ABSTRACT

REYNOLDS, WILLIAM CASEY. The Impacts of Athletic Field Paint on Light Spectral Quality, Turfgrass Photosynthesis, and Transpiration in Painted Turfgrass Canopies. (Under the direction of Dr. Grady Miller.)

Athletic field paints are applied to turf surfaces with little or no acute injury. However, field managers often notice chronic declines in turfgrass health after repeated applications. This study examines the impacts of athletic field paint on light spectral quality, photosynthesis, and transpiration in painted turfgrass canopies. Athletic field paints produce various colors through selective reflection, transmission, and absorption of visible light (400-700 nm). However, photosynthetically active radiation (PAR) also exists at these wavelengths, and as a result it was hypothesized that alterations in visible light to produce specific colors would lead to reductions in photosynthetically active radiation (PAR) and total canopy photosynthesis (TCP). Athletic field paints may also impact transpiration by obstructing gas exchange at the leaf surface, which could potentially lead to reductions in TCP and transpiration as well as increases in canopy temperature above optimal ranges.

Lab experiments using a spectroradiometer and integrating sphere examined the impacts of athletic field paint color and dilution on reflection, transmission, and absorption of PAR as well as wavelengths within PAR. Subsequent growth chamber experiments were used to examine how these impacts related to turfgrass photosynthesis and transpiration. Photosynthesis was evaluated in ‘Palmer V’ perennial ryegrass (*Lolium perenne* L.) using a gas exchange system 24 h after application of red and white athletic field paint at two dilutions as well as in ‘Tifway’ bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy] 24 h after application of ten colors. Transpiration of Tifway as a result of six paint colors was evaluated using mass balance methods. Canopy temperature

was measured in all experiments using an infrared digital thermometer immediately prior to measurements of photosynthesis and transpiration.

Spectroradiometry analyses revealed the significant effects of paint color ($P \leq 0.001$) and dilution ($P \leq 0.0001$) on reflection, transmission, and absorption of PAR. Lighter colors including white, yellow, orange and red reflected 47-92% of PAR, while darker colors including green, black, and dark blue absorbed 87- 95% of PAR. Accompanying gas exchange measurements revealed that all treatments reduced TCP based upon color ($P \leq 0.0001$) and dilution ($P \leq 0.0001$). Values for TCP were most negatively correlated with absorption of PAR ($r = -0.959$; $P \leq 0.001$) and was positively correlated with reflection and transmission of PAR. Transpiration in Tifway canopies was reduced by paint application ($P \leq 0.0001$) where lighter colors yellow and white reduced transpiration the least while black and blue reduced transpiration the most. Canopy temperature was affected by paint color ($P \leq 0.0001$) in all growth chamber experiments and was most positively correlated with PAR absorption ($r = 0.872$; $P \leq 0.001$) over the range of the ten colors examined. Black and blue resulted in the largest increases in canopy temperature (39.6 and 40.5^{o}C), which is above the optimal range of 27-35^{o}C, potentially resulting in heat stress.

The results presented in these experiments reveal the color-dependent relationship between available PAR, TCP, and transpiration in painted turfgrass canopies. The overlap of visible light and PAR results in secondary impacts on turfgrass growth including shading, stomatal obstruction, and heat stress. These factors clearly indicate that damage to turfgrasses with long-term painting will be difficult to avoid, and this is particularly true with darker colors of paint.

The Impacts of Athletic Field Paint on Light Spectral Quality, Turfgrass Photosynthesis, and Transpiration in Painted Turfgrass Canopies

by
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BIOGRAPHY

William Casey Reynolds was born on 28 September 1978 to Bill and Vivian Reynolds and has an older brother, Clifton Reynolds, who was born two years prior on 28 April 1976. He grew up in Midland, NC and graduated from Central Cabarrus High School in 1996. Upon graduation he moved to Raleigh, NC in pursuit of an education in the College of Agriculture and Life Sciences at North Carolina State University. After his sophomore year, he decided to focus on a Bachelor of Science Degree in Crop Science with a concentration in turfgrass management, which he received in May 2000.

Over the course of his undergraduate career, Mr. Reynolds spent his summers working in the landscape industry, the golf course industry, and athletic field construction. These combined experiences proved invaluable and were an integral part of his decision to further pursue his education by entering graduate school at NC State in the fall of 2000 in which he pursued a Master of Science degree in Crop Science with a concentration in Turfgrass Management and minor in Business Management.

In 2003, upon completion of his Master of Science degree from NC State, Mr. Reynolds' path diverged in two directions. He was offered a position at NC State as Dr. Art Bruneau's turfgrass research and extension associate while at the same time became owner/operator of a landscaping business he named Graduate Degree Turf. Over the course of the next five years, Mr. Reynolds worked both of these positions before deciding to re-enter graduate school at NC State in pursuit of a Doctor of Philosophy in Crop Science.

As of 2013, he is nearing the completion of this degree and currently resides in Raleigh, NC where he lives with his fiancée Diane Silcox, whom he will be married to on

October 19th, 2013, his golden retriever Ella, and the world's spottiest beagle, Mandy. Upon completion of his PhD, Mr. Reynolds is looking forward to continuing his career in the turfgrass industry.

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LITERATURE REVIEW

Athletic field paints are routinely applied to field surfaces for marking regulation lines, logos, advertisements, etc. in sporting events worldwide. These products are formulated with the intent that they do not cause any acute injury when properly applied, yet it is widely recognized that repeated paint applications often degrade turfgrass quality. Although the cause(s) of the damage is unknown, a potential explanation lies in secondary, chronic effects on plant growth processes. Two processes that are likely affected by athletic field paint applications are photosynthesis and transpiration. Photosynthesis is the most fundamental and important chemical reaction in plants and literally means "synthesis using light" (Taiz and Zeiger, 2010). Photosynthesis is a biological process unique to plants that allows them to use solar radiation to reduce atmospheric carbon dioxide (CO_2) into usable forms of energy. Atmospheric CO_2 enters the leaf in a process called transpiration, while photosynthesis produces the energy used to reduce it by oxidizing water (H_2O). These two processes are fundamental to the survival and performance of all plants, including turfgrasses, and it is reasonable to suspect that athletic field paint applications could have substantial impacts on each.

Photosynthesis

Photosynthesis was first discovered by Joseph Priestley in 1771 who discovered that a sprig of mint growing in the air in which a candle had burned out improved the air so another candle could burn (Bronkowski, 1973). This was used not only to explain fire, but also that oxygen was one component of the air that we breathe and that it is expelled by plants. Later

experiments established the essential role of light, CO_2, and H_2O as inputs in photosynthesis and that O_2 and carbohydrates were by-products. The balanced overall chemical reaction for photosynthesis is often written as follows:

$$\underset{\text{Carbon Dioxide}}{6\,CO_2} + \underset{\text{Water}}{6\,H_2O} \longrightarrow \underset{\text{Carbohydrate}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6O_2}$$

Photosynthesis most often occurs in leaf mesophyll cells which contain light absorbing pigments called chlorophylls. Specifically, chlorophyll pigments are found within leaf mesophyll cells in subcellular organelles called chloroplasts. These chloroplasts are the site of the light reactions of photosynthesis.

The light reactions are of importance in athletic field paint research due to the potential impacts of paint on the availability of light to drive these reactions. All solar energy (light) has properties of waves, measured in wavelengths (λ), as well as particles, called photons. These photons deliver energy that is dependent on the frequency (ν) at which waves pass a given place in a given time. However, only the wavelengths between 400 and 700 nm are capable of delivering energy that is usable in the light reactions of photosynthesis. As such, light within these wavelengths is commonly referred to as photosynthetically active radiation (PAR). It is also important to note that within PAR, there are particular spectral bands that are most effectively absorbed for photosynthesis. These bands include wavelengths between 400-500 nm and 600-700 nm (Taiz and Zeiger, 2010)**.** Light between 500-600 nm is not effectively absorbed for photosynthesis due to the properties of chlorophyll pigments that preferentially reflect light within this wavelength range. Within the 400-500 nm and 600-700 nm ranges, Chlorophyll a is known to have peak spectral

absorption at 410, 430, and 660 nm while peak absorption for Chlorophyll b occurs at 430 and 640 nm (Taiz and Zeiger, 2010).

In order to maximize absorption of PAR, and thus maximize photosynthetic rates, mesophyll cells containing chloroplasts are often located immediately below the upper epidermis of the leaf where they are most likely to receive incident radiation. As a result, athletic field paint applications that are applied to coat leaf surfaces may be capable of reducing incident PAR, thus reducing the amount of energy readily available to drive the light reactions of photosynthesis. This is particularly true given the fact that like PAR, visible light also exists between 400 and 700 nm. Visible light can be categorized by color and is a direct result of wavelength. Red, orange, yellow, green, blue, indigo, and violet are often the colors assigned to the visible spectrum and begin with violet as having the shortest wavelengths (~ 400nm) and red having the longest (~ 700nm). The overlapping wavelength range of PAR and visible light means that the ability of pigments to produce specific colors by altering visible light are also likely to alter PAR, as well as wavelengths within PAR, available for photosynthesis.

The impacts of reduced light quantity and altered light quality on turfgrass growth have been examined in studies of shading from trees, buildings, and weeds (Bell et al., 2000; Gaskin, 1965; McKee, 1963). Reductions and alterations in light have also been linked to reductions in turf performance as well as physiological changes within grasses (McBee, 1969; Dudeck and Peacock, 1992; Wilkinson and Beard, 1975)**.** Athletic field paint has yet to be linked to PAR reductions, but several studies have linked PAR reductions as a result of varying types of shade with reduced turfgrass performance. For example, decreased turfgrass

growth as a result of reductions in PAR has been reported by Baldwin et al. (2009) where it was found that shade fabrics filtering wavelengths 360 to 720 nm produced clipping yields in 'Tifway' bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burtt-Davy] of only 21.4% of treatments receiving no shade. These shade fabrics reduced PAR by 65% from an initial light intensity of 1,974 µmol m^{-2} s^{-1} to 895 µmol m^{-2} s^{-1}, which led to unacceptable turfgrass quality of Tifway.

Other research has linked overall reductions in PAR to light compensation points, the point at which CO_2 photosynthetic fixation equals CO_2 respiratory release. Edenfield (2001) reported light compensation points of Floradwarf and Tifdwarf to range between 265 and 429 µmol m^{-2} s^{-1} in various shade treatments. As such, reductions in PAR that would result in CO_2 fixation below these levels would likely result in plant health decline.

In regard to specific wavelengths within PAR, Baldwin et al. (2009) found that shade fabrics that selectively filtered wavelengths of light within PAR reduced growth. For example, shade fabrics filtering wavelengths 560 to 720 nm, yet allowing passage of blue light (400 to 500 nm) for 6 wk, resulted in a 38% reduction in clipping yields of Tifway. Shade cloths filtering 360 to 520 nm and 360 to 560 nm while allowing passage of red light (600 to 700 nm) also reduced clipping yields.

In addition to amount and type of shade, the duration under which turfgrasses are subjected to shade is also important. In the Baldwin et al. (2009) study, turfgrass quality and clipping yield of bermudagrass and zoysiagrass (*Zoysia matrella* (L.) Merr.) decreased as duration of shade increased. Reductions in traffic tolerance were also observed in several bermudagrass and zoysiagrass cultivars as the duration under shade and number of traffic

applications increased (Trappe et al., 2011). The notion that reductions in turfgrass quality and performance are caused by chronic shading by athletic field paint applications is consistent with athletic field paints not being acutely toxic to turfgrasses. Also, anecdotal evidence from professional athletic field managers indicates that decreased growth and density from athletic field paint applications are usually noticed only after multiple painting events. These decreases become more severe as the number of paint applications increase.

In addition to absorption of PAR by paint pigments that may result in shading effects, it is also worth investigating the reflection and transmission of PAR within painted turfgrass canopies. This is due to the fact that reflection, transmission, and absorption are all inter-related. For example, pigments found in red athletic field paint selectively reflect red wavelengths while transmitting and absorbing all other wavelengths. Pigments found in white paint reflect light at all wavelengths, while pigments found in black paint absorb all wavelengths.

Previous research performed in other crops has shown that available PAR can be altered by reflection of visible light from various colors of paint and is sufficient to affect plant growth. Kasperbauer (2000) found that upwardly reflected light from painted plastic covers beneath cotton (*Gossypium hirsutum* L.) canopies differed by color. Plants grown over plastic surfaces painted white received substantially more PAR than plants grown over plastics painted red and green. In a separate study, it was found that carrots (*Daucus carota* L.) grown over plastic mulches painted white, yellow, red, blue, and green received varying amounts of reflected PAR (Antonious and Kasperbauer, 2002). Up to this time, however, no such studies have been conducted with paint applied to turfgrass.

Transpiration

As previously discussed, the impacts of various colors of athletic field paint on reflection, transmission, and absorption of PAR are only one component of photosynthesis. In addition to PAR driving the light reactions, transpiration provides the necessary atmospheric CO_2 to facilitate the dark reactions, which also has the potential to be impacted by paint. Stomata serve as the entry point of atmospheric CO_2 into the plant as well the exit point for H_2O vapor and oxygen. Stomata are enclosed on either side by guard cells which are specialized cells in the epidermis that are morphologically distinct from general epidermal cells (Franks and Farqhuar, 2007). Location and frequency of stomata are species dependent, but they have been documented to occur only on the lower (abaxial) leaf surface, only on the above (adaxial) leaf surface), and on both surfaces. However, in most plant species, stomata can be found on both surfaces with the majority on the abaxial surface (Ticha, 1982). Within grasses commonly used as turf, stomata can vary by species and carbon fixation pathway but are commonly found on both the abaxial and adaxial surfaces (Green et al., 1993).

Stomata are some of the most important features of plants within all species because of their integral role in gas exchange and temperature regulation. The delicate balance of opening and closing stomata is regulated by many environmental factors including atmospheric CO_2 concentration, temperature, humidity, soil/plant moisture status, etc. However, one of the most important external factors regulating stomatal opening and closing is the availability of light, specifically in the blue (400-500nm) and red (600-700nm)

wavelengths. These are deemed the “blue-light” response, which is independent of photosynthesis (PS) and the “red-light” response, which is tied closely to photosynthesis.

The blue-light response occurs only in guard cells while the red-light response occurs in both guard cells and mesophyll cells (Shimazaki, 2007). In guard cells, blue light activates a plasma membrane H+-ATPase that pumps protons out of the guard cells resulting in a lowered pH in the apoplastic space surrounding the guard cells. This lower pH generates a gradient that allows ions to flow into guard cells resulting in increased turgor and stomatal opening.

The signaling response of blue light via the H+-ATPase is countered by a somewhat disputed signaling response of red light. The red-light response has traditionally been thought of as a photosynthesis driven response where stomata respond to a decrease in the internal carbon dioxide concentration (C_i) due to active photosynthesis under saturating red light capable of driving photosynthesis.

Regardless of the individual blue and red light responses there is little doubt that there is a synergistic response resulting from illumination with both blue and red wavelengths of light. Red-light driven photosynthesis in mesophyll and guard cell chloroplast result in increased stomatal aperture while blue-light signaling has the capacity to open stomata even further. If athletic field paint applications are capable of reducing PAR, as well as wavelengths within PAR, it is also reasonable to suspect that decreases in blue and red light reaching the leaf as result of paint application and color may impact stomatal opening.

Another means by which transpiration may be negatively affected by athletic field paint is through the physical obstruction of stomata. If athletic field paints are capable of

clogging stomata then the rate at which CO_2 enters into the leaf could be slowed or even prevented all together. As such, decreased CO_2 entry into the leaf would most certainly have negative impacts on turfgrass health and performance. As is the case with the effects of athletic field pain on photosynthesis, the effects of athletic field paint on transpiration is an area of research that has yet to be conducted.

Heat Stress

In addition to providing CO_2 as a substrate for the carbon fixation reactions, transpiration's ability to exchange CO_2 for O_2 and H_2O vapor has a secondary benefit to plants. Transpiration allows plants to lower their internal temperature by converting internal liquid H_2O to H_20 vapor. As this phase conversion occurs, the temperature of the H_2O itself does not change, but the surface from which the H_2O evaporates is lowered. This process helps to moderate the temperature of transpiring leaves which may otherwise increase substantially with absorption of solar radiation. The temperature optimum for turfgrasses is generally considered to range from 16-24 ^oC in cool-season turf and 27-35 ^oC in warm-season turf while supra-optimal temperatures are often considered to be 10^oC above optimal (Dipaola and Beard, 1992; Huang et al., 2009). Negative impacts of increasing temperature above these optimal ranges include excessive H_2O loss, increased C losses from photorespiration, lower rates of photosynthesis, and decreased activation of the ribulose 1,5-bisphosphate carboxylase-oxygenase (Rubisco) enzyme.

The impacts of increasing soil and air temperature on turfgrass health and performance have been widely documented in un-painted turfgrasses, particularly with

regard to increased C losses from photorespiration and lower rates of photosynthesis. Huang and Gao (2000); Huang and Xu (2000); Huang et al., 2008 found that creeping bentgrass whole plant and root respiration both increased as soil and air temperatures increased, with soil temperatures having greater impacts. Furthermore, as the duration at elevated temperatures increased, carbon consumption by respiration began to exceed carbon production by photosynthesis resulting in many negative impacts on the plant including reductions in turf quality, leaf chlorophyll content, root growth, photosynthesis, and total non-structural carbohydrates. With regard to Rubisco, Crafts-Brander and Salvucci (2000) reports decreases in Rubisco activation in cotton (*Gossypium hirsutum*) and tobacco (*Nicotiana rusticum*) leaves when leaf temperatures exceeded 35^{o}C. Furthermore, Salvucci and Crafts-Brander (2004) reports that direct inhibitions on photosynthesis as a result of the kinetic properties of Rubisco occur at temperatures higher than 30^{o}C and defines moderate heat stress as ranging from 30-42^{o}C.

The impact of athletic field paint on temperature within the turfgrass canopy have been an area of limited study, but there is certainly the potential for canopy temperatures to increase as a result of paint application. This is due to the fact that many pigments, especially those found in darker colors, are selected for their ability to absorb light (radiation). It is also possible that if athletic field paint applications obstruct stomata then transpiration, and thus evaporative cooling, may be reduced. Like photosynthesis and transpiration, the relationship between athletic field paint applications and their effect(s) on turfgrass canopy temperature has yet to be established.

Paint Chemistry

In order to fully understand the capacity for athletic field paint to affect PAR, photosynthesis, transpiration, and canopy temperature it is important to explore the basic fundamentals of paint chemistry and application. Manufacturers focus much of their efforts on producing bright, distinct, uniform paints that are both affordable and non-injurious to grass species commonly used on athletic field surfaces. Within the athletic field paint industry, latex, water-based paints are the most commonly applied products. Athletic field paints are no different than other paints in that they are formulated with enough opacity to hide the painted substrate, in this case the turfgrass leaf, while at the same time producing the perception of a desired color. Furthermore, all paints are composed of four main components: resins (also called binders), pigments, solvents, and additives. Volatile components of paint formulations include water, other solvents, and coalescing agents, each of which allows the paint to remain in liquid suspension prior to application. However, these components are designed to evaporate off of the leaf after application. Non-volatile components include resins, pigments, extenders, and additives, and unlike volatile components they are each designed to remain intact after application. These non-volatile components produce a paint film consisting of pigments, extenders, and additives uniformly dispersed within the resin that coats turfgrass tissues and remains intact after application. Therefore, any effects on reflection, transmission, and absorption of visible light and PAR are a result of the non-volatile components of the formulation. Furthermore, because pigments are selected for use in various colors based almost solely on how they reflect, transmit, or absorb visible light it is

reasonable to conclude that pigments have the greatest potential to impact PAR and plant growth processes.

