USE OF TARTRAZINE DYE AS A TRACER TO MEASURE FOLIAR SPRAY RETENTION ON TURFGRASS

BY

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THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Crop Sciences
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2018

Urbana, Illinois

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ABSTRACT

A well-managed turf is functional, recreational and ornamental. Professional management is commonly required to maintain the quality of turfgrass, among which, golf courses require the most complicated and intensive management practices to maintain the playability and performance of the turf. Foliar spray applications are widely used on athletic fields due to their precise application and efficiency. However, it is often necessary to modify spray methods to meet different needs and situations. Adjustments in spray volume, nozzle type and adjuvant can have significant influence on the distribution and retention of active ingredients on plant surface.

Experiments were conducted in Urbana, IL to determine the influence of spray volume, nozzle type, adjuvant, surface wetness and their interactions on foliar spray retention on a bentgrass (*Agrostis stolonifera* L.) golf fairway. For water-based spray mixtures, the results indicated that increasing spray volume decreased foliar recovery to a plateau at around 85%. Compared to flat fan nozzles, air induction nozzles delivered the same level of foliar retention under typical spray volumes used on golf courses. However, flat fan nozzles provided higher spray uniformity and coverage. Adding nonionic surfactants (NIS), organosilicone adjuvants (OSA) and methylated seed oils (MSO) at the median recommended concentration maintained foliar recovery rates at approximately 93% to 90% under both low and high spray volumes. Without adjuvants, increasing spray volume reduced recovery rates from 96% to 87%. However, no differences were observed between adjuvants. When dew was present, increasing spray volume noticeably reduced recovery rates at high spray volumes, 750L/Ha and 1125L/Ha, compared to low spray volume. Adding adjuvants had limited influence on spray retention with the presence of dew.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor Dr. Bruce Branham of the Department of Crop Science at the University of Illinois for his constant help and support of my Master’s study and for his patience in teaching, communicating and conducting my study. I would also like to thank the other members of my committee, Dr. Thomas B. Voigt and Dr. Gary Kling for their help and support throughout my experiments and my career plan.

I would like to acknowledge William Sharp and other staff members of the University of Illinois Landscape Horticulture Research Center for training me in turf management and for maintaining my trials and allowing me land space, plant material, and equipment to conduct my research.

I thank my fellow lab mates and office mates and all my friends for the encouragement and help for all the fun we had in last three years.

Finally, I would like to express my profound gratitude to my parents Yingchi Zhang and Ping Jin, for providing me the chance to pursue a Master’s degree abroad. I would also like to thank my girlfriend, Yan Mao, for her unfailing support and encouragement throughout my study and research process. This accomplishment would not have been possible without the help and support of my parents and girlfriend. Thank you all.

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CHAPTER 1: SPRAY APPLICATION ON GOLF COURSES

Well-managed turfgrass is a critical feature in modern landscape architecture, especially in the United States. According to 2005 data (Milesi et al., 2005), roughly 163,800 km^2 of the continental land in the USA was estimated as functional turf areas. Due to the high demands for functional, recreational, and ornamental benefits from cultivated turf grasses, turfgrass is the largest irrigated crop in this country (Milesi et al., 2005). Professional management of athletic field turfgrass systems is often required to meet performance and functional requirements. Experts have predicted a constant and rapid growth of turf industry (Haydu et al., 2008). However, the green industry experienced a depression during the Great Recession that began in Dec. of 2007. Years later, with the recovery of economy, more than 94% percent of the landscaping companies are confident about the growth of the turf industry and their own business (Golf course industry, 2016).

While the future looks promising, the turf industry faces challenges but also opportunities. Individual turf businesses are confronted with increasing pressures from competition, more stringent regulations, and stricter environmental policies (Haydu et al., 2008; Lyman et al., 2007, 2012a, 2012b). Techniques and services will need to be improved to provide more effective and environmentally sound practices and maintenance strategies, especially for athletic fields which receive the highest level of inputs.

Golf is a popular recreational activity in the USA. According to Golf Course Industry (2016), about 15,300 golf courses are distributed throughout the US. Golf courses receive the most intensive management practices to maintain the playability and performance of the turf.

The area occupied by golf courses varies with the number of holes and the land available for the golf course. The total area of a typical 18-hole golf course is approximately 607,000 m^2, 65% of which is maintained turfgrass. Roughs, driving range/practice areas and clubhouse grounds comprise 259,000 m^2 of area under moderate management, while more intensive management practices are conducted on 121,400 m^2 of fairways and 24,280 m^2 of greens and tees (Lyman et al., 2007). Fertilizer and pesticides applied on these highly managed turf systems can contribute nutrients and pollutants to surrounding surface water, raising environmental concerns. To maintain turfgrass quality while minimizing the potential environmental problems, foliar spray applications that allow effective and precise crop management have been widely using on golf courses.

1.1 Foliar application technology

Effective spray applications can save money, reduce labor costs, and reduce potential environmental problems caused by mis-application. Spray efficiency is determined by the quantity of active materials deposited on target surface; the coverage of the target surface; and the persistence of active ingredients remaining on target surface (Furmidge, 1962). To achieve an effective spray application, the active ingredient must be applied uniformly to the target site. The target site is often determined by the site of uptake of the chemicals by the plants. A turf system can be divided into three zones: foliage, thatch/mat layer and the soil. The above ground layer, foliage and thatch/mat layers, and surface soil are usually the two main target sites for sprayed chemicals. Contact, locally systematic and symplastically-transported chemicals provide the best response when deposited on foliage. Apoplastically-transported chemicals need to be delivered to the thatch/mat layer to function most appropriately. Understanding the distribution of chemicals can help turf managers modify the spray parameters to deliver the active ingredient to the right site. In most cases on turf, increasing foliar retention leads to a better response, because the majority of products are usually foliarly absorbed.

Foliar retention is closely related to the physical properties of the spray mixture, spray method, and the properties of the plants (Furmidge, 1962; Gossen et al., 2008). In particular, spray volume, nozzle type, travel speed, and adjuvant are generally adjusted to improve spray application performance.

1.2 Spray volume

Modifying spray volumes can influence the spray application performance in several ways. Foliar retention and coverage are the primary factors affected (Gossen et al., 2008). Typical spray volumes used on golf courses range from 200 L/ha to 1000L/ha (Shepard, et al., 2006). There are three main factors to consider when selecting a spray volume: drift potential, coverage, and the target site (Kammerer & Whitlark, 2017).

A lower spray volume allows a higher droplet density and a more thorough coverage of plant surface by producing finer droplets (Gossen et al., 2008). When applications are made at low spray volumes (<100L/ha), foliar-applied herbicide performance improves as droplet size decreases (Knoche, 1994). However, smaller droplets are susceptible to drift, in windy and even nearly wind-free environments (Reichard et al., 1992). Drift decreases product performance by reducing the uniformity, coverage, and amount of active ingredient reaching the target site. Additionally, drift leads to non-target injury and other environmental issues. As previously written , low spray volumes, less than 200 L/ha (Matthews, 2008), are rarely used on golf courses. In particular, golf course superintendents often choose a higher spray volume to diminish the potential problems caused by drift, because an increase in spray volume increases the size of spray droplet, reducing the drift potential. Since golf courses are often surrounded by residences with a variety of plant material and concerns about pesticide exposure to children and pets, a premium is put on drift reduction.

The target sites for a spray application can either be the foliage or the thatch/mat surface. Some products are absorbed by both foliage and roots. Several products that target root uptake recommend at extremely high spray volumes, 1900L/ha to 3800L/ha, to move the product into the root zone (Kammerer & Whitlark, 2017). It is not commercially feasible to apply such high spray volumes with commonly used spray equipment on golf facilities. Whatever the target, the product label is the most reliable source to determine spray volume. However, common recommended spray volumes for foliarly-absorbed products are typically between 240L/ha and 950L/ha (Kammerer & Whitlark, 2017). Within this wide range, increasing spray volume may result in a reduced drift potential, but increases the risk of product running off the foliage and into thatch/mat layer.

