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ASSESSING EVIDENCE ON THE AGRONOMIC AND ENVIRONMENTAL IMPACTS OF TURFGRASS IRRIGATION MANAGEMENT

Carlos Gómez-Armayones[1], Agnar Kvalbein[2], Trygve S. Aamlid[2], Jerry W. Knox[1] *

[1] *Cranfield Water Science Institute, Cranfield University, Bedford MK43 0AL, UK*

[2] *NIBIO – Norwegian Institute of Bioeconomy Research, Landvik Research Centre, N-4886 Grimstad, Norway*

*Corresponding author (j.knox@cranfield.ac.uk)

ABSTRACT

In recent years, rising competition for water coupled with new environmental regulations has exerted pressure on water allocations for turfgrass irrigation. In this paper, we reviewed published scientific and industry evidence on the agronomic and environmental impacts of turfgrass irrigation using a robust systematic review methodology. Our focus was on the links between (i) irrigation management (amount and frequency), (ii) agronomic responses to irrigation (turf quality, growth rates and rooting) and (iii) environmental impacts (nitrogen leaching). Based on an initial screening of 653 studies and data extracted from 83 papers, our results show that in most cases, under moderate levels of deficit irrigation (50-60% of actual evapotranspiration, ETa), turf quality can be maintained at an acceptable level but with lower water consumption compared to irrigating back to field capacity. Irrigation beyond field capacity was found to increase the risk of nutrient leaching. However, evidence also showed that the concentration and total loss of NO_3^- in leachate was influenced more by nitrogen (N) rates, soil characteristics, turfgrass species and turfgrass growth rates than by irrigation practices. Our analyses suggest that turfgrass irrigation should be scheduled to apply water at moderate levels of deficit irrigation, sufficient to maintain turfgrass quality but limited to promote a deep and extensive rooting system. The findings provide new insights and valuable evidence for both scientists and practitioners involved in turfgrass research and management.

Abbreviations: DMP, Dry matter production; Epan, pan evaporation, ETo, reference evapotranspiration; ETa, actual evapotranspiration; N, nitrogen; SR, Systematic review.

Keywords: Deficit irrigation, irrigation management, leaching, turfgrass maintenance, turfgrass quality.

Turfgrass has an important multifunctional role, contributing to urban development (green spaces) and supporting multiple environmental (ecosystems), societal and wellbeing (sports surfaces and leisure), and economic (source of direct and indirect employment) benefits (Beard and Green, 1994; Haydu et al., 2008). To maintain high-quality turf surfaces, a range of maintenance activities is required, including mowing, irrigation, aeration and the application of topdressing, fertiliser and pesticides (Beard, 1973). Adequate inputs of water and fertiliser are crucial for maintenance of high-quality standards in turfgrass, but inappropriate management can lead to an increase of nutrients and pesticides in ground and surface water through leaching (Branham, 2006) and runoff (Shuman, 2002). It is therefore essential to understand the agronomic requirements for managing turf quality while ensuring that negative environmental impacts are minimised. Over the last 20 years, the focus of turf research has shifted away from improving aesthetic quality to reducing environmental impacts (Stier et al., 2013), mainly in response to concerns regarding diffuse pollution from nutrients and their impacts on the aquatic environment (Strandberg et al., 2012; Cisar, 2012). Rising competition for water between leisure, agriculture and residential water supply, coupled with new environmental regulations, is adding further pressure on the turfgrass sector (Carrow, 2006; Rodríguez Díaz et al., 2007). Improvements in irrigation management to enhance turf quality, while reducing water and energy consumption and environmental impacts, have become major ‘drivers for change’ in the turfgrass industry.

The aim of this study was to critically review and assess published evidence on the links between irrigation management, turfgrass performance (turf quality, growth and rooting) and environmental impacts (nitrogen fate). A systematic review (SR) approach was adopted; this provides an internationally recognised highly robust technique for identifying, synthesising and evaluating published evidence from the scientific and grey literature (industry documents and technical reports that have not been subject to a peer-review process). Although originally developed for use in medical research, its application has spread into natural and environmental sciences [e.g. Knox et al. (2016)] to support decision-making and policy formulation.