The effects of paint color on specific wavelengths of light are a direct result of the wide range of pigment sources used to produce various colors. Pigment sources for athletic field paints include both inorganic and organic sources, each of which contribute various properties with regard to color and application. Classification of all pigments into a comprehensive system is difficult due to constantly evolving manufacturing methods, recent improvements in paint properties, and new products. However, pigment classification in this review will be defined using the traditional properties associated with inorganic and organic pigments as defined by Lambourne and Strivens (1999).

Inorganic pigments possess excellent hiding power, extreme fastness to light and weathering, and excellent color stability (Endrib, 1998). They also produce various optical effects through non-selective or selective reflection and absorption of light. White, for example, is produced by the non-selective scattering of visible light while black is a result of the non-selective absorption of visible light. Various colors like red and yellow that are derived from inorganic sources are produced by reflection and absorption of light that, unlike white and black, is wavelength-dependent (Buxbaum and Pfaff, 2005). Regardless of reflective and absorptive properties, many inorganic pigments like TiO_2 (white), Fe_2O_3 red (red) and C (black) are limited in the range of colors they can produce. Furthermore, most inorganic pigments, with the exception of molybdate red, chrome yellow, and cadmium-based pigments, lack tinting strength and therefore produce dull shades when added to white to produce various colors (Herbst and Hunger, 2004). Other inorganic pigment sources such

as natural and synthetic Fe_2O_3 produce a wide variety of colors including yellow, orange, red, and brown. Among natural and synthetic products, synthetic Fe_2O_3 pigments are more widely used due to their pure hue, consistent properties, and tinting strength (Buxbaum and Pfaff, 2005).

Other pigment sources for orange and red include the organic pigments pyrazolone orange and naphthol red, respectively. Pyrazolone orange is a low-cost, bright pigment with good tinting strength, and as a result it is one of the most popular pigments for use in orange paints (Lambourne and Strivens, 1999). It is also commonly added in small amounts to yellow Fe_2O_3 to produce yellow. Napthol red is capable of producing a range of colors from orange to mid-red, and like pyrazolone orange it is also widely used due to its low cost. Other organic pigments like phthalocyanine green and blue, quinacridone magenta, and carbazole violot are used to produce green, dark blue, maroon, and purple, respectively.

Phthalocyanine pigments are the most popular source of pigments for use in green and blue paints. Phthalocyanine blue pigments cover a wide range of shades from greenish blue to reddish blue, while phthalocyanine green pigments can range from bluish green to yellowish green (Herbst and Hunger, 2004). Despite the range and popularity of phthalocyanine pigments in producing many shades of blue and green, they are incapable of producing shades of violet. Violet consists of wavelengths between 400-435 nm, which is adjacent to blue (435-480 nm) on the visible spectrum. Carbazole violet, the pigment used in purple, is not only capable of producing various shades of violet, but can also be used to impart a bluish tint to red paint as well as a reddish tint to blue paint. It is also an important

pigment used to mask the slight yellow undertone commonly encountered with the TiO_2 pigments (Herbst and Hunger, 2004).

Organic sources typically have the capacity to absorb more light than they reflect as well as have higher tinting strength and color purity (Stoye and Freitag, 1998). For these reasons, organic pigment sources are often combined with inorganic sources to produce colors that either alone cannot. Colors that contain both organic and inorganic pigment sources include light blue (phthalocyanine blue; TiO_2) and yellow (pyrazolone orange; yellow Fe_2O_3).

The extremely high absorption of light throughout the visible spectrum is characteristic of all black pigments, including carbon black. Absorption of light by black pigments can reach up to 99.8%, including infrared and ultraviolet light (Buxbaum and Pfaff, 2005). The ability of black pigments to absorb an extremely high percentage of visible light is further shown by the low percentage of pigment needed in black paints, relative to the amount of pigment needed in other colors.

Experimental Methods

There is currently little known information about how these various pigments and colors affect turfgrass photosynthesis, transpiration, and canopy temperature. However, there is a considerable amount of information available on more generally applied concepts and proven methods that may be used to investigate athletic field paint and plant health. For example, spectroradiometry measurements of light quality, portable gas exchange system

measurements of photosynthesis, and weighing lysimetry measurements of transpiration losses have all been well-documented in previous turfgrass research.

Photosynthetically active radiation and the specific wavelengths of light that lie within it are measured using radiometry techniques. Radiometry is defined as the measurement of the properties of radiant energy and is often measured in Joules (J). The rate of flow of radiant energy is referred to as the radiant flux and is often measured in watts (W), where $1W = 1\ J\ s^{-1}$. Radiant flux can be measured as it flows from a source through one or more reflecting, absorbing, or transmitting media (the earth's atmosphere, plant canopy, athletic field paint) to the receiving surface, which is often a photosynthesizing leaf (Biggs, 1984). Measurements of this radiant flux are defined by the wavelength(s) at which they are measured and include all solar radiation (Irradiance; $W\ m^{-2}$), radiation between 400 and 700 nm capable of driving photosynthesis (PAR; $W\ m^{-2}$), or radiation at specific wavelengths ($W\ m^{-2}\ nm^{-1}$). When measuring irradiance at specific wavelengths, the term spectral is added, and thus spectral irradiance is defined as the irradiance at a given wavelength per unit time and is measured using a technique called spectroradiometry.

Spectroradiometry can be used to measure the effects of athletic field paint on PAR, as well as wavelengths within PAR, available for use in painted turfgrass canopies. Specifically, the ability of various colors of athletic field paint to selectively reflect, transmit, and absorb visible light can be examined using experimental techniques modified from previous research. In a method described by Earl and Tollenaar (1997), reflection and transmission of PAR through maize (*Zea mays* L.) leaves can be performed through the use of an integrating sphere (LICOR 1800-12, LI-COR) and spectroradiometer (Apogee

Instruments). In this method, a maize leaf is placed on the exterior of the integrating sphere while a light source is used to illuminate the sphere from different locations according to the manufacturer's instructions. After a series of measurements, reflection and transmission are determined which allows for calculations of absorption using the equation: Sample absorption = 1 – reflection – transmission.

Similar measurements can be performed on various colors of athletic field paint when uniformly applied to transparency film (3M PP2500, 3M) using a wet film applicator (Gardco 8-Path, Gardco). This device allows a small quantity of liquid to be applied to surfaces at a known wet thickness for subsequent testing. The dried paint film can then be placed on the exterior of the integrating sphere as described by Earl and Tollenaar (1997) to determine the reflection, transmission, and absorption of PAR as well as wavelengths within PAR that pass through various colors and thicknesses of athletic field paint. The two main objectives of these types of measurements are to determine the ability of athletic field paint to intercept PAR which would create a shading effect, and to determine the ability of paint to differentially alter wavelengths within PAR in a color-dependent manner.

Any shading effect created by athletic field paints may have the potential to negatively affect total canopy photosynthesis (TCP) rates in painted turfgrass canopies. Reductions in photosynthesis have been documented in turfgrass research as a result of applications of humic acids (Liu et al., 1998), plant growth regulators (Beasley and Branham, 2007**;** Gaussoin et al., 1997), and selective herbicides (Willard et al., 1990). However, reductions in photosynthesis as a result of athletic field paint applications have not yet been documented.

Total canopy photosynthesis is often measured in turfgrass systems using a portable gas exchange system (LI-6400, LI-COR Inc.) connected to a transparent mylar or plexiglass chamber (Singh et al., 2011**;** Willard et al., 1990**;** Bremer and Ham, 2005). This method is performed by measuring the C exchange rate during the daytime in full light when photosynthesis is actively occurring. In this method, C exchange rates are first measured in full light in the growth chamber and then in total darkness immediately after the light measurements are recorded (achieved by covering the plexiglass chamber with opaque black fabric). Measured C exchange rates under dark conditions are considered to represent canopy, root, and soil respiration. Total canopy photosynthesis (TCP) is then calculated by adding the absolute value of dark respiration to the observed carbon exchange rate in the light (Singh et al., 2011). Measurements of TCP using this method in painted and un-painted turfgrass canopies could potentially provide insight into the extent to which TCP is reduced by applications of athletic field paint.

While the interception of PAR by paint pigments is an area of study that may provide insight into the impacts of athletic field paint on TCP, it is likely not the only factor implicated in reductions of turfgrass quality in painted turfgrass canopies. As previously mentioned, the ability of athletic field paint to impact gas exchange via transpiration is also likely problematic for plant health. The impacts of various management practices and environmental factors on turfgrass transpiration have been widely documented and include nitrogen rate, mowing height, herbicide application, and soil composition (Barton et al., 2009; Biron et al., 1981; Erickson and Kenworthy, 2011; Wherley and Sinclair, 2009; Miller, 2000.) as well as species and variety (McGroary et al., 2011; Beard et al., 1992.).

Transpiration, or evapotranspiration (ET), is often measured gravimetrically using mass balance techniques in closed or open-system lysimeters. Lysimeters are commonly considered the standard method for directly measuring evapotranspiration from plants in agricultural systems (Payero and Irmak, 2007). When this is the primary point of interest, weighing lysimeters are often the standard method for direct measurement. These lysimeters measure crop evapotranspiration by measuring the change in soil mass from an isolated soil volume over a specific amount of time. In turfgrass research, lysimeters are typically much smaller than in agricultural crop research and are frequently made from materials like polyvinyl chloride (PVC) or other plastics. These smaller lysimeters are sometimes referred to as 'microlysimeters' (Bremer, 2003). The benefits of these smaller lysimeters are typically lower cost and easier installation than their larger, agricultural counterparts.

However, one drawback to microlysimeters is that because they are not used in their natural setting as agricultural lysimeters often are, it is sometimes difficult to uniformly apply and compact soils to similar bulk densities in a manner that will not affect the objectives of the research. One way to overcome this variability is by using consistent root-zone materials including sand, sand/peat mixtures, or inorganic soil amendments like Profile, a porous ceramic soil amendment (Profile Porous Ceramic Greens Grade, Profile). Profile has been shown to produce high quality turfgrass in previous research regarding inorganic soil amendments and is desirable for use in transpiration studies due to its uniformity and adequate soil moisture retention (Miller, 2000). Feldhake et al. (1983) used microlysimeters to demonstrate that water use increases in a linear manner with incident solar radiation. However, paint is unique in the fact that it has the potential to confound the relationship

between incident solar radiation and transpiration through decreases in TCP, stomatal obstruction, and changes in canopy temperature. If stomata are obstructed by paint, then transpirational water loss would potentially decrease due to the inability of water vapor to diffuse through the pigments and resin that remain on the leaf after application. Obstruction of stomata could also lead to reductions in evaporative cooling and thus, increased canopy temperatures.

The many questions presented in this review represent a vast area of research that has yet to be conducted with regard to the impacts of athletic field paint on turfgrass health and performance. Despite potential impacts, athletic field paints are a necessary component of sporting events worldwide and will continue to be used. Therefore, a thorough understanding of their impacts on turfgrass health is vital to mitigating injury and maintaining safe, functional, and attractive athletic turf.

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ATHLETIC FIELD PAINT IMPACTS LIGHT SPECTRAL QUALITY AND TURFGRASS PHOTOSYNTHESIS

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Abbreviations: PAR, Photosynthetically active radiation; PMS, Pantone matching system; TCP, Total Canopy Photosynthesis.

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Abstract

Athletic field paints are applied to turf surfaces with little or no acute injury. However, field managers notice chronic declines in turfgrass health after repeated applications. This study examines athletic field paint impacts on spectral quality and associated turfgrass photosynthesis. Growth chamber experiments evaluated effects of red and white athletic field paint as well as one, two, three, and four repeated weekly applications on total canopy photosynthesis (TCP) of perennial ryegrass (*Lolium perenne* L.). Paint treatments were applied weekly for 6 wk with TCP recorded 24 h after each application using a gas exchange system. Spectroradiometry experiments evaluated reflection, absorption, and transmission of light at various wavelengths based on paint color, dilution, and thickness. Over a six week period all treatments reduced TCP based upon color ($P \leq 0.0001$) and dilution ($P \leq 0.0001$). Red no dilution paint produced a 75% reduction in TCP over 6 wk while white 1:1 diluted paint only produced a 19% reduction. Spectroradiometry data suggests this is likely due to reductions in photosynthetically active radiation (PAR) with red paint absorbing 51% of incident PAR while transmitting and reflecting 6% and 43%, respectively. White paint transmitted 5% of PAR while reflecting 95%. Alterations in light spectral quality resulting from athletic field paint applications can impact PAR, which may result in reduced turfgrass health.

Introduction

Athletic field paints are routinely applied to field surfaces for marking regulation lines, logos, advertisements, etc. in sporting events worldwide. Manufacturers focus much of their efforts on producing bright, distinct, uniform paints that are both affordable and non-injurious to grass species commonly used on athletic field surfaces. Within the industry, latex, water-based paints are some of the most commonly applied products. Latex paint consists of four major components: pigments, resins, solvents, and additives. Each of the components provides a different function within paint chemistry, any of which may be problematic for turfgrass health. Among these four components, pigments likely have the most potential for damage, because one of the two primary roles of pigments is to create opacity to hide or cover a surface (turfgrass leaves) by blocking visible wavelengths of light. Pigments consist of dry powders and are dependent upon desired color. Common pigments in white, black, and red paint are TiO2 (titanium dioxide), C, and Fe2O3 (iron oxide), respectively. Each is very effective in blocking light, thereby providing the required opacity. Pigments also provide color to paint through selective absorption of specific wavelengths, which may lead to turfgrass damage by altering light intensity and spectral quality.

Athletic field paints are formulated with the intent that ingredients do not cause acute injury when properly applied. However, field managers routinely notice turf injury from repeated applications (G. Miller, unpublished data, 2011). Although the cause(s) of the damage is unknown, a potential explanation lies in secondary, chronic effects on plant growth processes. One important plant process that is likely impacted by repeated paint applications is photosynthesis. Pigments may block specific wavelengths of light in the

visible spectrum and reduce photosynthetically active radiation (PAR) at leaf surfaces. Visible light and PAR share the same range of wavelengths, from 400-700 nm. Within PAR, there are also particular spectral bands that are most effectively absorbed for photosynthesis. These bands are often grouped by color; blue light is considered to be 400-500 nm and red light is considered to be 600 to 700 nm (Taiz and Zeiger, 2006). Chlorophyll a is known to have peak spectral absorption at 410, 430, and 660 nm while peak absorption for chlorophyll b occurs at 430 and 640 nm (Taiz and Zeiger, 2006). Paint pigments designed to alter visible light in order to produce a specific color may also potentially alter reflection, transmission, and absorption of PAR available for photosynthesis within turfgrass canopies.

The impacts of reduced light quantity and altered light quality on turfgrass growth have been examined in studies of shading from trees, buildings, and weeds (Bell et al., 2000; Gaskin, 1965; McKee, 1963). Reductions and alterations in light also have been linked to reductions in turf performance as well as physiological changes within grasses (McBee, 1969; Dudeck and Peacock, 1992; Wilkinson and Beard, 1975). Up to this time, however, no such studies have been conducted with paint applied to turfgrass.

This study was initiated to investigate the underlying processes responsible for declining turfgrass health with repeated painting. Using red and white paint, lab experiments first examined impacts on PAR as a result of selective color reflection, transmission, and absorption by pigments. Subsequent growth chamber experiments then examined how these impacts related to turfgrass photosynthesis.

Materials and Methods

Spectroradiometry Experiments

An experimental system was designed to quantify reflection, transmission, and absorption of PAR by red and white paint. Paint treatments were uniformly applied to transparency film (3M PP2500, 3M) using a wet film applicator (Gardco 8-Path, Gardco). The device allowed a small quantity of liquid to be applied to surfaces at a known wet thickness for subsequent testing. Paint at no dilution and a 1:1 dilution with water was applied at a uniform wet thickness of 0.125, 0.250, 0.375, 0.500, 0.625, or 0.750 mm. The final dried thickness of each film was recorded using a digital micrometer to ensure uniformity.

Reflection and transmission of light through the paint was measured between 400 and 700 nm at 0.5-nm intervals using an integrating sphere (LICOR 1800-12, LI-COR) and spectroradiometer (Apogee Instruments). Measurements were performed on each of the six wet thicknesses. The reflection reference was newly pressed BaSO4 (barium sulfate). The painted side of the transparency film faced the inside of the integrating sphere for the reflection reference and sample readings. For transmission sample and reference readings, the painted side of the transparency film faced the outside of the integrating sphere. The light source used to illuminate the integrating sphere was constant, but its location within the sphere varied between reference and sample readings as well as between reflection and transmission readings. Sample absorption was calculated as sample absorption = 1 – reflection – transmission. Data were used to calculate regression equations that described percent incident PAR reflected, transmitted, and absorbed at the various thicknesses.

Narrowband and broadband spectral data were collected at specific wavelengths to determine effects on light quality. The narrowband wavelengths were 410, 430, 640, and 660 ± 10 nm, and the broad-band wavelengths were blue (400-500 nm), red (600-700 nm), and PAR (400-700nm). To remove thickness as a potential confounding variable, a uniform thickness of 0.050 mm dried thickness was selected from the six levels of wet thickness previously mentioned. This dried thickness was obtained using 0.250 mm wet thickness for the red no dilution, red 1:1 dilution, and white 1:1 dilution treatments, and a 0.125 mm wet thickness for the white paint treatment with no dilution. The resulting 0.050 mm dried thicknesses (3 replications) were not different using Fischer's protected LSD test at $\alpha < 0.05$. Measurements of reflection and transmission, and calculations of absorption were determined as previously mentioned using the integrating sphere and spectroradiometer.

Growth Chamber Experiments

The research was conducted at the Southeastern Plant Environment Laboratory at North Carolina State University in Raleigh, NC. Sixty pots were prepared with a 50:50 v/v sand and peat substrate based on the original "Cornell Mix" (Boodley and Sheldrake, 1972). The substrate was steam-sterilized, placed into 15.8-cm diameter pots, and seeded on 19 Feb. 2009 with 'Palmer V' perennial ryegrass at a rate of 55 g m-2. Perennial ryegrass was selected due to its widespread use as an overseeding crop on bermudagrass (Cynodon spp.) athletic fields. After seeding, the pots were placed into a growth chamber maintained at 22/18oC (day/night) with a 9-hr photoperiod (0730 to 1620 h) and a photosynthetic photon flux density of 650 µmol m-2 s-1 provided by a combination of incandescent and fluorescent

lamps. Water and nutrient solution were applied twice daily throughout the ryegrass establishment period and then once daily during experimental periods. The "standard nutrient solution" is described in detail in the North Carolina State University Phytotron Procedural Manual (NCSU, 2011). After initial establishment, all pots (experimental units for both studies) were re-seeded two additional times on 6 and 16 Mar. 2009 at 55 g m-2 to ensure a dense, uniform turf canopy prior to application of paint treatments. Pots were mowed twice weekly at 2.5 cm using a handheld shear (194380 Oster Showmaster).

