The (New) Fundamentals of Turfgrass Nutrition

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This is the handout for my presentation on this topic at the 2016 Northern Green Expo. I'm the Chief Scientist at the Asian Turfgrass Center, `www.asianturfgrass.com`, and an Adjunct Assistant Professor in the Department of Plant Sciences at the University of Tennessee. Contact me at micah@asianturfgrass.com or find me on Twitter at @asianturfgrass. I've posted the slides for this presentation at `https://speakerdeck.com/micahwoods`.

Most seminars, presentations, articles, and even semester-long courses about turfgrass nutrition discuss the functions of different elements. Potassium is involved in stomatal regulation, phosphorus is essential for root development, calcium for cell wall strength, and so on. All true, but largely irrelevant for the turfgrass manager. What the turfgrass manager must know is not the function of each element, but the quantities – is enough of this element present to meet the grass requirements, or is it not? If it isn't present in adequate quantities, how much must be added to ensure the grass has enough? In this seminar, the fundamentals of turfgrass nutrition will be explained, with a focus on an understanding of the amount of each nutrient that is required.

A quick preview

I'M GIVING FIVE PRESENTATIONS at this conference. I'll talk about grass growth and the major factors that influence that growth – leaf nitrogen content, temperature, plant water status, and photosynthetically active radiation (PAR). Each of those factors can limit or stop growth. With no nitrogen in the leaf, or freezing temperatures, or no plant available water in the soil, or complete shade, grass can't grow at all. By putting numbers to these factors, one can make an estimate of how much each of these factors is influencing growth.

In a way, this is a theory of everything, based on the environmental productivity index (EPI) of Nobel.[1]

[1] P.S. Nobel. Productivity of *Agave deserti*: measurement by dry weight and monthly prediction using physiological responses to environmental parameters. *Oecologia*, 64:1–7, 1984. DOI: 10.1007/BF00377535. URL `http://dx.doi.org/10.1007/BF00377535`

There is no magic here, no way to get the desired turf conditions just from calculating a bunch of numbers on a spreadsheet.

But this approach can serve as a foundation, or a way of understanding the general principles, and I would argue the most important ones, of turf growth. Upon that foundation, one can then evaluate the current grass conditions, compare them to how one wants the grass to be, and apply the necessary management practices.

Turfgrass nutrition fits prominently into this foundation, for the simple reason that grass grows. As grass grows, it uses nutrients. When the grass is mown, some portion of the leaves are removed from the plant, and those leaves contained nutrients. One wants to be sure that the grass is always supplied with enough of each essential element – deficiencies need to be avoided.

With application of these new fundamentals, one can simplify turf nutrition and focus on things that are more important or that require more time and effort.

The fundamentals

FIRST, a disclaimer. I'm not going to talk about a lot of these details, but everyone should know these things, or better yet, have a good reference guide handy.

If you want a complete guide to the topic of turf nutrition, I recommend *Turfgrass fertilization: a basic guide for professional turfgrass managers*[2] by Pete Landschoot at Penn State. This guide has all the details about different sources of elements, what the elements do in the plant – boron (B), for example, "plays a role in DNA synthesis and translocation of sugars" – and all kinds of things that I *won't* be discussing. Two excellent reference guides are *Fertilizing lawns*[3] by Rosen, Horgan, and Mugaas, and *Soil test interpretations and fertilizer management for lawns, turf, gardens and landscape plants*[4] by Rosen, Bierman, and Eliason. For a full book on this topic, I recommend Carrow et al.[5]

[2] This guide is available at http://plantscience.psu.edu/research/centers/turf/extension/factsheets/turfgrass-fertilization-professional

[3] http://www.extension.umn.edu/garden/turfgrass/fertilizers/fertilizing-lawns/index.html

[4] http://bit.ly/umn_soil_test

[5] R.N. Carrow, D.V. Waddington, and P.E. Rieke. *Turfgrass soil fertility and chemical problems*. John Wiley and Sons, 2001

I won't be discussing them, not because they are not important, but because I think many of those details are best used as reference material, to be studied as needed. What is really important is knowing a few things about the soil, largely related to the quantities of macronutrients, with little regard for the function of the various elements.

The new fundamentals

THIS IS WHAT I think is really important. If the grass is growing, it is using nutrients. If it is not growing, it uses nothing. I want to make sure that when the grass is growing, there will be an adequate supply of all essential elements. I don't want to mess around with deficiencies. Also, I don't want to think about this too much. I would like to manage turf just by adjusting the growth rate as necessary – basically by adjusting nitrogen (N) supply up or down – and to be confident that all the other elements are available in adequate amounts.

Here's a list of important things, not in order of importance, but in order of how I think about them.

1. A normal soil will have pH in the range from 5.5 to 8.3. If the pH is lower than 5.5 or higher than 8.3, I would find out why and would consider making some adjustments.

2. I want to know the soil organic matter content. That is an indication of how much water the soil will hold and of how much N will

be mineralized.

3. I would pay close attention to how much N fertilizer has been supplied. This is the primary way I'll adjust the growth rate. More N if I determine the grass needs to grow faster, and less N if I determine the grass should grow slower.

4. Make sure phosphorus (P) is above 21 ppm.[6]

5. Make sure potassium (K) is above 37 ppm.[7]

6. Basically that's all.

7. There has to be more to it, you might think. Well, not necessarily. Calcium (Ca) and magnesium (Mg) are pretty much taken care of by ensuring the pH is in the range given above. There are MLSN guidelines for Ca (331 ppm) and Mg (47 ppm), and both of those are based on a Mehlich 3 extraction. But if your Ca or Mg are lower than the MLSN level, I wouldn't worry too much. One is just growing grass in a soil with an exceedingly low nutrient holding capacity. I would just supply the Ca and Mg on a regular basis as fertilizer, in the amount the grass can use. More about that later. Same goes for sulfur (S). And micronutrients? Soil tests aren't a great way to assess micronutrients. Tissue testing is not a great way either. Probably micronutrients won't be a problem. But if you are worried about this, just to be sure, make a couple applications of a complete microntrient fertilizer. That was cheap. Or maybe just add a little iron and manganese.

[6] This is based on the minimum levels for sustainable nutrition (MLSN) guidelines, which use the Mehlich 3 extractant. We have not done this analysis for Bray-1 P. I see that in Minnesota no P is recommended for established turf when Bray-1 P is above 25 ppm. Version 1 of the MLSN guidelines had a level of 25 ppm for Bray-2 P and 6 ppm for Olsen P. Based on conversion equations developed by Ketterings et al. for New York soils (`http://nmsp.cals.cornell.edu/publications/soilconversion.html`), a Mehlich 3 P of 21 ppm would be equivalent to about 15 ppm Bray-1 P.

[7] This is also based on MLSN and the Mehlich 3 extraction; a value of 37 ppm would be slightly lower if measured by ammonium acetate extraction. The conversion equation of Ketterings et al. gives a value of 31 ppm equivalent if 37 ppm by Mehlich 3 were converted to ammonium acetate.

For a look at how nutrients are distributed in a range of soils that are producing good turf around the world, see these reports, which also explain the analyses that have been done to identify the MLSN guidelines:

- Global Soil Survey year 1 report: `https://www.paceturf.org/PTRI/Documents/2014_gss_report.pdf`
- Global Soil Survey year 2 report: `https://www.paceturf.org/PTRI/Documents/2015_gss_report.pdf`

How to find the amount required as fertilizer?

THIS INVOLVES the estimation or the measurement of three quantities.

The amount the grass will use. We want to be sure that the grass is supplied with as much of each element as it will use. I denote this amount as a.

The amount we need to keep as reserve in the soil. We can't just supply exactly the amount the grass will use, because the grass grows in soil, and if the soil went to a zero level, and we missed a fertilizer application, the grass wouldn't have enough. The MLSN guideline serves as a minimum level in the soil, an amount that one doesn't want to drop below, but based on analysis of thousands of samples, a level that I'm confident provides enough of the element to produce excellent turf. I denote this amount as b.

The amount that is actually present in the soil. This is measured by a soil test.

One can express the quantity of an element required as fertilizer as Q. This equation can be used to calculate Q.

$$a + b - c = Q$$

where,
a is the quantity of the element used by the grass
b is the quantity of the element required in the soil
c is the quantity of the element present in the soil
Q is the quantity of the element required as fertilizer

One can intuit this because the amount needed, minus the amount we have, must be the amount required as fertilizer. Conversely, if the amount we have is more than we need, then none of that element is required as fertilizer.

$$\overbrace{a + b}^{\text{amount needed}} - \overbrace{c}^{\text{amount present}} = \overbrace{Q}^{\text{fertilizer requirement}}$$

a we don't know and will have to estimate it. I do this based on the quantity of N supplied, because that is controlling growth.[8] b is the MLSN guideline.[9] c is the soil test result. After doing a soil test, one will know b and c, and the only quantity to calculate is a.

The next presentation, *Nutrient use by the grass and nutrient supply by the soil*, will demonstrate these calculations.

[8] As the grass grows, it uses N and other elements. By estimating the amount of N used, we can get an estimate of the use of all the other elements too.

[9] See the current guidelines at `https://www.paceturf.org/PTRI/Documents/1202_ref.pdf`

Nutrient Use by the Grass and Nutrient Supply by the Soil

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Grass grows in soil, and nutrients used by the grass come either from the soil or from fertilizer. When the soil contains enough of an element to meet all of the grass requirements, none of that element is required as fertilizer. When the grass can use more of an element than can be supplied by the soil, that element must be applied as fertilizer. This seminar will explain how to estimate the maximum amount of an element the grass can use, how to identify the quantity that can be supplied by the soil, and how to use those two amounts to get an estimate of the amount that may be required as fertilizer.