MATERIALS AND METHODS

We adopted a SR approach originally developed by the Collaboration for Environmental Evidence (CEE) and Centre for Evidence Based Conservation (CEBC, 2010). This included the drafting of a protocol to define the research method, followed by systematic search and selection of relevant literature based on a defined set of ‘inclusion criteria’. Methods for data reporting, synthesis and study quality assessment were also carefully defined. The underpinning element in a systematic review is the primary research question. For this study, the following question was formulated: *Turfgrass irrigation management: what are the agronomic benefits and environmental impacts?* The primary question was split into four components referred to as PICO or PECO terms, which are acronyms for *Population*, *Intervention/Exposure*, *Comparator* and *Outcome*. For this SR, the targeted population was turfgrass; the intervention/exposure was irrigation and other turfgrass maintenance practices such as N fertilisation, mowing or application of surfactants; comparators were turfgrass visual quality, growth, rooting, leaching and runoff; and as outcomes, we expected to find evidence on the most appropriate irrigation management strategies to maximise turf quality, growth and rooting and to mimimise environmental impacts. The search strategy included drawing on evidence from a number of well-established scientific bibliographic databases (Web of Science, Scopus, Science Direct and Turfgrass Information File from Michigan State University, MSU) and grey literature from selected websites (turf federations, societies, associations). Searches were limited to publications in English. Following a number of trial searches, the final search term used for the systematic review was: “*TITLE-ABS-KEY ((turf* OR golf) AND (irrigat*) AND (management OR (irrigat* AND (frequency OR calendar OR* *practic*)) OR "water* regime" OR sprinkler OR uniformity OR efficiency OR strategy OR drought OR deficit OR "irrig* sched*" OR mowing OR feritiliz* OR surfact*) AND (quality OR leaching OR "water consu*" OR environ* OR impact OR evapo*) AND NOT wastewater)"*, where *TITLE-ABS-KEY* limits the scope of the search to the publication title, abstract and keywords; *AND*, *OR* are Boolean inclusion operators; and *AND NOT* is a Boolean exclusion operator.

All relevant literature was screened based on a set of inclusion criteria. These were first applied to the title, then to the abstract, and finally to the full text. Selected literature had to comply with the following requirements: (i) the population had to be turfgrass species, (ii) all papers had to be based on irrigated turf (not other grassland crops) and (iii) the research had to describe turfgrass performance as a response to irrigation and/or turf management, or related to environmental impacts such as nutrient leaching. Literature that focused on grasslands without frequent mowing (e.g. permanent leys and/or pastures), turf resistance to pests, runoff losses, pesticide fate, water quality or use of wastewater for turfgrass irrigation were all excluded. Justification on the exclusion of irrigation using wastewater is provided in the methodologial limitations section. Literature preferably had to include quantitative data to allow comparison between individual studies. Quantitative and qualitative data were then extracted from each publication and a database created. Relevant data embedded within published sources (figures) were extracted using *WebPlotDigitizer* (Rohatgi, 2017).

From each source we extracted data relating to irrigation management, distinguishing between irrigation amount and frequency. Irrigation amount was expressed as a percentage (%) of either (i) water evaporated from a US Class A evaporation pan (Epan), (ii) reference evapotranspiration (ETo) or (iii) actual evapotranspiration (ETa) since the last irrigation. For ETa, water replaced was expressed as a percentage of water consumed by the plant under non-limiting water conditions (100% ETa). Data from ETa scheduled studies were those in which the irrigation amount was calculated as a function of weight loss by lysimeters or from measured soil water content, or based on the equation ETc = Kc × ETo, where ETc is crop evapotranspiration, Kc is a crop coefficient (Allen et al., 1998). We used this approach because it was the main expression of irrigation amount in the literature and since it was assumed to be the most appropriate approach to compare results between studies. Using the total amount of water consumed by the plant or the soil water content depletion in absolute terms would not have allowed comparison of results between different studies. Data in which irrigation amount was expressed as Epan, ETo or ETa were analysed and presented separately as these values were derived from various scheduling approaches (Allen et al., 1998). The term ‘deficit irrigation’ which is the practice of under-irrigating turfgrass below its maximum water demand (Wherley, 2011) was used to refer to irrigations where water was supplied at a lower rate than 100% ETa. For irrigations below 100% Epan or ETo, we only expressed the values as “below 100%”, or the reported irrigation amount. Regarding irrigation frequency, we refer to two strategies, either ‘light-frequent’ or ‘deep-infrequent’ irrigation. For ‘light-frequent’, less water was applied and on a shorter interval compared to ‘deep-infrequent’ irrigation.

To assess turfgrass quality, we used a visual quality index ranging from 1 to 9, where 1 represented uneven and poor quality turf, and 9 represented even (uniform) and ideal quality turf (Espevig and Aamlid, 2012). The minimum acceptable quality varied among the reported studies between 5 and 6 (Krans and Morris, 2007). For this reason, we considered scores of minimum acceptable turfgrass quality as being those values between 5 and 6. In research where other scales were used, turfgrass quality scores were converted to correspond to the 1-9 scale. Although we used this scale to assess turfgrass quality, it is important to recognise other methods for quantifying turfgrass quality exist such as assessing ground cover, the use vegetation indices, turf hardness or ball roll. However, we used visual turfgrass quality scoring regime due to the lack of references reporting quantitative data on turf quality in relation to irrigation practices using the alternate approaches. Data presented in our results reflect the average value from each irrigation treatment. We distinguished published data between cool- and warm-season grasses and considered 'treatment' as the different irrigation replacement levels in each study, for each species and variety. Turfgrass growth rate, total N leaching and N uptake by turf were expressed as the sum of samples from each irrigation treatment. Turfgrass growth rate was defined as the dry matter production (DMP) in clippings per day (g m^{-2}, g m^{-2} d^{-1}) or increment in canopy height per day (mm d^{-1}). N uptake was defined as the amount of N in clippings (g N m^{-2}) and was, where possible, expressed as a daily value (g N m^{-2} d^{-1}). Data to describe root development were dry root biomass (g m^{-2}) and root length (cm cm^{-3}) as well as the distribution at different soil depths. For turfgrass growth, N uptake and N leaching it was necessary to standardise the data extracted from the literature. Thus, to present the results from research as a daily rate (g m^{-2} d^{-1} for clippings and g N m^{-2} d^{-1} for N uptake and leaching) the published data were aggregated and then divided by the duration of each treatment to derive equivalent daily values.