Paint Application

Before application of paint treatments, turf in all sixty pots was allowed to reach maturity and then experimental units were randomly divided into two sets, each for a separate study . The first study (hereafter referred to as "Study 1") began on 27 May 2009 and consisted of six weekly applications of two colors (red and white), two dilutions of each (no dilution and 1:1 dilution with water), and an un-painted control. The second study (hereafter referred to as "Study 2") began on 3 June 2009 and consisted of weekly applications of red non-diluted paint for 1, 2, 3, or 4 wk, as well as an un-painted control. In Study 2, all treatments received paint applications during week one, then three treatments during week two, two treatments during week three, and one treatment during week four. Red non-diluted paint was selected for Study 2 due to it having the most negative impacts on photosynthesis during Study 1. Both studies were repeated over two 6x-wk experiments (hereafter referred to as Exp. 1 and 2), and treatments in each experiment had three replications. In both studies, Exp. 2 began one week after the conclusion of Exp. 1. All paint

treatments consisted of Pioneer Brite Stripe Airless paint (Pioneer Athletics). The Pantone Matching System (PMS), a standardized color reproduction system, was used to define the red treatment as PMS 186. The 1:1 dilution treatment was a 1:1 volumetric dilution of paint and water. Paint treatments were applied using a CO2-pressurized sprayer with flatfan nozzles (Teejet8004VS, Teejet Spraying Systems Co.) calibrated to apply approximately 168 L ha-1. This rate was achieved by four applications in multiple directions to each pot, which ensured uniform coverage of turfgrass leaves.

Photosynthesis Measurements

Carbon exchange rates were measured in Study 1 24 h after each of six weekly paint applications as well as 3 wk after all paint applications ceased. In Study 2, C exchange rates were measured 25 h after each of four paint applications as well as 1 and 2wk after all paint applications ceased. Carbon exchange rates were determined by enclosing the turfgrass canopy in a transparent plexiglass chamber (956.42cm3) connected to a portable gas exchange system (LI-6400, LI-COR Inc.). Measurements of C exchange rate were always taken between 1000 and 1500 h. Carbon exchange rates were measured in full light in the growth chamber and in total darkness immediately after light measurements were recorded (achieved by covering the plexiglass chamber with opaque black fabric). Measured C exchange rates under dark conditions were considered to represent canopy, root, and soil respiration. Total canopy photosynthesis (TCP) was calculated by adding the absolute value of dark respiration to the observed carbon exchange rate in the light (Singh et al., 2011). Canopy temperature was measured immediately prior to enclosure of the turfgrass in the

transparent plexiglass chamber using an infrared digital thermometer (Fluke 63IR, Fluke Inc.).

Statistical Analysis

Data from spectroradiometry and growth chamber experiments were subjected to ANOVA to determine treatment effects. TCP and canopy temperature data showed significant treatment effects but also showed interactions with experiment. Therefore, growth chamber data from both 6-wk experiments within Study 1 and Study 2 were analyzed and presented separately with treatment x experiment interactions reported in appropriate ANOVA tables. Treatments within all experiments were subjected to Fischer's Protected LSD test at the 0.05 probability level when F-tests indicated significant treatment effects. Orthogonal contrasts were produced for analysis of reflection, transmission, and absorption of PAR averaged over six wet-applied paint thicknesses. Orthogonal polynomials were used to produce regression curves for analysis of reflection, transmission, and absorption of PAR. Only highest-order interactions (quadratic or cubic) for each treatment were reported. Orthogonal contrasts also were produced to compare treatment effects on net canopy photosynthesis and canopy temperature in growth chamber experiments.

Results

Spectroradiometry Experiments

The ability of paints to reflect, transmit, and absorb PAR was found to be different ($P \leq 0.0001$) when averaged over six wet thicknesses and based on orthogonal contrasts (Table

1). Differences also were found between and within paint treatments (color and dilution). Red 1:1 dilution and red no dilution paint reflected the least amount of PAR at 41.8 and 42.9%, respectively, while the white paint treatments reflected much higher amounts (94.5 and 97.0%). A small difference in absorption of PAR was seen between the red treatment (52.7%) and when it was diluted (48.5%), while no absorption was found in either treatment of white paint. Differences in transmission of PAR were less dramatic, although still significant, with the highest amount transmitted through red 1:1 dilution (9.7%) and the lowest through white paint with no dilution (3.0%).

Regression plots revealed that with increasing thickness, the percent transmitted decreased rapidly to minimal levels (Fig. 1; Table 2). As seen with results in Table 1, reflection of PAR was always higher for white paint compared to red paint over all six wet thicknesses, while absorption by red was always higher than white.

The narrow- and broadband experiments also illustrate the highly reflective characteristics of white paint when measured at a uniform dried thickness (Table 3). Narrowband data indicate reflection of PAR by white paint and diluted white paint is between 94.4 and 100% at wavelengths of 430, 640, and 660 nm. Reflection was slightly lower at 410 nm, being 80.9%. As expected from the PAR results above, red paint treatments had higher absorption at all broad and narrow-band wavelengths. Red non-diluted and 1:1 diluted paint exhibited a capacity for increased absorption of PAR compared to white where red non-diluted paint absorbed 45.0% PAR at 0.125 mm wet thickness and 55.9% PAR at 0.75 mm wet thickness (Fig. 1). Likewise, red 1:1 diluted paint absorbed 41.8 and 53.1%, respectively, at the same thicknesses. Narrow- and broadband wavelength data

support PAR data as well as indicate red paint's ability to selectively absorb various wavelengths within PAR. Red non-diluted and diluted treatments exhibited high absorption at 410 and 430 nm by absorbing 90.2 and 91.0%, respectively, at these wavelengths. However, at 640 nm red non-diluted paint only absorbed 12.8% of light along with 12.4% at 660 nm. This absorption was further reduced in red 1:1 diluted paint to 4.0 and 4.5%.

Reflection of PAR by red non-diluted paint was 70.9% in the 600-700 nm red broadband wavelengths while only reflecting 8.0% of light in the blue broad-band wavelengths. Narrowband wavelength data also indicate that more light is reflected in the 640 and 660 nm wavelengths than the 410 and 430 nm wavelengths as a result of red paint. The 640 and 660 nm wavelengths reflected 75.9 and 75.2% of light, respectively, while the 410 and 430 nm wavelengths only reflected 9.7 and 8.9%.

Growth Chamber Experiments

Study 1

Reductions in TCP as a result of all paint treatments were documented and were consistent over both 6-wk experiments ($P \leq 0.0001$) despite an interaction between treatment and experiment ($P \leq 0.0006$) as indicated by ANOVA (Table 4). Red no-dilution paint produced the greatest reduction in TCP followed by red 1:1 dilution, white no dilution, and white 1:1 dilution, respectively (Table 5). Red no-dilution paint reduced TCP by 75% in Exp. 1 and by 79% in Exp. 2. Red 1:1 dilution paint reduced TCP by 48% and 54%, in Exp. 1 and 2, respectively while white paint treatments were less injurious. Orthogonal contrasts indicate the importance of both color and dilution on TCP in both experiments ($P \leq 0.0001$). Red

paint was more damaging to TCP than white paint, although diluting each color reduces these negative effects. An orthogonal contrast used to compare TCP of all paint treatments to the un-painted control was also significant ($P \leq 0.0001$).

In addition to decreases in TCP, increases in canopy temperature were also significant among paint treatments ($P \leq 0.0001$) with the highest increase in temperature resulting from red no-dilution paint in both experiments (Table 5). Furthermore, red 1:1 dilution, white no-dilution and white 1:1 dilution all increased temperatures relative to the control in Exp. 1, but only red 1:1 dilution produced further increases in canopy temperatures in Exp. 2. In reference to canopy temperature, dilution did not affect canopy temperature whereas paint and color had an impact in both experiments.

Study 2

Red no-dilution paint was selected for use in Study 2 due to its ability to cause the highest reductions in TCP during Study 1. In Study 2, repeated applications of red no-dilution paint that were applied for 1, 2, 3, or 4 wk were found to produce reductions in TCP as well as increases in canopy temperature that were most strongly attributed to treatment effects ($P \leq 0.0001$) as indicated by ANOVA (Table 6). Date, experiment, and treatment interactions with each also contributed to the model. In both experiments, each additional week that red non-diluted paint was applied resulted in further decreases in TCP over the entire six week experiment (Table 7). One, two, three, and four applications of red non-diluted paint resulted in 12, 24, 37, and 53% reductions, respectfully in TCP during Exp. 1 and results were similar results in Exp. 2.

To assess the ability of perennial ryegrass to recover after application of paint treatments ceased, TCP data for each treatment were normalized to the control for weeks one through six and presented in Fig. 2. In each treatment, photosynthetic recovery began within 1 wk after final application of one, two, three, or four paint treatments. Perennial ryegrass subjected to only one application of red no-dilution paint was able to achieve 84% of TCP compared to the untreated control within 1 wk after application and up to 94% recovery by 3 and 4 wk after the last application. Further applications of red no-dilution paint resulted in less photosynthesis recovery. At week six, for example, perennial ryegrass receiving one, two, and three applications of paint recovered to TCP rates similar to the control while perennial ryegrass receiving four applications was only able to recover to 84% of the untreated control.

Discussion

Spectroradiometry

A primary objective of this study was to examine the impact of athletic field paint on PAR. Varying effects on PAR and net canopy photosynthesis as a result of painting are a direct result of paint chemistry and pigment composition. Red and white athletic field paints differ fundamentally in their pigment source, with white paint being composed primarily of TiO_2 pigments while red paint is composed primarily of Fe_2O_3 pigments. These pigments produce different colors due to their varying ability to reflect, transmit, or absorb PAR at specific wavelengths. Titanium dioxide is widely used as a white pigment due to its superior light-scattering properties over all wavelengths in the visible spectrum (Buxbaum and Pfaff, 2005). Alternatively, light-scattering by colored pigments, such as red, is much more

wavelength dependent. Red Fe2O3 reflects approximately 20 to 30% more visible light in the 600-700 nm range than in the remaining wavelengths of the visible spectrum (Endrib, 1998), an effect shown in the broad- and narrowband data in Table 3, which produces the characteristic red color.

The importance of color in altering PAR is clearly shown in our data sets. Orthogonal contrasts ($P \leq 0.0001$) illustrate the effects of color on PAR (Tables 1 and 2) while treatment effects ($P \leq 0.0001$) illustrate the effects of color on broad- and narrowband wavelengths (Table 3). Furthermore, broad- and narrowband wavelength data are consistent with PAR data in that much larger amounts of PAR are reflected by white paint treatments than red paint treatments over all wavelengths.

Reflection of PAR by white no-dilution paint was so large at 640, 660, and 600-700 nm that it produced summed values of reflection, transmission, and absorption of PAR exceeding 100%. The likely explanation for values exceeding 100% lies in the higher refractive index of TiO2 relative to BaSO4. As the refractive index increases, so does the ability of a pigment to scatter light. Two TiO2 pigments commonly used in paints are rutile and anatase, which have refractive indices of 2.80 and 2.55, respectively. Barium sulfate, which makes up the interior wall of the Licor 1800-12 integrating sphere only has a refractive index of 1.64 (Buxbaum and Pfaff, 2005). Therefore, the highly reflective nature of TiO2 produced reflection readings near or greater than 100% while still transmitting light in the 640, 660, and 600-700 nm range.

The methodology used for measurements of narrowband effects influenced the absolute values for reflection and transmittance of white paint. Data indicate that wet

thicknesses of white non-diluted paint dried much thicker than similar wet thicknesses of red paint (Fig. 3). Paints are fundamentally different due to varying sources and amounts of pigments required to produce different colors. White paint possesses a much higher percentage of pigment solids than red paint and therefore dries thicker. (G. Sajner, personal communication, 2011). The wet thickness selected for the white non-diluted treatment was 0.125 mm whereas wet thicknesses for other treatments were 0.250 mm. When dried, each of these produced a uniform dried thickness of 0.050 mm for comparison. The 0.125 and 0.250 mm wet thicknesses were among the thinnest treatments produced for observation, so it is not surprising these thicknesses would transmit light. However, it is worth noting that PAR data collected over all six wet thicknesses and averaged together resulted in reflection, transmission, and absorption values that summed to 100%, as expected.

Differences in transmission over broad and narrow-band wavelengths based on color were small and in most cases insignificant. The largest difference over any measured wavelength was recorded in the broad-band wavelength 400 to 700nm where transmission of PAR through red 1:1 dilution paint was 14.8% while transmission through white no-dilution paint was only 4.7%. However, as indicated in Fig. 1, transmission of light through paint decreases as paint thickness increases. Athletic field managers routinely apply paint at high levels of thickness to achieve uniform coverage as well as bright, distinct lines and logos. As a result of this, transmission of PAR likely has much less potential impact on turfgrass photosynthesis than either reflection or absorption.

Impacts on Photosynthesis

The second objective of this study was to determine if alterations in PAR and light spectral quality were sufficient to affect TCP of perennial ryegrass. As previously mentioned, results from growth chamber experiments indicate that alterations and reductions in PAR, as well as broad- and narrowband wavelengths, have the capacity to reduce TCP of perennial ryegrass. The high absorption of PAR by red paint, coupled with extremely high reflection of PAR by white paint result in dramatic differences in available PAR within the turfgrass canopy. Previous research with crop plants has shown that available PAR can be altered by reflection from various colors of paint and is sufficient to affect plant growth. Kasperbauer (2000) found that upwardly reflected light from painted plastic covers beneath cotton (Gossypium hirsutum L.) canopies differed by color. Plants grown over plastic surfaces painted white received substantially more PAR than plants grown over plastics painted red and green. In a separate study, it was found that carrots (Daucus carota L.) grown over plastic mulches painted white, yellow, red, blue, and green received varying amounts of reflected PAR (Antonious and Kasperbauer, 2002). As in our experiments, white mulches reflected substantially more PAR than red mulches. The PAR that is reflected within the turfgrass canopy by pigments is likely still available for absorption by chlorophyll in areas with cracked leaf surfaces or partial paint coatings and on abaxial leaf surfaces or lower portions of the canopy that may not have received paint. Furthermore, as turfgrasses grow and remaining pigments are mowed off, increased reflectance of light by white paint can be useful for photosynthesis by newly formed leaves. This increased reflection of PAR by white

paint relative to red paint is likely responsible for the smaller reductions in TCP found in growth chamber Study 1.

The absorption of PAR by pigments in red paint has the potential to reduce TCP, an analogous effect to that of shading. Shade is typically considered to be a result of light interception by trees, structures, or weeds. However, light that is intercepted and absorbed by paint pigments can also produce reductions in available PAR, as indicated by our spectroradiometry experiments. Decreased turfgrass growth as a result of reductions in PAR has previously been reported. Baldwin et al. (2009) found that shade fabrics filtering wavelengths 360 to 720 nm produced clipping yields of only 21.4% of treatments receiving no shade. Similarly, in our experiments, red paint treatments absorbed 50.6% more PAR than white paint treatments which resulted in much lower rates of net canopy photosynthesis. Also in the Baldwin et al. (2009) study, shade fabrics that selectively filtered wavelengths of light within PAR reduced growth. For example, shade fabrics filtering wavelengths 560 to 720 nm, yet allowing passage of blue light (400 to 500 nm) for 6 wk, resulted in clipping yields of 'Tifway' bermudagrass [Cynodon dactylon (L.) Pers. X Cynodon transvaalensis Burtt-Davy] that were only 38.2% of control. Shade cloths filtering 360 to 520 nm and 360 to 560 nm while allowing passage of red light (600 to 700 nm) also reduced clipping yields. Spectroradiometry experiments conducted in our study show that absorption of blue light in broad- and narrowband wavelengths was particularly high for red paint treatments due to the selective nature of the Fe2O3 pigments. Red no-dilution paint absorbed 90.2, 91.0, and 91.9% of blue light at 410, 430, and 400-500 nm, respectively. The absorption of PAR, as well as light in selective broad and narrow-band wavelengths produces a similar effect to

shading because the quantity and quality of light has been reduced through absorption by paint pigments. Any light absorbed by these pigments is no longer available for use by plants and can produce reductions in TCP seen in the growth chamber experiments.

Results from growth chamber Study 2 indicate the chronic nature of the red non-diluted effects. The ability of TCP to recover from the painting decreased as application number increased. Reductions in turfgrass performance over time as a result of excessive shade have been routinely documented. In the Baldwin et al. (2009) study, turfgrass quality and clipping yield of bermudagrass and zoysiagrass (Zoysia matrella (L.) Merr.) also decreased as duration of shade increased. Reductions in traffic tolerance were observed in several bermudagrass and zoysiagrass cultivars as the time under shade and number of traffic applications increased (Trappe et al., 2011). The notion that reductions in turfgrass quality and performance are caused by chronic shading by athletic field paint applications is consistent with athletic field paints not being acutely toxic to turfgrasses. Also, anecdotal evidence from professional athletic field managers indicates that decreased growth and density from athletic field paint applications are usually noticed only after multiple painting events. These decreases become more severe as the number of paint applications increase.

To fully understand the capacity pigments have to affect turfgrass photosynthesis, it is important to understand the role that pigments play in paint relative to the other ingredients (resins, solvents, and additives). Pigments are dispersed into the resin portion of the paint, which provides adhesion for the paint to stick to turfgrass leaves. Solvents are then used to dilute the paint as well as provide uniformity in application thickness. Additives often serve as wetting agents that help incorporate the dry pigments into the liquid paint as well as

surface tension modifiers that aid in coating the leaf surface. Once the paint is applied, the solvent evaporates leaving a dried paint film on the leaf surface that is made up primarily of pigments. As such, pigments play the greatest role in alterations of PAR within the turfgrass canopy and resulting photosynthesis because unlike the other three components of paint, they remain in the turfgrass canopy after application.

Pigments present in athletic field paint have the capacity to reduce turfgrass growth through the absorption of PAR that would otherwise be available for plant use. They also have the capacity to alter spectral quality through selective reflection, transmission, and absorption of various wavelengths within PAR. Photosynthetically active radiation, broad-band, and narrow-band spectroradiometry data support the theory that TCP can be affected by these alterations and reductions in light spectral quality and quantity as a result of paint color, thickness, and dilution. This data suggests that potential exists for paint manufacturers to identify and use pigments that are more selective in their ability to reflect specific wavelengths necessary to produce a certain color while not excessively absorbing other wavelengths useful for photosynthesis. It also suggests that field managers may alter their painting habits, especially with darker, more injurious colors, to lower rates and raise dilution factors to still allow for active turfgrass photosynthesis. However, the delicate balance between producing bright, distinct logos and preserving turfgrass health is one that field managers need to dictate based on their individual situation.

There is need for further exploration into the impacts of athletic field paint on turfgrass photosynthesis and growth including the evaluation of additional colors, products, rates, and timings. Athletic field paint applications are a necessary component of popular

athletic events worldwide and establishing the relationship between paint and turfgrass health not only has the potential to improve the safety and aesthetics of athletic turf, but also the potential to fundamentally change the nature of paint products themselves.

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Table 1. Reflection, transmission, and absorption of photosynthetically active radiation (400-700nm) by red and white paint averaged over six wet thicknesses (0.125, 0.250, 0.375, 0.500, 0.625, and 0.750 mm) using an integrating sphere and spectroradiometer.

Treatment	Reflection	Transmission	Absorption
	%		
Red no dilution	42.9 c[†]	4.4 bc	52.7 a
Red 1:1 dilution	41.8 c	9.7 a	48.5 b
White no dilution	97.0 a	3.0 c	0.0 c
White 1:1 dilution	94.5 b	5.5 ab	0.0 c
	Analysis of variance		
Treatment	***	***	***
	Orthogonal contrasts		
Red no dilution vs. 1:1 dilution	***	***	***
White no dilution vs. 1:1 dilution	***	***	***
Red vs. white	***	***	***

***Significant at the 0.001 probability level
†Means within columns followed by the same letter are not significantly different according to Fisher's Protected LSD (P=0.05)

Table 2. Intercepts, linear, quadratic, cubic coefficients and standard error for regression equations of reflection, transmission, and absorption of photosynthetically active radiation (PAR) (400-700nm) by red and white paint at six wet thicknesses (0.125, 0.25, 0.375, 0.5, 0.625, and 0.75 mm) using an integrating sphere and spectroradiometer.

