REDUCING WATER AND AGROCHEMICAL MOVEMENT FROM CONTAINER NURSERY PRODUCTION USING BIOREACTORS AND IRRIGATION MANAGEMENT

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ABSTRACT

REDUCING WATER AND AGROCHEMICAL MOVEMENT FROM CONTAINER NURSERY PRODUCTION USING BIOREACTORS AND IRRIGATION MANAGEMENT

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Container crop production is an input intensive agricultural sector, oftentimes demanding frequent, typically daily irrigation, substantial fertilizer use, and multiple pesticide applications throughout the production cycle. The combination of these factors increases the risk for agrochemical movement in irrigation return flow (IRF). Over the course of two studies, a model nursery designed to collect surface and subsurface IRF was used to investigate water use and agrochemical movement in a model nursery. An overhead control was compared to micro-irrigation (SS) and substrate volumetric moisture content (θ) sensor based overhead irrigation (OH) in the volume of water applied, volume of water lost to IRF, and associated fertilizer and pesticide content transported.

Irrigating using OH and SS reduced the volume of irrigation applied by 49% and 78% compared to the control. Surface IRF was reduced by 80% using OH and was largely eliminated using SS; however, subsurface IRF was generally equivalent between the control and treatments. Surface IRF movement of nitrate and phosphate was reduced by 72% - 76% when irrigating using OH, and up to 98% when irrigating using SS. Pesticide mobility in irrigation return flow was reflective of pesticide physiochemical properties, with more soluble pesticides exhibiting greater movement than less soluble pesticides, particularly in subsurface IRF. OH reduced surface IRF movement of the 10 pesticides by 43-89%, while SS reduced surface IRF movement by 77-100%. There were typically no differences in subsurface IRF pesticide movement between the control and treatments.

For all studied taxa (*Cornus obliqua* 'Powell Gardens', *Cornus sericea* 'Farrow', *Hydrangea paniculata* 'Limelight', *Physocarpus opulifolius* 'Seward', *Rosa x*'Meipeporia', *Spiraea japonica* 'SMNSJMFP', and *Weigela florida* 'Elvera') an equivalent growth index to the control was achieved when irrigating based on θ. Irrigation treatments were capable of producing an equivalent weight of shoot dry biomass for all taxa except *C. obliqua, P. opulifolius, and S. japonica* where the control was greater than all treatments. For the three species where root dry biomass was investigated (*H. paniculata, R. x.,* and *S. japonica*), only *S. japonica* exhibited reduced root dry biomass under the OH and SS treatment compared to the control. Irrigating based on θ, regardless of the delivery method, can produce woody ornamental species of equivalent quality, while also reducing water use and agrochemical export in irrigation return flow; however, bioactive concentrations of agrochemicals may still be present.

Woodchip bioreactors (WB) and adsorbent aggregate filters (AF) are treatment technologies that are capable of remediating or sequestering contaminants from IRF via biological and sorptive processes, provided a sufficient hydraulic retention time (HRT). A 72 hour HRT reduced over 99% of influent nitrate in WB and up to 87% of phosphate in AF; whereas, an HRT of 21 minutes was insufficient for nutrient remediation. An HRT of 21 minutes was effective in reducing the movement of bifenthrin, chlorpyrifos, and oxyfluorfen by 76%, 63%, and 31%, respectively, using WB. Microbial analysis of WB identified shifts in species composition when exposed to pesticides, enriching for a number of species within the *Pseudomonas* and *Exiguobacterium* genus, while decreasing the number and diversity of *Bacillus* species compared to the nutrient only control.

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INTRODUCTION

Agriculture represents the majority of freshwater use across the globe (Döll, 2009; Pimentel et al., 2004). As the world population continues expanding, improving the management of this precious resource will require sustainable solutions, particularly in the production of specialty crops such as ornamental nurseries, as water will likely be preferentially allocated towards crops of direct human consumption (Godfray et al., 2010; Rodell et al., 2018). The input intensive nature of nursery crop production, especially when grown in containers, requires substantial amounts of irrigation, fertilizers, and pesticides. Inefficient irrigation practices not only consume large volumes of water, but also produce irrigation return flow (IRF) which is capable of transporting applied agrochemicals out of production (Mangiafico et al., 2008; Pershey et al., 2015; Tyler et al., 1996; Warsaw et al., 2009b). In order to ensure the sustainability of this industry in the future, production nurseries will need to devise effective ways to reduce water use and mitigate the movement of agrochemical contaminants off-site.