The three numbers we need

THE AMOUNT OF an element to apply as fertilizer depends on how much of the element is present in the soil. As an example, if there is enough phosphorus (P) in the soil to meet all the grass requirements, then P should not be applied. In fact, adding P can encourage *Poa annua* encroachment in creeping bentgrass.[1] At the same time, one wants to make sure the grass is supplied with all of each element that it requires. Nutrient deficiencies are not something one wants to see, or to worry about.

[1] R.B. Raley, P.J. Landschoot, and Brosnan J.T. Influence of phosphorus and nitrogen on annual bluegrass encroachment in a creeping bentgrass putting green. *International Turfgrass Society Research Journal*, 12:649–655, 2013

To ensure that nutrients are supplied at an amount that takes advantage of nutrients in the soil, while accounting for the amount that the grass will use, one can find the quantity needed, subtract from that the amount present, and the difference between the amount needed and the amount present is the fertilizer requirement for that element. Expressed in the form of an equation, this is:

$$a + b - c = Q$$

where,
a is the quantity of the element used by the grass
b is the quantity of the element required in the soil
c is the quantity of the element present in the soil
Q is the quantity of the element required as fertilizer

A note about units of measure

The amount of an element used by the grass, a, we will calculate. b is the MLSN level[2] for that element, and c is the amount measured by

[2] Micah Woods, Larry Stowell, and Wendy Gelernter. Just what the grass requires: using minimum levels for sustainable nutrition. *Golf Course Management*, pages 132–138, January 2014. URL `http://bit.ly/gcm_mlsn`

the soil test. If we are going to add and subtract these values to find Q, then these values will need to be expressed in the same units of measure.

The MLSN guidelines use units of parts per million (ppm). The units of ppm in this case are shorthand for milligrams of an element per kilogram of soil. Soil test results are generally reported in ppm. When applying fertilizers, one would tend to think in units of mass per unit area, something like pounds of element per 1000 square feet.[3] After a fertilizer is spread on the surface, it can be expected to change the quantity of that element in the soil, which can be expressed as a change in ppm. Likewise, when the grass roots take up an element, and then the grass is mown and the clippings removed, the soil concentration of the element will go down – usually expressed in ppm – and one can think of what mass of that element has been harvested, in lbs/1000 ft^2.

Really, the units are interchangeable, which one can do by assigning a rootzone depth and then accounting for the bulk density of the soil. I like to use a rootzone depth of 4 inches and a soil bulk density of 1.5 g/cm^3. This gives a conversion factor of 33.5 ppm change[4] for every change of 1 lb/1000 ft^2. That is, for every 1 lb/1000 ft^2 applied to the surface, one can expect an increase of 33.5 ppm in the top 4 inches of soil. And for a harvest of 1 lb/1000 ft^2, one can expect a decrease of 33.5 ppm in the top 4 inches of soil.[5]

We could convert all the units to ppm, expressing a and b and c all as ppm, but then we would end up with a quantity of fertilizer to apply in units of ppm, and would then have to convert back to mass per area. So I generally, when making calculations, will convert the b and c values to mass per area.

[3] Or my preference, grams per square meter. For the presentations here, I'll use primarily United States customary units. To convert between the two, 1 lb/1000 ft^2 is equivalent to 5 g/m^2.

[4] Or 6.7 ppm change for every increment of 1 g/m^2.

[5] Of course it is not this exact. We don't deal with a rootzone of exactly 4 inches depth. Soil bulk density is not exactly what we estimate it to be. You can adjust for your site to get a different conversion factor if you like. These values are not exact, but with repeated soil testing, and comparison with applied nutrients, one can correct any errors in the assumptions described here.

An example calculation for potassium

Let's say the grass at a particular site uses 2 lbs K/1000 ft^2/year. The MLSN guideline for K is 37 ppm. We want to make sure there is at least that much K in the soil after the grass has used its 2 lbs. And let's say the soil test K is 50 ppm.

1. We have a, the estimate of grass use. We have b, the amount needed as reserve in the soil. We have c, the amount present as measured by the soil test. But the units must all be the same. To convert 37 ppm to units of lbs/1000 ft^2, divide by 33.5 as explained above. Then, $b = \frac{37}{33.5} = 1.1$. The same conversion is applied to the soil test amount of 50 ppm, giving $c = \frac{50}{33.5} = 1.5$.

2. Now that the required quantities are in the same units, we can use the $a + b - c = Q$ equation to calculate the amount of K required.

This is $2 + 1.1 - 1.5 = 1.6$.

3. In this example, the minimum amount of K to apply, when the grass uses 2 lbs K/1000 ft^2/year, the MLSN guideline for K is 37 ppm, and the soil test K is 50 ppm, comes to 1.6 lbs K/1000 ft^2/year.[6]

Nutrient supply by the soil

I would think of the MLSN level as a minimum that one doesn't want to drop below. It is not that good turf can't be produced in soils with some elements below the MLSN level – more than 17% of the soils in the Global Soil Survey[7] are at or below the MLSN guideline for K, 22% are below the guideline for Mg, and 19% are below the guideline for Ca. The MLSN minimum level has a margin of safety built in. I wouldn't be too worried if the soil was close to the MLSN level, but at the same time, I want to be sure the soil can supply enough of each nutrient. If the soil can't supply it, then I want to be sure I apply enough of that element as fertilizer.

The $a + b - c = Q$ approach makes that calculation explicitly. To break down one part of that equation to look at the nutrients that can be supplied by the soil, we can look at the difference between b and c. If c is the amount measured by the soil test, and b is the amount that we want to make sure stays in the soil as a reserve, untouched by the grass, then the amount that can be supplied by the soil is $c - b$.

An example calculation, soil supply of calcium, compared to grass use

1. Let's say we have bentgrass in Minneapolis and a soil with a normal amount of Ca. The median soil through the first two years of the Global Soil Survey has a Mehlich 3 Ca of 623 ppm. Using the same conversion as previously, this amount of Ca expressed in mass per area terms is $\frac{623}{33.5} = 18.6$. Thus, 623 ppm Ca is equivalent to 18.6 lbs Ca/1000 ft^2.

2. The amount of Ca that one wants in the soil as a reserve is the MLSN guideline level, 331 ppm. This, expressed in mass per area (2-dimensional) terms is $\frac{331}{33.5} = 9.9$. That's 9.9 lbs Ca/1000 ft^2.

3. The amount the soil can supply before reaching the MLSN level that one wants to keep untouched is $18.6 - 9.9 = 8.7$. We can think of that as 8.7 lbs Ca/1000 ft^2 present in the soil for use by the grass. How much does the grass use anyway?

4. Let's say we have bentgrass in Minneapolis. Let's say I used 2.9 lbs N/1000 ft^2 in 2015.[8] Grass uptake of N is not 100% efficient, so

[6] I've been asked when this calculated amount should be applied. If possible, I would divide the amount required into multiple applications and apply it through the year. It comes down to equipment and resources available to apply the nutrients, and to the product choice. When the grass is growing, it is using a small amount of potassium every day. In an ideal situation, one could supply the grass with a small dose of potassium every day. Daily application is not feasible, although fertigation in desert climates comes pretty close.

[7] See details in the year 2 report: `https://www.paceturf.org/PTRI/Documents/2015_gss_report.pdf`

[8] Where did I get 2.9 lbs? I estimated it from the temperature-based growth potential (GP) model of PACE Turf, using 2015 daily temperature data from Minneapolis St. Paul International Airport and assuming maximum N use of 0.6 lbs N/1000 ft^2/month when GP is 1. More about this method at `http://www.files.asianturfgrass.com/201306_growth_potential.pdf`

I use the amount of N applied as an upper bound on the expected N harvest by the grass. In soils with extensive organic matter, the soil can supply a lot of N, so one should adjust the estimate accordingly. Bentgrass usually has 4% N in the leaves and 0.5% Ca. So the Ca use is 1/8 the N use. Thus, with 2.9 lbs N, I expect 0.36 lbs Ca to be used.

5. The amount in the soil in excess of the MLSN guideline is 8.7 lbs Ca/1000 ft^2. The estimated use by the grass in one year is 0.36 lbs Ca/1000 ft^2. Those 8.7 pounds are approximately $\frac{8.7}{0.36} = 24$ years' worth of Ca.

Estimating grass use

THIS MIGHT BE the trickiest part of this. I'm not sure that turf managers think about the quantity of nutrients harvested by the grass as much as they think about the quantity of nutrients supplied as fertilizer. To make the estimate, I use a couple of techniques.

Nutrient levels in the leaves fluctuate a bit up and down through the year, but on average I expect the nutrient levels to be as shown in Table 1.

Element	%
Nitrogen	4
Potassium	2
Phosphorus	0.5
Calcium	0.5
Magnesium	0.2
Sulfur	0.2
Iron	0.01
Manganese	0.005

Table 1: Normal levels of mineral elements in the dry matter of cool-season turfgrass leaves

As grass grows, and leaves are cut off through mowing, mineral nutrients are removed from the plant. If the clippings are harvested, the effect is the same as if the soil had been mined of those elements. But the concentration of elements in leaves is not a mystery. The elemental content remains relatively constant, with the normal concentrations shown in Table 1. These values are consistent with the ratios of the elements in hundreds of leaf samples I've studied in my research, and with research on different species of cool-season grass[9].

[9] David Lawson. Leaf nutrient analysis. *International Turfgrass Bulletin*, (205): 26–29, July 1999

If you happen to measure the tissue nutrient content at your site[10] or think your turf has different nutrient levels then you can substitute in different values for the elements as necessary.