The foliar retention volume, the volume of water held by the foliage on a ground area basis, and the recovery rate, defined as the ratio of the foliar retention volume to the actual applied volume, are tools to assess the efficacy of a spray method. A higher foliar retention volume implies that more of the spray mixture is retained on foliage, which usually translates into better coverage and hence better performance for fungicides and herbicides (Vincelli and Dixon, 2007). Unfortunately, an increasing retention volume does not necessarily lead to an additional retention of active ingredients (AI). Within a spray mixture, the total amount of AI remains constant, while its concentration decreases with the increase of spray volumes. The retained AI on target equals the volume of spray mixture retained times the concentration of AI within the spray liquid. A higher efficacy of spray application can be achieved when the spray volume remains constant while the retention volume increases. Thus, recovery rate is measured to determine the percentage of AI remaining on the target surface. For optimal foliar uptake, higher retention volume and higher recovery rate are achieved simultaneously.

Several researchers have analyzed the retention of spray droplets on plants. When spray volumes of approximately 500, 1000, 2000 L/ha were applied to round-leaved mallow (*Malva rotundifolia* L.) recovery rates decreased from 26%, 22%, and 20% respectively (Byer et al., 2006). Retention volumes were not included in the original data in Byer et al.'s study, but multiplying recovery rate by applied spray volume implied increasing foliar retention with increasing spray volume. Within a narrower range of spray volumes, the retention volume increased with increasing spray volume on chickpea (*Cicer arientinium* L.); however, recovery rate decreased as spray volume increased (Armstrong-Cho et al., 2008). A similar trend was also observed on chamomile (*Matricaria inodora* L.) and green foxtail (*Setaria viridis*) (Byer et al., 2006; Peng et al., 2005)

A different trend was measured on citrus trees (*Citrus maxima*). The same amount of copper was applied as a tracer in 5 spray volumes to measure foliar retention. The amount of tracer recovered from leaf surface decreased from 59 µg/cm^2 to 47 µg/cm^2 as the spray volume increased from 470 L/ha to 2350 L/ha, respectively. However, increasing spray volume from 2350 L/ha to 4700 L/ha did not reduce copper recovery, which implied that the recovery rate remained similar at high spray volumes (Salyani and McCoy, 1990).

A thorough search of the literature did not find any studies that analyzed foliar retention by turfgrasses. Several researchers studied the biological responses of pesticides applied at different spray volumes (Armstrong-Cho et al., 2008; Kennelly and Wolf, 2009; McDonald et al., 2006; Vincelli and Dixon, 2007). Though the level of control is influenced by multiple variables, greater foliar retention of active ingredients should lead to better control. Thus, visual observations of control can be used to infer foliar retention. The influence of increasing spray volume on dollar spot (*Sclerotinia homoeocarpa* F. T. Bennett) control was inconsistent. McDonald et al. (2006) found increasing spray volume reduced the level of control, suggesting a decline in foliar retention, while other researchers observed similar level of control within the evaluated range of spray volumes (Kennelly and Wolf, 2009) .

1.3 Nozzle types

The correct nozzle assures minimal waste and optimized efficacy of a spray application. The pattern of spray produced by a nozzle is closely correlated to the risk of spray drift, and the retention and distribution of the spray on the target (Hall et al., 1993). To understand the impact of nozzle types on a given spray application, the size and velocity of the spray droplets, volume distribution pattern and spray structure are commonly measured (Miller and Butler Ellis, 2000).

Several nozzles are available for professional turf managers. On golf courses, the most commonly used nozzles are flat fan nozzles, air induction nozzles, and flooding jet nozzles (Shepard et al., 2006).

Flat fan nozzles are typically hydraulic pressure nozzles, which rely on the kinetic energy of spray mixture to break the spray liquid into droplets. A flooding jet nozzle is a surface-impingement nozzle. The impingement breaks up the stream of liquid into droplets. Air induction nozzles utilize the Venturi effect to mix air and liquid inside the nozzle as the spray is formed. Different types of nozzles are designed to meet the variable needs of spray applications. Flat fan nozzles as are preferred when uniform distribution of chemicals is needed. Flooding jet nozzles have pre-orifice design that increases the size of spray droplets while keeping a good pattern of uniformity while reducing the possibility of clogging. Air induction nozzles are designed to diminish drift by forming much coarser droplets with lower density. (Spray Systems Co., 2014)

Though several environmental factors have impact on drift potential, researchers consider that spray droplets smaller than 100µm (Grover et al., 1978) or 200µm (Bouse et al., 1990) are most susceptible to drift. Taking 200µm as a cutoff, air induction nozzles reduced drift potential, the portion of spray droplets with a diameter smaller than 200µm, from 43.2% to 3.7% compared to flat fan nozzles at the same nozzle size and pressure (Nuyttens et al., 2007),.

However, increasing spray droplet size reduces the uniformity of a spray application, which might lead to undesirable response, especially for contact pesticides. More coarse droplets may also lead to a reduced foliar retention due to the potential for foliar run-off. Increasing average droplet size from fine, 175 µm, to coarse, 491 µm, decreased the retention rate on corn (*Zea mays* L.) foliage from 47% to 38%. Nevertheless, the change of droplet size from medium to coarse did not change the foliar retention significantly (Feng et al., 2003). A decline in foliar retention was observed on wheat (*Triticum aestivum* L.) at an early growth stage when the plant canopy density is relatively low (Butler Ellis et al., 2004).

A successful spray application deposits as much active ingredients as possible on the target site. Air induction nozzles diminish the loss from drift, but traditional flat fan nozzles provide the highest foliar retention rate and better coverage. Choosing the nozzle to achieve the right droplet size is important to improve application efficacy.

1.4 Adjuvants

Adjuvants are materials designed to enhance or modify the action of the spray mixture. The classification of adjuvants can be based on the categories of chemicals or the mechanisms of functions. For agricultural management, there are three main classes of adjuvants: 1) modifying the interaction between chemicals inside the spray tank; 2) modifying how the spray mixture interaction with the target surface; and 3) modifying the pathway of uptake and absorption (Somervaille, 2011).

Inside the spray tank, there are two categories of adjuvants applied to modify the spray mixture. Compatibility agents are designed to stabilize and enable the co-existence of hydrophobic ingredients in a water-based formulation. Another group are called drift retardant agents, which increase the surface tension and viscosity of the spray mixture to reduce the atomization at nozzle tips (Somervaille, 2011) .

Modifying the surface tension of spray liquid is the main approach to change the interaction between spray droplets and plant surface. A formulation with a high surface tension tends to form spherical shaped droplets on target surfaces, which are more likely to bounce off. Formulations with a lower surface tension can rapidly deform and spread on target surfaces leading to better retention. Particularly in a spray application, reducing surface tension as much as possible might not be beneficial. Droplets are more likely to run off the target surface as they coalesce together, especially when the carrier volume is high. On the other hand, the spreading of droplets on plant surface can lead to higher levels of uptake and better response with the increase in coverage (Somervaille, 2011). Many active ingredients, however, require a liquid state to be adsorbed by plants, such as glyphosate (Macisaac et al., 1991). Spreading might reduce the time for uptake because of more rapid evaporation and drying. The increasing drift potential is another concern because a decreased surfaced tension provides smaller spray droplets.

Adjuvants can also change the process of uptake and transport. Based upon function, adjuvants are classified into four principal groups. Oils are commonly used to reduce evaporation and extend the active life of certain chemicals by elongating the period of uptake. Some surfactants are designed to sufficiently decrease the dynamic surface tension to increase the uptake through stomata. Adjuvants may also facilitate the progress of uptake by changing the properties of target surface, such as physically disrupting cuticles (Somervaille, 2011).