Irrigation is commonly applied via overhead sprinkler, where water is provided to the entire production area (Beeson and Knox, 1991). An alternative to this is implementing micro-irrigation, or irrigation systems which apply water directly to the container itself rather than the entire area. This practice reduces water use and increases application efficiency; however, it is often used in the production of larger container plants (over 19 L), considering the added infrastructure and maintenance costs that accompany this method (Garber et al., 2002). The implementation of micro-irrigation systems in producing plants in smaller containers (11.3 L) is not as common, as the increased density of containers within an area and smaller plant canopies make overhead irrigation the predominant method of applying water. In order to foster adoption of micro-irrigation technologies in smaller containers, production of a crop of equivalent or

greater quality and reduction in water use (leading to cost reductions as well) must be demonstrated to justify the added expense.

Improving the efficiency with which water is applied can furthermore reduce the amount of irrigation water lost to IRF, and in some cases may allow more precision with which fertilizers are applied (Majsztrik et al., 2017; Pershey et al., 2015; Warsaw et al., 2009). One method to improve irrigation application efficiency is the use of substrate moisture sensors to apply water to match crop evapotranspiration, catering the volume of irrigation to actual crop needs (Incrocci et al., 2019; Lea-Cox et al., 2013). The implementation of substrate sensors can reduce the amount of container leachate, thus limiting the amount of applied fertilizer being lost, and offering the potential to reduce the amount of fertilizer applied.

Concerns over the movement of agrochemicals in IRF are legislative, ecological, and economical in nature. In the U.S. and Europe, the Clean Water Act (Clean Water Act; https://www.epa.gov/laws-regulations/summary-clean-water-act) , European Water Framework Directive (European Water Framework Directive EWFD: https://ec.europa.eu/environment/water/water-framework/index_en.html), and European Nitrate Directive (European Nitrate directive END: https://ec.europa.eu/environment/water/water-nitrates/index_en.html) set limitations to the amount of allowable contaminants exiting production areas in order to mitigate eutrophication concerns. Pesticides in IRF may also pose a threat to receiving water bodies, particularly if present in bioactive concentrations (Beggel et al., 2011; Graves et al., 2014; Ilhan et al., 2012; Weston et al., 2005). Furthermore, agrochemicals transported from production areas represent a loss in applied product, which may reduce crop quality in addition to representing a financial loss for growers.

Growers may desire to reduce agrochemical presence in IRF in order to adhere to legislative thresholds, and/or if they seek to capture and recycle IRF for irrigation. Treatment methods for remediating agrochemicals from IRF include the use of woodchip bioreactors and adsorbent aggregates (Christianson et al., 2017; Sarris and Burberry 2018; Borno et al., 2018; Chouyyok et al., 2013). Woodchip bioreactors harness the capabilities of naturally occurring microbes, where denitrification and biodegradation are the predominant processes of removing nitrates and pesticides from IRF. Furthermore, the woodchips in bioreactors are a lipophilic sorption site for hydrophobic pesticides (Cederlund et al., 2016; Grant et al., 2019; Camilo et al., 2013; Ilhan et al., 2012; Kourtev et al., 2006). Adsorbent aggregates offer charged sites which can adsorb phosphate and polar pesticides as IRF passes through (Chouyyok et al., 2013).

The intent of these series of studies is to investigate methods to reduce water use without affecting crop quality, reduce agrochemical movement in IRF, and optimize water treatment technologies in nursery production systems. Two of these studies seek to quantify the growth of 7 common ornamental taxa, produced in 11.3 L containers, when using micro-irrigation. The potential to reduce water use, and possibly the amount of applied fertilizer, may offer an effective means to limit IRF and concomitant transport of agrochemicals, which may justify the added infrastructure that is often reserved for larger containers. Four of these studies investigate the movement of nutrients and pesticides in both surface and subsurface IRF. While the movement of agrochemicals in surface IRF has received substantial attention, less research has been performed in monitoring agrochemical movement in subsurface channels. Finally, two studies were conducted to investigate the remediation of nutrients and pesticides from simulated IRF using a two stage system comprised of woodchip bioreactors and adsorbent aggregates. The treatment systems were operated under different hydraulic retention times in an effort to assess

nutrient and pesticide remediation for different operational goals, as well as to assess whether the presence of pesticides in IRF would affect the potential for nutrients to be remediated.

LITERATURE CITED

LITERATURE CITED

Beeson, R.C. Jr., Knox, G.W., 1991. Analysis of efficiency of overhead irrigation in container production. HortScience. 26, 848-850.

Beggel, S., Connon, R., Werner, I., Geist, J., 2011. Changes in gene transcription and whole organism responses in larval fathead minnow (Pimephales promelas) following short-term exposure to the synthetic pyrethroid bifenthrin. Aquat. Toxicol. 105, 180-188.

Borno, M.L., Müller-Stöver, D.S., Liu., F., 2018. Contrasting effects of biochar on phosphorus dynamics and bioavailability in different soil types. Sci. of the Total Environ. 627, 963-974.