To assess environmental impacts, we only considered data relating to nutrient uptake by turfgrass and N losses via leaching. Units were expressed as the total amount of nutrient taken up or lost (g m^{-2} d^{-1}) or concentration of N in leachate (mg L^{-1}). Due to the importance of other factors known to affect leaching from irrigated turfgrass, we also considered research where fertilisation rates and dates, soil types or turfgrass age were included.

The SR methodology followed four discrete stages (Figure 1). Based on the search criteria, 653 articles were identified. The scientific and grey literature was then subjected to assessment using the inclusion criteria. Ultimately, 83 documents were selected, including 76 peer-reviewed papers and seven documents from the grey literature. Most articles stemmed from research conducted in the USA (79%), Australia (6%), Norway (6%) and Turkey (6%).

Other relevant studies were reported from Canada, Italy, Puerto Rico and Thailand (see Supplementary Information for the complete list of references included in the SR). The statistical analyses for the regression curves, fitting parameter (R^2) and significance tests was conducted using the Statistics Toolbox in Matlab R2014a ® software (MathWorks, 2014). The significance of the regressions were calculated for $p<0.05$, where the null hypothesis was that there was no relationship between irrigation and the variable being studied.

RESULTS AND DISCUSSION

Effects of irrigation management on turfgrass visual quality

The SR outputs confirmed that the approach adopted for scheduling irrigation can significantly impact turfgrass quality. We observed a positive correlation between the amount of irrigation applied and turfgrass quality. When the reported turfgrass quality scores were compared between different irrigation scheduling methods for cool season turfgrasses the R^2 values for the logistic curve $f(x) = \frac{a}{1+e^{-bx}}$, where a = 9, were 0.77, 0.37 and 0.32 for Epan, ETo and ETa, respectively (Figure 2). For warm season turfgrasses, the corresponding R^2 values were 0.45, 0.34 and 0.44 for Epan, ETo and ETa (Figure 2). In all cases, the *p-values* for the regressions between irrigation amount and turfgrass quality were <0.001. Based on the regression analyses, a stronger correlation was observed between irrigation amount and turf quality for Epan based scheduling methods. Whilst a strong correlation based on irrigation using ETa might be expected, since these were mostly based on field measurements, the weak correlation was likely due to the inherent variability between individual studies rather than the method itself *per se*. Although the use of Epan and ETo to schedule irrigation are useful methods for comparing different irrigation amounts (ETo and Epan values are usually available to course managers), the application of incorrect crop coefficients (Kc) can lead to over-estimation in irrigation need and thus make these methods less reliable than ETa based methods using soil moisture sensors or lysimeters. Although Kc values of 0.8 for cool season turfgrass and 0.6 for warm season turfgrass are widely accepted as industry standards, several studies report that Kc varies significantly depending on the site, local weather, seasons, turfgrass species, mowing height and N fertilization (Meyer and Gibeault, 1986; Poro et al., 2016; Aamlid et al., 2016). Readers interested in crop coefficients for turfgrass are referred to Romero and Dukes (2016) who provide a recent updated review .

Considering the points above, when variations in % Epan or ETo irrigation amount are reported in studies, they indicate a variation in water applied, but not necessarily in the amount of water consumed by the plant. Thus, irrigations below 100% Epan or ETo do not necessarily result in deficit irrigation. Thus, where we present the impacts of different irrigation amounts on turfgrass expressed as % Epan or ETo, those results show the impact of different irrigation levels on turfgrass performance but do not indicate the amount of water consumed by the plant or if a deficit irrigation strategy was adopted. When we use the term deficit irrigation, we only to refer to % ETa.

We found that both cool and warm season turfgrasses followed a similar trend in their response of visual turfgrass quality to deficit irrigation. In general, the highest turfgrass quality was obtained for irrigation close to 100% ETa. Regarding Epan and ETo irrigation strategies, higher irrigation amounts also led to improved turfgrass quality scores. However, in most cases, an average acceptable turfgrass quality (≥6) could also be maintained with deficit irrigation above 40% ETa. We also observed that the irrigation amount required to maintain an acceptable turfgrass quality varied between studies, which in many cases was related to other factors such as the drought resistance of the species and variety, season and ambient weather conditions, turf management practices, including the use of soil surfactants or growth regulators, and the duration of the study. These factors explain the moderate R^2 value when comparing different studies (Figure 2).