A number of researchers have sought to understand the performance and potential interaction between adjuvants and pesticides (Butler Ellis et al., 2004; Hall et al., 1998; Hart et al., 1992; Pacanoski, 2010; Young and Hart, 1998). On giant foxtail (*Setaria faberi*), Young and Hart (1998) found that when mixed with isoxaflutole, nonionic surfactants (NIS), crop oil concentrates (COC) and methylated seed oil (MSO) increased foliar retention from 38% to roughly 60% compared to isoxaflutole alone. No differences in foliar retention among these three adjuvants were detected. A similar trend was also reported on giant foxtail (*Setaria faberi*) when NIS, COC, MSO and organosilicone adjuvant (OSA) were tank mixed with primisulfuron alone or in combination with atrazine, dicamba or bentazon. However, when the same treatments were applied to shattercane (*Sorghum bicolor* L.), different foliar retentions patterns were observed among adjuvants. Compared to MSO and NIS/COC, OSA generally increased foliar retention (Hart et al., 1992). Three oil-type adjuvants, prepared as emulsifiable concentrates and oil-in-water emulsions, all increased the foliar retention on peas (*Pisum sativum* L.) and barley (*Hordeum vulgare* L.) compared to water (Hall et al., 1998). However, adding organosilicone at 0.15% v/v to water significantly decreased foliar retention on wheat (*Triticum aestivum* L.)(Butler Ellis et al., 2004).

Interactions have been detected between adjuvant and nozzle types. With the addition of phospholipid, spraying by a flat fan nozzle did not increase foliar retention on wheat (*Triticum aestivum* L.) at growth stage 30-33, but foliar retention was enhanced by roughly 33% with an air induction nozzle (Butler Ellis et al., 2004). Unfortunately, no clear trend describes how nozzle type influences the performance of different adjuvants.

Adjuvants have many uses and only a fraction of them are designed to enhance foliar retention, while other adjuvants enhance the performance of pesticides through a variety of means. Previous research (Hart et al., 1992; Young and Hart, 1998) observed that different adjuvants lead to variable plant uptake and resulted in noticeably different control even when the foliar retention was similar. Sufficient retention of the active ingredient on the target surface should yield a successful spray application. Quantifying the foliar retention of a spray solution will help to better understand the complex interactions among spray volume, adjuvants, and nozzle type.

1.5 Dew

Dew is the diurnal accumulation of condensates and plant exudates on the foliage and is the main source of leaf wetness in turfgrass systems (Williams et al., 1998). A strong correlation between duration of dew and the occurrence and severity of many diseases has been reported since free moisture is a critical external factor that influences the life cycle of many pathogens (Delvalle et al., 2011; L Huber and Gillespie, 1992).

The formation of dew on turfgrass is dominantly influenced by soil moisture content (Hughes and Brimblecombe, 1994; Williams et al., 1998). Under soil-saturated and air-saturated conditions, which usually happens during humid summers, 0.07mm-0.09mm of dew may form within an hour (Garratt and Segal, 1988). A two-year study found that the accumulation of dew on a creeping bentgrass *(Agrostis stolonifera* L.) fairway reached the peak at 0800 with an accumulation of 0.195mm of dew, within which, 33% of plant surface wetness was plant exudates. The duration of dew was positively correlated to the volume of dew retained on plant surface (Williams et al., 1998). Further, guttation fluids contain variety of ingredients including C and N that may support the growth of a pathogen.

On the other hand, the surface wetness may also reduce the efficacy of spray application. Spray droplets can coalesce with the dew on the target surface leading to a dilution of AI followed by run-off, especially when heavy dew is present. With an artificial dew of 840L/ha on a vineyard, plant surface wetness lead to a 72% reduction of spray retention compared to dry leaves (Saab et al., 2017).

A regular dew removal routine is recommended for golf superintendents to achieve better diseases control. There are multiple ways to remove dew on fairways and greens. Syringing turfgrass surface to remove dew; dragging hoses across the turf; blowing, mowing or rolling to knock down dew are normally conducted on golf courses. However, the intensive requirements of labor and time and the corresponding cost limits the implementation of dew removal practices on many golf courses. Additionally, the majority of spray applications are preferred to be done early in the morning before play begins. The time limitation makes it even more infeasible for those golf courses that are open every day to remove dew before a spray application.

1.6 Measurement of foliar spray retention

Tracers are usually used to replace the active ingredient in agriculture sprays to assess the retention and coverage (Holownicki et al., 2002; Pergher, 2000; Sanchez-Hermosilla et al., 2008)**.** Tracers are either chemicals that can be optically quantified (e.g. visible dye) or chemicals that can be chemically measured based on known reactions (e.g. chelated copper) (Holownicki et al., 2002). According to Cooke and Hislop, fluorescent compounds, visible dyes or metal salts are normally applied as the tracer (1993).

Previous studies (Holownicki et al., 2002; Pergher, 2000; Sanchez-Hermosilla et al., 2008; Zhu et al., 2004) conducted in the early 1950s used fluorometric methods to analyze spray retention. These methods were widely used by other researches due to their ease and accuracy. However, photodegradation has been the principle disadvantage of using fluorescent dyes as tracers. Metal tracers, such as magnesium (Pezzi and Rondelli, 2000), aluminum (Tu et al., 1986), zinc, and strontium (Cross et al., 2001) have been utilized in spray retention studies and analyzed using inductively coupled plasma atomic emission analysis (Moor et al., 2002) and atomic absorption spectrophotometry (Murray et al., 2000; Pezzi and Rondelli, 2000).

The methods mentioned above required complex laboratory facilities and procedures, which is usually time-consuming and costly. Further, metals salts are more prone to be taken up by plants compared to other tracers (Murray et al., 2000).

Colorimetric analysis is the most widely used method to analyze spray retention because spectrophotometric detection is easy and relatively low cost (Sanchez-Hermosilla et al., 2008). A review of the available literature on foliar retention showed that tartrazine, a yellow food dye, was commonly recommended as a tracer since it exhibits the least photodegradation and plant uptake (Holownicki et al., 2002; Murray et al., 2000; Sanchez-Hermosilla et al., 2008).

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CHAPTER 2: USE OF TARTRAZINE DYE AS A TRACER TO MEASURE FOLIAR SPRAY RETENTION ON TURFGRASS

2.1 Abstract

Experiments were conducted to evaluate the impact of spray volume, nozzle type, adjuvant, the presence of dew and their interactions on foliar spray retention of creeping bentgrass (*Agrostis stolonifera* L.). The results indicated that increasing spray volume from 95L/ha to 1500L/ha decreased the foliar recovery rate from 98% to approximately 85%. Compared to flat fan nozzles, air induction nozzles delivered the same level of foliar retention at all spray volumes evaluated. However, flat fan nozzles provided higher uniformity and more thorough coverage. Adding nonionic surfactants (NIS), organosilicone adjuvants (OSA) and methylated seed oils (MSO) at typical concentrations yielded recovery rates of approximately 90% to 93% regardless of spray volumes. In contrast, with water alone, increasing spray volume reduced recovery rate from about 95.9 % to 87.3 %. No differences were observed between adjuvants. With the presence of dew at 1950L/ha on bentgrass turf, increasing spray volume reduced recovery rate by roughly 11-14 %. Adding adjuvants did not influence spray retention when dew was present.

2.2 Introduction

Foliar spray applications are widely used in modern agriculture, especially on golf courses where intensive management practices are conducted to maintain turf quality and performance. Improving the performance of spray applications while reducing costs, labor, and potential environmental problems is a goal for all turf managers and researchers. To achieve an effective spray application, the active ingredient must be applied uniformly to the target site and persist for enough time to exert control (Furmidge, 1962). Turf managers can adjust the physical properties of spray mixtures and spray methods to optimize the response of a spray application under different situations (Gossen et al. 2008). In particular, spray volume, nozzle types, travel speed, and adjuvant can be varied to increase the efficacy of the application.

A number of researchers have studied turf responses to different spray techniques (Delvalle et al., 2011; Kennelly and Wolf, 2009; McDonald et al., 2006). However, a thorough search of literature did not find any studies that quantified foliar retention on turfgrasses. The evaluation of retention is important because it determines the coverage and the total amount of active ingredient available for foliar uptake. In most cases for golf course turf management, enhancing foliar retention leads to a better response to the applied chemicals.

Several studies have reported the influence of spray volume, nozzle type, adjuvant and their interaction on foliar retention on other crops, such as wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), giant foxtail (*Setaria faberi*), and shattercane (*Sorghum bicolor* L.).(Armstrong-Cho et al., 2008; Butler Ellis et al., 2004; Feng et al., 2003; Hart et al., 1992; Kells and Wanamarta, 1987; Peng et al., 2005; Ramsdale and Messersmith, 2001; Young and Hart, 1998). In general, increasing spray volume decreased the foliar retention of active ingredients. Increasing the size of the spray droplets increases the likelihood of foliar run-off. Adding adjuvants usually increased foliar retention, while a few researchers reported reduced foliar retention depending upon the concentration of product (Butler Ellis et al., 2004).