[10] I *don't recommend* tissue testing because I don't think the data from tissue testing can be used as a decision making tool in routine turf maintenance. I think tissue testing is great for research but less so for turf maintenance.

Over the course of a year, nutrient ratios in the leaf will be similar to what is listed in Table 1. You'll notice that K (2%) is $\frac{2}{4} = 0.5$ of N. P is $\frac{0.5}{4} = 0.125$ of N. Mg is $\frac{0.2}{4} = 0.05$ of N. If we just know how much N the grass uses, we can make an estimate of the harvest of all the other elements.

The amount of nitrogen supplied to the grass controls growth and uptake of the other nutrients

Turfgrass managers know that adding more nitrogen will cause grass to grow more quickly. This necessarily results in more uptake of the other nutrients. In an intensive investigation[11] of nitrogen, growth,

[11] W.R. Kussow, D.J. Soldat, W.C. Kreuser, and S.M. Houlihan. Evidence, regulation, and consequences of nitrogen-driven nutrient demand by turfgrass. *International Scholarly Research Network*, 2012:1–9, 2012. DOI: 10.5402/2012/359284. URL `http://www.hindawi.com/isrn/agronomy/2012/359284/`

and nutrient demand, Kussow et al. found:

> N supply was the primary determinant of turfgrass growth rate, plant nutrient demand, and nutrient uptake. Nitrogen uptake accounted for over 88% of uptake of all other nutrients. Uptake of P and K were strongly related to tissue N content irrespective of soil test levels.

One way to estimate N use is to consider it to be the amount of N applied. That is probably a slight overestimate in soils with low organic matter, because N use is not 100% efficient. Not all the N applied gets used by the grass. But a slight overestimate of N use in this case is useful, because it means we have built in a slight overestimation of plant use, which is another buffer against underestimating the fertilizer requirement of the other elements. In soils with high organic matter, there will be mineralization of nitrogen from organic matter. In those soils, one can expect the annual N use to be more than the quantity of N applied as fertilizer.

To get another estimate of N use, one can look at temperature.

A temperature-based growth potential can predict how much nitrogen the grass will use

THE GROWTH POTENTIAL (Equations 1 and 2) was developed by PACE Turf [12] to describe the relationship between turfgrass growth and temperature. Cool season (C_3) grasses have their greatest growth rate when the temperature is about 68°F, with slower growth at lower or higher temperatures; warm-season grasses (C_4) have their greatest growth rate when the temperature is about 88°F, with slower growth at cooler temperatures. The growth potential equations[13] provide a simple way to predict that growth.

[12] W. Gelernter and L. Stowell. Improved overseeding programs 1. The role of weather. *Golf Course Management*, pages 108–113, March 2005

[13] The equations below give optimum temperature and variance values suitable for measures in Fahrenheit. For temperatures in Celsius degrees, see `www.files.asianturfgrass.com/201306_growth_potential.pdf`

$$GP = e^{-0.5(\frac{t-t_o}{var})^2} \tag{1}$$

GP = growth potential, on a scale of 0 to 1

e = 2.71828, a mathematical constant

t = actual temperature in F, the average, not the high or the low

t_o = optimum temperature in F, 67.5 for C_3 grass, 87.5 for C_4 grass

var = adjusts the change in GP as temperature moves away from t_o; 10 for C_3 and 12 for C_4

This equation gives the same result.

$$GP = \frac{1}{e^{0.5(\frac{t-t_o}{var})^2}} \tag{2}$$

We can make use of the growth potential by relating the nitrogen requirement of the grass to the growth potential. Empirical observations of turfgrass growth rates and nitrogen amounts to create the desired playing conditions for turfgrass in 2016 allow us to estimate a *maximum* monthly nitrogen use rate[14]. My estimates are about 0.4 lbs N/1000 ft^2/month^2 for fine fescue, 0.6 lbs N for creeping bentgrass and tall fescue, and 0.8 lbs N (or more) for *Poa annua*, kentucky bluegrass, and perennial ryegrass. We can then calculate the estimated nitrogen use for a given amount of time by multiplying the growth potential times the maximum nitrogen use rate.

[14] This estimate is general and only serves as a starting point. Every site will have a slightly different maximum level, based on the grass species and the desired growth rate of the grass. We can make the grass grow faster with more nitrogen, and slower with less nitrogen, and these values are based on standard conditions.

The growth potential can be calculated on a daily, weekly, or monthly basis, with a corresponding nitrogen amount, to estimate how much nitrogen fertilizer may be used by the grass during that time period.

Does this really work?

There are a lot of estimates talked about here. Estimates of plant use, estimates of growth rate, estimates of the concentration of element in leaf tissue, estimates of how much N a particular species may use when managed the way turf is managed in 2016, at a given temperature.

I think these estimates are useful, and I think they do work, but here are a few reminders.

1. One can set up a spreadsheet and make all these calculations and get predictions for required nutrient inputs based on the estimates. This is a great way to get mediocre turf conditions. It is no substitue for looking at the grass and making adjustments based on how the grass is responding.

2. For N specifically, I think turf managers have traditionally applied N based on visual assessment of grass color, based on assessment of growth rate, and based on past experience. I don't say that GP is a substitute for those, but I do think it is a useful number to look at in addition to the traditional assessments.

3. For N rate also, this should be self-correcting, because one applies a known amount of N, evaluates the turf response, and then adjusts N, and then evaluates again.

4. Because soil testing is repeated – I recommend soil testing for professionally-managed turfgrass sites be conducted once a year – the actual changes in soil nutrient levels can be compared to the predicted changes based on the estimate of a and the known Q and the calculation of $a + b - c = Q$. Discrepancies can be corrected and the model can be further fine-tuned for a particular site.

For an alternative description of nutrient use[15] and recommendations for nutrient inputs, see *Precision fertilisation – from theory to practice*.[16] I think that is a good approach, but I prefer what I have just described because the $a + b - c = Q$ method makes use of nutrients in the soil.

[15] But strikingly similar in many ways!

[16] T. Ericsson, K. Blombäck, and A. Kvalbein. *Precision fertilisation – from theory to practice*. STERF, 2013. URL `http://sterf.golf.se/Media/Get/1228/precision-fertilisation-from-theory-to-practice.pdf`

Calculating the Fertilizer Requirement for Any Turfgrass, Anywhere

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This presentation builds on the fundamentals of the turfgrass nutrition talk, and the nutrient use and nutrient supply talk, by explaining a system by which a turfgrass manager can calculate the amount of any element required by any turfgrass, under any growing condition, anywhere in the world. Some common misapprehensions about turfgrass nutrition and soil testing will also be discussed. The minimum levels for sustainable nutrition (MLSN) guidelines for interpreting soil test results, and the temperature-based turfgrass growth potential (GP), which were introduced in the two previous seminars, will be discussed in even more detail.

An example, 2015 in Minneapolis

Here's how I would apply the MLSN guidelines and GP. I'm trying to calculate the quantity of K, P, Ca, Mg, and S to apply. I'm going to use Equation 1.

$$a + b - c = Q \tag{1}$$

For each element, I want to find Q, the amount to apply as fertilizer while still keeping the amount b as a reserve in the soil that the grass won't touch. That amount b is the MLSN guideline level, and it serves as a buffer against the element getting *too* low. c represents the quantity measured by the soil test, and quantity a is going to be my estimate of plant use. How much of the element does the grass use? That's a.

I'll go through this step-by-step, showing how I make these calculations and pointing out some of the assumptions I make.

The scenario

I'm going to use 2015 weather data from the station at Minneapolis St. Paul International Airport.[1] I'll imagine this is a hypothetical course near that location, with creeping bentgrass greens, doing 30,000 rounds of golf per year. I want to calculate how much K, P, Ca, Mg, and S to apply to the greens. I'm going to use Equation 1 to get this. First I need to find a, my estimate of how much of each element the grass will use.

[1] Data are from http://www.ncdc.noaa.gov/cdo-web/

Estimating plant use, a

If I already knew how much N I was going to apply, this would be straightforward. I'd take that amount and from it calculate K as 1/2 the N, P as 1/8 the N, and so on. But I've never grown grass in Minneapolis, and certainly don't have last year's application amounts, and my assessment of the turf results, to help me decide. So I'll show here how the GP can be used to get an estimate.

I'll start with 2015 temperature data for Minneapolis. Figure 1 shows the temperature each day in 2015. The average daily temperature is highlighted in maroon, because that is the number used to calculate the GP.

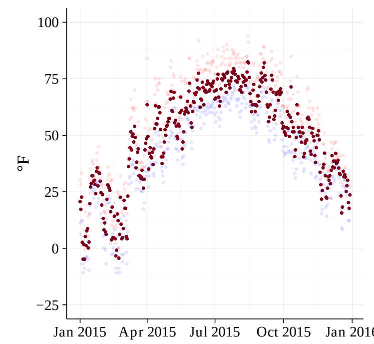

Figure 1: Daily high, low, and average temperature at Minneapolis St. Paul International Airport in 2015.

I find it useful to express the temperature as a value between 0 and 1, with values closer to 0 being far from the optimum temperatures for growth, and values closer to 1 approaching the optimum temperatures for growth. This is the temperature-based growth potential (GP) of PACE Turf.[2] In Figure 2, the daily GP for 2015 ranges from 0 to 1, giving an approximation of the growing season.