PAR	Treatment	r^2	Intercept	Coeffecients (SE)		
				Linear	Quadratic	Cubic
Reflection	Red no dilution	0.986	33.78 (1.15)	7.36 (1.31)	-1.69 (0.42)	0.13 (0.03)
	Red 1:1 dilution	0.981	32.80 (0.97)	4.31 (0.63)	-0.40 (0.08)	
	White no dilution	0.995	89.32 (0.53)	6.21 (0.61)	-1.45 (0.19)	0.11 (0.01)
	White 1:1 dilution	0.981	71.88 (3.60)	16.98 (4.20)	-3.72 (1.34)	0.26 (0.12)
				Orthogonal contrasts		
	Red no dilution vs. red 1:1 dilution			***	NS†	*
	White no dilution vs. white 1:1 dilution			***	***	***
	Red vs. white			***	***	***
Transmission	Red no dilution	0.998	28.23 (1.35)	-17.03 (1.54)	3.57 (0.49)	-0.25 (0.04)
	Red 1:1 dilution	0.989	30.16 (1.80)	-9.04 (1.18)	0.73 (0.16)	
	White no dilution	0.999	16.25 (0.19)	-8.50 (0.22)	1.67 (0.07)	-0.11 (0.01)
	White 1:1 dilution	0.994	30.96 (2.79)	-14.86 (3.18)	2.75 (1.02)	-0.18 (0.09)
				Orthogonal contrasts		
	Red no dilution vs. red 1:1 dilution			***	***	***
	White no dilution vs. white 1:1 dilution			***	***	NS
	Red vs. white			***	***	**
Absorption	Red no dilution	0.999	37.97 (0.21)	9.67 (0.24)	-1.88 (0.07)	0.13 (0.01)
	Red 1:1 dilution	0.995	39.52 (1.84)	1.62 (2.09)	0.69 (0.67)	-0.09 (0.06)
	White no dilution	0.984	0.73 (0.50)	-1.04 (0.57)	0.36 (0.18)	-0.02 (0.01)
	White 1:1 dilution	0.976	-0.37 (0.24)	0.56 (0.27)	-0.23 (0.08)	0.03 (0.01)
				Orthogonal contrasts		
	Red no dilution vs. red 1:1 dilution			***	***	***
	White no dilution vs. white 1:1 dilution			***	NS	NS
	Red vs. White			***	***	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01probability level.
***Significant at the 0.001 probability level.
†NS, not significant at $P \leq 0.05$

Table 3. Reflection, transmission, and absorption of light at narrow-band and broad-band wavelengths by red no dilution, red 1:1 dilution, white no dilution, and white 1:1 dilution paint when applied to transparency film at 0.050mm dried thickness.

		Narrowband				Broadband		
PAR†	Treatment	410 nm	430 nm	640 nm	660 nm	400-700 nm	400-500 nm	600-700 nm
		%				%		
Reflection	Red no dilution	9.74 c‡	8.95 b	75.97 b	75.22 b	43.64 c	8.01 d	70.94 b
	Red 1:1 dilution	10.28 c	9.55 b	67.92 c	66.47 c	39.96 d	8.58 c	63.85 c
	White no dilution	80.91 a	95.02 a	100.26 a	100.18 a	95.27 a	91.68 a	97.64 a
	White 1:1 dilution	79.46 b	94.40 a	100.23 a	100.04 a	92.98 b	90.93 b	97.35 a
		Analysis of variance						
	Treatment	***	***	***	***	***	***	***
Transmission	Red no dilution	0.02 b	0.01 b	11.17 b	12.37 b	5.76 c	0.01 b	10.56 b
	Red 1:1 dilution	0.02 b	0.02 b	28.04 a	29.04 a	14.87 a	0.01 b	26.73 a
	White no dilution	0.84 a	3.81 a	10.89 b	11.01 b	4.72 d	4.86 a	10.64 b
	White 1:1 dilution	1.08 a	4.36 a	11.45 b	11.54 b	7.01 b	5.39 a	11.15 b
		Analysis of variance						
	Treatment	***	***	***	***	***	***	***
Absorption	Red no dilution	90.23 a	91.04 a	12.84 a	12.40 a	50.59 a	91.98 a	18.48 a
	Red 1:1 dilution	89.69 a	90.42 a	4.03 b	4.47 b	45.12 b	91.40 a	9.41 b
	White no dilution	18.24 c	1.17 b	NC‡	NC	0.00 c	3.44 b	NC
	White 1:1 dilution	19.45 b	1.23 b	NC	NC	0.00 c	3.66 b	NC
		Analysis of variance						
	Treatment	***	***	***	***	***	***	***

***Significant at the 0.001 probability level.

†PAR, photosynthetically active radiation.

‡Means within columns followed by the same letter are not significantly different according to Fisher's Protected LSD (*P*=0.05)

§ NC, not calculated. Absorption not calculated due to ability of white paint to reflect and transmit a sum >100%.

Table 4. Analysis of variance for perennial ryegrass photosynthetic response from weekly applications of red and white paint (no dilution and 1:1 dilution) treatments and unpainted control in a controlled environment growth chamber during two 6-wk experiments at the Southeastern Plant Environment Laboratory in Raleigh, NC.

	Analysis of variance			
Source	df	Mean square	*F*	*P* > *F*
Treatment	4	513.2	857.6	<0.0001
Experiment	1	0.1	0.1	0.7682
Replication	2	0.1	0.1	0.9106
Date	5	11.5	19.3	<0.0001
Treatment x date	20	0.9	1.6	0.0540
Treatment x experiment	4	3.1	5.2	0.0006

Table 5. Perennial ryegrass total canopy photosynthesis and temperature responses from various paint applications treatments during two six-week experiments at the Southeastern Plant Environment Laboratory in Raleigh, NC.

	Experiment 1				Experiment 2			
Treatment	CER† in light	CER in dark	Total canopy photosynthesis	Canopy temperature	CER in light	CER in dark	Total canopy photosynthesis	Canopy temperature
	μmol CO_2 m^{-2} s^{-1}			°C	μmol CO_2 m^{-2} s^{-1}			°C
Untreated	8.7a‡	3.5 a	12.2 a	23.2 c	9.3 a	3.8 a	13.1 a	24.7 c
White 1:1 dilution	6.5b	3.3 a	9.8 b	24.0 b	6.3 b	3.7 a	10.1 b	24.7 c
White no dilution	3.4c	3.4 a	6.8 c	23.9 b	2.4 d	3.8 a	6.2 c	24.5 c
Red 1:1 dilution	3.4c	2.9 b	6.3 d	24.1 b	3.1 c	2.9 b	6.0 c	25.8 b
Red no dilution	-0.3d	3.4 a	3.0 e	24.7 a	-1.0 e	3.7 a	2.7 d	26.3 a
	Analysis of Variance							
Treatment	***	***	***	***	***	***	***	***
Date	***	**	***	NS§	***	***	***	***
Treatment x date	***	*	***	NS	***	***	**	NS
	Orthogonal Contrast							
Paint vs. no paint	***	***	***	***	***	*	***	***
Red vs. white	***	**	***	***	***	***	***	***
No dilution vs. 1:1 dilution	***	**	***	NS	***	***	***	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
***Significant at the 0.001 probability level
†CER, carbon exchange rate, where sum of CER in light and absolute value of CER in dark equal total canopy photosynthesis
‡Means within columns followed by the same letter are not significantly different according to Fisher's Protected LSD (P=0.05)
§NS, not significant at $P \leq 0.05$

Table 6. Analysis of variance for perennial ryegrass photosynthetic response due to zero, one, two, three, or four weekly treatments of red non-diluted paint during two 6-wk experiments in a controlled environment growth chamber at the Southeastern Plant Environment Laboratory in Raleigh, NC.

	Analysis of variance			
Source	df	Mean square	*F*	*P* > *F*
Treatment	4	346.3	281.9	<0.0001
Experiment	1	47.2	38.4	<0.0001
Rep	2	3.2	2.5	0.0807
Date	5	140.2	114.1	<0.0001
Treatment x Date	20	29.7	24.2	<0.0001
Treatment x Experiment	4	7.2	5.9	0.0002

Table 7. Perennial ryegrass total canopy photosynthesis and temperature responses from 0, 1, 2, 3, or 4 applications of red no dilution paint during two six-week experiments at the Southeastern Plant Environment Laboratory in Raleigh, NC.

	Experiment 1				Experiment 2			
Treatment	CER[†] in light	CER in dark	Total canopy photosynthesis	Canopy temperature	CER in light	CER in dark	Total canopy photosynthesis	Canopy temperature
	μmol CO_2 m^{-2} s^{-1}			°C	μmol CO_2 m^{-2} s^{-1}			°C
Untreated	9.5 a[‡]	3.7 a	13.2 a	23.5 c	9.5 a	3.9 a	13.5 a	22.2 c
One application	7.9 b	3.7 a	11.5 b	23.5 c	7.7 b	3.2 b	10.9 b	23.2 b
Two applications	6.7 c	3.2 b	10.0 c	23.9 bc	5.1 c	2.7 c	7.9 c	23.3 ab
Three applications	4.9 d	3.2 b	8.2 d	24.2 ab	3.9 d	2.7 c	6.6 d	23.2 b
Four applications	3.3 e	2.7 c	6.1 e	24.3 a	2.4 e	2.4 d	4.9 e	23.9 a
	Analysis of variance							
Treatment	***	***	***	**	***	***	***	***
Date	***	***	***	***	***	***	***	***
Treatment x date	***	NS	***	***	***	***	***	*

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
***Significant at the 0.001 probability level.
[†]CER, carbon exchange rate, where sum of CER in light and absolute value of CER in dark equal total canopy photosynthesis
[‡]Means within columns followed by the same letter are not significantly different according to Fisher's Protected LSD (P=0.05)
NS, not significant at $P \leq 0.05$

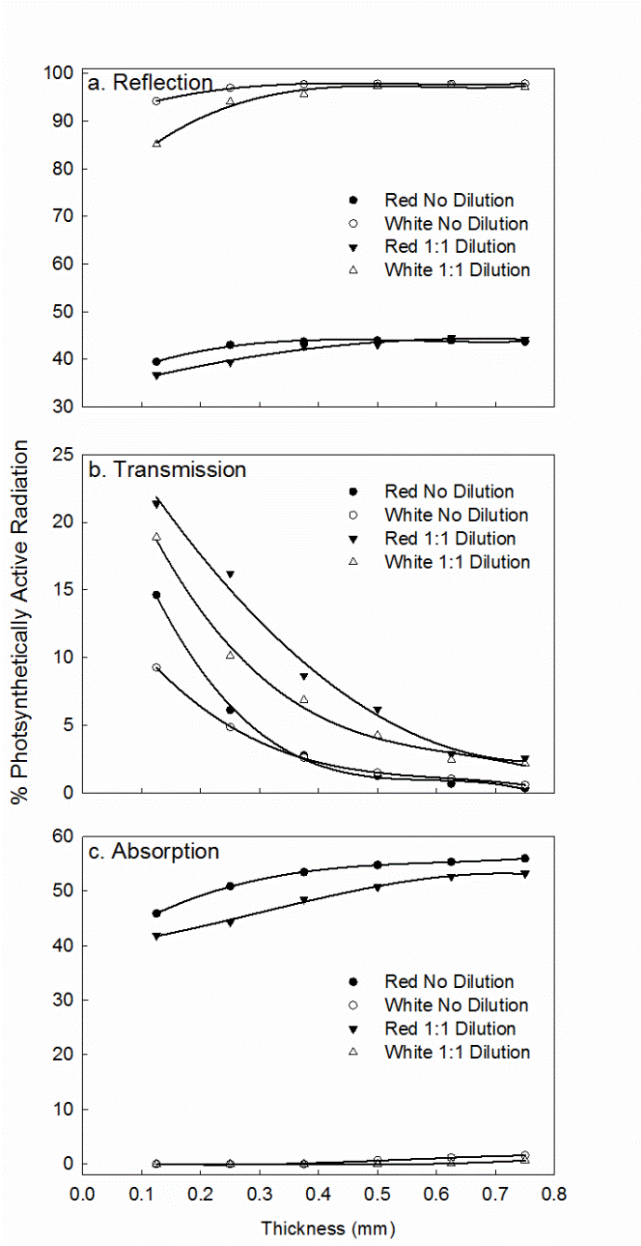

Figure 1. Reflection (a), transmission (b), and absorption (c) of photosynthetically active radiation (400-700nm) of red non-diluted, red 1:1 diluted, white non-diluted, and white 1:1 diluted paint when applied to transparent film at six wet thicknesses (0.125, 0.250, 0.375, 0.500, 0.625, and 0.750 mm). Each data point is the mean of three replicates. Scales for each y-axis are based on minimum and maximum percent photosynthetically active radiation for each observation.

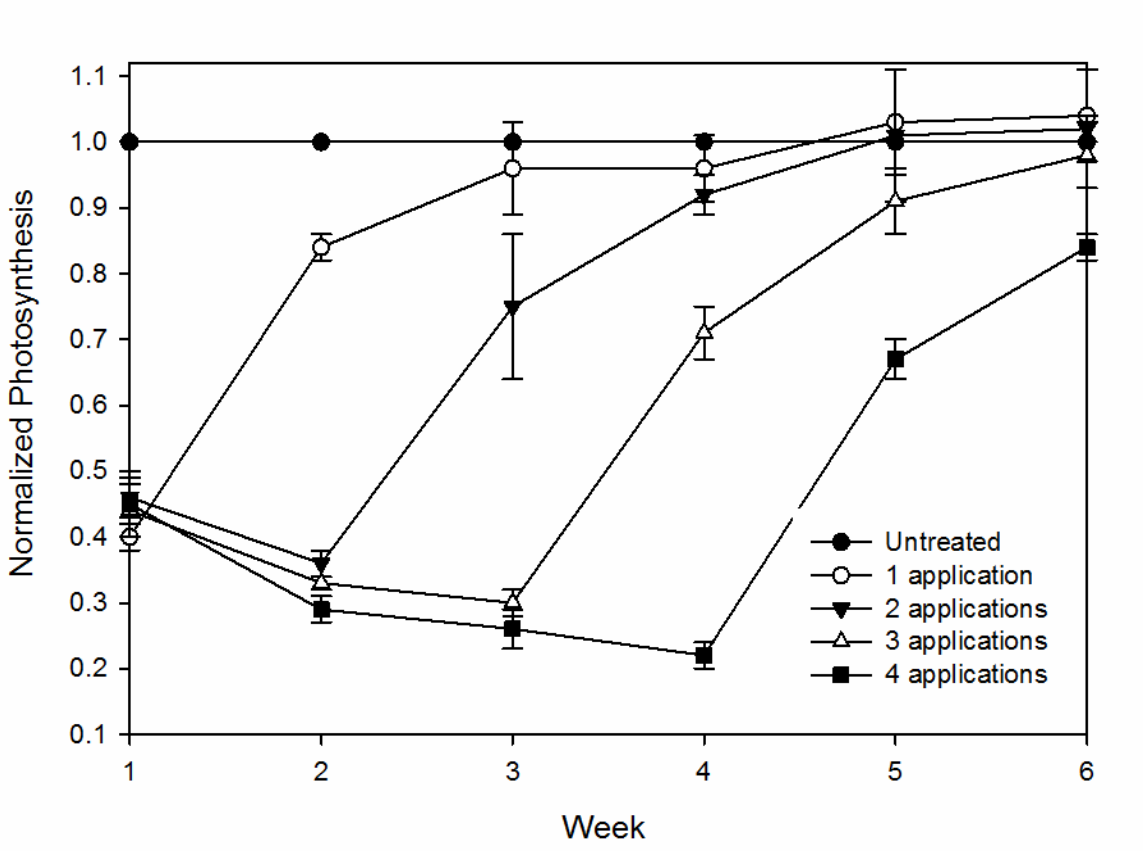

Figure 2. Normalized photosynthetic rates of perennial ryegrass measured 24 h after zero, one, two, three, or four successive weekly applications of red non-diluted paint in a controlled environment growth chamber at the Southeastern Plant Environment Laboratory in Raleigh, NC. Data points at weeks five and six were collected 1 and 2 wk, respectively, after the last paint application.

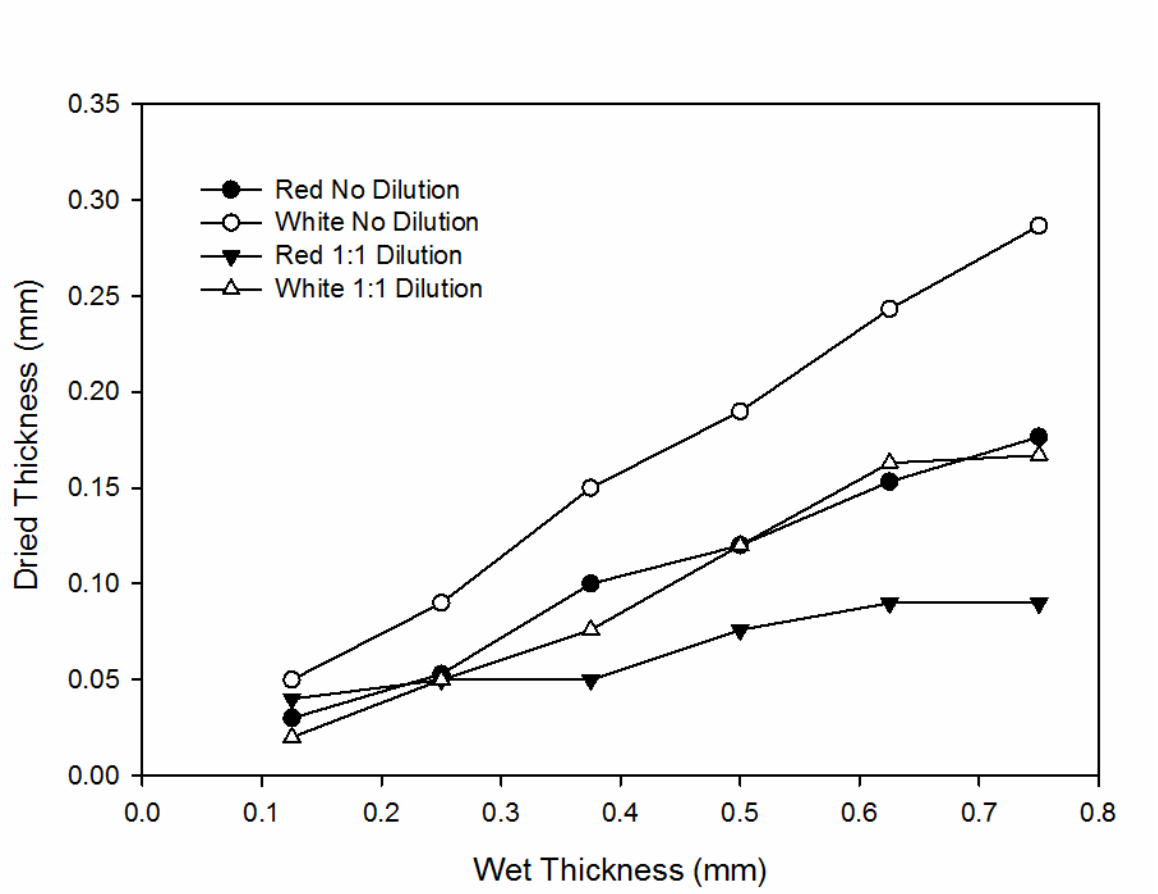

Figure 3. Dried thickness of paint treatments applied at 0.125, 0.250, 0.375, 0.500, 0.625, and 0.750 mm wet thickness. Standard Error (SE) is for the treatment mean of each applied wet thickness.