The properties of plant surfaces are a critical factor that influences the behavior of spray droplets (Ruiter et al., 1990). The response can be different on golf fairways because of the high turfgrass density. Additionally, dew is often present during spray applications on golf courses (Delvalle et al., 2011; Williams et al., 1998). Dew has been shown to reduce the foliar retention on vine grapes (*Vitis vinifera* L.) by 75% (Saab et al., 2017).

Tracers can be used in agriculture sprays as a means to assess retention and coverage (Holownicki et al., 2002; Pergher, 2000; Sanchez-Hermosilla et al., 2008). Among the widely used tracers are fluorescent compounds, visible dyes, or metal salts. Tartrazine, a yellow food dye, has been successfully used as a tracer in previous work on spray retention with a high accuracy and ease of measurement (Cross et al., 1997, 2001; Holownicki et al., 2002; Murray et al., 2000; Pergher, 2000; Sanchez-Hermosilla et al., 2008).

The objective of this research was to quantify the foliar retention of spray solutions as influenced by different spray volumes, nozzle types, adjuvants, the presence of dew and their interactions on bentgrass fairways. This research can provide growers with techniques to maximize foliar coverage and retention to achieve optimum control.

2.3 Materials and methods

2.3.1 Spray retention validation

In order to validate that tartrazine could be quantitatively recovered from turfgrass foliage, several experiments were conducted to determine optimal recovery and stability of tartrazine. In the first experiment, above-ground green tissue and thatch were carefully removed from each core with scissors and placed into a 100 cm Petri dishes (Fisherbrand, USA). One milliliter of tartrazine solution (10mg/L in distilled water) was uniformly added to plant materials by pipette. Plant materials were stored in the dark at 20 °C for 4h, 12h, 24h, and 48h. Each time interval was replicated three times. Tissue samples were extracted four times with 75 ml of distilled water. The rinsates were combined, filtered through cheesecloth, then through a Whatman #1 qualitative filter, and finally a 7 ml subsample was filtered through a 0.2 μm, 25 mm diameter syringe filter (CHROMAFIL Xtra PES-20/25, Macherey-nagel INC., PA, USA). Filtered samples were stored in 7ml glass bottles in the dark for later measurements. In the second experiment, which was necessary to confirm that tartrazine not recovered on leaf tissue had moved into the thatch layer, turf cores were treated with spray volumes of 190 L/Ha, 750 L/Ha and 1500 L/Ha containing tartrazine at 10 mg/L. Each spray volume was replicated three times. After collecting all green leaf tissues, the top 0.5 cm of thatch was collected separately. The leaf tissue and thatch were extracted and measured as above.

2.3.2 Plant material

Turf cores were collected from the University of Illinois Landscape Horticulture Research Center. Creeping bentgrass (cultivar L93), was established in August of 2010, and maintained at a mowing height of 1.3 cm. Cores were collected for each study using a golf-course cup cutter with a diameter of 10.6 cm. The cores were transported to the laboratory one day prior to treatment. Approximately 2.5 cm of soil was preserved so that the height of each experimental unit was 3.8 cm. The turf cores were covered with moistened towels before treatment to prevent wilting. Plastic bands were put around each core to maintain the surface area at 86.2 cm^2 and to prevent spray deposition on the exposed sides of the turf.

2.3.3 Experimental design

All experiments were conducted in 2017 at the Plant Science Laboratory Greenhouse in Urbana, Illinois. In each experiment, a completely randomized design with 4 replications was utilized. Each experiment was repeated within 10 days to minimize differences in leaf area of plant material.

All experiments were conducted using a Generation III Research Track Sprayer (DeVries Manufacturing, MN, USA) The spray height for the flat fan nozzles was 41 cm, while the spray height was 46 cm for the air induction nozzles (Teejet technologies, IL, USA). The pressure of the sprayer was set at 276 kPa for all experiments.

Tartrazine (Sigma-Aldrich, MO, USA) was added to each spray solution as a tracer. At spray volumes of 95 and 190 L/ha, the tartrazine concentration was 50 mmol/ L. At the 380 L/ha spray volume, tartrazine was added at a concentration of 20 mmol/ L. At spray volumes of 770L/ha, 1125L/ha or 1500L/ha, the tartrazine concentration was 10 mmol/ L.

2.3.3.1 Influence of spray volume

Six spray volumes were evaluated using flat fan nozzles (Teejet technologies, IL, USA) (Table 1). The experiments were conducted on 26 and 29 Jul. 2017.

2.3.3.2 Influence of Spray Volume and Nozzle Types

Four spray volumes, 190 L/ha, 380 L/ha, 750 L/ha, and 1125 L/ha, were applied using either flat fan nozzles or air induction nozzles to determine the influence of nozzle types and spray volume on foliar retention (Table 1). These experiments were conducted on 12-14 and 20-23 Sep. 2017.

2.3.3.3 Influence of spray volume and adjuvants

Three adjuvant classes, nonionic surfactants (NIS) (Induce, Helena Chemical Company, Memphis, TN, USA), organosilicone adjuvants (OSA) (Kinetic, Helena Chemical Company) and methylated seed oil (MSO) (BASF corporation, Research Triangle Park, NC, USA) were mixed with distilled water at a concentration of 0.25% v/v, 0.125% v/v, or 0.75% v/v, respectively. Distilled water, i.e. no adjuvant (NA), was included as a control. Three spray volumes, 190, 750, and 1125 L/ha, were used. The experiments were conducted on 21-23 Aug. and 1-3 Sep. 2017.

2.3.3.4 Influence of spray volume and adjuvants in the presence of dew

Naturally occurring dew at University of Illinois Landscape Horticulture Research Center was measured on five separate occasions (Figure 1). Based upon those results, the Generation III sprayer was used to apply artificial dew at 1950 L/ha to turf cores using a flat fan nozzle (EVS8001, Teejet technologies, IL, USA). The same three adjuvant classes as described above were used in the dew study and at the same concentrations in the spray solution. Three spray volumes, 190, 750, and 1125 L/ha, were applied to measure the impact of spray volume and adjuvants on foliar retention when dew is present. These experiments were conducted on 18- 20 and 28- 30 Oct of 2017.

2.3.4 Application methods

Filter paper with a diameter of 185 mm (Whatman #1, Buckinghamshire, UK) was placed before and after four bentgass cores and treated with one pass of the sprayer. The filter papers were used to measure the applied spray volume. For spray volumes lower than 750L/ha, one filter paper was placed at each end while two layers of filter paper was needed to fully absorb spray droplets produced by higher spray volumes (higher than 750L/ha).

Following spray application, the cores were allowed to air dry for 1 hour in a fume hood prior to leaf removal. After drying, all green tissue was carefully removed, extracted, and filtered following the procedure outlined in spray retention validation section.

2.3.5 Measurement and analyses

Sample absorbance was measured using a spectrophotometer (SPECTRONIC 20D, Milton Roy Co., PA, USA) at 425nm where the absorbance of tartrazine is maximized (Pergher, 2000). Standard curves were determined for each experiment. Applied volume, recovery rate and foliar retention volume were calculated using the following formulas:

Applied volume (AV) = $(0.32C_fV_f) \times S/C_{tracer}V_{tracer}$

Recovery rate (RR) = $(C_tV_t - 0.112)/0.32C_fV_f$

Retention volume (*RV*) = $AV \times RR = (C_t V_t - 0.112) \times S / C_{tracer} V_{tracer}$

Coefficient of variance (*CV*) = σ / Marginal mean

Where

0.32 = the ratio of the area of experimental unit (86.22 cm^2) to the area of each filter paper (268.80 cm^2)

$C_f =$ the concentration of the rinsate extracted from filter papers (*mg/ml*)

V_f = the volume of rinsate determined from the filter paper (*ml*)

S = targeted spray volume (*L/ha*)

C_{tracer} = the concentration of tracer in spray mixture (*mg/ml*)

V_{tracer} = the volume of spray mixture deposited within each experimental unit area (86.22 cm^2) based on targeted spray volume (*ml*)

C_t = the concentration of the rinsate extracted from turf clippings (*mg/ml*)

V_t = the volume of rinsate collected from turf clippings (*ml*)

0.112 = absorbance due to clipping rinsate, i.e. background

Analysis of variance was performed using JMP Pro v 11.2 (SAS Institute, Cary, NC, USA). Several experiments (nozzle types by spray volumes; adjuvant types by spray volumes) were analyzed as a 2-factor factorial. In all studies, means were compared by the Fisher's LSD test at the 0.05 probability level.