[2] W. Gelernter and L. Stowell. Improved overseeding programs 1. The role of weather. *Golf Course Management*, pages 108–113, March 2005

With the temperature data now converted to GP, all the temperatures are expressed as a number with a minimum of 0 and a maximum of 1. When it is too cold, grass won't grow, can't grow, and won't be using any nutrients. That's what Figure 2 shows. Then as temperatures warm in the spring the GP goes up, eventually getting close to 1 on days when the average temperature is close to the optimum temperature for cool-season grass growth. When the GP is high, it doesn't mean the grass *will* grow rapidly, but it means the temperature *is not restricting* growth.

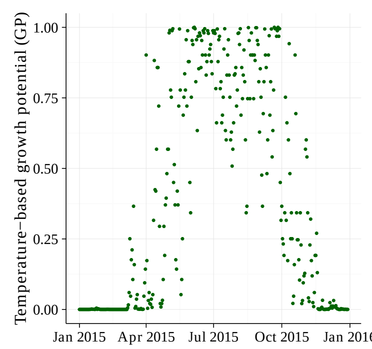

Figure 2: The temperature-based growth potential for cool-season grass calculated from the temperature data in Figure 1.

That is, if photosynthetically active radiation (PAR) is good, and if the plant water status is good, and if the plant is supplied with N, and then the temperature is also close to an optimum for growth, I would expect there to be good growth. I make an assumption here, which I think averages out pretty well over the course of a year. That assumption is, I want the grass to always have an optimum amount of nutrients in the leaves,[3] and I am trying to plan my nutrient applications so that the grass is always supplied with enough of each nutrient. Another assumption I make is that for this hypothetical course in Minneapolis with creeping bentgrass greens, doing 30,000 rounds per year, is that the maximum amount of N I ever expect it to use is 0.6 lbs N/1000 ft^2/month. What that means to me is that the growth rate that I am trying to achieve is a growth rate at which the grass is, at the time of fastest growth, using 0.6 lbs N/1000 ft^2/month.

[3] See Table 1 in the *Nutrient use and supply* handout for full details. I expect 4% N and 2% K and 0.5% P.

If we combine these two assumptions, we get something interesting. The first assumption is that the grass will have 4% N. The second is that during the time of fastest growth, the grass will harvest 0.6 lbs N/1000 ft²/month. From this we can estimate the dry weight clipping production during that month as $\frac{0.6}{0.04} = 15$. That's an expectation that we would get 15 lbs of dry clippings per 1000 ft² in a month when the grass is growing at its fastest rate.

Now I will link together the GP and this estimate of maximum N use. When the GP is 1, then I expect that to be a time of the year when the grass has potential to grow at its most rapid rate, and if it is so doing then it may use N at about the amount I predict for my desired growth rate – 0.6 lbs N/1000 ft²/month. Expressed on a daily basis, taking an average day, the maximum N use per day would be 0.02 lbs N/1000 ft²/day. And I know that when GP is 0, the grass won't be growing, and the N use will be 0. Because the GP is expressed on a scale of 0 to 1, I multiply the daily GP by the expected maximum N use per day to get a temperature-adjusted expected N use. That is shown in Figure 3.

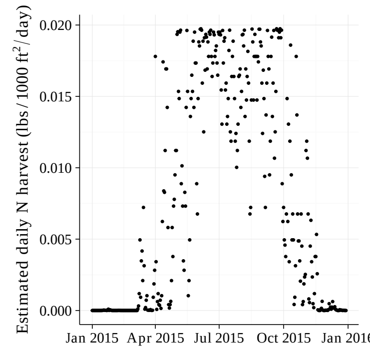

Figure 3: Estimated daily N use adjusted by temperature-based GP.

I can add up those daily amounts to get weekly or monthly or annual totals. Figure 4 shows the expected use of N through the year, coming to a total of 2.9 lbs N/1000 ft².

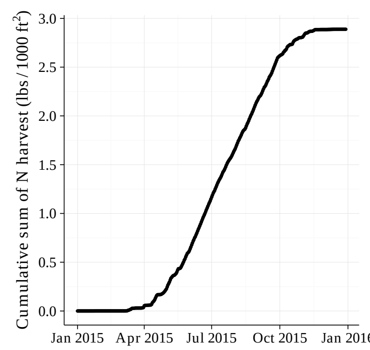

Figure 4: Cumulative sum of expected N use based on the daily values shown in Figure 3.

Because the ratios of N to the other elements can be predicted, based on the normal amounts of those elements in the leaves, then once I have an estimate of clipping yield, or of N harvest, I can also make an estimate of how much of the other elements will be used by the grass. Figure 5 shows the cumulative sum of expected use of N, K, P, Ca, Mg, and S.

Adjustments and micronutrients

Now we've got estimates of plant use. I'd like to point out three things related to these estimates of *a* shown in Figure 5.

1. I've made these estimates of *a* for these elements with the assumptions of maximum N rate that I like, and with assumptions of nutrient ratios in the leaves that I expect. Remember, *this is customizable*. If you have a different grass type, you'll very likely use a different maximum N. If you want the grass to grow faster, use a different maximum N. Want it to grow slower, reduce maximum N. If you think or know that tissue content and tissue ratios are different at your site than what I've shown, then change the model to fit your location.

2. These are only estimates. N controls the growth, so by checking the growth rate, and the color of the turf, and using your knowledge of how the grass is likely to respond to a known amount of N, you can optimize this type of model for your location.

3. The grass use of micronutrients is so small that it wouldn't even

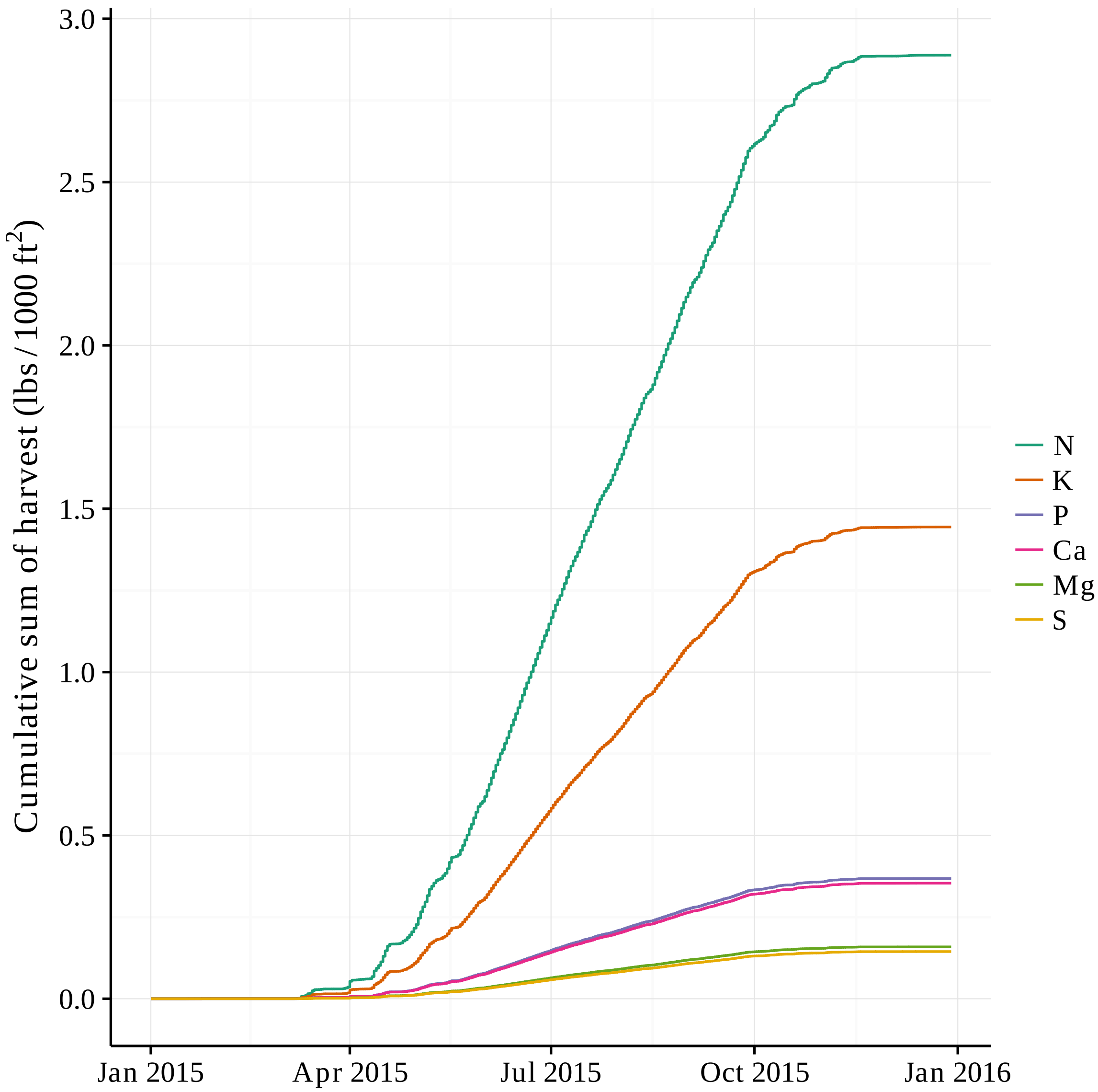

Figure 5: Cumulative sum of expected element use based on the daily values shown in Figure 3 and the ratios between N and the other elements.

show on a chart like this. That's why I don't really worry about micronutrients. Apply them judiciously if it makes you feel better. Don't worry much about soil tests or tissue tests for micronutrients.

The amount needed in the soil, b

Continuing to assemble all the numbers needed to calculate the fertilizer requirement, we move on to *b*, the amount we want to be sure is in the soil, untouched by the grass. In this way it serves as a buffer against getting too low, or as a reserve amount. The amount *b* is the MLSN guideline level. Or, if you want to have a different amount in the soil, adjust it.