Differences in turfgrass quality among species and varieties became more noticeable as the irrigation amount was reduced. In two studies conducted in Turkey, Candogan et al. (2014, 2015) reported on the effects of irrigating perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.) at 25%, 50%, 75%, 100% and 125% Epan. In both studies, the average turfgrass quality over five months (May to September) did not fall below 6 for irrigation treatments above 50% Epan in tall fescue and above 75% Epan in the perennial ryegrass. However, only irrigations above 100% Epan for both species maintained a consistent turfgrass quality >6.0. In New Jersey (USA), DaCosta and Huang (2006a; 2006b) reported that it was not necessary to irrigate to 100% ETa to maintain turfgrass quality in bentgrass *(Agrostis* spp.). However, they noted that different irrigation amounts were required to maintain acceptable turfgrass quality between species and different treatment years. During the growing season in the first year, the irrigation amount varied from 80% to 100% ETa in colonial bentgrass (*Agrostis capillaris* L.), while for velvet (*Agrostis canina* L.) and creeping (*Agrostis stolonifera* L.) bentgrass the irrigation amounts varied between 60% and 80% ETa. In the second year, the irrigation amount to maintain turfgrass quality across all species studies was 60% ETa. In Colorado (USA), Feldhake et al. (1984) reported that there were no significant differences in turfgrass quality between Kentucky bluegrass (*Poa pratensis* L.) and tall fescue when irrigated at 80 and 100% ETa, respectively. However, when the turf was subjected to 40% and 60% ETa, tall fescue showed a higher turfgrass quality compared to Kentucky bluegrass. In a study in Kansas (USA), Fu et al. (2004) also showed that Kentucky bluegrass needs to be irrigated to 100% ETa to maintain an acceptable turfgrass quality, while tall fescue responded well to 60% in the first year and 80% in the second year trials.

Shahba et al. (2014) reported that irrigating three varieties of seashore paspalum (*Paspalum vaginatum* Sw.) at 100% ETa maintained a high turfgrass quality regardless of variety. However, reductions in irrigation to 75% and 50% ETa led to reductions in quality between varieties. In Texas (USA), for example, Qian and Engelke (1999) reported that the irrigation amount required to maintain a minimum acceptable turfgrass quality varied from 26% Epan in buffalograss (*Buchloe dactyloides* Engelm) to 68% Epan in zoysiagrass (*Zoysia japonica* Steud.). Other factors in combination with irrigation also influence turfgrass quality. Su et al. (2007) observed that in Kentucky bluegrass, hybrid bluegrass (*Poa pratensis* L. × *Poa arachnifera* L.) and tall fescue, high temperatures severely reduced turfgrass quality when combined with drought stress (35/25°C and 60% ETa). Seasonal differences may also influence the impact of irrigation amount on turfgrass quality. For example, DaCosta and Huang (2006a) reported that during autumn, irrigation in bentgrass species could be reduced to 40% ETa without observing any severe decline in turfgrass quality. The higher water stress resistance showed by turfgrass during autumn and winter seasons was mainly associated with lower temperatures and a reduction in activity, which resulted in lower water consumption and therefore lower and slower soil moisture depletion. These authors also observed greater water use efficiency during autumn for lower irrigation amounts. Conversely, lower turf quality is usually observed during summer months under deficit irrigation (Su et al., 2009; Marchione and Fracchiolla, 2016), when hot and dry conditions make plants more susceptible to water shortages. Aydinsakir et al. (2016) reported a decline in bermudagrass (*Cynodon dactylon* L.) quality for 50% and 75% Epan, while in autumn months, when temperatures were lower, turfgrass quality recovered. This suggests that the aesthetic requirements of turfgrass might also be a contributory factor in determining the irrigation strategy adopted during the warmest months. In those areas where periods with lower turfgrass quality are acceptable, moderate deficit irrigation could be applied for limited periods. Although this might compromise turfgrass quality, this strategy can lead to lower water consumption compared to irrigating back to field capacity, and could be useful in regions where water is increasingly scarce and/or expensive.

No major impacts of cutting height on turf quality were identified in the literature when turfgrass was well-watered [25, 35 and 45 mm in seashore paspalum (Shahba et al., 2014); 20 and 50 mm in Kentucky bluegrass (Feldhake et al., 1984)]. However, where low irrigation amounts were applied, higher mowing heights resulted in greater turfgrass quality compared to lower mowing. These findings differ from those reported by Su et al. (2009) who did not observe any significant differences due to the interaction between mowing height and irrigation amount for Hybrid and Kentucky bluegrass, based on mowing heights of 38 and 76 mm and irrigation of 60% and 100% ETo.