2.4 Results

2.4.1 spray retention validation

The tartrazine recovery rate was 99.5 ± 0.9% from filter paper (n=9). From clippings and thatch, the recovery rates of tartrazine decreased linearly with time (Figure 2), which suggested that analyzing tartrazine within 4 hours after treatment would provide a quantitative recovery (97%) of tartrazine.

The recovery of tartrazine in the foliage plus thatch layer, when averaged over all three spray volumes, was 102.0 ± 5.3%. The recovery in the thatch layer was higher at 1500 L/ha spray volume than at lower spray volumes (Table 2).

2.4.2 Influence of spray volume on foliar retention

Foliar retention decreased as spray volume increased from 95 L/ha to 750 L/ha. The highest recovery, 98.3%, was achieved at the lowest spray volume, 95 L/ha. (Table 3). At spray volumes above 750 L/ha, the recovery rate plateaued at around 85% (Figure 3). Foliar retention volume was linearly correlated with the applied spray volume (R^2=0.99) (Figure 4).

2.4.3 Influence of nozzle type on foliar retention

No difference in foliar recovery rate was detected between flat fan nozzles and air induction nozzles (*P*=0.9699). Additionally, no interactions were observed between nozzle type and spray volume (*P*=0.8188). Only spray volume had a significant impact on foliar retention and followed the same trend as the previous spray volume study (Table 4). We did find that air induction nozzles produced a significantly higher coefficient of variation (6.6) than flat fan nozzles (3.3), suggesting less uniformity of application.

2.4.4 Influence of adjuvant and spray volume on foliar retention

The main effects of spray volume and adjuvant were significant as was the spray volume × adjuvant interaction (Table 5). At 190 L/ha, recovery rates were similar with or without adjuvants. At 750 L/ha, adding NIS, OSA and MSO increased foliar recovery by roughly 4% compared to the water only treatment (NA), however, there was no difference between adjuvants. At 1125 L/ha, differences among adjuvants were observed. The addition of NIS and MSO increased foliar retention compared to NA. Organosilicone provided the same recovery as NA. At 1125 L/ha, MSO increased spray retention compared to the other adjuvants or NA.

The impact of spray volume was different for each adjuvant treatment. Without adding any adjuvant, as observed in previous experiments, increasing spray volume from 190 L/ha to 750 L/ha decreased foliar retention by 7.9%, but at spray volumes of 750 L/ha and 1125 L/ha, the recovery rate did not change. When NIS or MSO were added, increasing spray volume did not reduce foliar retention. As for OSA, recovery at 1125 L/ha decreased by 3.7% compared to 190 L/ha.

2.4.5 Influence of adjuvant and spray volume on foliar retention when dew is present

Analysis of variance indicated significant differences between the two runs of experiments and thus results are reported separately (Table 6). In the first run, High spray volumes reduced the recovery rate from 88.2 % at 190 L/ha to 79.5 % at 750L/ha, while no differences in recovery were observed between 750L/ha and 1125 L/ha. The same trend was observed in the second run where the highest recovery rate was achieved at 190 L/ha, which was about 14% higher than recovery rates at 750 L/ha and 1125 L/ha. Adding adjuvant only significantly affected foliar retention in the first run, within which, compared to NA, adding NIS decreased recovery rate from 84.0% to 79.4%, while MSO or OSA did not affect foliar retention compared to NA. No interactions were observed between spray volumes and adjuvants in both studies.

2.5 Discussion

2.5.1 Spray retention validation

Tartrazine is safe and reliable when used as a tracer to measure the foliar spray retention on turfgrass. Recovery rate from filter paper, clippings, and thatch were near 100%. The quantitative recovery of tartrazine from clippings plus the thatch layer indicate that the method accurately reflects spray retention in turfgrass. These results show that the different foliar recovery rates are caused by the different distributions of tartrazine within plant canopies instead of degradation or loss of tracer during analysis.

Degradation of tartrazine was observed during the timecourse study, which may be the main limitation of choosing tartrazine as a tracer. Our data suggested that on turfgrass, completing the extraction within 4 hours will yield accurate and reliable results. For other cropping systems, the rate of tartrazine degradation should be determined prior to beginning experiments. Timely measurement of tartrazine is needed to guarantee the accuracy of results.

2.5.2 Influence of the spray volume on foliar retention

The six spray volumes evaluated were typical of spray volumes applied on golf courses. Our data shows a roughly 10% decrease in foliar retention as spray volume increased from 190 L/ha to 1125 L/ha.

Previous researchers analyzed the foliar retention on other plants (Armstrong-Cho et al., 2008; Byer et al., 2006; Peng et al., 2005) and suggested a steady decline in recovery rates as spray volume increased. In our research, recovery rates initially declined, but then plateaued at about 85% for spray volumes from 750L/ha to 1500L/ha. Several variables, such as droplet velocity and the size of spray droplets (Miller and Butler Ellis, 2000), will affect foliar retention. Particularly, higher spray droplet velocity enhances foliar run-off. In this study, the traveling speed of spray nozzle was reduced from 0.89m/s at 750L/ha to 0.50m/s at 1500L/ha to achieve the high spray volumes. The reduced velocity may decrease the likelihood of droplets running off the foliage.

The maximum foliar retention volume was not reached with the spray volumes evaluated. Dense turf has the ability to retain the majority of foliar applied chemicals. If the target site of application is the thatch layer or surface soil, irrigation immediately following spray application will be more effective than increasing spray volumes.

2.5.3 Influence of nozzle type and spray volume

When the spray volume and orifice size are similar, using an air induction nozzle doubles the droplet size compared to flat fan nozzle (De et al., 2006). However, the change of nozzle type did not result in reduced foliar retention, which runs counter to the idea that larger spray droplets are more prone to run-off (Butler Ellis et al., 2004; Feng et al., 2003). The high density of turf, with a leaf area index of 2.4 in June and 3.1 in September (averages of 5 measurements), may explain why runoff does not occur at these spray volumes. The canopy is able to retain the majority of the spray droplets and reduce run-off.

Air induction nozzles can reduce spray drift. However, the lower uniformity and coverage (Figure 5) produced by air induction nozzles may lead to reduced control, especially for pesticides requiring thorough leaf coverage.

2.5.4 Influence of adjuvant and spray volume

In this study, each adjuvant was applied at the median rate of the recommended concentration by the manufacturers. Adding NIS, OSA, MSO generally resulted in recovery rates that remained unchanged at 90% to 93% under the three spray volumes evaluated. Conversely, spraying water alone yielded a 9% decrease in recovery as spray volume increased. Turf managers commonly believe that increasing either the rate of surfactant and/or the spray volume can lead to run-off, which is theoretically sound because adding surfactant and increasing spray volume can both facilitate the convergence of spray droplets. However, our results suggest that at the spray volumes typically used on golf course fairways, the impact of increasing spray volume is insignificant when adjuvants were added at the standard concentrations.

On the other hand, modifying the concentration of adjuvant can influence foliar retention (Prado et al., 2016). This research group observed a non-linear response of foliar retention rate on *Eucalyptus* leaves using eight concentrations of adjuvant from six different adjuvants. As the adjuvant concentration increased from 0 v/v % to 2v/v %, spray retention (µg/cm^2) increased to a peak and then dropped to a plateau. This curve described the general response of foliar retention as influenced by increasing adjuvant concentration, which can be applied on turfgrass. However, it is difficult to predict the change in foliar retention as the concentration of a given adjuvant is increased. Previous studies (Feng et al., 2003; Furmidge, 1962; Hall et al., 1993; Holloway et al., 2000; Ramsdale and Messersmith, 2001) have shown the impact of MSO, NIS, OSA and other adjuvants on foliar retention was site specific. The rate of adjuvant used, and characteristics of plant surfaces have a critical influence of foliar retention. There is a lack of understanding about how the change of the adjuvant concentration influences the foliar retention on turfgrass. Excessive adjuvants rates could lead to more foliar run-off. Pesticide formulations are complex and contain multiple compounds, such as adjuvants, to achieve the desired level of pest control. However, adding an adjuvant is still a routine strategy when tank mixing chemicals for spray application. It is unclear how these adjuvants may influence foliar retention of these complex mixtures.