ATHLETIC FIELD PAINT DIFFERENTIALLY ALTERS LIGHT SPECTRAL QUALITY AND BERMUDAGRASS PHOTOSYNTHESIS

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Abbreviations: PAR, Photosynthetically active radiation; PMS, Pantone matching system; TCP, Total Canopy Photosynthesis.

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Abstract

Painting of athletic fields is widespread throughout the world and can often cause declines in turfgrass health. Visible light and photosynthesis share the same wavelengths (400-700 nm), and it was hypothesized that alterations in visible light to produce specific colors would lead to reductions in photosynthetically active radiation (PAR) and total canopy photosynthesis (TCP). Lab experiments using a spectroradiometer and LICOR 1800-12 integrating sphere examined the impacts of ten colors of athletic field paint on PAR as well as wavelengths within PAR. These colors were then applied weekly for five weeks to 'Tifway' bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy], and TCP was measured using a gas exchange system 24 h after each application. Spectroradiometry analyses revealed the significant effects of paint color ($P \leq 0.001$) on reflection, transmission, and absorption of PAR. Lighter colors including white, yellow, orange, and red reflected 47-92% of PAR, while darker colors including green, black, and dark blue absorbed 87- 95% of PAR. Accompanying gas exchange measurements revealed that TCP was most negatively correlated with absorption of PAR (r = -0.959; $P \leq 0.001$) and that darker colors negatively impact TCP more than lighter colors. The results clearly indicate that damage to turfgrasses with long-term painting will be difficult to avoid, and this is particularly true with darker colors of paint.

Introduction

Painting of turfgrass athletic fields is a common practice throughout the world. It is widely recognized that repeated paint applications degrade turfgrass quality. The underlying basis for decline in quality, and thus the question of whether it can be avoided, has yet to be resolved. It is conceivable that the negative impact of paint on turfgrass quality can be traced to properties of the pigments used to produce each paint color. The wavelength range for visible light overlaps with PAR, between 400 and 700 nm, and alterations in visible light to produce specific colors could have negative effects on photosynthetically active radiance (PAR), and the associated rate of turfgrass photosynthesis. This cause and effect relationship was implied in a recent study where red and white paint were applied to perennial ryegrass (*Lolium perenne* L.) (Reynolds et al., 2012). Applications of red paint absorbed 51% of PAR and reduced total canopy photosynthesis (TCP) up to 75%, while applications of white paint reflected 95% PAR and reduced TCP by only 20-45%.

Commonly used colors of athletic field paint influence light across the entire visible spectrum. Paint colors are produced using varying pigment sources that selectively reflect, transmit, and absorb specific wavelengths of light (Fig 1.). For example, red Fe_2O_3, a commonly used pigment in red paint, produces a red color by reflecting approximately 20-30% more visible light in the 600-700 nm range than in the remaining visible wavelengths (Endrib, 1998). Because different colors would impact different spectral bands in the 400 to 700 nm range, it is likely that the degree of effects on TCP could differ greatly.

In addition to differences in pigments based on color, all pigments are designed to be opaque such that the painted surface, in this case the turfgrass leaf, is hidden. As a result, not

only are various wavelengths of light altered in painted turfgrass canopies, but the total amount of visible light hitting the leaf surface may be greatly reduced due to absorption by paint pigments. Thus, there is the potential for painting to disrupt the light reactions of photosynthesis and regulation of stomatal opening which may affect the supply of C for the dark reactions (Taiz and Zeiger, 2010; Shimazaki et al., 2007).

In the experiments described in this manuscript, previous research (Reynolds et al., 2012) is extended by evaluating changes in PAR and photosynthesis over a range of ten paint colors. Lab experiments were performed to analyze how different paint colors altered reflection, transmission, and absorption of PAR at specific broad- and narrow-band wavelengths. Subsequent growth-chamber experiments evaluated the extent that the alterations in PAR affected TCP of 'Tifway' hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy]. The results provide a basis for understanding declines in turfgrass quality associated with repeated applications of various colors of athletic field paint.

Materials and Methods

Spectroradiometry

Ten colors of Pioneer Brite Stripe Airless Paint (Pioneer Athletics) were selected for study. Pioneer Brite Stripe was chosen due to its widespread use on athletic fields as well as its ability to be diluted at various ratios ranging from 1:1 to 4:1 v/v based on the product label. It also allowed for uniform dilution across all colors, as opposed to pre-mixed products that are not designed to be diluted. The ten colors selected were defined using the

Pantone Matching System (PMS) which is a standardized color reproduction system that assigns specific reference numbers to each color (Hunt, 2011). Colors examined in this study were selected to include the entire visible spectrum, and their respective PMS numbers are presented in Table 1. Reflection, transmission, and absorption of PAR by each of these colors was measured using a method established by Reynolds et al. (2012) that involves uniform application of paint treatments to transparency film (3M PP2500, 3M) using a wet film applicator (Gardco 8-Path, Gardco). This device allows a small quantity of liquid to be applied to surfaces at a known wet thickness for subsequent testing. Each of the ten colors of athletic field turf paint was diluted at a 1:1 ratio with water prior to application to the transparency film. In order to achieve similar dried thicknesses for comparison, black, dark blue, green, light blue, maroon, orange, purple, red, and yellow were each applied at a uniform wet thickness of 0.625 mm while white was applied at a wet thickness of 0.375 mm. This distinction was made due to the high amount of pigment solids present in white paint, relative to other colors, and its characteristic ability to dry thicker. The final dried thickness of each film was recorded using a digital micrometer to ensure uniformity among colors.

Reflection and transmission of PAR through each color (Fig. 1) was measured between 400 and 700 nm at 0.5 nm intervals using an integrating sphere (LICOR 1800-12, LI-COR) and spectroradiometer (Apogee Instruments). Measurements were performed on three replications of each of the ten colors. The interior of the integrating sphere was newly pressed barium sulfate and was used as the reflection reference as described in the manufacturer's instructions (LICOR 1800-12). The painted side of the transparency film faced the inside of the integrating sphere for the reflection reference and sample readings.

For transmission sample and reference readings, the painted side of the transparency film faced the outside of the integrating sphere. The light source used to illuminate the integrating sphere was constant, but it's location within the sphere varied between reference and sample readings, as well as between reflection and transmission readings. Sample absorption was calculated as sample absorption = 1 – reflection – transmission.

In addition to PAR, broad and narrowband spectral data were collected at specific wavelengths to determine effects on light quality. Broadband wavelengths were defined as 400-500 nm and 600-700 nm, and narrowband wavelengths were defined as 410, 430, 640, and 660 ± 10 nm. These bands are often grouped by color where blue light is considered to be 400-500 nm and red light is considered to be 600 to 700 nm**.** Within these bands, chlorophyll a is known to have peak spectral absorption at 410, 430, and 660 nm while peak absorption for chlorophyll b occurs at 430 and 640 nm (Bell, 2000**).** Measurements of reflection and transmission, and calculations of absorption at each of these wavelengths were determined as previously described using the integrating sphere and spectroradiometer.

Growth Chamber Experiments

Growth chamber experiments were conducted at the Southeastern Plant Environment Laboratory at North Carolina State University in Raleigh, NC. Sixty pots were prepared with a 50:50 v/v sand and peat substrate based on the original "Cornell Mix" (Boodley and Sheldrake, 1972). The substrate was steam-sterilized, placed into 15.8-cm diameter pots, and planted with washed Tifway bermudagrass sod which was selected due to its widespread use on athletic fields. After sodding, the pots were placed into a growth chamber maintained at

29/24^{o}C (day/night) with a 12 h photoperiod (0700 h to 1900 h) and a photosynthetic photon flux density of approximately 1000 µmol m^{-2} s^{-1} provided by a combination of incandescent and fluorescent lamps. Water and nutrient solution were applied twice daily throughout the bermudagrass establishment period and then once daily during experimental periods to support adequate growth by preventing water or nutrient deficiencies. The 'standard nutrient solution' is described in detail in the North Carolina State University Phytotron Procedural Manual (NCSU, 2011). Pots were mowed one day prior to paint application and two days after photosynthesis measurements at 2.5 cm using a handheld shear (194380 Oster Showmaster, Oster).

Paint Application

Prior to application of paint treatments, turf in all sixty pots was allowed to reach maturity, defined as uniform coverage, maximum density and quality, and then experimental units were randomly divided into two sets for replication over time. Each replicate experiment, referred to hereafter as Exp. 1 and 2, consisted of ten colors of athletic field turf paint (Table 1) and three replications per color. Paint applications were made every seven days for five consecutive weeks within each experiment, and Exp. 2 began after completion of Exp. 1. Paint treatments were applied to pots using a CO_2-pressurized sprayer with flatfan nozzles (Teejet8004VS, Teejet Spraying Systems Co.) calibrated to apply approximately 168 L ha^{-1}. This rate was achieved by four applications in multiple directions to each pot, which ensured uniform paint coverage on turfgrass leaves.

Photosynthesis Measurements

Carbon exchange rates were measured twenty-four hours after each of five weekly paint applications and were determined by enclosing the turfgrass canopy in a transparent plexiglass chamber (956 cm^3) connected to a portable gas exchange system (LI-6400, LI-COR Inc.). Measurements of carbon exchange rate were always taken between 1000 and 1500 h. Carbon exchange rates were measured in full light in the growth chamber and in total darkness immediately after light measurements were recorded (achieved by covering the plexiglass chamber with opaque black fabric). Measured carbon exchange rates under dark conditions were considered to represent canopy, root, and soil respiration. Total canopy photosynthesis (TCP) was calculated by adding the absolute value of dark respiration to the observed carbon exchange rate in the light (Singh et al., 2011). Canopy temperature was measured immediately prior to enclosure of the turfgrass in the transparent plexiglass chamber using an infrared digital thermometer with an error range of $\pm 3^{o}C$. (Fluke 63IR, Fluke Inc.).

Statistical Analysis

Data from spectroradiometry and growth chamber experiments were subjected to ANOVA to determine treatment effects using PROC GLM (version 9.3, 2012; SAS Institute Inc., Cary, NC). Total canopy photosynthesis and canopy temperature data produced significant treatment effects, but TCP also showed interactions with experiment. Therefore, TCP data from Experiments 1 and 2 were analyzed and presented separately with treatment x experiment interactions reported in the appropriate ANOVA table. Canopy temperature data

showed no interaction with experiment and were therefore pooled for analysis. Treatments within all experiments were subjected to Fischer's Protected LSD test at the 0.05 probability level when F-tests indicated significant treatment effects. Pearson's correlation coefficients were calculated to examine the relationship between TCP and reflection, transmission, and absorption of light at various wavelengths using PROC CORR (version 9.3, 2012; SAS Institute Inc., Cary, NC).

Results

Spectroradiometry Analyses

Reflection, transmission, and absorption of PAR and light in the broad and narrow-band wavelengths were found to be different ($P \leq 0.001$) for all colors (Table 2). Broadband spectroradiometry indicated that white paint reflected the highest amount of PAR and black paint reflected the least. Reflection of PAR varied strongly by color with white reflecting 92.6% followed by yellow (63.1%), light blue (51.6%), orange (47.0%), and red (41.2%) reflecting the highest amounts. Reflection of PAR by the darker colors was much smaller and included maroon (20.9%), green (11.9%), purple (10.7%), dark blue (6.8%), and black (4.5%) reflecting the least. Inversely, absorption of total PAR was much higher by the darker colors than the lighter colors, with black absorbing the most (95.4%) and white the least (0.0%). Transmission of PAR also varied by color, but the magnitude of differences was much smaller. Transmission ranged from 12.4% to 18.0% in the lighter colors white, yellow, orange, and red, while in the darker colors maroon, green, purple, dark blue, and black, transmission ranged from 0.1% to 4.7%.

A comparison of spectroradiometry data in the 400-500 nm and 600-700 nm broadband wavelengths indicate the different impacts that pigments have within PAR. White and black did not vary as much by broadband wavelength, as can be seen in Table 2 where white reflected 91.8% of light between 400-500 nm and 94.1% between 600-700 nm and black paint reflected < 5% of both, effects that aligned with those on overall PAR. However, all other colors varied greatly by broadband wavelength. Yellow, for example, reflected 76.1% of light between 600-700 nm but only 13.2% between 400-500 nm. Orange reflected almost ten times more light between 600-700 nm than 400-500 nm, while red reflected almost nine times as much. Green paint reflected light within 400-500 nm and 600-700 nm ranges at approximately equal amounts while light blue, dark blue, and purple were the only colors to reflect more light between 400-500 nm than 600-700 nm.

The effects of color on transmission of light were also wavelength dependent for all colors, yet the magnitude of differences between broadband wavelengths were much smaller within each color. The effects on absorption of light were also wavelength dependent in all colors except white and black and were inversely related to reflection, as expected. Although narrowband data are not presented, they support the broadband wavelength data in that differences in narrowband data based on color were similar to the reported differences in broadband data with regard to reflection, transmission, and absorption at all measured wavelengths.

Growth Chamber Experiments

Reductions in TCP as a result of all paint treatments were different ($P \leq 0.0001$) in Exp. 1 and 2 despite an interaction between treatment and experiment ($P \leq 0.0006$; ANOVA Table 3). Experiment ($P = 0.6276$) and replication ($P = 0.8414$) were not different, while week and treatment by week interaction were both different ($P \leq 0.0001$).

White paint proved to have the least impact on TCP of Tifway bermudagrass in both experiments (Fig 2). Total canopy photosynthesis was maintained at 78% of the unpainted control throughout five weeks in Exp. 1 and 83% in Exp. 2. Applications of yellow and orange paint resulted in higher TCP rates than all other colors except white in both experiments, ranging from 65-69% of the control in Exp. 1 and 71-75% in Exp. 2. Further reductions in TCP based on severity included red paint, which had TCP rates of 50 and 53% of the un-painted control in Exp. 1 and 2, light blue (48 and 47%), purple (36 and 33%), maroon (41 and 32%), green (26 and 25%), black (15 and 18%), and dark blue (13 and 8%).

Canopy temperature was influenced by paint color and was different ($P \leq 0.001$) within and across Exp. 1 and 2. Canopy temperature data for both experiments were pooled due to no effect of date, experiment, or treatment by experiment interaction. There were no differences among white (31.4°C), yellow (32.3°C), orange (32.5°C) and untreated (32.3°C) canopy temperatures. However, canopy temperatures did increase for red (33.4°C), light blue (33.8°C), purple (35.9°C), green (36.9°C) and maroon (36.9°C), while the highest canopy temperatures were produced by black (39.9°C) and dark blue (40.5°C) treatments. Standard error values of canopy temperature measurements ranged from 0.3^{o}C in orange to 0.7^{o}C in green.

Pearson's correlation coefficients in Table 4 and Fig. 3 define the relationship between PAR and TCP over the range of paint colors. In Exp. 1, TCP was most highly correlated with absorption of PAR (r = - 0.96; $P \leq 0.001$), followed by positive correlations with reflection (r = 0.93; $P \leq 0.001$) and transmission of PAR (r = 0.84; $P \leq 0.001$). In Exp 2, the correlations were similar. The correlations between TCP and the reflection, transmission, and absorption of light within the 600-700 nm wavelengths were approximately one and a half to two times higher than within the 400-500 nm wavelengths in both experiments. For example, in Exp. 1, Pearson's correlation coefficient for TCP and reflection of 600-700 nm wavelengths (r = 0.95; $P \leq 0.001$) was more than twice as high as the correlation coefficient for TCP and reflection of the 400-500 nm wavelengths (r = 0.45; $P \leq 0.05$). Also in Exp. 1, Pearson's correlation coefficient for TCP and absorption of 600-700 nm wavelengths (r = - 0.93; $P \leq 0.001$) was also more than twice as high as the coefficient for TCP and absorption of 400-500 nm wavelengths (r = - 0.45; $P \leq 0.05$). Pearson's correlation coefficients for narrowband wavelengths and TCP support the relationships between broadband wavelengths and TCP (data not shown).

Canopy temperature increases as a result of paint color were most positively correlated with absorption of PAR in Exp. 1 (r = 0.87; $P \leq 0.001$) and Exp. 2 (r = 0.87; $P \leq$ 0.001). Canopy temperature was negatively correlated with reflection and transmission of PAR and broadband wavelengths. Correlation coefficients for canopy temperature and reflection, transmission, and absorption were higher and more significant between 600-700 nm than between 400-500 nm in both experiments. Like TCP, data for correlations of canopy temperature and narrowband wavelengths supported the broadband data.

Discussion

The hypothesis being tested in this research was that alterations in visible light by paint pigments to produce a specific color would be coupled with alterations in PAR and TCP within a painted turfgrass canopy. This hypothesis was based on the overlap of visible light and PAR between 400 and 700 nm as well as the requirement that all paints be opaque enough to adequately cover a leaf surface. Each of these has the potential to reduce total PAR, as well as 'filter' wavelengths within PAR, reaching leaf surfaces.

The results of the spectroradiometry analyses and the measurement of TCP of Tifway bermudagrass clearly support this hypothesis. A significant negative correlation was present between absorption of PAR and Tifway bermudagrass TCP over the broad range of colors examined. Darker colors absorbed a larger proportion of PAR, resulting in greater suppression of TCP. Thus, it is reasonable to conclude that alterations in the amount of light reaching the leaf surface and inhibited TCP are a major cause of suppressed growth and subsequent declines in turfgrass health when painting occurs. Furthermore, it would be expected that darker colors lead to greater damage to turfgrass health over extended periods. This is supported by observations of the clipping collections throughout both experiments. Darker colors had more suppressed growth than lighter colors, particularly in the later weeks of both experiments. This likely results in less paint being removed through mowing as a result of less vertical growth, more paint remaining in the turfgrass canopy, and thus more shading. Attempts to collect and weigh clippings for analysis by color were unsuccessful due to the inability to separate clippings from paint residue.

In addition to the effects of shading, another potential factor contributing to lower TCP may have been increased plant and root respiration rates caused by increased canopy temperatures. Leaf canopies painted with darker paint colors had higher canopy temperatures, and it is generally understood that respiration increases with temperature until 40 to 50^{o}C (Taiz and Zeiger, 2010).

Increases in respiration as a result of increased canopy temperatures based on paint color could potentially contribute to the observed reductions in TCP given that TCP was calculated by adding the absolute value of dark respiration to the observed carbon exchange rate in the light. However, an analysis of dark respiration data used for TCP calculations minimize that possibility as a confounding variable in painted turfgrass canopies. Dark respiration data indicate that respiration actually decreases in canopies painted with darker colors, despite any implications that respiration rates may increase as a result of increased temperature. This likely reflects the dependence of respiration on concurrent photosynthesis and its supply of carbohydrate.

Our results with paint are somewhat analogous with those from shading studies (e.g. Bell et al., 2000; McBee, 1969; Ngouajio and Ernest, 2004; Trappe et al., 2011). More specifically, Baldwin et al. (2009) found that shade fabrics filtering wavelengths from 360 to 720 nm reduced warm season grass clipping yields by as much as 79%. Decreases in Tifway bermudagrass quality were wavelength-dependent, with yellow and red shade cloth less damaging than cloth that was blue or black. For example, blue shade cloth that allowed only passage of blue light for one and four weeks resulted in lower visual quality ratings than yellow and red shade cloths that only allowed passage or yellow and red light. After eight

weeks of filtered light, blue and yellow shade cloths resulted in lower visual quality ratings than red shade cloths. These results indicate the importance of red light on the health of Tifway bermudagrass. Pearson's correlation coefficients presented in Table 4 support this in that TCP of Tifway bermudagrass was less affected by paint colors which absorbed a higher percentage of blue light as opposed to red light. For example, darker colors including black, dark blue, purple, and green absorbed the highest percentage of red light and also had the greatest impacts on TCP, in addition to maroon. Inversely, lighter paint colors including white, yellow, and orange that reflected the highest percentage of red light were the least harmful to TCP.