The use of soil surfactants was reported to enhance turfgrass quality at low irrigation amounts [30% ETa, Soldat et al. (2010)] compared to treatments with no surfactant. This was reportedly due to reductions in soil hydrophobicity and higher soil moisture uniformity. Candogan et al. (2014; 2015) and Wang et al. (2014) observed that turfgrass water consumption and the irrigation amounts required to produce acceptable turfgrass quality increased with increasing N fertilisation levels. Under non-limiting water conditions, turfgrass quality was more dependent on N than irrigation amount (Shaddox et al., 2016). Other researchers reported that unfertilized turf leads to low turfgrass quality irrespective of irrigation amount (Wu et al., 2010; Carey et al., 2012; Telenko et al., 2015), as N is the main limiting factor in turfgrass performance. The use of growth regulators also helped to maintain turf quality in Seashore paspalum (*Paspalum vaginatum*) (Elansary and Yessoufou, 2015), especially under drought conditions (<50 ETa).

The impacts of irrigation frequency on turfgrass quality for cool and warm season turfgrasses are summarised in Figure 3. Overall, no major turfgrass quality impact was reported for intervals of up to four days. In contrast, when the irrigation interval was longer, the average turfgrass quality declined as irrigation frequency was lower (Peacock and Dudeck, 1984; Baldwin et al., 2006; Fry et al., 1989). Both cool and warm season turfgrasses followed a similar trend of declining turfgrass quality as the interval between irrigation events became longer. The differences in turfgrass quality between studies with the same irrigation interval as shown in Figure 3 were caused by different (i) irrigation amounts (Fry et al., 1989, Aamlid et al., 2012), (ii) varieties of the same species (Baldwin et al., 2006), and (iii) years of study (Fry et al., 1989, Fu and Dernoeden, 2009a, Jordan et al., 2003); this last factor possibly being related to both weather conditions and turf age.

In two studies turfgrass quality was reported to be higher with light frequent irrigation compared to deep-infrequent in the first year of treatment, while the opposite effect occurred the following year (Fu and Dernoeden, 2009a; Espevig and Aamlid, 2012). This was reported to be due to turfgrass adaptation to wilt stress over time, allowing the plants to maintain a higher turfgrass quality during summer stress periods. Similar results were reported by Jordan et al. (2003) who found better turfgrass quality related to irrigation every four days compared with daily and alternate irrigation, which can be linked with an adaption of creeping bentgrass to drier conditions when irrigation intervals were increased. When comparing irrigation on a weekly and two times per week cycle in three different locations, Shaddox et al. (Shaddox et al., 2016) only found significant differences between irrigation frequency and turfgrass quality in one location. In contrast to other studies, turfgrass quality was slightly higher for more infrequent irrigation treatments. Conducting research in Michigan (USA), Lee (2014) observed that during the hottest part of the season tall fescue performed better when irrigated twice weekly compared to once a week. From these studies, two deductions can be made: firstly, weekly or less frequent irrigation might not improve drought adaption of turfgrass species, and secondly, that the impacts of irrigation frequency on turfgrass quality might be more evident in long-term trials, as irrigation frequency affects the adaptation of turfgrass to drought stress, rather than showing a direct response to varying the irrigation amount. However, further research is required to investigate irrigation frequency on turf performance.

Although light-frequent irrigation to field capacity appears to be the optimum strategy to achieve a high turfgrass quality, it also results in more water being transpired (Peacock and Dudeck, 1984; Aamlid et al., 2016). For example, in Norway, Aamlid et al. (2016) observed that water consumption of cool season turfgrasses was more than double on the first day after irrigation to field capacity (Kc=1.67 to 2.85) compared to the following days (mean Kc=0.76 to 0.99). We recognise that the maximum values of Kc observed in that research were far higher than those reported in other studies. However, these findings suggest that the water consumption will be high if irrigation is applied at low deficits and with a frequent schedule, corroborating with research by DaCosta and Huang (2006a) and Aamlid et al. (2012). Achieving water savings whilst maintaining turfgrass quality may also be attained by selecting turfgrass species and varieties well adapted to local climatic conditions (Huang, 2008), by improving the uniformity of soil moisture through the use of soil surfactants (Soldat et al., 2010; Cisar, 2012), using growth regulators (Elansary and Yessoufou, 2015) and/or by improving irrigation uniformity, accuracy and efficiency by using new technology of irrigation controllers and sensors (McCready et al., 2009). Bell et al. (2013) also highlighted the potential opportunities for integrating new technologies adapted from precision agriculture into turfgrass irrigation management, including for example, determining turfgrass quality derived from digital image analysis from small unmanned aerial vehicles (Phan et al., 2017), wireless soil moisture and climate sensors for computer-based irrigation monitoring (scheduling) and variable rate irrigation.