The MLSN guidelines are at `https://www.paceturf.org/PTRI/Documents/1202_ref.pdf`. They are in units of parts per million (ppm). To convert from ppm to lbs/1000 ft^2, divide the MLSN value in ppm by 33.5. This is based on a 4 inch rootzone depth and a bulk density[4] of 1.5 g/cm^3.

As an example, to express the MLSN guideline for Ca, which is 331 ppm, in units of lbs Ca/1000 ft^2, divide 331 by 33.5. Thus, the MLSN guideline for Ca can also be expressed as $\frac{331}{33.5} = 9.9$ lbs Ca/1000 ft^2.

That's how to get *b*.

[4] As with other things, if you want to use a different rootzone depth, or know that you have a different bulk density, make the adjustments to refine the conversion factor to your location.

The amount present, c

We get this from a soil test. The MLSN guidelines are for the Mehlich 3 test, so if you have Mehlich 3 soil test data then you can use it directly. The same conversion factor applies to convert from units of ppm to lbs/1000 ft^2.

If you are not using a Mehlich 3 extraction for the soil, then you need to be very careful in how you use the MLSN guidelines. You can convert[5] your soil test data into expected quantities on a Mehlich 3 test, but be aware that the conversion introduces some error into the estimate.

That's how to get *c*.

But what soil test data will I use for this hypothetical scenario? I'm going to use the median values from the Global Soil Survey. You can find them in the 2015 Global Soil Survey report.[6]

[5] A number of conversion equations developed by Ketterings et al. for common soil tests in the US are available at `http://nmsp.cals.cornell.edu/publications/soilconversion.html`

[6] `https://www.paceturf.org/PTRI/Documents/2015_gss_report.pdf`

The quantity of each element required

Based on the scenario and assumptions described so far, Table 1 shows the values and the quantity required. Remember, the *a* column is the estimated use of each element as described previously. The *b* column is the MLSN guideline expressed in units of lbs/1000 ft². And the *c* column is the median value for the element through the first two years of the Global Soil Survey.

Element	*a*	*b*	*c*	*Q*
K	1.4	1.1	1.8	0.7
P	0.4	0.6	2.1	-1.1
Ca	0.4	9.9	18.6	-8.4
Mg	0.1	1.4	2.5	-0.9
S	0.1	0.2	0.4	-0.1

Table 1: For each element of interest, the estimated use in 2015 (*a*), the amount needed in the soil (*b*), and the amount from a soil test (*c*), with the amount required as fertilizer (*Q*). When *Q* is negative, that means the amount present is more than the amount required, and none is needed as fertilizer.

The same procedure can be used to estimate nutrient use and to calculate *Q* for any grass in any location. Because soil testing of professionally-managed turfgrass is usually done annually, one can check the changes in soil test values, compare to the inputs and estimated harvest, and can make updates to improve the accuracy of the model for a particular site.

Common misapprehensions about soil testing and turf nutrition

BEWARE! THESE TOPICS are misleading or irrelevant or just plain wrong. When you think about turf nutrition, and about soil testing, you should be aware of these things.

- Locked-up nutrients are not a real thing. When you do a soil test, you are measuring a nutrient availability index. By comparing the soil test result to a guideline, as has been described here, you are able to determine if enough of that element is available to meet the grass requirements, or if that element must be applied as fertilizer.[7]

[7] I've written about all of these things on the ATC blog. If you want to read more, scroll through `http://www.blog.asianturfgrass.com/fertilizer/` and I'm sure you'll find plenty of material.

- It doesn't really matter what an element does. What does matter is that enough of that element is available to meet the grass requirements. If there is enough P, all the benefits to the plant from P will occur. Adding more P when there is already enough? Useless, and in some places illegal too. It's not illegal to overapply other elements but it is a waste of time, effort, and money.
- It's not useful to look at percentages or ratios of nutrients in the soil. Just look at the quantities. For salinity issues, which is a completely different topic, one looks at certain percentages and ratios.
- Don't use water or saturated paste extracts to look at *availability* of nutrients. Do a standard soil test, compare to a guideline level – I

recommend MLSN – and calculate how much to apply. The standard soil test already contains all the available nutrients. The only extra information you get from a water extract is confusion, higher testing cost, and some probability that you'll be recommended fertilizers that are not required.

- Don't be tricked into thinking that an element can be exchangeable but not available. This is what a soil test measures. If you aren't going to interpret tests properly, you'd be better off not soil testing. One can just apply the quantity a, which ensures the grass is supplied with all of each element it will use, and never soil test.
- Some people might tell you that stressed turf requires more nutrients. That's incorrect. What stressed turf needs is a reduction in stress. Adding more nutrients doesn't solve that problem, and in fact may exacerbate it because the real problem is not being addressed. Stressed turf actually requires less nutrients than healthy turf. Stressed turf grows less, thus it uses fewer nutrients.

Soil Water Management: Timing, Amount, and Syringing

Micah Woods

14 January 2016

This is the handout for my presentation on this topic at the 2016 Northern Green Expo. I'm the Chief Scientist at the Asian Turfgrass Center, www.asianturfgrass.com, and an Adjunct Assistant Professor in the Department of Plant Sciences at the University of Tennessee. Contact me at micah@asianturfgrass.com or find me on Twitter at @asianturfgrass. I've posted the slides for this presentation at https://speakerdeck.com/micahwoods.

Fifteen years ago, it was rare to use a soil moisture meter. Today, it seems that almost every turfgrass manager has some idea of the soil moisture content. In this presentation, I show that daily irrigation can use less water than infrequent irrigation while maintaining a lower soil moisture content than deep and infrequent irrigation. I also explain how soil moisture meters can be used to prove that, how they can be used to measure the real evapotranspiration rate, and why syringing turf for the purpose of cooling the surface is a waste of time, water, and energy.

Frequent or infrequent

When I was a superintendent, I tried to apply irrigation as infrequently as possible. When I did irrigate, I tried to do a deep irrigation, applying enough water to saturate the rootzone. I thought that was the best way. I no longer think that.

There are a number of advantages to light and frequent irrigation:

- Use less water
- More consistent surfaces
- More air in the soil
- Reduced risk of localized dry spots (theoretically)

I've put a document I wrote about irrigation[1] at the end of this handout. That document explains, and gives references, for a way of thinking about irrigation that makes sense to me today. Today rather than trying to do deep and infrequent irrigation I would try to identify an optimum soil moisture level and then supply water so the soil was consistently at about that level.

[1] Available online at http://www.files.asianturfgrass.com/201306_summer_irrigation.pdf.

Soil moisture meters

Aren't these meters a useful tool? Meters that provide an instantaneous and accurate measurement of soil water content make possible the refined soil water management that I described in the previous section. One can try to manage the soil at a consistent level of soil moisture.

Evapotranspiration (ET) is a good number to know, but the ET as calculated by an equation may not be equal to the amount of water transpired and evaporated in one day. In fact, we shouldn't expect it to be, because of microclimates on a property, different mowing heights, different grass species, different soil types, and so on. Let's say we have an ET of 0.2 inches (5 mm) for a day. Have you used a soil moisture meter to check that?

Measure the soil moisture at about sunrise. Measure it again at the same location at the end of the day. The difference in soil moisture is the real ET at that location. If you check this at different areas on the property, you can find the average, and you may be able to refine the irrigation management by measuring how the real ET differs from that predicted by a model, and how the ET varies across a property.

This works with a couple of assumptions. First, we have to assume the soil moisture meter is measuring an accurate value. Second, we have to make some assumptions about soil water content at different depths in the rootzone. If we would use soil moisture probes a foot deep, then a measurement like this might be really accurate. But what about using probes at 3 inches deep? Now we aren't actually measuring all the moisture in the rootzone. So one has to make an assumption about the depth of the rootzone, and about how the soil water content is changing through the rootzone.

I like to use metric units.[2] This particular measurement works really well in metric. Irrigation or rain are in depth. That's millimeters (mm). Soil volume is in liters (L). A square meter (surface area) to a depth of 10 cm has a rootzone volume of 100 L. And 1 mm of water spread across 1 square meter has a volume of 1 L.

[2] For more about why that is, see `http://files.asianturfgrass.com/201409_woods_gcm_metric.pdf`

Thus, a measurement of 19% volumetric water content (VWC) in the morning and then 15% VWC at the end of the day corresponds to a loss of 4 L of water from that 100 L rootzone and that is 4 mm of water if it were applied as irrigation. Working with a 100 L rootzone volume allows one to get a quick measurement of ET by using a soil moisture meter.

In U.S. standard units, there may be an easier way to do it. But I am not sure what that is. What I've just described is a surface area of about 11 square feet, to a depth of 4 inches, and then a 19% to 15% decrease in soil VWC is a decrease of just over 1 gallon of water. I can't figure that depth out in my head, like I can when using metric, but I know that it will be about 4 mm, which is 0.16 inches. So if the ET predicted by a weather station was 0.2 inches, one can check it and make site specific adjustments by measuring how much water is actually leaving the soil on such a day.

Wetting agents

ANOTHER THING I'd do differently today than I did when I was a superintendent – I would make more use of soil surfactants (wetting agents). Wetting agents do two things.[3] First, they improve the uniformity of water distribution in soil, which means one should have fewer dry spots and fewer wet spots, and that one can have an improved effect with a lower volume of water applied. Second, they make it easier to rewet the soil, and that reduces the incidence of localized dry spots.

[3] Read more about this in a recent article by Karcher and Richardson: `http://bit.ly/wetting_UArk`

Syringing for the purposes of cooling the grass

I WOULD NOT do this today. If the grass is suffering from drought stress, it doesn't require cooling, it requires an alleviation of the drought stress. Thus, it is irrigation that is required, not syringing. Read more about that in the following pages.