Spectroradiometry data presented in Tables 2 and 4 indicate the ability of paint to selectively absorb wavelengths within PAR and are important for several reasons. First, they accurately represent the expected properties with regard to the pigments used to produce a specific color, i.e., blue paints reflect more blue light than red light, red paints reflect more red light than blue light, etc. Second, previous research has shown that various sources of shade can selectively alter wavelengths within PAR, red/far-red ratios, etc. (Baldwin et al., 2009; Bell et al., 2000). This supports the notion that various colors of paint can also create various shading effects much like varying tree species, buildings, etc. create various shading effects. Lastly, while blue light is important in many plant growth processes, red light is more often associated with photosynthetic responses including the enhancement effect and the red light response to stomatal opening (Taiz and Zeiger, 2010; Shimazaki et al., 2007).

In other types of studies with cotton (*Gossypium hirsutum* L.), higher reflection of PAR had positive effects on plant growth when plastic surfaces painted white were placed

beneath canopies (Kasperbauer, 2000). Similarly with carrot (*Daucus carota* L.), lighter colored plastic mulches had greater benefits than darker mulches (Antonious and Kasperbauer, 2002). With athletic field tarps covering 'Midnight' Kentucky bluegrass (*Poa pratensis* L.) at different times during the year, Minner et al. (2000) found that orange, white, yellow, and red tarps consistently had the most positive effects on turf color after tarp removal, while darker colored tarps were much more injurious. Goatley et al. (2007) showed that various colored tarps altered PAR available for use on ultradwarf bermudagrass putting greens where black, green, gray, white, and translucent tarps reduced PAR by 91-99%, 69-79%, 36-49%, and 34%, respectively. It is worth mentioning that increased temperatures as a result of all tarps, especially the darker colored tarps, have the potential to confound shading effects in a manner that is different from painted turfgrass canopies given that paint and tarps cover the turfgrass canopy by different means. However, the effects of different colored tarps on turfgrass health are consistent with results from our paint experiments and illustrate the dependence upon color.

Ultimately, the key for understanding color effects on PAR lies within the optical properties of the pigments that produce different colors. Pigment sources for athletic field paints include both organic and inorganic sources, each of which contribute various properties with regard to color and application. Pigment classification in this paper will be defined using the traditional properties associated with organic and inorganic pigments as defined by Lambourne and Strivens (1999).

Inorganic pigments possess excellent hiding power, extreme fastness to light and weathering, and excellent color stability (Endrib, 1998). They also produce various optical

effects through non-selective or selective reflection and absorption of light. The extreme reflectiveness of white is produced by the non-selective scattering of visible light by the base pigment TiO_2, which is recognized as having the highest brightening power of all industrially produced pigments (Stoye and Freitag, 1998). In contrast, the extremely high absorption (> 95%) of visible light/PAR by black is characteristic of the non-selective inorganic pigment C black (Buxbaum and Pfaff, 2005). Carbon black is so effective at absorbing light that it comprises approximately only 10% of the paint formulation (v/v) whereas other colors contain as much as 31% pigment (v/v). Therefore, even at the lowest pigment concentration of any color tested, black was still capable of absorbing the highest amount of visible light based solely on the optical properties of black pigments.

Unlike with white and black, colors like red and yellow that are derived from inorganic pigments selectively reflect and absorb light in a wavelength-dependent manner (Herbst and Hunger, 2004). Yellow Fe_2O_3, for example, is known to reflect up to three times more light in the longer wavelengths than in shorter wavelengths (Endrib, 1998), as was seen in the spectroradiometry measurements (Table 2).

Regardless of reflective and absorptive properties, many inorganic pigments like TiO_2, C, and Fe_2O_3 are limited in the range of colors they can produce. Furthermore, most inorganic pigments lack tinting strength and therefore produce dull shades when added to white to produce various colors (Herbst and Hunger, 2004). Therefore, organic pigment sources are often incorporated to produce colors that inorganic sources alone cannot (Table 1). For example, colors used in this study that contain both organic and inorganic pigment

sources include light blue (TiO_2; phthalocyanine blue) and yellow (yellow Fe_2O_3; pyrazolone orange).

Spectroradiometry analysis of each of the paint colors tested in this study accurately represents the reflection and absorption characteristics one would expect based on the pigment properties found in each color. Furthermore, low transmission (relative to reflection and absorption) accurately represents the fact that all paints, regardless of color, must meet the basic opacity requirement of blocking enough visible light to hide the turfgrass leaf.

The results presented in these experiments illustrate the color-dependent relationship between available PAR and subsequent TCP within painted turfgrass canopies. This is a direct result of the fact that visible light and PAR overlap between 400 and 700 nm and therefore any alterations by paint pigments to produce a specific desired color are also very likely to impact PAR and turfgrass growth. Reflection and transmission of PAR by lighter colors of paint is likely still available for use within the turfgrass canopy in areas with cracked leaf surfaces or partial paint coatings as well as on abaxial leaf surfaces and lower portions of the canopy that may not have received paint. Furthermore, as painted turfgrasses are mowed, reflection and transmission of PAR by lighter colors of paint can be useful for photosynthesis in newly formed, unpainted leaves. However, the overwhelming ability of pigments found in darker colors of paint to absorb PAR create such a profound shading effect that it is unclear how damage to painted turfgrass can be avoided when using these colors. Further research is needed on paint application techniques, rates, and product selection as well as turfgrass management strategies that may reduce the amount of time leaves remain painted, thus reducing duration under shade.

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Table 1. Pantone Matching System (PMS) numbers for ten colors of athletic field turf paint.

Color	PMS number	Pigment	Pigment classification
Black	Pantone Black C	Carbon black	Inorganic
Dark blue	287	Phthalocyanine blue	Organic
Green	349	Phthalocyanine green	Organic
Light blue	278	Titanium dioxide, phthalocyanine blue	Inorganic, Organic
Maroon	202	Quinacridone magenta	Organic
Orange	158	Pyrazolone orange	Organic
Purple	2735	Carbazole violet	Organic
Red	186	Naphthol red	Organic
Yellow	124	Yellow iron oxide, pyrazolone orange	Inorganic, Organic
White	Not applicable[†]	Titanium dioxide	Inorganic

[†] There is no PMS number for white paint.

Table 2. Reflection, transmission, and absorption of light in the 400-500 nm, 600-700 nm, and 400-700 nm wavelength ranges by ten colors of athletic field paint.

	Reflection			Transmission			Absorption		
Treatment	400-700	400-500	600-700	400-700	400-500	600-700	400-700	400-500	600-700
	%								
White	92.6 a†	91.8 a	94.1a	12.4 c	9.1 a	13.9 c	0.0 j	0.0 i	0.0 i
Yellow	63.1 b	13.2 e	76.1 b	15.5 b	0.1 d	21.7 b	21.3 i	86.5 e	2.1 h
Light blue	51.6 c	76.2 b	45.8 d	0.6 f	2.5 c	0.3 f	47.6 f	21.2 h	53.7 e
Orange	47.0 d	6.6 h	65.7 c	18.0 a	0.1 d	28.5 a	34.9 h	93.1 b	5.7 g
Red	41.2 e	7.5 g	65.5 c	12.4 c	0.1 d	22.3 b	46.3 g	92.3 c	12.1 f
Maroon	20.9 f	9.1 f	30.3 e	4.7 d	0.2 d	8.4 d	74.2 e	90.5 d	61.2 d
Green	11.9 g	9.6 f	10.1 f	0.6 f	0.2 d	0.1 f	87.4 c	90.1 d	89.4 b
Purple	10.7 h	22.4 c	10.3 f	2.5 e	8.3 b	2.4 e	86.7 c	69.1 g	87.2 c
Dark blue	6.8 i	18.2 d	4.5 g	0.1 g	0.2 d	0.1 f	93.1 b	81.4 f	95.4 a
Black	4.5 j	4.7 i	4.4 g	0.1 g	0.1 d	0.1 f	95.4 a	95.1 a	95.4 a
	Analysis of variance								
Treatment	***	***	***	***	***	***	***	***	***

*** Significant at the 0.001 probability level.
†Means within columns followed by the same letter are not significantly different according to Fisher's Protected LSD (*P*=0.05).

Table 3. Analysis of variance for normalized total canopy photosynthesis (TCP) from weekly applications of ten colors of athletic field paint in a controlled environment growth chamber during two 5-wk experiments at the Southeastern Plant Environment Laboratory in Raleigh, NC.

		Analysis of variance		
Source	df	Mean square	*F*	*P* > *F*
Experiment	1	0.1	0.2	0.6276
Treatment	9	1.7	277.8	<0.0001
Replication	2	0.1	0.2	0.8414
Week	4	0.1	17.2	<0.0001
Treatment x week	40	0.1	3.5	<0.0001
Treatment x experiment	9	0.1	3.4	0.0006

Table 4. Pearson's correlation coefficients for reflection, transmission, and absorption of light through black, dark blue, green, light blue, maroon, orange, purple, red, white, and yellow paint when correlated to total canopy photosynthesis (TCP) and canopy temperature during two, 5-wk experiments.

		Experiment 1		Experiment 2	
PAR	Wavelength	TCP	Canopy temperature	TCP	Canopy temperature
Reflection	400-700 nm	0.93***	-0.84***	0.92***	-0.83***
	400-500 nm	0.45*	-0.43*	0.41*	-0.41*
	600-700-nm	0.95***	-0.84***	0.95***	-0.87***
Transmission	400-700 nm	0.84***	-0.75***	0.87***	-0.76***
	400-500 nm	0.45*	-0.30	0.30	-0.31
	600-700-nm	0.76***	-0.68***	0.78***	-0.71***
Absorption	400-700 nm	-0.96***	0.87***	-0.96***	0.87***
	400-500 nm	-0.45*	0.43*	-0.41*	0.41*
	600-700-nm	-0.93***	0.85***	-0.94***	0.87***

*Significant at 0.05 probability level.
**Significant at 0.01 probability level.
***Significant at 0.001 probability level.

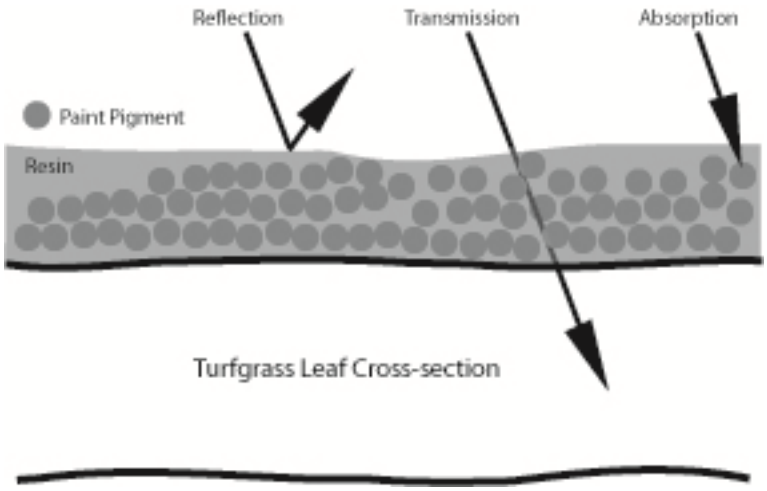

Figure 1. Illustration of reflection, transmission, and absorption of light by athletic field paint applied to a turfgrass leaf.

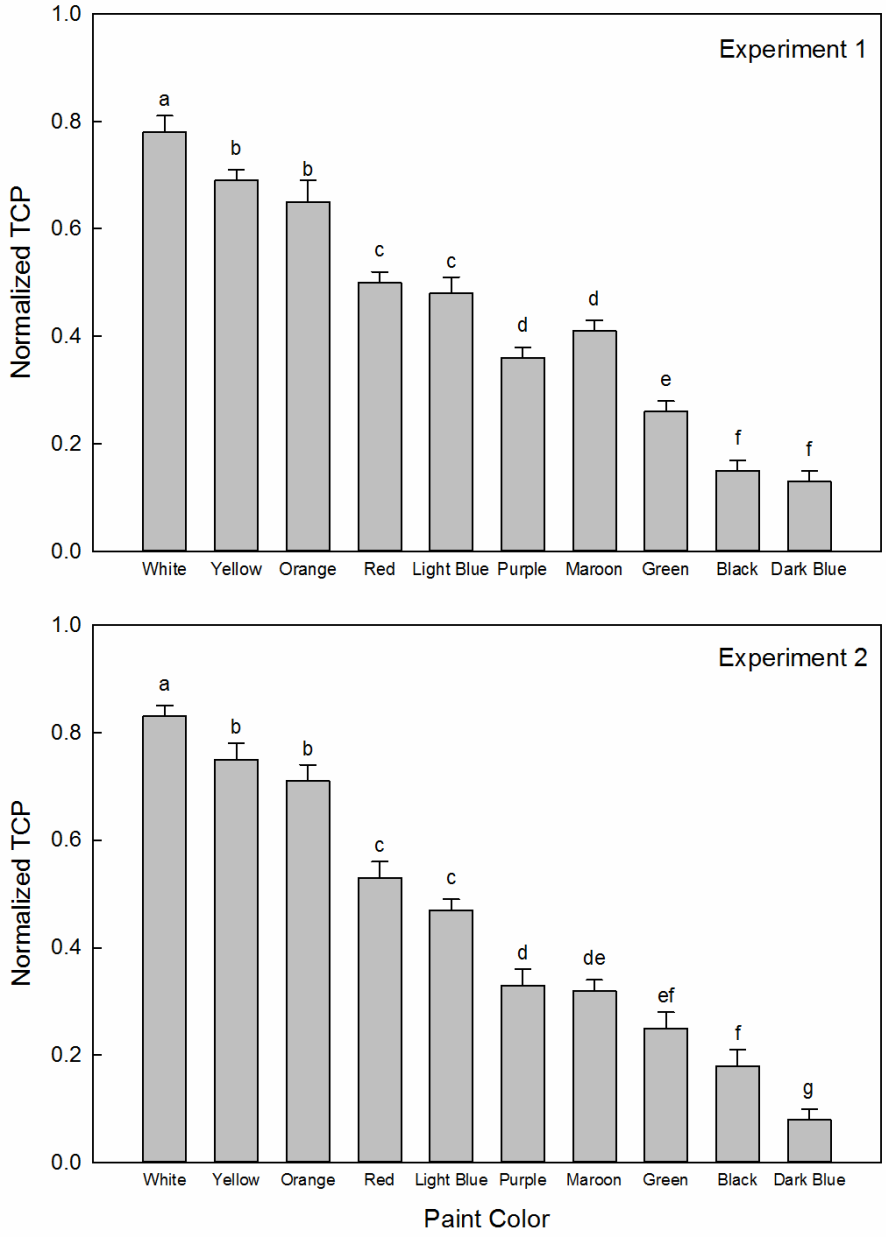

Figure 2.Normalized total canopy photosynthesis (TCP) rates of ‘Tifway’ bermudagrass 24 h after application of ten colors of athletic field paint during two 5-wk experiments in a controlled environment growth chamber. Values for TCP were averaged over five weeks and are reported as percent of un-painted control. Bars above each treatment represent standard error.

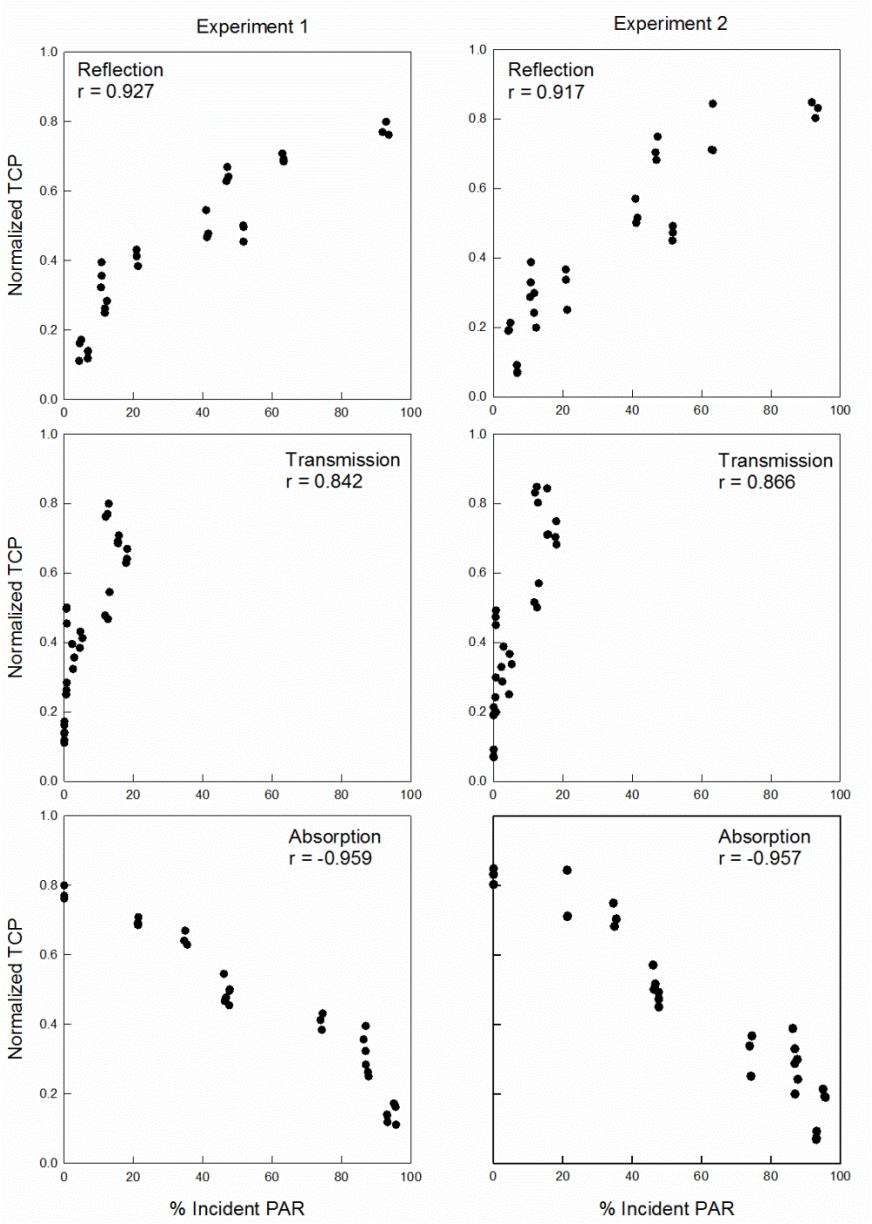

Figure 3. Correlations of reflection, transmission, and absorption of PAR (400-700 nm) with normalized total canopy photosynthesis (TCP) rates of 'Tifway' bermudagrass 24 h after application of ten colors of athletic field paint during two 5-wk experiments in a controlled environment growth chamber. Values for TCP were averaged over five weeks and are reported as percent of un-painted control.

ATHLETIC FIELD PAINT COLOR IMPACTS TRANSPIRATION AND CANOPY TEMPERATURE IN BERMUDAGRASS

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Abbreviations: PAR, Photosynthetically active radiation; PMS, Pantone matching system; TCP, Total Canopy Photosynthesis.