Effects of irrigation management on root development

We observed that root development at moderate levels of reduction in irrigation amount is more related to the intrinsic drought resistance of different species and varieties than to the amount of irrigation applied *per se* (Bowman et al., 1998; Ervin and Koski, 1998; Su et al., 2007; Sinclair et al., 2011). Overall, no significant changes were observed in rooting at different irrigation amounts between 60% and 100% ETa (Fu et al., 2007; Su et al., 2007). However, under a more severe deficit irrigation regime (20% ETa), Fu et al. (2007) observed a greater number and length of roots, but this was accompanied by a reduction in turfgrass quality. For larger irrigation amounts applied to bermudagrass (140% vs. 70% Epan), Barton et al. (2006) reported that the total root biomass decreased by 30% when the turf was over-irrigated. In addition to the reported variation in rooting as a response to different irrigation treatments, the authors also observed that the total root biomass increased with time, up to ten times when comparing the first with the fourth treatment. Hejl et al. (2016) also reported an increase in root weight from the first to second year of study. In the second year, significant differences between irrigation treatments were found, but the maximum root dry weight did not coincide with the lowest irrigation amount: maximum root biomass was observed for 45% ETo, followed by 60% and 30%, respectively. Hejl et al. (2016) reported that the observed differences between treatments in root biomass during the second year might be attributable to developmental changes in response to long-term exposure to contrasting irrigation treatments.

Several studies report on how moderate drought induced by an increase in irrigation interval can have a positive effect on root development [e.g. Fu and Dernoeden (2009b)]. Thus, rooting at deeper soil layers can be stimulated by infrequent irrigation and periods of induced drought stress (Bowman et al., 1998). Infrequent irrigation allows turf to adapt to wilt stress over time, as a result of a more expansive root systems and improved carbohydrate status (Fu and Dernoeden, 2009a). However, those strategies, in addition to promoting deeper root systems, may also lead to a reduction in turfgrass quality. Baldwin et al. (2006) reported that the root biomass of bermudagrass (*Cynodon* spp.) was 46%, 61% and 78% greater when irrigated at 5, 10 and 15-day intervals compared to daily irrigation. However, setting these irrigation intervals also resulted in a decline in the average turfgrass quality between the 12 and 29 % compared with plots irrigated on a daily basis. To maintain the balance between a good root system while maintaining turfgrass quality, Johnson (2003) recommended deep infrequent irrigation to promote rooting, combined with more frequent irrigation to avoid adverse impacts of drought stress during hot periods.

In many cases, under limiting water conditions, those species and varieties that were able to develop deeper, more extensive root systems not only performed better in terms of turfgrass quality (Ervin and Koski, 1998; Fu et al., 2004) but also showed more rapid drought stress recovery (Qian and Fry, 1996; Jordan et al., 2003). High temperatures may also lead to less root biomass in cool season species (Su et al., 2007; Abraham et al., 2008); during hot periods irrigation should be applied more lightly and frequently which helps to reduce canopy temperature (Ervin and Koski, 1998; Bañuelos et al., 2011) so that transpiration can be maintained. In addition to being able to keep healthy turf under more severe drought conditions, turf with deep, extensive root systems may reduce nitrate leaching risks due to greater N uptake (Bowman et al., 1998; Paré et al., 2006; Wu et al., 2007). Thus, irrigation schedules that promote rooting may also help to reduce N losses.

Effects of irrigation management on turfgrass growth rate

In contrast to most agricultural systems, for turfgrass, any reductions in shoot growth are perceived to be beneficial, as long as visual and functional quality are not significantly sacrificed (Wherley, 2011). As with turfgrass quality, turf irrigated with larger irrigation amounts showed higher dry matter production (DMP). It is important to highlight the positive correlation between turfgrass quality and daily DMP in irrigated turfgrass. Where both variables were recorded in the same study, we observed a positive correlation, with R^2 values for the logistic regression ranging between 0.60 and 0.97 (Qian and Engelke, 1999; Su et al., 2007; Bañuelos et al., 2011; Wherley, 2011; Candogan et al., 2014, 2015; Lee, 2014; Telenko et al., 2015). This non-linear relationship shows that although low or zero growth rates might compromise turf quality, maximum turf quality scores are achieved before DMP rates reach their maximum. Therefore, high visual turf quality can be achieved with reduced rates of turfgrass growth, providing the turfgrass is maintained in a healthy condition. The growth rates necessary to achieve high-quality scores will vary depending on other factors such as species, season and environment conditions.