Irrigation Management in Summer: timing, amount, syringing, and water quality

Micah Woods, Ph.D.*

ABSTRACT

Creeping bentgrass (*Agrostis stolonifera*) grows best when the average temperature is about 20°C. During the summer in most parts of Japan, the average temperature is more than 25°C. In such high temperatures, bentgrass greens must be supplied with just the right amount of water, at the right time. Any prolonged deficit or excess of water in the rootzone is likely to result in severe damage to the grass. Turfgrass quality is improved, and bentgrass root systems tend to be more extensive, when the soil moisture content is maintained at a low level. The timing of irrigation is less important than is the amount of water applied. Wilting grass has a very high surface temperature, but transpiring grass has a surface temperature similar to the air temperature. Syringing greens does not have a meaningful impact on surface temperatures. In addition to the quantity of water applied, it is important to know what is in the water. Specifically, the salinity and the sodium adsorption ratio (SAR) should be known, so that any potential problems can be managed before the grass is damaged.

Figure 1: Summer irrigation of the 9th green at Golden Cross CC, Chiba-ken

Irrigation management is one of the most important greenkeeping jobs. In the hot summer weather, bentgrass supplied with too little water will fail rapidly. Bentgrass supplied with too much water will fail rapidly also. Ensuring that the grass is supplied with just the right amount of water is a crucial component of summertime greenkeeping.

We should always remember that grass gets its water from the soil. So when we are irrigating (Figure 1), we are really managing the amount of water in the soil. If we succeed in maintaining the optimum amount of water in the soil, the grass will respond well. The maximum amount of water the soil can hold is called **field capacity**. This is the amount of water in the soil shortly after a saturating rain or irrigation, when excess water has drained by gravity.

There is also a **wilting point**, the level of soil moisture at which the grass will wilt. Even at the wilting point, there is still some water in the soil, but it is held tightly in the small soil pores and is not enough to meet the grass demand for water. In most situations, we try to maintain the soil moisture somewhere above the wilting point, but at or below field capacity.

On putting greens, the roots, and consequently most of the water uptake, tend to be at a depth of about 10 cm. I usually consider the rootzone to be the top 10 cm of the soil. The amount of water in the soil is often expressed in terms of volumetric water content (VWC) and given as a percentage. In 100 L of soil, for example, there may be 20 L of water. The VWC in that case is 20%. As another example, if we took completely dry soil with a volume of 500 cm^3, and then we added 100 cm^3 of water, the VWC of that soil would also be 20%.

The amount of water used by the grass through transpiration, combined with the amount of water evaporated from the surface, is called **evapotranspiration** and is often abbreviated as ET. This is expressed in mm. The ET is essentially the consumptive water use of an area. It is useful to remember that 1 mm of water spread over 1 m^2 has a volume of 1 L.

Irrigation Timing and Amount

Let's consider a few ways we might apply irrigation. Imagine that we have a putting green with a field capacity of 27% and a wilting point of 10%. The soil will never hold more than 27% water, and we want to always keep the soil at more than 10% water. In Figure 2, we see what the VWC would be

*This document is based on a handout (http://www.files.asianturfgrass.com/201306_summer_irrigation_jp.pdf) prepared for the 2nd KGM Private Seminar, held 27 June 2013 at Takarazuka Golf Club, Hyogo prefecture, Japan.

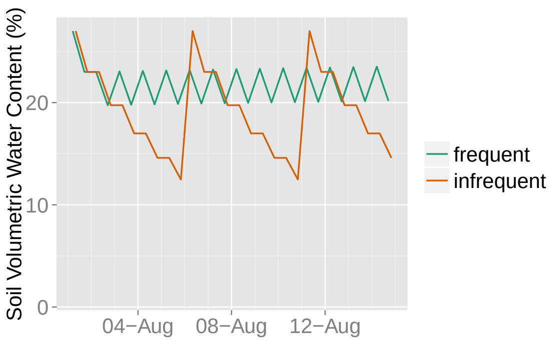

Figure 2: Calculated rootzone (10 cm depth) volumetric water content (VWC) for the first 14 days of August, assuming there is no rain, the daily evapotranspiration (ET) is 4 mm, the VWC on 1 August is at the field capacity (FC) of 27%, the frequent irrigation regime applies just enough irrigation to prevent the VWC from dropping below 18% on the next day, and the infrequent irrigation regime applies enough water to return the soil to FC when the VWC is predicted to drop below 11% on the next day.

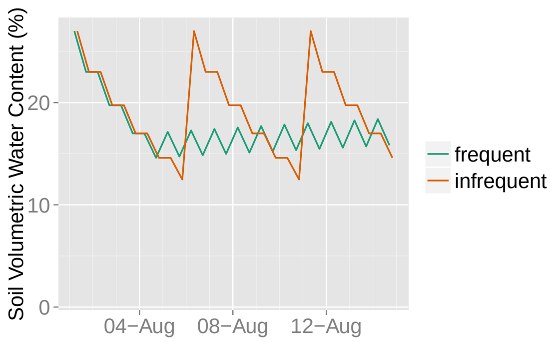

Figure 3: Calculated rootzone (10 cm depth) volumetric water content (VWC) for the first 14 days of August, assuming there is no rain, the daily evapotranspiration (ET) is 4 mm, the VWC on 1 August is at the field capacity (FC) of 27%, the frequent irrigation regime applies just enough irrigation to prevent the VWC from dropping below 14% on the next day, and the infrequent irrigation regime applies enough water to return the soil to FC when the VWC is predicted to drop below 11% on the next day.

for the first 14 days of August, assuming no rain and a daily ET of 4 mm. For the infrequent regime (orange line), irrigation is only applied to keep the soil moisture from dropping below 11%. For the frequent regime, irrigation is applied daily, but just enough to keep the VWC, on the next day, from dropping below 18%.

In the two irrigation regimes shown in Figure 2, the average VWC over the first 14 days of August are 21.9% for the frequent irrigation regime and 19.2% for the infrequent regime. In this case, the average soil moisture content is maintained at a higher level by frequent irrigation than by infrequent. But one can actually maintain a lower VWC by irrigating frequently than by irrigating infrequently. This counterintuitive result is shown in Figure 3.

This case keeps the infrequent irrigation regime the same, applying irrigation to return the soil to field capacity only to prevent the VWC from dropping below 11% on the next day. But the frequent irrigation regime shown in Figure 3 now is managed to apply just enough water to keep the VWC from dropping below 14% on the next day.

Now the average VWC for the first 14 days of August using the infrequent regime is the same, 19.2%, but the frequent (almost daily) irrigation regime has an average of 17.6%. Some advantages to the frequent irrigation regime as shown here include:

- Lower VWC, on average, which can produce firmer surfaces and fewer ballmarks
- More air in the soil
- More consistent playing conditions
- VWC never drops as low as it does in the infrequent regime, thus minimizing the chance of drought stress or the initiation of localized dry spots

Experiments to evaluate the effect of irrigation frequency have usually used an approach similar to that shown in Figure 2, namely, the soil in the frequent irrigation regime is kept very close to field capacity. In experiments in which the treatments are applied in this way (Jordan et al., 2003; Fu and Dernoeden, 2009a,b), the turf quality is better, and the roots are more extensive at the end of summer, when turf is irrigated infrequently. However, those experiments also maintain average VWC higher in the frequent irrigation treatments than in the infrequent treatments. In fact, Fu and Dernoeden (2009b) applied twice as much water to the frequently irrigated plots as they did to the infrequently irrigated plots.

A study of these experiments leads me to the conclusion that maintaining VWC at a lower level will give the best chance for improved turf quality and more extensive roots. As a practical matter, the best approach will usually be a combination of infrequent irrigation events interspersed with frequent irrigation events (Johnson, 2003). For turfgrass managers, I suggest focusing not so much on whether irrigation is applied frequently, or infrequently, but rather on applying just the right amount of water for a particular situation, and on keeping the VWC as low as possible.

Advice on the use of soil moisture meters

One can estimate how much water is in the soil, or one can measure it. Soil moisture meters al-

Figure 4: The surface temperature of 4 surfaces at 14:00 on 3 May 2013 in Bangkok when the air temperature was 38°C: a) concrete, 53.6°C; b) wilting *Zoysia matrella*, 48.8°C; c) transpiring *Axonopus compressus*, 39.2°C; d) transpiring *Zoysia matrella*, 36.2°C.

low turfgrass managers to make a precise measurement of how much plant available water is in the soil and how much water will need to be applied at the next irrigation event. Every location, because of different soil type, grass type, climate, management practices, season, desired turfgrass performance, and innumerable other factors will have a different range of VWC and optimum VWC at any time.

However, there are a few things that are consistent across all of those variables. Here are some things to remember.

1. After a saturating rain, when the soil is sure to be at its maximum VWC, but after gravity has pulled any excess water from the soil, use the moisture meter to measure VWC. In practical terms, this is equivalent to field capacity for a particular soil.
2. When the soil becomes so dry that the grass starts to wilt,[1] measure the VWC just as the grass starts to wilt. In practical terms, this is equivalent to the wilting point of the grass.
3. The difference between the wilting point VWC and the field capacity VWC is the amount of plant available water in the soil.
4. If we are using a 10 cm rootzone for our calculations, then each change of 1% in VWC is equivalent to 1 mm of water and equivalent to 1 L of water per m^2.

[1]If the grass never wilts, or the grass never starts to experience drought stress, then too much water is being applied. Or, it just rains too much!

With that information, one can attempt to maintain the VWC at any desired level, or within any desired range.

