigation schedule calculated the monthly water allocation as for the ‘Budget’ schedule, however irrigation only proceeded if the soil water content was below a critical value.

Fig. 3. Influence of water allocation and soil wetting agent application rate on the weekly kikuyugrass growth (‘clippings’) when allocated 7500 kL ha^{-1} yr^{-1} (a), 6250 kL ha^{-1} yr^{-1} (b), and 5000 kL ha^{-1} yr^{-1} (c) of water, at the study site in Perth, Australia. Wetting agent applied at either nil rate (0WA), manufacturer’s recommended ‘label’ rate (1WA) or double manufacturer’s recommended ‘label’ rate (2WA). Values are means (+/- standard errors) of nine values averaged across irrigation schedule treatments. Filled-triangles indicate fertilizer

application dates and open-triangles represent wetting agent application dates [shown in (a) only, but applicable also to (b) and (c)].

Fig. 4. Influence of water allocation and soil wetting agent application rate on kikuyugrass color with time when turfgrass was allocated 7500 kL ha^{-1} yr^{-1} (a), 6250 kL ha^{-1} yr^{-1} (b), and 5000 kL ha^{-1} yr^{-1} (c) of water distributed using the 'Budget' irrigation schedule, at the study site in Perth, Australia. Increasing hue angle indicates increasing greenness, with measurements taken with a Chroma Meter. Wetting agent applied at either nil rate (0WA), manufacturer's recommended 'label' rate (1WA) or double manufacturer's recommended 'label' rate (2WA). Values are means (+/- standard errors) of three values. Filled-triangles indicate fertilizer application dates and open-triangles represent wetting agent application dates [shown in (a) only, but applicable also to (b) and (c)]. Dashed line represents the local industry minimum requirement (a hue angle >97°; Barton et al., 2009a).

Fig. 5. Influence of water allocation and soil wetting agent application rate on the molarity of ethanol droplet (MED) test with time when kikuyugrass is allocated 7500 kL ha^{-1} yr^{-1} (a), 6250 kL ha^{-1} yr^{-1} (b), and 5000 kL ha^{-1} yr^{-1} (c) of water distributed using the 'Budget' irrigation schedule, at the study site in Perth, Australia. Increasing MED indicates increasing soil water repellence, and was measured in the surface soil (0–25 mm). Wetting agent applied at either nil rate (0WA), manufacturer's recommended 'label' rate (1WA) or double manufacturer's recommended 'label' rate (2WA). Values are means (+/- standard errors) of three values. Open-triangles represent wetting agent application dates [shown in (a) only, but applicable also to (b) and (c)]. Soil water repellence is ranked as follows: Low (MED<1.2), moderate (1.2<MED<2.4), severe (2.4<MED<3.2), very severe (MED>3.2) (King, 1981).

Fig. 6. Influence of water allocation and soil wetting agent application rate on soil volumetric water content (0–25 mm of soil) with time when kikuyugrass was allocated 7500 kL ha^{-1} yr^{-1} (a), 6250 kL ha^{-1} yr^{-1} (b), and 5000 kL ha^{-1} yr^{-1} (c) of water distributed using the 'Budget' irrigation schedule, at the study site in Perth, Australia. Wetting agent applied at either nil rate (0WA), manufacturer's recommended 'label' rate (1WA) or double manufacturer's recommended 'label' rate (2WA). Values are means (+/- standard errors) of three values. Open-triangles represent wetting agent application dates [shown in (a) only, but applicable also to (b) and (c)].