The variation in DMP for low irrigation amounts depends on various factors such as site conditions, the turfgrass species/variety (Sinclair et al., 2011) and season (Candogan et al., 2014, 2015). Figure 4 shows the reported variation in DMP for studies where the irrigation amount was varied. By irrigating at 50% Epan or less, DMP decreased markedly [e.g. Candogan et al. (2014, 2015)]. However, the variation in DMP for different irrigation amounts also differed between studies. For example, Su et al. (2007) observed 45 to 48% less DMP when tall fescue, Kentucky bluegrass and hybrid bluegrass were irrigated at 60% compared to 100% ETa. Conversely, excessive irrigation may also lead to reduced DMP (Nektarios et al., 2014). Qian and Engelke (1999) also reported negative impacts of over irrigation (115 % vs. 55 % Epan) in buffalograss due to too poor tolerance of the species to high irrigations, while tall fescue, bermudagrass and St. Augustine grass (*Stenotaphrum secundatum*) produced more dry matter in their clippings under regimes with high irrigation amounts. Despite the positive relation between DMP and irrigation, turfgrass DMP is more closely dependent on levels of N fertilisation (Candogan et al., 2014, 2015). Figure 5 shows the positive correlation between both variables based on reported observations from four studies. As expected, an increase in DMP leads to a proportional increase in N uptake. Thus, any reduction in growth rate induced by adopting a moderate deficit irrigation strategy would not only lead to a reduction in water use, but also a reduction in N fertilisation need and mowing.

Effects of irrigation management on nitrogen fate

As expected, the evidence showed that an increase in irrigation amount resulted in higher drainage and hence an increase in total N losses in leachate. The data also showed a direct relationship between nutrient leaching and fertilisation rates which were evident when turf was over-irrigated. In three cases (Morton et al., 1988; Shuman, 2002; Barton et al., 2006b), no substantial changes in nutrient leaching were reported when fertiliser rates were increased but at a lower irrigation application amount (Figure 6). However, when irrigation increased and/or was applied beyond field capacity, a marked increase in nutrient leaching occurred. Scheduling irrigation to maximise N uptake and minimise N leaching also needs to consider irrigation frequency. Although deep infrequent irrigation might lead to more N leaching because larger volumes of water are applied in a single event, Espevig and Aamlid (2012) reported that higher drainage volumes occurred when the same irrigation amount was given as light-frequent irrigation. They related this to the fact that light-frequent irrigation kept the soil water content closer to field capacity thus allowing less buffering capacity for natural rainfall. The effect of irrigation frequency on total N and nitrate leaching was, however, much less than that of rootzone composition. Trenholm et al. (2012) reported that light-frequent irrigations led to a slight increase in nitrate leaching, but with variations between species (zoysiagrass and St. Augustinegrass). Shaddox et al. (2016) only found significant differences on N leached when comparing normal irrigation with over-irrigation. However, when turf was irrigated 26 mm per week applied in one or two irrigations, no significant differences between total NO_3^{-}N in leachate and irrigation treatment were reported. Shaddox et al. (2016) also reported an increase of NO_3^{-}N leching for stressed turfgrass (also related to low visual quality).

In addition to irrigation, other factors were found to affect the amount of N lost in leachate. Bowman et al. (1998) observed that the proportion of N lost could be decreased by increasing the interval between the last fertilisation and the following irrigation (75-100% reduction in N leached when irrigation was delayed by three to five days after fertilisation). This may be explained by an increasing residence time of N in the rootzone leading to greater absorption by the roots. Irrigating on sand-based golf greens may increase nitrate leaching risk. Sandy soils have lower water retention capacity, and usually lower organic matter content than more fine-textured soils (Nektarios et al., 2014). However, heavier soils with more organic matter and higher moisture retention will facilitate N denitrification, which may result in less leaching of NO_3^- (Nektarios et al., 2014). Sand-based rootzones with higher organic matter content may be attained by amending the sand with compost (Espevig and Aamlid, 2012), by having older turf with a deeper thatch-mat layer (Barton et al., 2009) or by maintaining a healthier, actively growing and denser canopy (Paré et al., 2006; Trenholm et al., 2012; Shaddox et al., 2016), which promotes higher N uptake (Wu et al., 2010; Telenko et al., 2015). These results are consistent with Kvalbein and Aamlid (2014) who suggested that the risk of N leaching from dense and healthy golf greens is usually quite low, but that it may increase dramatically if the turfgrass cover becomes incomplete due to diseases, winter damage, wear or management. High amounts of NO_3^- -N in leachate from young or recently established turf may be related to a thinner thatch/mat layer containing less organic matter (Barton et al., 2009; Telenko et al., 2015), and therefore less N is immobilised.

We observed that higher growth rates were closely related with increased N uptake (Paré et al., 2006; Paulino-Paulino et al., 2008; Barton et al., 2009; Wu et al., 2010) (Figure 5) resulting in lower nitrate leaching (Paré et al., 2006). Evidence suggested that N uptake was less related to irrigation than to the maximum potential growth rates for different turfgrass species and varieties (Paré et al., 2006; Ericsson et al., 2012). The maximum potential growth rate is the maximum possible plant growth under a favourable and healthy environment and non-limiting inputs. While applied N is not taken up by the plant, a portion that remains in the soil is susceptible to leaching, runoff, and gaseous losses through volatilization and denitrification. The gaseous N losses through denitrification are relatively higher when N fertilisation exceeds plant needs (Wang et al., 2014). The gaseous losses of nitrogen in turfgrass can also be affected by irrigation. Bowman et al. (1987) observed that irrigating after fertilisation reduces N losses by volatilization, whilst recognising that volatilization is also affected by soil pH. In contrast, an increase in soil water content, accompanied by high temperatures, might increase N gaseous losses by denitrification (Wang et al., 2014). Irrigation strategies where irrigation is applied frequently and back to field capacity might increase the risk of N losses due of denitrification.