Morning vs. afternoon irrigation

Is there a time of day when it is best to irrigate the turf? I think that the best time to irrigate the turf is at the time we identify that the grass requires water. Practically it may not be possible to irrigate at that time, so the best time to irrigate would then become as soon as possible.

Guertal and Han (2009) compared the effect of morning (08:00) irrigation to afternoon (16:00) irrigation on soil temperatures. They found that morning irrigation sometimes had a greater effect in cooling soil temperatures than did afternoon irrigation.

However, when fans were used, the soil temperatures were consistently lower than when fans were not used. The use of fans also increased the root length density, no matter whether irrigation was applied in the morning or afternoon.

Syringing to Cool Bentgrass Greens

For this discussion, I will consider **syringing** (or misting) to be the application of a small amount of water to the turfgrass leaves for the purpose of cooling the surface. If I were managing bentgrass greens in the summer, I would not syringe. Here's why.

Figure 5: In an experiment conducted on a bentgrass green in Chiba, ice, ice water, and 26°C tapwater were applied and the soil and surface temperature were measured.

Temperature of transpiring vs. wilting turf

Figure 4 shows the surface temperature of four surfaces on a sunny day at Bangkok when the air temperature was 38°C. When the roots cannot take up enough water from the soil, the grass wilts. And when the grass wilts, the surface temperature on a sunny day can rise much higher than the air temperature. However, when there is adequate soil moisture, the transpiring grass usually has a canopy temperature within 1 or 2°C of air temperature.

Temperature change after syringing

Given that turf supplied with adequate soil moisture will have a canopy temperature very close to air temperature, what happens when the turf is syringed? How does the temperature change? DiPaola (1984) conducted an extensive investigation and found that water application of 50 or 100 mL m^{-2} resulted in no change in canopy temperature 30 minutes after application. Adding more than 1.4 mm (1.4 L m^{-2}) resulted in a decrease of about 0.7°C in canopy temperature 30 minutes after application. By 1 hour after application, there was no change in canopy temperature between syringed and non-syringed plots, no matter how much water had been applied.

When more than 100 mL m^{-2} is applied, I hesitate to call it syringing, because most of the applied water is going to the soil rather than staying on the canopy. In that case, I call it irrigation.

I measured (Figure 5) the effect of ice, ice water (1.5°C), and tap water (26°C) on the soil and surface temperatures of a bentgrass green in Chiba.[2] This was not syringing, because the amount of H_2O applied in each treatment was equivalent to 7.8 mm. Application of ice or ice water reduced the soil and surface temperatures by a few degrees for a few hours. Application of tap water reduced the surface temperature by about 0.5°C when applied in the morning, and caused a slight increase in surface temperature when applied at sunset.

The difference in canopy temperature between transpiring turf and non-transpiring turf can be more than 10°C (Figure 4). Application of water to the turf, in the extensive studies of DiPaola (1984), has minimal to no effect on canopy temperature, unless the grass is wilting, in which case the application of water does result in a reduction of canopy temperature.

Irrigation Water Quality

When irrigation water is applied, it is important to know what is in the water. The content of the water, and the chemical properties of the water, can have an impact on turfgrass performance and on soil physical properties. These potential problems can be managed, but only if one knows what is in the water. There are two important water quality parameters.

Salinity

The first is **salinity**, which is the amount of inorganic ions (salts) in solution. Table salt is sodium chloride, which in water dissolves to be Na^+ and Cl^-. There will also be sulfate and calcium and magnesium and potassium and ammonium and nitrate dissolved in the water, along with other ions; these ions, taken together, are called total dissolved solids (TDS) and are a measurement of the amount of salt (salinity) in the water.

The TDS is reported as mg L^{-1} and is measured directly by taking 1 L of water, evaporating all the water, and weighing how much solid matter remains in the container.[3] When irrigation water with salt is applied to turfgrass, the grass uses the water, but it may not take up all of the salts, and those salts accumulate in the soil. For example, irrigation water with TDS of 1000 mg L^{-1}, applied for one month at a rate of 4 mm d^{-1}, could cause 120 g m^{-2} of salt to accumulate in the the rootzone. That is a lot! Fortunately, irrigation water in Japan rarely contains that much salt. But unless it is measured, one doesn't know how much salt is being applied to the turf.

Salinity is managed by applying more water than the grass can use. This results in leaching, and as some of the applied water leaches below the rootzone, some of the salt also leaches below the rootzone.[4]

[2] The results of these experiments were described in articles I wrote for *Golf Course Seminar* magazine in the July 2012, October 2012, and August 2013 issues.

[3] The TDS is also estimated by measuring the electrolytic conductivity (EC) of the water. An EC of 1 dS m^{-1} is approximately equivalent to a TDS of 640 mg L^{-1}.

[4] The leaching fraction with example calculations was discussed in an article I wrote in the July 2011 issue of *Golf Course Seminar* magazine.

Sodium adsorption ratio

If there is a high amount of sodium in the water compared to the amount of calcium and magnesium in the water, there can be some problems in the soil. Over time, that water applied to the soil will cause sodium to accumulate on the cation exchange sites, and as this happens, the small clay-sized soil particles can deflocculate and swell. This reduces air space in the soil and slows the water infiltration. The sodium adsorption ratio (SAR) is an indication of how the water may cause a problem with infiltration and soil structure.

One can consult various interpretation tables to evaluate how a particular SAR may be a problem; for most irrigation water in Japan, an SAR of about 6 or above would be an indication of potential problems. To manage the potential problems of high SAR, calcium is applied to the soil, or injected into the irrigation water, usually in the form of gypsum (calcium sulfate).

Additional information

- On the subject of irrigation water quality, a particularly comprehensive yet concise guide is *Interpreting Turfgrass Irrigation Water Test Results* by Ali Harivandi: http://anrcatalog.ucdavis.edu/pdf/8009.pdf
- For a clear explanation of leaching requirement to maintain soil salinity at a tolerable level, I recommend *Leaching for Maintenance* from the University of Arizona: http://ag.arizona.edu/pubs/water/az1107.pdf
- An annotated chart of soil VWC with more detail than shown in Figures 2 and 3 is available for viewing or download: http://www.flickr.com/photos/asianturfgrass/8922147839/
- During the seminar, I showed some video clips from the classic *Water Movement in Soils* movie. This film is available for purchase from the Department of Crop and Soil Sciences at Washington State University: http://css.wsu.edu/merchandise/

Figure 6 shows that new roots can develop even during the hot temperatures of summer, provided there is adequate air space in the soil. By monitoring the VWC, it is possible to supply the grass with just enough water while still maximizing air space in the soil.

In many parts of Japan, the average temperature during August is more than 28°C and creeping bentgrass is subjected to severe heat stress. Managing the soil moisture at an optimum level, so that dry spots (water deficit) are avoided, while still keeping the soil as dry as possible so that air space is at a maximum, is an essential part of successful greenkeeping during summer.

Figure 6: On 8 September 2008, the average temperature for for the previous 39 days had been 26.8°C including an average of 26.4°C in the first 8 days of September; even with these high temperatures, well above the optimum for creeping bentgrass, new roots are growing where air space had been created in the soil by a slicing treatment at the end of August.

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Instead of Shade, Let's Talk About Light

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This is the handout for my presentation on this topic at the 2016 Northern Green Expo. I'm the Chief Scientist at the Asian Turfgrass Center, www.asianturfgrass.com, and an Adjunct Assistant Professor in the Department of Plant Sciences at the University of Tennessee. Contact me at micah@asianturfgrass.com or find me on Twitter at @asianturfgrass. I've posted the slides for this presentation at https://speakerdeck.com/micahwoods.

Shade from trees, buildings, clouds or mountains affects a lot of turfgrass areas, and shade can make it impossible to produce the desired turfgrass conditions. Rather than talk about the impossible, in this presentation I talk about light. Specifically, I discuss photosynthetically active radiation (PAR), the photosynthetic photon flux density (PPFD), and the daily light integral (DLI). These sound complicated but are quite simple and can be easily measured or estimated. With an understanding and ability to measure and communicate about PAR, PPFD, and DLI, it makes it a lot easier to manage those previously impossible shade problems.

The units of photosynthetic light

Shade can be an impossible problem. Grass can tolerate extreme temperatures and wide variations in soil moisture, but without enough light, the quality of the grass will never reach the desired level. Because the solution to shade problems often involves removing whatever is causing the shade, or making some big changes to the way turf is managed, I think it is especially useful for turfgrass managers to be familiar with measurements of photosynthetic light. If you are familiar with these units, you will be able to assess shade problems and communicate about them like a pro, hopefully leading to improved solutions to shade problems.

Light that grass uses for photosynthesis is light with wavelengths from 400 to 700 nanometers. This spectral band is similar to visible light.[1] When talking about photosynthetic light, here are three terms that you should know.

[1] Wikipedia tells me that visible light is 390 to 700 nanometers (nm).

Photosynthetically active radiation (PAR) This is the light with wavelengths from 400 to 700 nm.

Photosynthetic photon flux density (PPFD) This is how PAR is measured, and the measurement is an instantaneous one, of how much PAR reaches a surface in one second. The units are micromoles of photons per square meter per second ($\mu mol\,m^{-2}\,s^{-1}$). That sounds pretty complicated.[2] But it is just a number. At night the PPFD is 0. At sunrise the PPFD starts increasing, reaching about $2000\,\mu mol\,m^{-2}\,s^{-1}$ at midday when there are no clouds in summer. Then PPFD decreases until it reaches 0 again when the sun goes down. The PPFD is the measurement of how much PAR there is at any one second, and it ranges from 0 to 2000.