2.5.5 Influence of adjuvant and spray volume when dew is present

Due to the challenges of conducting a three-factor study, we applied the same amount of artificial dew to all treatments and focused on the influence of spray volume and adjuvant in the presence of a typical volume of dew in Urbana, IL during late summer.

Analysis of variance indicated significant differences between the two experiments, which might be because of the differences in leaf area or orientation. All turf cores were collected from the same site as the first study. However, the site of the first run of the study did not have enough area to collect turf cores for the second run. The turf cores for the second study were collected at another site where the turf quality was visually similar. Additionally, the temperature was warm before and during the first run of experiment. However, temperatures dropped after 22 Oct. 2017 and lower temperatures (Figure 6) lasted through the end of the second run of study, which reduced the growth of turf and may have changed the leaf area of the cores. Even though the turf quality was similar in the field, a reduction of clipping biomass was observed during sampling in the second run of the study, which suggests a decrease in density compared to the first run.

Recovery rates differed between the two runs of study, but the influence of spray volume and adjuvant were similar. With dew present, reducing the spray volume for application is recommended to achieve a higher rate of foliar retention. The changes in foliar retention varied with the presence of adjuvants. We expected more run-off when adjuvants were applied to foliage with dew present, especially at higher spray volumes. However, the data showed only a slight decrease in foliar recovery at high spray volumes compared to NA. Statistically insignificant differences, roughly 5% decrease in recovery rates, were observed during the second run of study at 1125L/ha with the addition of adjuvants, which suggests that adding an adjuvant may lead to noticeable decline of foliar retention at high spray volume. In future studies, increasing replication may be a strategy to achieve statistically significant results with these treatments.

2.5.6 Choosing a lower spray volume

As mentioned previously, for decades, medium to high spray volumes were preferred in turfgrass spray applications. Additionally, several studies also supported that relatively high spray volumes were needed to achieve acceptable control, especially for pesticide applications.

However, this study has demonstrated that a lower spray volume can deposit more active ingredients on a target surface, which increases the efficacy of a spray application. Lower spray volumes are also economically sound because more time is required to complete a spraying regime when the spray tank needs to be refilled more often at increased spray volumes. Choosing a lower spray volume can provide greater foliar retention while reducing labor costs.

Potential drift is one main problem that discourages turf managers from choosing a lower spray volume. Covered spray booms could be utilized by turf managers, which would allow a uniform spray pattern at very low spray volume even in windy conditions. Besides, conventional spray nozzles usually produce spray droplets with a wide range of diameters, where smaller droplets are prone to drift while larger droplets reduce the efficacy of spray because larger the droplet, lower the coverage and uniformity. The improvement of nozzles aims at producing more uniform spray droplets in size and distribution that allows more throughout coverage and lower spray volume.

A liquid form of active ingredient is commonly required in the process of plant uptake. The rapid drying of spray droplets under low spray volumes may decrease efficacy by decreasing the time available for pesticide absorption. However, recent research conducted on bentgrass fairways indicated that using conventional spray methods at 561L/ha and ultra-low spray method at 19L/ha provided the same level of brown patch (*Rhizoctonia solani* Kuhn) control when spraying propiconazole or azoxystrobin (Ferguson et al., 2016). For specific products, low spray volumes may give acceptable control on turfgrass. The ultra-low volume technology is not widely used nor well understood on turfgrass, which is worth analyzing.

2.6 Conclusion

Tartrazine is an effective tracer to measure foliar retention on turfgrass with a relative simple analysis. Overall, the results of this study indicate that a dense turf system is able to retain the majority of spray droplets. Reducing the spray volume can permit greater foliar retention and possibly increase the effectiveness of spray application. Additionally, increasing spray volume will not move a significant amount of the active ingredient to the thatch/mat surface for root uptake. For those products, irrigating immediately after spray application is more effective. On dry leaves, adding nonionic surfactants (NIS), organosilicone adjuvants (OSA) and methylated seed oil (MSO) can maintain high foliar recovery rates even as spray volume increases.

2.7 Tables and figures

Table 1. Nozzle type and traveling speed required to reach desired spray volumes

Spray volume (L/ha)	Nozzle type	Nozzle tip number	Size of droplet	Traveling speed (m/s)
95	Flat fan	Evs8001	F	0.73
190	Flat fan	Evs8002	F	0.82
380	Flat fan	Evs8004	M	0.93
750	Flat fan	Evs8008	M	0.89
1125	Flat fan	Evs8010	C	0.66
1500	Flat fan	Evs8010	C	0.50
190	Air induction	Alxr11003	VC	0.96
380	Air induction	AI9504E	XC	0.70
750	Air induction	AI9508E	UC	0.76
1125	Air induction	AI9508E	UC	0.50

F = fine droplet with a volume median diameter (VMD) between 136 to 177 microns.

M = medium droplet with VMD between 177 to 218 microns.

C = coarse droplet with VMD between 218 to 349 microns

VC = very coarse droplet with VMD of 349 to 428 microns.

XC = extremely coarse droplet with VMD between 428 to 622 microns.

UC = ultra-coarse droplet with VMD larger than 622 microns.

Table 2. The quantitative recovery rates of tartrazine deposited on creeping bentgrass (*Agrostis stolonifera* L.) foliage and thatch under different spray volumes.

	Plant canopy [z]		
	Foliage	Thatch	Total (foliage + thatch)
Spray volume (L/ha)	Recovery rate (%) [x]		
190	91.1	9.8 a	101.0
750	84.8	13.5 ab	98.3
1500	89.4	16.5 b	106.7
LSD (0.05)	NS	3.8	NS

[z] Above ground green tissues and top 0.5cm of thatch were carefully collected and analyzed separately.

[x] The recovery rates are averaged across two runs of study due to insignificant interactions. Different letters indicate significant differences as determined by protected Fisher's LSD test at a probability level of α=0.05.

Table 3. The recovery rates of tartrazine deposited on creeping bentgrass (*Agrostis stolonifera* L.) foliage under different spray volumes.

Spray volume(L/ha)	Pooled Recovery rate (%) [z]
95	98.3 a
190	95.2 a
380	90.8 b
750	85.3 c
1125	88.3 bc
1500	85.3 c
LSD (0.05)	——— 3.5 ———

[z] The recovery rates are averaged across two runs of study due to insignificant interactions. Different letters indicate significant differences as determined by protected Fisher's LSD test at a probability level of α=0.05.

Table 4. The recovery rates of tartrazine across two nozzle types on creeping bentgrass (*Agrostis stolonifera* L.) as influenced by different spray volumes.

Spray volume(L/ha)	Pooled recovery rate (%) [z]
190	93.7 a
380	89.1 b
750	85.1 c
1125	84.2 c
LSD (0.05)	3.4

[z] The recovery rates are averaged across two experiments due to insignificant interactions. Mean separation was determined by protected Fisher's LSD test at a probability level of α=0.05. Different letters indicate different significance level.

Table 5. The recovery rate of tartrazine deposited on creeping bentgrass (*Agrostis stolonifera* L.) as influenced by spray volumes and adjuvants.

	Adjuvant [z]			
Spray volume (L/ha)	NA	NIS	OSA	MSO
	Pooled recovery rate % [x]			
190	95.9 a	93.7 abc	93.5 abc	93.6 abc
750	88.0 e	91.7 cd	91.9 bcd	92.0 bcd
1125	87.3 e	91.7 cd	89.8 de	94.9 ab
LSD (0.05)	3.1			

[z] Nonionic surfactants (NIS) (Induce, Helena Chemical Company, Memphis, TN, USA) , organosilicone adjuvants (OSA) (Kinetic, Helena Chemical Company) and methylated seed oil (MSO) (BASF corporation, Research Triangle Park, NC, USA) were mixed with distilled water at a concentration of 0.25%V/V, 0.125%V/V, or 0.75%V/V respectively. NA= No addition of adjuvant.