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Abstract

Athletic field paints have varying impacts on turfgrass health which have been linked to their ability to alter photosynthetically active radiation (PAR) and photosynthesis based on color. It was further hypothesized they may also alter transpiration and canopy temperature by disrupting gas exchange at the leaf surface. Growth chamber experiments evaluated the effects of air temperature and six colors of paint on daily water loss and canopy temperature in 'Tifway' bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy]. Daily water loss and canopy temperature were measured every 24 h using gravimetric techniques and an infrared digital thermometer, while lab experiments examined the thickness of white and black paint on the leaf surface. In un-painted bermudagrass canopies, daily water loss increased ($P \leq 0.0001$) with canopy temperature from 29 to 36^{o}C while in painted bermudagrass canopies, it decreased ($P \leq 0.0001$) as canopy temperature increased from 29 to 40^{o}C. Yellow and white impacted transpiration and canopy temperature the least, while black and blue caused the greatest reductions in transpiration and highest increases in canopy temperature. Cross-sections of painted Tifway indicate paint may limit evaporative cooling by clogging stomata. Increased absorption of radiant energy coupled with limited evaporative cooling result in increased heat stress and decreased turfgrass performance in painted canopies.

Introduction

Athletic field paints have increasingly become an integral part of sporting events worldwide with an ever-increasing desire to produce bright, distinct, and often intricate logos and designs. While these products are specifically designed and labeled for use on athletic turf, repeated applications commonly result in declines in turfgrass quality, density, and performance. The underlying basis for this decline has been linked to reductions in photosynthetically active radiation (PAR) reaching the leaf surface due to absorption by paint pigments, and is often color-dependent (Reynolds et al., 2012 and 2013). However, Reynolds et al. (2013) also indicates that the interception of PAR by paint pigments is likely not the only factor implicated in reductions of turfgrass quality in painted turfgrass canopies. For example, in that study white paint absorbed 0.0% of PAR yet still produced total canopy photosynthesis (TCP) rates in 'Tifway' hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy] of only 78% and 83% of the un-painted control in two separate experiments. Consequently, it is likely that other detrimental effects resulting from athletic field paint applications are contributing to turfgrass decline, in addition to the effects of shading.

One potential explanation for this may be that while photosynthesis is driven by PAR, which would most certainly be affected by shading, transpiration relies upon adequate gas exchange of carbon dioxide (CO_2) and oxygen (O_2) through leaf stomata. Given that paints are designed to entirely coat leaf surfaces, it is reasonable to suspect that gas exchange may be impeded by stomatal obstruction, potentially leading to carbon (C) starvation and reduced evaporative cooling. Each of these could contribute to previously reported decreases in TCP

and increases in canopy temperature in painted turfgrass canopies (Reynolds et al. 2012 and 2013).

The impacts of various management practices and environmental factors on turfgrass transpiration have been widely documented and include nitrogen rate, mowing height, shade, herbicide application, and soil composition (Barton et al., 2009; Biron et al., 1981; Erickson and Kenworthy, 2011; Feldhake et al., 1983; Wherley and Sinclair, 2009; Miller, 2000) as well as species and variety (McGroary et al., 2011; Beard et al., 1992.). The impacts of increasing temperature on turfgrass physiology and performance have also been documented within and above optimal ranges (Du et al., 2010; Huang et al., 2009). While Reynolds et al. (2012 and 2013) has documented increases in canopy temperature based on paint color, research has yet to be conducted to explore the relationship between these temperature increases and subsequent rates of transpiration.

The experiments described in this manuscript were initiated to investigate the impacts of paint color on transpiration and canopy temperature in painted Tifway bermudagrass. Growth chamber studies were conducted to establish the effects of paint color on Tifway bermudagrass canopy temperature and subsequent rates of transpiration, while separate lab experiments were conducted to determine the ability of paint to obstruct stomata. The results presented in this research provide a further understanding of the effects of athletic field paint color on turfgrass health and performance with specific focus on turfgrass transpiration and canopy temperature.

Materials and Methods

Experimental Units and Paint Application

The research was conducted at the Southeastern Plant Environment Laboratory at North Carolina State University in Raleigh, NC. Experimental pots were prepared with Profile Greens Grade porous ceramic soil amendment (Profile Porous Ceramic Greens Grade, Profile) and sodded with Tifway bermudagrass, which was selected due to its widespread use on athletic fields. Each pot was 14-cm in diameter and 19-cm in depth and had a total volume of 2,924 cm^3. After sodding, the pots were placed into growth chambers maintained at 26/22^oC (day/night) with a 12 h photoperiod (0700 h to 1900 h) and a photosynthetic photon flux density of approximately 1000 µmol m^{-2} s^{-1} provided by a combination of incandescent and fluorescent lamps. Water and nutrient solution were applied twice daily throughout the bermudagrass establishment period and then once daily during experimental periods. The 'standard nutrient solution' is described in detail in the North Carolina State University Phytotron Procedural Manual (NCSU, 2011). Pots were mowed twice weekly at 2.5 cm using a handheld shear (194380 Oster Showmaster, Oster).

Prior to the initiation of Study 1 and 2, turf in all pots was allowed to reach maturity and then experimental units were randomly divided into two sets per study for replication over time. Each replicate experiment within Study 1, hereafter referred to as Exp. 1 and 2, consisted of three replications of un-painted Tifway. Replicate experiments within Study 2, hereafter referred to as Exp. 3 and 4, consisted of an un-painted control and six colors of Pioneer Brite Stripe athletic field paint (Pioneer Athletics) with three replications per treatment. Colors were defined using the Pantone Matching System (PMS) which is a

standardized color reproduction system that assigns specific reference numbers to each color (Hunt, 2011). Colors examined in this study and their respective PMS numbers are presented in Table 1. Paint applications were made every seven days for five consecutive weeks within Exp. 1 and 2 using a Pioneer Brite Striper 3000 high pressure field marking machine (Pioneer Athletics) with an Airless nozzle (Airlessco 219ST, Airlessco) calibrated to apply 9,903 L ha^{-1}. This rate was selected after calibration experiments with professional and university field managers in order to apply a pressure and rate similar to that often used in highly managed athletic turf.

Apparent Transpiration

Study 1

Apparent transpiration as a result of air temperature was determined gravimetrically by the mass balance method. All pots were placed into a growth chamber at 26/22 ^{o}C, saturated and allowed to drain to field capacity for 24 h prior to measurements of daily water loss. Sod, roots, and substrate for all pots were then transferred to pots without drainage holes to prevent further water loss due to drainage. The dense root structure and fine texture of the porous ceramic substrate allowed for transferal of pots after the 24 h drainage period to pots without drainage holes with no loss of substrate, roots, or water. Daily water loss was determined by weighing the pots every 24 h for six days, and the amount of water lost each day was returned to the pot after weighing. This allowed each pot to remain at the original weight recorded on day one such that the pots did not encounter drought stress at any point during the experiments. Apparent transpiration was calculated in mm $day^{-}1$. At the end of

each week, all pots were transferred back to drainage pots before being re-saturated, allowed to drain to field capacity for 24 h, and re-potted back into solid pots. Solid pots were placed back into the growth chamber and the daytime temperature was raised by 3 ^{o}C. Daily water loss measurements were collected in the same manner as week one, and this continued as daytime temperatures were raised by 3^{o}C per week for five weeks. The day/night temperatures for weeks 1 through 5 were 26/22 ^{o}C, 29/22^{o}C, 32/22^{o}C, 35/22^{o}C, and 38/22^{o}C, respectively. These values were chosen based on the chamber's ability to reach 38^{o}C as its maximum limit. Canopy temperature was measured immediately prior to weighing using an infrared digital thermometer (Fluke 63IR, Fluke Inc.), while air temperature and relative humidity were recorded every 24 h using a temp/RH data logger (HOBO pro V2, Onset Computer Corp.)

Study 2

Apparent transpiration as a result of paint color was determined gravimetrically in the same manner as Study 1. However, in Study 2, the chamber temperature was maintained at 26/22^{o}C throughout the entire five weeks of Exp. 3 and 4, while paint treatments were applied weekly for each of the five weeks within both experiments. All pots were saturated and allowed to drain to field capacity for 24 h prior to application of paint treatments. At the end of each week, all pots were transferred back to drainage pots before being re-saturated, allowed to drain to field capacity for 24 h, re-potted back into solid pots, and then re-painted before being placed back into the growth chamber. Canopy temperature, air temperature, and relative humidity were each recorded in the same manner as Study 1.

Paint Thickness

The thickness at which paint dries on the turfgrass leaf was determined by randomly selecting three leaves one day after application of white and black paint. White and black were selected to provide a range of potential dried thicknesses due to white containing the most pigment on a v:v basis of pigment to solution and black containing the least. Each of the three leaves selected in both colors was visually inspected for uniform paint coverage and then cut to a length of 1-cm measured from the leaf tip towards the leaf sheath. Leaves were blocked in hot paraffin with the leaf-tip down and allowed to cool prior to sectioning. A microtome (Leica RM2255, Leica Biosystems) with an Extremus Low Profile Disposable Blade (C.L. Sturkey, Inc.) set at an angle of zero degrees was used to section each leaf. Leaves were sectioned by location on the leaf and included tip, center, and base where each was 2.5mm, 5.0mm, and 7.5mm from the leaf tip, respectively. Ten sections within each leaf location were cut at a thickness of 20µm each, floated on water, and placed onto glass microscope slides. Images were taken of each 20µm section using a digital camera (Sony DSC707) attached to a 50i microscope (Nikon Eclipse) with a 10X objective and 30W halogen lamp. Thickness of each color was measured using a 10X scale in µm increments at five randomly selected places on each 20µm section. Each of the five paint thickness measurements per leaf section was analyzed as a sub-sample within the ten sections per location per leaf.

Statistical Analysis

Data from growth chamber and paint thickness measurements were subjected to ANOVA to determine treatment effects (PROC GLM, SAS Institute Inc., Cary, NC). Apparent transpiration data in the un-painted experiments produced significant effects based on day/night temperature treatments as well as an interaction with temperature. Painted experiments produced significant color effects as well as a color by experiment interaction. All apparent transpiration data were analyzed and presented separately by experiment due to interactions with temperature (Exp. 1 and 2) and color (Exp. 3 and 4). Canopy temperature data in the painted experiments were not different by experiment, but did produce color interactions with experiment and were therefore also separated by experiment for further analysis. Treatments within all experiments were subjected to Fischer's Protected LSD test at the 0.05 probability level when F-tests indicated significant treatment effects.

Discriminant analysis was also performed to further determine the impact of color on canopy temperature and water loss. Discriminant analysis was performed in SAS using PROC DISCRIM (version 9.3, 2012; SAS Institute Inc., Cary, NC) to determine whether information about canopy temperature (^{o}C) and daily water loss (mm day^{-1}) expressed through a quadratic discriminant rule is useful in characterizing the color that grass was painted, or equivalently, the group that the observation belongs to.

Results

Transpiration in un-painted bermudagrass canopies increased between 26 and 38^{o}C in Exps. 1 and 2 (Table 2) and were dependent upon daytime air temperature in the growth

chamber (Table 3). In Exp. 1, daily water loss increased from 8.4 mm day^{-1} at 26/22^{o}C to 10.5 mm day^{-1} at 38/22^{o}C, while in Exp. 2 it increased from 10.5 mm day^{-1} to 15.2 mm day^{-1} over the same range of temperatures. Furthermore, daily water loss in Exp. 1 was higher each week that daytime air temperature increased, while in Exp. 2 it increased each week except for weeks two and three, despite a 3^{o}C increase in daytime air temperature from 29/22 to 32/22^{o}C.

Canopy temperature increased with air temperature throughout all five weeks of Exps. 1 and 2 and was slightly above the respective air temperatures of 26/22, 29/22, and 32/22^{o}C, but slightly below the respective air temperatures of 35/22 and 38/22^{o}C. For example, during weeks one through three in Exp. 1 the daytime air temperature in the growth chamber was 26, 29, and 32^{o}C, respectively, while the average daily canopy temperature was 29.3, 31.8, and 33.7^{o}C. However, average daily canopy temperature during weeks four and five were 34.6^{o}C and 36.2^{o}C, and even though they increased from weeks one through three, they were below their respective daytime air temperatures of 35 and 38^{o}C. The relationship between canopy temperature and air temperature in Exp. 2 was similar.

Transpiration in painted bermudagrass canopies was affected by color, as indicated in Table 5. In Exp. 3, average daily water loss in the un-painted control was 9.1 mm day^{-1} and was less affected by yellow (8.3 mm day^{-1}) and white (8.2mm day^{-1}) than red (7.8 mm day^{-1}) and orange (7.8 mm day^{-1}). Applications of black (7.0 mm day^{-1}) and blue (5.1 mm day^{-1}) had the most negative impacts. In Exp. 4, the range of effects based on color was similar, but the absolute values for transpiration were higher for all colors. For example, average daily water loss in the un-painted control was 2.6 mm day^{-1} higher than the control in Exp. 3, while

yellow, white, red, and orange were between 2.2 and 2.5 mm day^{-1} higher, and black and blue were 1.8 and 1.6 mm day^{-1} higher than in Exp. 3. In Exps. 3 and 4, yellow impacted transpiration the least and blue impacted transpiration the most. Percent reductions relative to the control ranged from 8.8% by yellow to 43.9% by blue in Exp. 3 and 8.5% by yellow to 42.7% by blue in Exp. 4.

Analysis of transpiration by week (Fig. 1) reveals that in addition to reductions throughout all weeks of Exp. 3 and 4 there were differences within weeks as well. The effects of blue on daily water loss were more harmful over all weeks, and were also more immediate. By week two of Exp. 3 and 4, blue resulted in the lowest daily water loss of all colors and remained the lowest throughout all five weeks of both experiments. By week three in both experiments, black resulted in the lowest daily water loss of all colors except blue. Orange, red, and yellow resulted in daily water loss similar to the un-painted control early in both experiments, but were each lower by week three in Exp. 1 and week two in Exp. 2. White also resulted in daily water loss less than the un-painted control in both experiments except during week five of Exp. 1 and week four of Exp. 2 where they were no different.

Paint color also impacted canopy temperature in painted bermudagrass canopies, where it increased from the un-painted control in all colors except white (Table 5). In Exp. 1, black (40.5^{o}C) caused the largest increase in canopy temperature from the un-painted control (28.9^{o}C) followed by blue (39.6^{o}C), red (33.2^{o}C), yellow (30.7^{o}C), and orange (30.0^{o}C). In Exp. 2 black (40.2^{o}C) and blue (39.6^{o}C) caused the largest increase from the un-painted control (29.4^{o}C) followed by red (32.5^{o}C), orange (30.7^{o}C), and yellow (30.5^{o}C). White,

however, resulted in a lower canopy temperature (28.3^{o}C), relative to the control in Exp. 1, and a canopy temperature (29.3^{o}C), no different than the control in Exp. 2.

The relationship between transpiration and canopy temperature in painted bermudagrass canopies is revealed by Fig. 2 as well as Table 6. Average daily water loss in painted turfgrass canopies decreased as canopy temperature increased and was dependent upon color (Fig. 2). Black and blue resulted in higher canopy temperature and less water loss, while orange, yellow, and white resulted in canopy temperatures and water loss more similar to the un-painted control (Fig. 2). Red paint appeared to increase canopy temperature and decrease water loss relative to the un-painted control, but its effects were not as great as black and blue.

The cross-validation summary using quadratic discriminant analysis (Table 6) supports Fig. 2 in that transpiration and canopy temperature resulting from applications of orange, yellow, and white were more similar to the un-painted control than applications of red, black, and blue. Results from Table 6 also indicate the ability to distinguish between light and dark colors, but not within light and dark colors. For example, quadratic discriminant analysis of transpiration and canopy temperature reveals that the un-painted control was wrongly classified as yellow 10.0% of the time, orange 12.7% of the time, and white 30.5% of the time. Furthermore, similarities between the un-painted control and light colors of paint result in error count estimates of 53.8%, which illustrate the inability to distinguish between the un-painted control and light colors. Yellow had the highest error count estimates (78.3%) due to it being mistaken for the un-painted control, orange, red, and white between 11.1 and 31.1% of the time.

Despite the inability of quadratic discriminant analysis to distinguish between the un-painted control, white, yellow, and orange, it never misclassified them as black or blue. Inversely, black and blue were never mis-classified as the un-painted control, orange, white, or yellow which resulted in the lowest error count estimates (28.8 to 39.4%) of any color. However, black and blue were wrongly classified for each other between 18.3 and 28.3% of the time. Red was the only color that was wrongly classified as black or blue, occurring 9.3% of the time.

Analysis of paint thickness revealed that the dried thickness of paint on the leaf is dependent upon color ($P \leq 0.001$) and not leaf location ($P \leq 0.317$), yet there was a color by leaf location interaction ($P \leq 0.002$). White paint dried thicker than black at the tip, center, and base of each leaf as well as the average of all locations. The thickness of white paint measured at the tip, center, and base of turfgrass leaves was 43.3, 46.7, and 42.1 µm, respectively. For black paint, measured thickness for each of these three locations was 21.8, 21.9, and 26.9µm, respectively.

Discussion

Increases in transpiration with increasing air temperature (26 to 38^{o}C) in Study 1 indicate the ability of un-painted bermudagrass to maintain stomatal apertures sufficient to actively transpire within, and slightly above, previously reported temperature optimum of 27-35^{o}C (Dipaola and Beard, 1992). This is consistent with previous research in other warm-season turfgrass species where transpiration rates increase with air temperature. Green et al. (1991a) reported average daily water loss in zoysiagrass (*Zoysia* spp.) to be between 6.1 and

8.5 mm day^{-1} when daily maximum air temperatures ranged from 24.6 to 31.6^{o}C, respectively. Green et al. (1991b) reported similar results in St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntz] where water loss ranged from 7.6 to 9.7 mm day^{-1}, with daily maximum air temperatures ranging from 32.8 to 36.6^{o}C, respectively. Increased transpiration in Exp. 2 relative to Exp. 1 is likely a result of lower relative humidity in the growth chamber during Exp. 2. The relative humidity in the growth chamber during Exp. 2 was 27.7% while in Exp. 1 it was 44.6%, which resulted in higher water loss at all days and weeks in Exp. 2 than in Exp. 1.

Throughout the entire five weeks of both Exp. 1 and 2, canopy temperatures in the un-painted bermudagrass pots fluctuated ±6.9^{o}C in Exp. 1 and ±7.0^{o}C in Exp. 2. This is approximately 58% of the range of air temperatures (26-38^{o}C) the pots were exposed to throughout the study. Furthermore, canopy temperature was within 1.1% to 12.6% of the air temperature in the growth chamber at any single point during the study. As such, data from Study 1 illustrate the ability of transpiration to moderate canopy temperature in un-painted bermudagrass canopies throughout the optimum range of 27-35^{o}C, and even up to 38^{o}C, which is the maximum temperature of the growth chambers used in this study. This is particularly true at higher air temperatures during weeks four and five where transpiration was able to maintain canopy temperature below the air temperature in the growth chamber.

However, results from Study 2 demonstrate that the relationship between transpiration and canopy temperature changes dramatically in painted bermudagrass canopies. This is supported by Fig. 2 in that as canopy temperature increases in painted bermudagrass canopies, daily water loss decreases, an effect contrary to that which was

established in Study 1. A potential explanation for this lies in the fact that athletic field paint has other impacts on painted turfgrass canopies that likely supersede the relationship between transpiration and canopy temperature. These include reductions in total canopy photosynthesis (TCP), stomatal obstruction by paint pigments, and heat stress due to increased light absorption.