[2] Reading about this from different sources may help improve understanding. An excellent description of PAR by Richardson and Mattina is on pages 25 to 28 of http://turf.uark.edu/education/FieldDayProgram2014.pdf. You can also find information there about light meters and what they measure and how to use them.

Daily light integral (DLI) The DLI is the daily total of PAR. By adding together the PPFD for every second of the day, one gets the DLI. There are a lot of seconds in a day, so adding all the PPFD values together makes a big number. For convenience, instead of units of $\mu mol\,m^{-2}\,d^{-1}$, the DLI is expressed in units of $mol\,m^{-2}\,d^{-1}$. The DLI ranges from less than $5\,mol\,m^{-2}\,d^{-1}$ on a cloudy day in winter to about $60\,mol\,m^{-2}\,d^{-1}$ on a sunny day in summer.

I don't worry so much about wavelengths, photons, or moles. I think of PAR as being light the grass can use, of the instantaneous light being 2000 at a maximum and 0 at a minimum, and the total daily amount as being in the range of 1 to 60. From these values, one can measure the magnitude of shade.

Measuring shade by measuring PAR

Let's say there is corner of a putting green that is shaded by trees until 10:00 a.m. in summer. One can communicate about that by saying that the green is shaded until 10:00 a.m. But I think a more accurate assessment of the shade would be to do one of two things.

First, this is a corner of a green. On a sunny day, one would expect that a portion of the green will be in full sun, and the corner of the green will be in shade. With a light meter than can measure PPFD, such as the model 3415F[3] from Spectrum Technologies, you can measure the difference in PPFD between the shaded and unshaded area. Trees usually reduce PPFD by about 80%. You might find at 9 a.m. that the sunny area has a PPFD of $1221\,\mu mol\,m^{-2}\,s^{-1}$ and the shaded corner of the green, a few seconds later after you walk over there and make the measurement, has a PPFD of $189\,\mu mol\,m^{-2}\,s^{-1}$. By measuring that difference, one can then make a note that the shaded area only has $\frac{189}{1221} = 0.15 = 15\%$ the PPFD of the sunny area. That's an example of the difference in light in an instant.

[3] http://www.specmeters.com/lightmeters/quantum-meters/

One can measure the difference at various times to get a better understanding of the average reduction in PAR caused by the shade. Knowing how much the PAR is reduced can help one to choose the most appropriate management, and I think it may also be useful in communicating about possible removal of the shade-causing trees. Or it can be an explanation for why the grass on the shaded corner of the green does not tolerate traffic. Having the PPFD measurement can be useful.

Second, one can measure the difference in DLI between the shaded corner of the green and an unshaded area. To measure DLI, either use meters that do that,[4] but you'll have to leave them in the locations – one in shade, another one in unshaded – for 24 hours. Or,

[4] For example, the DLI 100. http://www.specmeters.com/lightmeters/dli100/

measure the PPFD for 1 second each hour of the day, multiply each of those by 3600 to estimate the hourly total,[5] and then add together all the hours of the day. This will be a big number, because the units are micromoles. Divide by 1 million to have the number in standard DLI units of mol m^{-2} d^{-1}.

Now you have a daily total reduction in PAR caused by the shade. Let's say you do this on July 15, and it is a sunny day with no clouds. The DLI in the sunny area with no shade may be about 58. In the shaded area, let's say the DLI was 36. Now you have the numbers to explain, in addition to how many hours the corner of the green is shaded, the absolute quantity of PAR reduction over the day caused by that shade.

[5] Because there are 3600 seconds in an hour, and the PPFD is a measurement of PAR for 1 second.

DLI and PPFD in 2015 in Sandstone, Minnesota

I downloaded data[6] for Sandstone because I can get measurements of global solar irradiance from the station there. From the measurements of global solar irradiance, I convert to units of PAR by using a factor[7] of 2.04 mol m^{-2} for each 1 MJ m^{-2} of irradiance. The monthly DLI averages for 2015 are shown in Figure 1.

[6] H. J. Diamond, T.R. Karl, M.A. Palecki, C.B. Baker, J.E. Bell, R.D. Leeper, D.R. Easterling, J.H. Lawrimore, T.P. Meyers, M.R. Helfert, G. Goodge, and P.W. Thorne. U.S. climate reference network after one decade of operations: Status and assessment. *Bull. Amer. Meteor. Soc.*, 94(4):485–498, April 2013. DOI: 10.1175/BAMS-D-12-00170.1. URL `http://dx.doi.org/10.1175/BAMS-D-12-00170.1`

[7] D.W. Meek, J.L. Hatfield, T.A. Howell, S.B. Idso, and R.J. Reginato. A generalized relationship between photosynthetically active radiation and solar radiation. *Agronomy Journal*, 76:939–945, 1984. DOI: 10.2134/agronj1984.00021962007600060018x

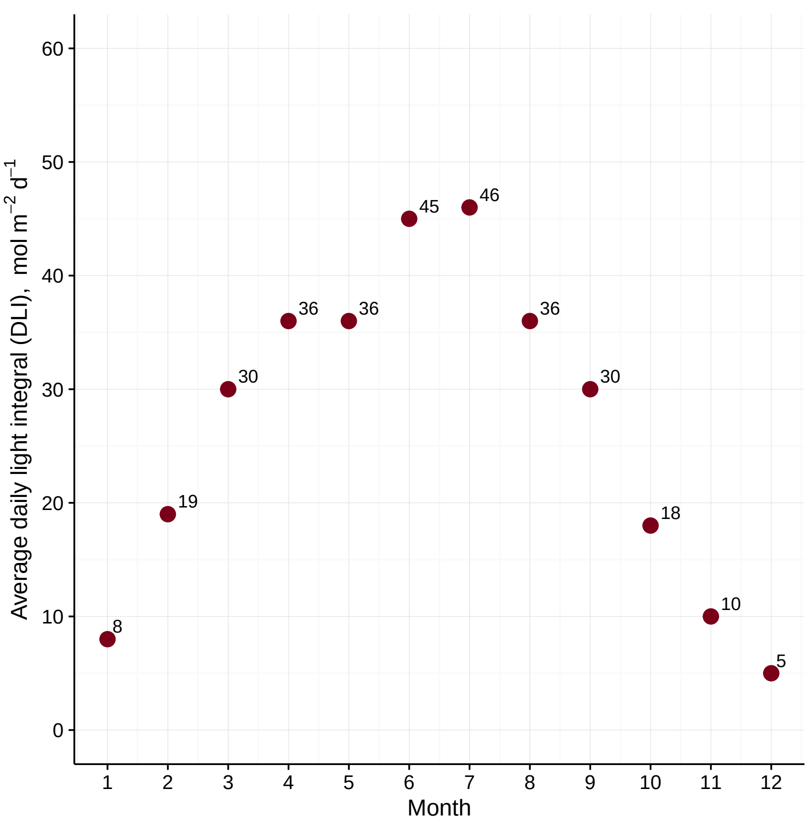

Figure 1: Average DLI by month in 2015 at Sandstone, Minnesota.

To see how the average PPFD will be at different times of the day throughout the year, I took the average PPFD for each hour, summarized by month. These data are shown in Table 1 to show what normal PPFD values would be.

Hour	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
5	0	0	2	6	2	0	0	0	0
6	0	8	70	145	90	22	0	0	0
7	14	165	274	374	314	207	71	8	0
8	168	445	469	660	583	469	303	148	20
9	448	740	703	929	860	745	571	364	140
10	765	1024	910	1184	1113	933	834	571	196
11	1009	1175	1031	1424	1334	1105	981	726	468
12	1201	1271	1085	1467	1528	1228	1115	735	534
13	1207	1317	1169	1421	1507	1199	1158	747	501
14	1145	1214	1211	1352	1419	1135	1064	645	448
15	989	1057	1052	1199	1306	1042	898	551	310
16	713	825	854	869	1116	838	685	349	152
17	429	520	633	691	793	575	408	144	20
18	113	249	401	493	512	305	138	7	0
19	1	44	123	231	217	91	4	0	0
20	0	0	6	31	24	4	0	0	0
21	0	0	0	0	0	0	0	0	0

Table 1: The average PPFD by hour from March through November in 2015 at Sandstone, Minnesota. Times are local standard time with no adjustment for daylight savings time.

You may notice that the average PPFD at midday during summer does not go all the way up to the maximum of 2000. That's because of clouds. Sometimes there are clouds, and that brings the average down. Also, in Figure 1, the average DLI is only 45 and 46 in June and July, but on sunny days in those months the DLI is close to 60. Again, this is caused by clouds that bring the average down.

To see how the PPFD changes through the year, and how the DLI changes from day to day, I've made a chart that shows PPFD and DLI for each day of 2015 at Sandstone.[8]

[8] This chart is available for download at full size from `https://www.flickr.com/photos/asianturfgrass/24117735302/sizes/o/`

Turf in shade: what can be done?

It's not easy to manage turf in shade. For turf growing in shade, one can try these things to improve the turf performance.[9]

[9] D.S. Gardner and R.M. Goss. Management of turfgrass in shade. *Turfgrass: Biology, Use, and Management*, pages 219–247, 2013. doi: 10.2134/agronmonogr56.c6

1. Choose grass species and cultivars that can perform better than the alternative species under shaded conditions.
2. Remove the source of shade by cutting trees, pruning trees, removing buildings.

3. Increase the mowing height.
4. Be vigilant in controlling fungal diseases.
5. Be extra careful to control traffic.
6. Reduce the nitrogen fertilizer application rate.
7. Use plant growth regulators that regulate gibberellic acid: trinexapac-ethyl, flurprimidol, or paclobutrazol.
8. Provide supplemental light.