[x] The recovery rates are averaged across two runs of study due to insignificant interactions. Measurements were separated by Fisher's LSD test at P=0.05. Different letters indicate different significance level.

Table 6. The recovery rate of tracers deposited on creeping bentgrass (*Agrostis stolonifera* L.) golf fairway as influenced by spray volumes and adjuvants with a presence of dew [z] (1950L/Ha).

	Run 1	Run 2		Run 1	Run 2
Spray volume (L/ha)	Recovery rate (%) [y]		Adjuvant [x]	Recovery rate (%)	
190	88.2 a	88.8 a	NA	84.0 a	81.1
750	79.5 b	75.2 b	NIS	79.4 b	77.9
1125	77.7 b	74.8 b	OSA	81.9 a	79.7
			MSO	82.0 a	79.6
LSD (0.05)	2.3	2.6		2.7	NS

[z] Generation III sprayer was used to apply artificial dew at 1950L/Ha to turf cores prior to treatment using a flat fan nozzle (EVS8001, Teejet technologies, IL, USA).

[x] Nonionic surfactants (NIS) (Induce, Helena Chemical Company, Memphis, TN, USA) , organosilicone adjuvants (OSA) (Kinetic, Helena Chemical Company) and methylated seed oil (MSO) (BASF corporation, Research Triangle Park, NC, USA) were mixed with distilled water at a concentration of 0.25%V/V, 0.125%V/V, or 0.75%V/V respectively. NA= No addition of adjuvant.

[y] The recovery rates under different spray volumes are reported separately due to significant differences between two runs of studies. The significant differences within each run of study were determined by Fisher's LSD test at P=0.05 with least significant difference (LSD) shown where significance was found. Different letters indicate different significance level. NS=not significant.

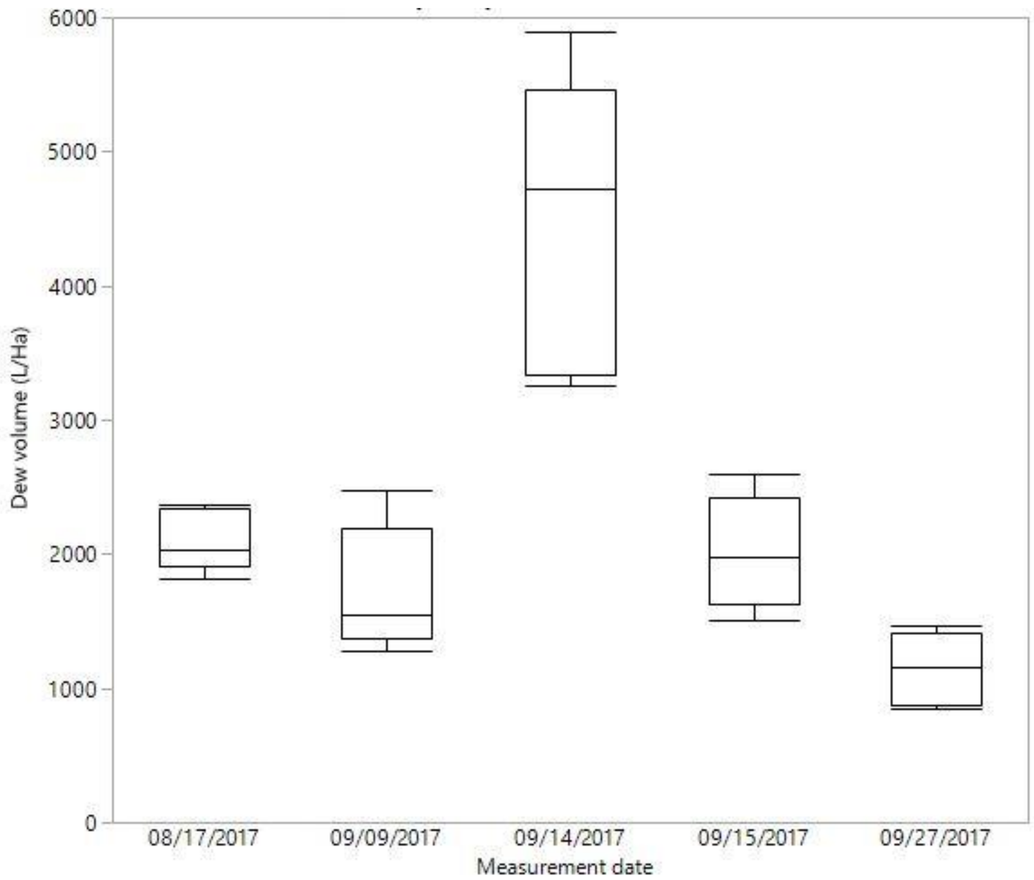

Figure 1. the measurement of naturally occurring dew in University of Illinois Landscape Horticulture Research Center, Urbana, IL, in 5 random dates during August to September 2017, between 7:00am to 9:00 am with 5 replications for each measurement.

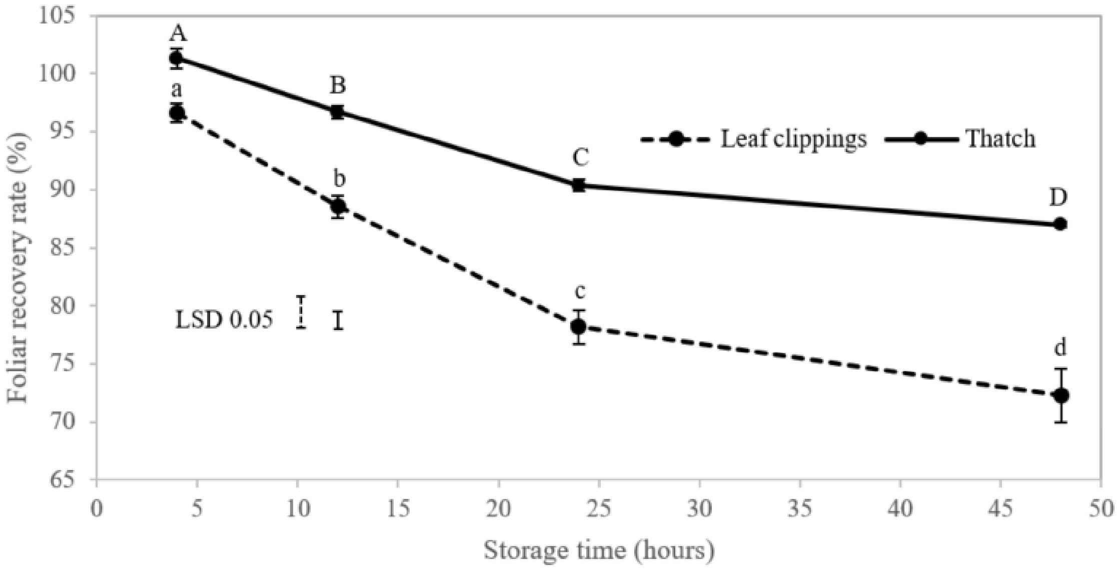

Figure 2. the recovery rates of 0.01 milligram of tartrazine on leaf clippings and thatch from creeping bentgrass (*Agrostis stolonifera* L.) as influenced by different storage time. Capitalized letters indicate the significant differences of foliar recovery rate in thatch. Lower letters indicate the significant differences in foliage.