Reynolds et al. (2012 and 13) established the color-dependent effects of athletic field paint on bermudagrass TCP, and they are similar to the effects established in this study where lighter colors were less damaging than darker colors. Reductions in TCP were linked to absorption of photosynthetically active radiation (PAR) in which darker colors of paint absorbed more PAR than lighter colors. For example, white, yellow, and orange, which absorbed between 0.0 and 34.9% PAR, were less harmful to TCP than red, which absorbed 46% PAR. Colors most harmful to TCP were blue and black, which absorbed 93.1 and 95.4% of PAR and reduced TCP by 83.5 and 89.5%, respectively.

Stomata are regulated in a temporal manner in which they open during the day and remain closed at night, closely following photosynthesis. Shading effects produced by darker colors of paint capable of reducing photosynthesis could also be responsible for decreases in transpiration due to the stomatal dependence on photosynthesis and light to regulate their opening. The dependence of stomatal opening on light, particularly blue (400-500 nm) and red (600-700 nm) light, is commonly referred to as the red light response and blue light response. While blue light stomatal opening is primarily a signaling response, red light stomatal opening is primarily driven by photosynthesis. These are spatially separated in the leaf where the blue light response occurs primarily in guard cells present on either side of

stomata, while the red light response occurs in guard cells and mesophyll cells (Shimazaki et al., 2007). Both of these cell types, and the light responses within them, are likely impacted by applications of athletic field paint that cover the turfgrass leaf, preventing adequate light interception (Fig. 3).

Furthermore, in addition to overall reductions in light interception, these reactions could also be affected in a color-dependent manner. The effects of various colors of athletic field paint on light interception at various wavelengths have previously been established. White paint has been shown to reflect > 90% of visible light/PAR across all wavelengths, but reflection of light by other other colors like orange, red, and yellow is more wavelength-dependent (Reynolds et al., 2013). For example, orange, red, and yellow reflect between 65.5 and 76.1% of light between 600-700 nm but absorb between 86.5 and 93.1% of light between 400-500 nm. Light that is reflected by paint pigments is still available for use in painted turfgrass canopies in areas with cracked leaf surfaces or partial paint coatings as well as on abaxial leaf surfaces and lower portions of the canopy that may not have received paint. Furthermore, as painted turfgrasses are mowed, reflection and transmission of PAR by lighter colors of paint can be useful for photosynthesis in newly formed, unpainted leaves. However, black and blue absorb > 93.1% of light across all wavelengths. Unlike light that is reflected or transmitted by paint pigments, light that is bound within paint pigments is unavailable for use by photosynthesis. As a result, it is reasonable to expect that applications of athletic field paint have the potential to reduce transpiration in a color-dependent manner by limiting signaling responses to blue light as well as limiting photosynthetic responses to red light. Furthermore, expected limitations on photosynthesis and transpiration would be greater in

darker colors of paint, due to their innate ability to absorb large proportions of PAR, as well as wavelengths within PAR.

In addition to limiting photosynthesis, which may impact transpiration, light interception by paint pigments also has the potential to impact transpiration through heat stress. Average daily canopy temperatures for white, yellow, orange, and red ranged between 28.3 and 33.2^{o}C in Study 2, which are well within the ideal temperature range of bermudagrass (27-35^{o}C). However, blue and black paint, which impacted transpiration the most (Table 5; Figs. 1 and 2) raised canopy temperature well above the ideal range of 27-35^{o}C to between 39.6 and 40.5^{o}C. Increased light absorption by paint pigments, particularly those found in black and blue, result in the necessity to dissipate this excess energy as heat.

The effects of heat stress on bermudagrass physiology and metabolism have previously been investigated. Du et al. (2010) and Shen et al. (2009) defined heat stress as day/night temperatures of 45/40^{o}C and 44/40^{o}C, respectively. In other species with C_4 metabolism, heat stress has been defined as 30-42^{o}C and has been linked to direct inhibitions of the Rubisco (ribulose 1,5-bisphosphate carboxylase-oxygenase) enzyme (Crafts-Brander and Salvucci, 2000; Salvucci and Crafts-Brander, 2004). Specific research to investigate the direct impacts of heat stress in painted turfgrass canopies has yet to be performed. However, results from Study 2 indicate that black and blue paint have the potential to raise canopy temperatures to within previously reported heat stress ranges, particularly in subtropical or tropical climates where temperatures reach or exceed the optimum growing range for warm-season turfgrasses.

In addition to increased absorption of radiant energy, the relationship between reduced transpiration and increased heat stress in painted turfgrass canopies is also likely linked to the ability of paint pigments to obstruct gas exchange at the leaf surface, as indicated by the images in Fig. 3. Pigments present in athletic field paint, regardless of color, are held in place on the leaf by a resin, which is the component of the formulation designed to adhere to leaf surfaces (Reynolds, 2012 and 2013). Images from Fig. 3 illustrate that paint noticeably coats the leaf surface with solid pigment particles being held in place by the resin. As such, the ability of CO_2 to enter the stomata, as well as O_2 to exit the stomata is likely impeded. Therefore, any reductions in gas exchange at the leaf surface would almost certainly reduce the ability of transpiration to moderate canopy temperature in painted turfgrass canopies, thus contributing to heat stress. Furthermore, the inherent properties of pigments found in dark colors of paint to absorb a larger proportion of incident light would certainly lead to greater potential for heat stress.

The importance of transpiration in moderating temperature fluctuations in plants is due to the fact that as water evaporates through leaf stomata into the atmosphere, the latent heat of vaporization of water moderates the temperature of transpiring leaves that would otherwise increase due to absorption of solar radiation (Taiz and Zeiger, 2010) As such, in painted turfgrass canopies there is likely a collective effect where increased absorption of light energy, particularly by darker colors, results in temperature increases that the plant cannot moderate through transpiration, due to stomatal obstruction and/or closure by photosynthetic or light responses.

It is worth mentioning that in Fig. 3, white paint was applied at a 1:1 dilution with water in the same manner as in Study 2. However, application of 1:1 dilutions of black paint resulted in a paint film that was too thin to uniformly coat the leaf, thus preventing adequate coverage and measurements of thickness. In order to obtain uniform coverage using black paint, it was applied without being diluted yet still produced a thinner coating than white paint at a 1:1 dilution. This is due to the lower percentage of pigment solids present in black paint, relative to white paint, and is consistent with previous research where black paint has been reported to contain approximately 20% less pigment than all other colors of paint (Reynolds et al., 2013). Therefore, even at the lowest pigment concentration of the six colors tested, black is able to raise canopy temperature and reduce transpiration more than any color except blue.

The relationship between canopy temperature, reduced transpiration, and heat stress in painted turfgrass canopies is likely all inter-connected. Previously reported photosynthetic reductions, combined with decreased transpiration and heat stress all contribute to commonly observed declines in turfgrass health and performance as a result of athletic field paint applications. These effects are more damaging in darker colors of paint including black and blue due to increased absorption of light that cannot as readily be dissipated as heat, likely due to stomatal obstruction and reductions in transpiration. These effects are an un-avoidable consequence of the innate properties of paint pigments as well as the necessity to apply sufficient amounts of paint to produce bright, uniform lines and logos on athletic turf.

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Table 1. Pantone Matching System (PMS) numbers for six colors of athletic field turf paint.

Color	PMS number	Pigment
Black	Pantone Black C	Carbon black
Blue	287	Phthalocyanine blue
Orange	158	Pyrazolone orange
Red	186	Naphthol red
Yellow	124	Yellow iron oxide, pyrazolone orange
White	Not applicable[†]	Titanium dioxide

[†] There is no PMS number for white paint.

Table 2. Un-painted 'Tifway' bermudagrass daily water loss (mm day^{-1}) , canopy temperature, and relative humidity as a result of six day/night air temperature treatments (26/22, 29/22, 32/22, 35/22, and 38/22^{o}C) in a controlled environment growth chamber during two 5-wk experiments at the Southeastern Plant Environment Laboratory in Raleigh, NC.

	Experiment 1		Experiment 2	
Temperature	Daily water loss	Average daily canopy temperature[†]	Daily water loss	Average daily canopy temperature
	mm day^{-1}	^{o}C	mm day^{-1}	^{o}C
26/22^{o}C	8.4 e	29.3 e	10.5 d	29.1 e
29/22^{o}C	8.9 d	31.8 d	12.1 c	31.6 d
32/22^{o}C	9.3 c	33.7 c	12.5 c	33.2 c
35/22^{o}C	10.2 b	34.6 b	14.3 b	34.2 b
38/22^{o}C	10.5 a	36.2 a	15.2 a	36.1 a
		Analysis of variance		
	***	***	***	***

***Significant at the 0.001 probability level

[†]Daily canopy temperature recorded every 24 h immediately prior to daily loss measurements.

Table 3. Analysis of variance for un-painted 'Tifway' bermudagrass daily water loss (mm day^{-1}) as a result of six day/night air temperature treatments (26/22, 29/22, 32/22, 35/22, and 38/22°C) in a controlled environment growth chamber during two 5-wk experiments at the Southeastern Plant Environment Laboratory in Raleigh, NC.

		Analysis of variance		
Source	df	Mean square	*F*	*P* > *F*
Experiment	1	521.2	1269.3	<0.0001
Week	4	65.6	159.7	<0.0001
Day(week)	25	5.7	13.9	<0.0001
Experiment x week	4	8.4	20.4	<0.0001
Experiment x day(week)	29	2.0	2.5	0.0006

Table 4. Analysis of variance for 'Tifway' bermudagrass daily water loss (mm day^{-1}) due to weekly applications of six colors of athletic field paint in a controlled environment growth chamber during two 5-wk experiments at the Southeastern Plant Environment Laboratory in Raleigh, NC.

	Analysis of variance			
Source	df	Mean square	*F*	*P* > *F*
Experiment	1	1481.6	2059.9	<0.0001
Color	6	378.4	526.1	<0.0001
Experiment x color	6	5.6	7.8	<0.0001
Week	4	123.3	171.5	<0.0001
Day(week)	25	33.9	47.1	<0.0001
Week x experiment	4	3.7	5.2	0.0004
Experiment x day(week)	25	0.6	0.8	0.7050
Week x color	24	23.1	32.1	<0.0001
Color x day(week)	150	1.2	1.6	<0.0001

Table 5. 'Tifway' bermudagrass daily water loss and temperature response from weekly applications of six colors of athletic field paint during two 5-wk experiments at the Southeastern Plant Environment Laboratory in Raleigh, NC.

	Experiment 3		Experiment 4	
Treatment	Daily water loss	Average daily canopy temperature†	Daily water loss	Average daily canopy temperature
	mm day^{-1}	^{o}C	mm day^{-1}	^{o}C
Control	9.1 a	28.9 f	11.7 a	29.4 d
Yellow	8.3 b	30.7 d	10.7 b	30.5 c
White	8.2 b	28.3 g	10.5 bc	29.3 d
Red	7.8 c	33.2 c	10.3 cd	32.5 b
Orange	7.8 c	30.0 e	10.0 d	30.7 c
Black	7.0 d	40.5 a	8.8 e	40.2 a
Blue	5.1 e	39.6 b	6.7 f	39.6 a
		Analysis of variance		
Treatment	***	***	***	***

***Significant at the 0.001 probability level

†Daily canopy temperature recorded every 24 h immediately prior to daily loss measurements.

Table 6. Quadratic discriminant analysis of canopy temperature (^{o}C) and daily water loss (mm day^{-1}) in Tifway bermudagrass as a result of weekly applications of six colors of athletic field paint and an un-painted control during two 5-wk experiments at the Southeastern Plant Environment Laboratory in Raleigh, NC.

	Actual						
Predicted	Black	Blue	Control	Orange	Red	White	Yellow
Black	109 (60.5)[†]	51 (28.3)	0 (0.0)	0 (0.0)	20 (11.1)	0 (0.0)	0 (0.0)
Blue	33 (18.3)	128 (71.1)	0 (0.0)	0 (0.0)	19 (10.5)	0 (0.0)	0 (0.0)
Control	0 (0.0)	0 (0.0)	83 (46.1)	23 (12.7)	1 (0.5)	55 (30.5)	18 (10.0)
Orange	0 (0.0)	0 (0.0)	25 (13.8)	64 (35.5)	19 (10.5)	33 (18.3)	39 (21.6)
Red	1 (0.5)	16 (8.8)	15 (8.3)	23 (12.7)	101 (56.1)	3 (1.6)	21 (11.6)
White	0 (0.0)	0 (0.0)	52 (28.8)	40 (22.2)	0 (0.0)	77 (42.7)	11 (6.1)
Yellow	0 (0.0)	0 (0.0)	34 (18.8)	56 (31.1)	31 (17.2)	20 (11.1)	39 (21.6)
	Error count estimates for color						
Rate	0.3944	0.2889	0.5389	0.6444	0.4389	0.5722	0.7833

[†] Values preceding parentheses represent the number of times a color was classified as another color while values within parentheses represent the percent of the total.

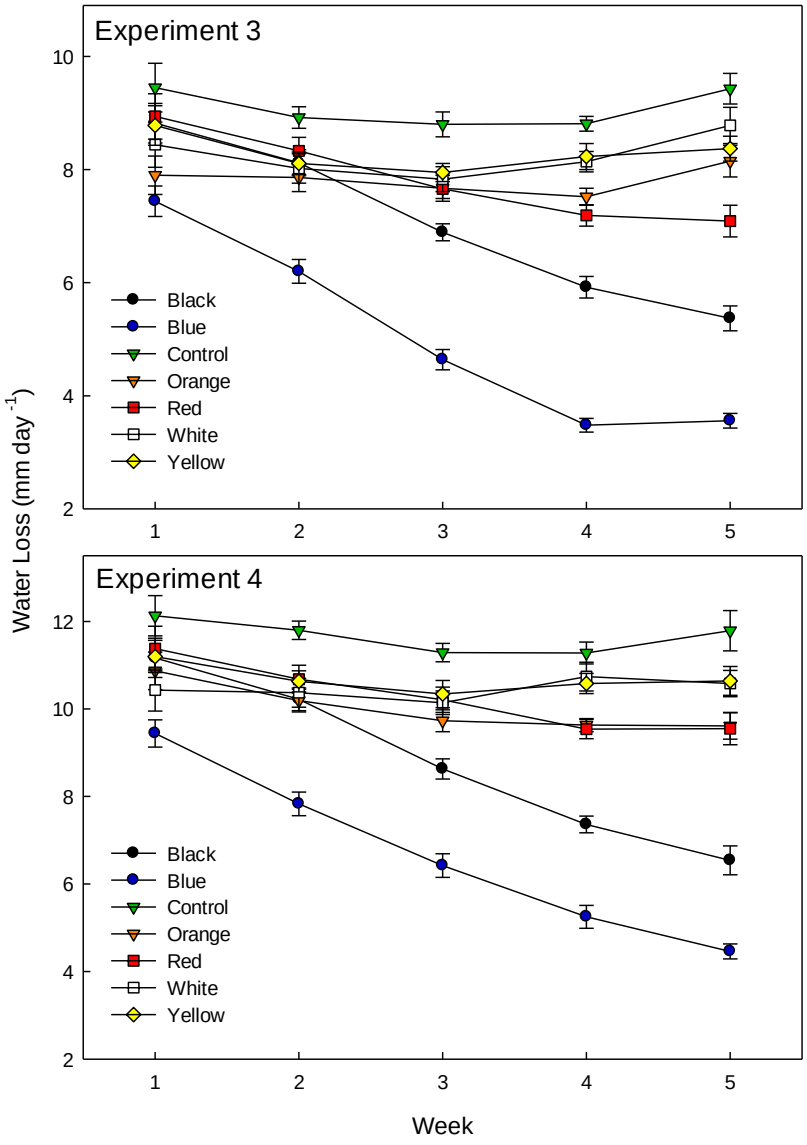

Figure 1. Average daily water loss (mm day^{-1}) of 'Tifway' bermudagrass measured every 24 h for six days per week during two 5-wk experiments in a controlled environment growth chamber at the Southeastern Plant Environment Laboratory in Raleigh, NC. Values represent daily average water loss, and bars for each treatment represent standard error.

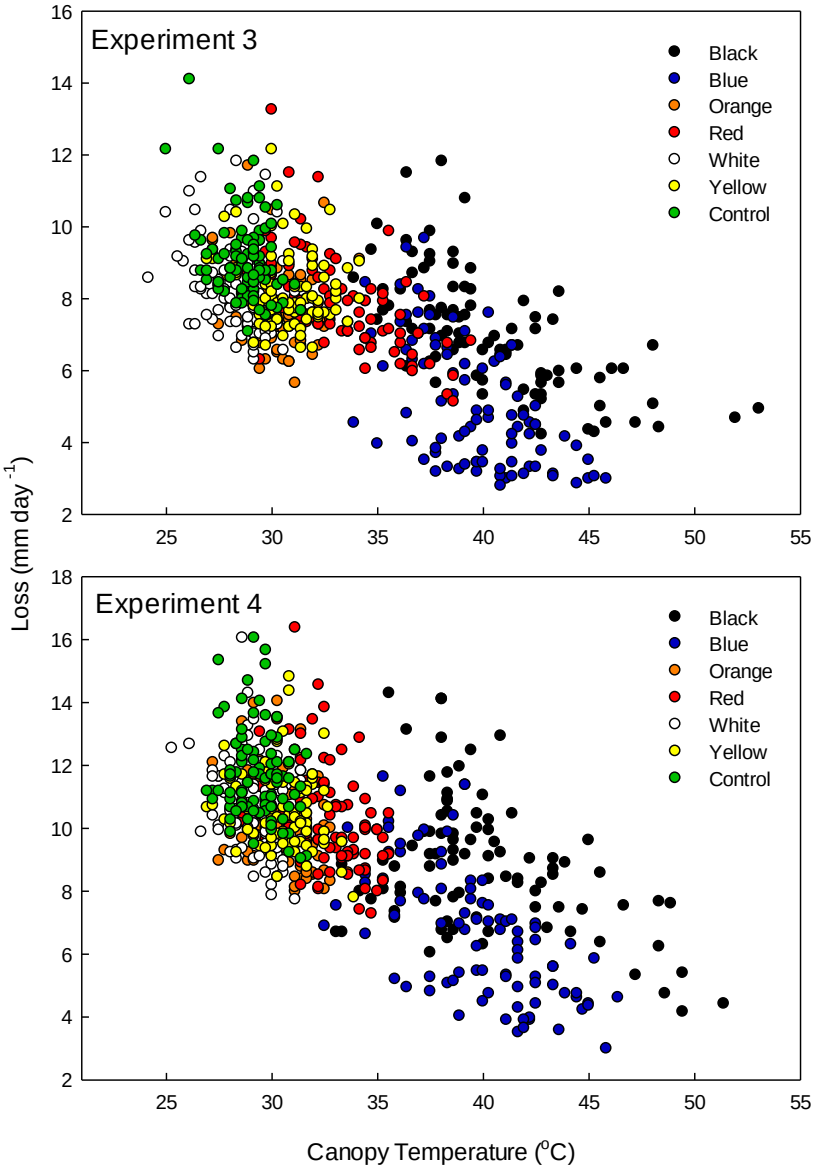

Figure 2. Daily water loss (mm day^{-1}) and canopy temperature (^{o}C) of 'Tifway' bermudagrass measured every 24 h for six days per week during two 5-wk experiments in a controlled environment growth chamber at the Southeastern Plant Environment Laboratory in Raleigh, NC.

A. White 1:1 dilution

B. Black no dilution

Figure 4. Digital images of 20µm cross-sections of 'Tifway' bermudagrass embedded in paraffin after one application of white (A.) and black (B.) athletic field paint. White paint has been diluted with water at v:v ratio of 1:1 and black paint was not diluted. Images were taken at 10x magnification and cropped to an image size of 856 x 560 pixels.