Variations observed in N uptake for the same species, at the same fertilizer rate and in the same study (Figure 7) were related to other factors such as fertilizer source (Barton et al., 2006a; Wu et al., 2010), frequency of fertilizer application (Quiroga-Garza et al., 2001; Barton et al., 2009), turfgrass age (Barton et al., 2009), varieties within the same species (Paré et al., 2006) and year of treatment (Wu et al., 2010). Paulino-Paulino et al. (2008) reported that bermudagrass leached 8% to 60% less NO_3^--N compared to centipedegrass (*Eremochloa ophiuroides* Hack.) and Manilagrass (*Zoysia Matrella* L.) which coincided with higher N uptake and DMP in the former species. Most importantly, Wu et al. (2010) showed that the irrigation and N application rates ought to be reduced towards the end of the growing season because of the slowdown in turfgrass metabolism.

Methodological limitations

This systematic review had a number of methodological limitations which need to be recognised. Some papers identified in the literature were not available; it was also difficult to source some conference papers. Although data were extracted from studies in which turf development was directly or indirectly influenced by irrigation, there were confounding factors, for example, the region and climate of the area where the research was conducted, trials using different turfgrass species, varieties, fertiliser rates and/or different methods for ET estimation. Although ET indicators can be directly related to irrigation need and are widely used in irrigation scheduling, their application is more suited to semi-arid environments rather than humid climates where irrigation is supplemental to rainfall. Some researchers have therefore developed drought stress indicators that combine both ET and rainfall to overcome this challenge (Haro-Monteagudo et al., 2017). Not all studies followed the same experimental design or methodology, and for turfgrass quality assessment the duration of each experiment, turf maintenance, the use of rainout shelter and any bias in turfgrass quality scoring may all have influenced our synthesis of results. Some errors may also have been introduced into the meta-database during data extraction from published data (graphs), but this is likely to be <±10%. Finally, there were also a range of so-called “effect modifiers”, which present opportunities to convey a deeper understanding of the topic across a wide variety of environments but also had influence in the final analysis of the results. Those include different scheduling methods, irrigation strategies, turfgrass species, mowing height, fertilisation rates, wear stresses,, weather/local conditions and treatment durations. Finally, although the use of wastewater is a growing trend in turfgrass irrigation, this topic was excluded to limit the impact of effect modifiers, one of which is water source. Understanding wastewater issues in the context of agronomic and environmental impacts in turf is worthy of a systematic review in its own right.

CONCLUSIONS

This systematic review summarises evidence on the effects of irrigation management on turf performance and complements research by Barton and Colmer (2006) by synthesising recent evidence on the impacts of irrigation on turfgrass quality, rooting and its relationships with turf growth and N fate. In general, during the growing season, average visual turf quality can be maintained at an acceptable level through deficit irrigation (up to 40 % ETa), while turfgrass quality can be achieved with irrigation above 60 to 80 % ETa. However, we found that it is difficult to define irrigation need precisely, as the impacts of irrigation on turfgrass quality also depend on other factors such as turfgrass species, location and year of study. Results from several studies showed that adverse effects of deficit irrigation on turfgrass quality are more evident when turf is subject to environmental and/or management stresses such as long intervals between irrigation, short mowing heights or high temperatures. Moderate deficit irrigation strategies can be applied during the year without significantly compromising on turfgrass quality. However, during high stress periods such as hot summer days or intense traffic, irrigation strategies should reflect the target use (sports, amenity, landscape) and accept there may be periods with reduced visual turfgrass quality. Deeper rooting was shown to be related to improved turfgrass quality particularly during drought events and faster recovery after drought stress. In contrast to most agricultural crops, high growth rates are not desirable in turfgrass as they lead to more frequent mowing and greater N and water consumption. Evidence showed that well-watered and fertilised turfgrass results in good turfgrass quality. However, the relationship is not linear. Although greater irrigation amounts lead to increases in dry matter production, N fertilisation appeared to be a more important driver of turfgrass growth than irrigation. Thus, adequate irrigation scheduling becomes crucial as N leaching risks may also be minimised by avoiding irrigation applications beyond field capacity and by avoiding fertiliser applications when growth rates are reduced due to the impact of plant stress, or the recent establishment of turfgrass. By maintaining a healthy, actively growing turf cover, the nutrient leaching risk will be minimised. This systematic review not only provides a valuable synthesis for turfgrass agronomy researchers, but also useful insights for practitioners involved in turfgrass management, including greenkeepers and sports facility groundsmen.

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