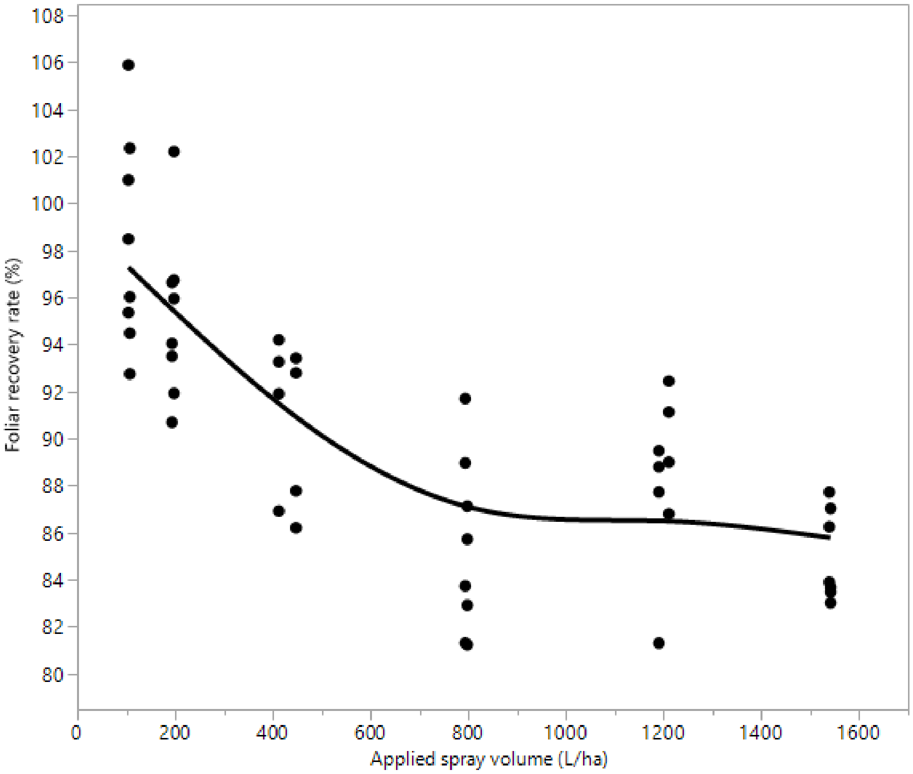

Figure 3. the recovery rates of tartrazine on leaf clippings from creeping bentgrass (*Agrostis stolonifera* L.) as influenced by different spray volumes.

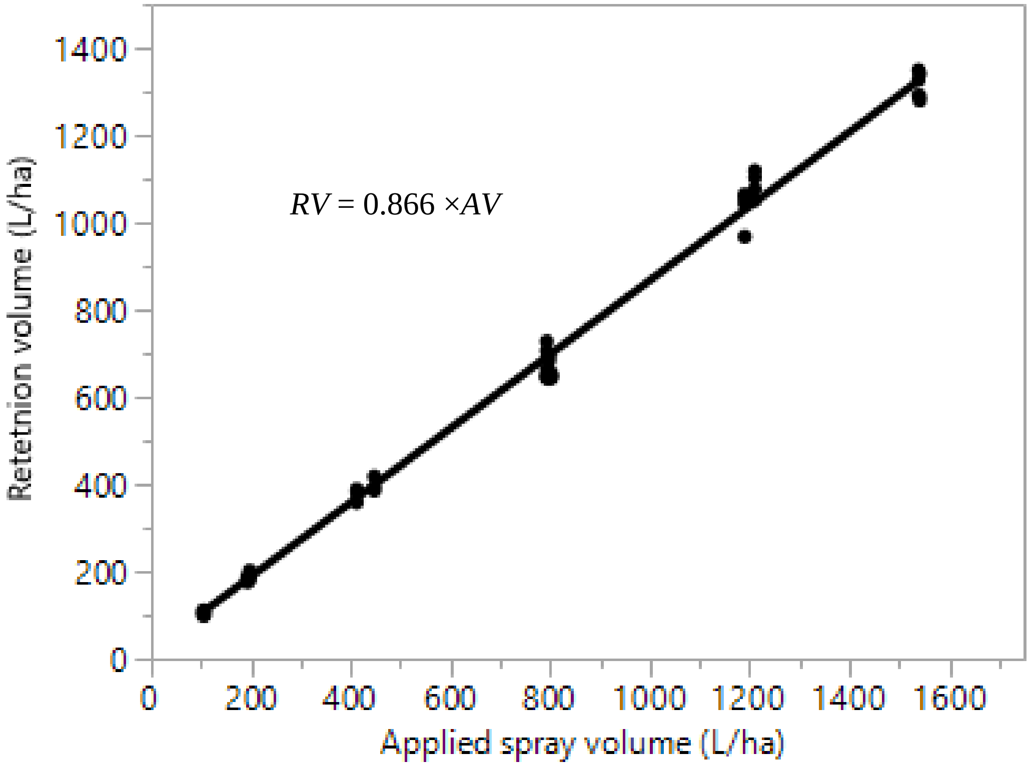

Figure 4. The linear regression between applied volume (L/Ha) and foliar retention volume (L/Ha) on creeping bentgrass (*Agrostis stolonifera* L.). Retention volume (*RV*) =0.866 ×applied volume (*AV*).

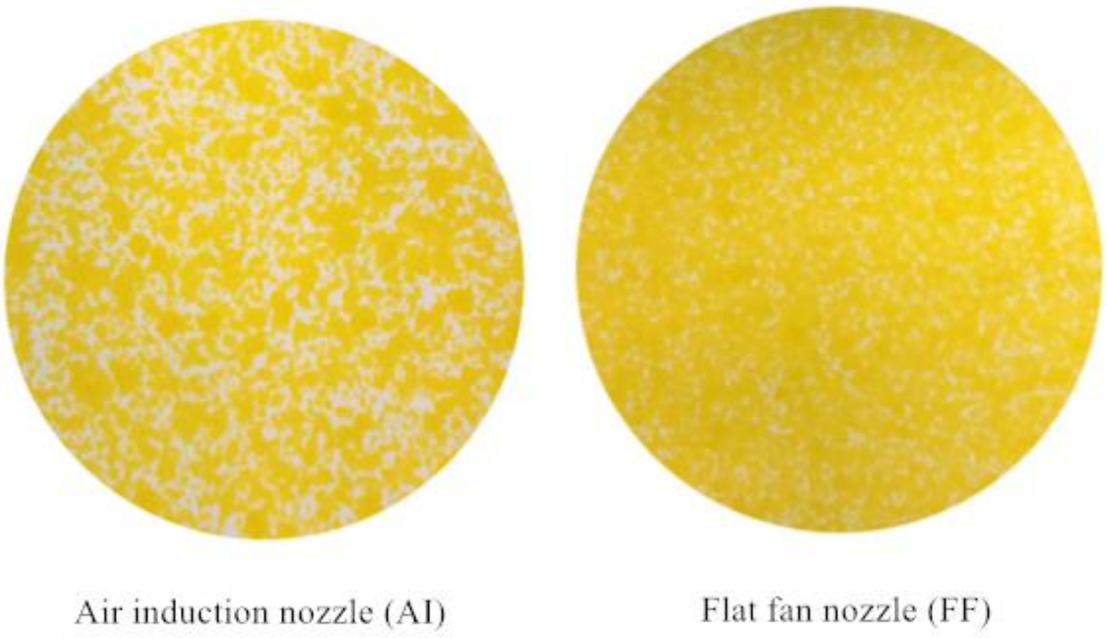

Figure 5. the spray retention (yellow color) of tartrazine as the tracer on filter paper using Generation III Research Track Sprayer (DeVries Manufacturing, MN, USA) at a spray volume of 190L/Ha by air induction (AI) and flat-fan Nozzle (FF).

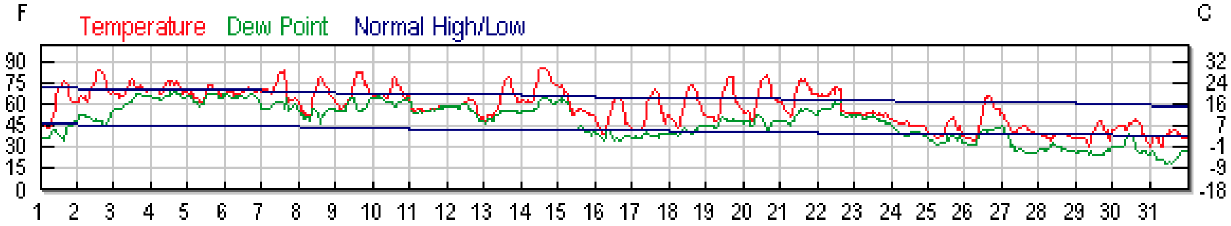

Figure 6. the daily temperature in Oct 2017 in Urbana, IL, USA. Reported by https://www.wunderground.com.

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