Camilo, B.K., Matzinger, A., Litz, N., Tedesco, L.P., Wessolek, G., 2013. Concurrent nitrate and atrazine retention in bioreactors of straw and bark mulch at short hydraulic residence times. Ecol. Eng. 55, 101-113.

Cederlund, H., Börjesson, E., Lundberg, D., Stenström, J., 2016. Adsorption of pesticides with different chemical properties to a wood biochar treated with heat and iron. Water Air Soil Pollut. 227, 1-12.

Christianson, L.E., Lepine, C., Sibrell, P.L., Penn, C., Summerfelt, S.T., 2017. Denitrifying woodchip bioreactor and phosphorus filter pairing to minimize pollution swapping. Water Res. 121, 129-139.

Chouyyok, W., Wiacek, R.J., Pattamakomsan, K., Sangvanich, T., Grudzien, R.M., Fryxell, G.E., Yantasee, W., 2013. Phosphate removal by anion binding on functionalized nanoporous sorbents. Environ. Sci. and Technol. 44, 3073-3078.

Clean Water Act (CWA); https://www.epa.gov/laws-regulations/summary-clean-water-act) (Accessed 23 September 2020). 33 U.S.C. §1251 et seq. (1972)

Döll, P. 2009., Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environ. Res. Lett. 4, 1-12.

European Nitrate Directive (END): (https://ec.europa.eu/environment/water/water-nitrates/index_en.html) (Accessed 23 September 2020). Adopted 12 December 1991.

European Water Framework Directive (EWFD): (https://ec.europa.eu/environment/water/water-framework/index_en.html) (Accessed 23 September 2020). Adopted 23 October 2000.

Garber, M.P., Ruter, J.M., Midcap, J.T., Bondari, K., 2002. Survey of container nursery irrigation practices in Georgia. HortTechnology. 12, 727-731.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Sci. 327, 812-818.

Grant, G.A., Fisher, P.R., Barrett, J.E., Wilson, P.C. 2019. Removal of agrichemicals from water using granular activated carbon filtration. Water Air Soil Pollut. 230, 1-12.

Graves, G.M., Vogel, J.R., Belden, J.B., Rebek, E.J., Simpson, A.M., 2014. Investigation of insecticide leaching from potted nursery stock and aquatic health benefits of bioretention cells receiving nursery runoff. Environ. Sci. Pollut. Res. 21, 8801-8811.

Ilhan, Z.E., Ong, S.K., Moorman, T.B., 2012. Herbicide and antiobiotic removal by woodchip denitrification filters: sorption processes. Water Air Soil Pollut. 223,2651-2662.

Incrocci, L., Marzialetti, P., Incrocci, G., Di Vita, A., Balendonck, J., Bibbiani, C., Spagnol, S., Pardossi, A., 2019. Sensor-based management of container nursery crops irrigated with fresh or saline water. Agr. Water Mgmt. 213, 49-61.

Kourtev, P.S., Nakatsu, C.H., Konopka. A., 2006. Responses of the anaerobic bacterial community to addition of organic c in chromium(VI)- and iron (III) – amended microcosms. Appl. and Environ. Microbiol. 72, 628-637.

Lea-Cox, J.D., Bauerle, W.L., van Iersel, M.W., Kantor, G.F., Bauerle, T.L., Lichtenberg, E., King, D.M., Crawford, L., 2013. Advancing Wireless Sensor Networks for Irrigation Management of Ornamental Crops: an Overview. HortTechnology. 23, 717-724.

Majsztrik, J.C., Fernandez, R.T., Fisher, P.R., Hitchcock, D.R., Lea-Cox, J., Owen, J.S. Jr., Oki, L.R., White, S.A., 2017. Water use and treatment in container-grown specialty crop production: a review. Water Air and Soil Poll. 228, 1-27.

Mangiafico, S.S., Gan, J., Wu, L., Lu, J., Newman, J.P., Faber, B., Merhaut, D.J., Evans, R., 2008. Detention and recycling basins for managing nutrient and pesticide runoff from nurseries. HortScience. 43, 393-398.

Pershey, N.A., Cregg, B.M., Andresen, J.A., Fernandez, R.T., 2015. Irrigating based on daily water use reduces nursery runoff volume and nutrient load without reducing growth of four conifers. HortScience. 50, 1553-1561.

Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., Clark, S., Poon, E., Abbett, E., Nandagopal, S., 2004. Water resources: agricultural and environmental issues. Bioscience. 54, 909-918.

Rodell, M., Famigletti, J.S., Wiese, D.N., Reager, J.T., Beaudoing, H.K., Landerer, F.W., Lo, M.H., 2018. Emerging trends in global freshwater availability. Nature. 557, 651-659.

Sarris, T.S., Burberry, L.F., 2018. Stochastic multi-objective performance optimization of an in-stream woodchip denitrifying bioreactor. Ecol. Eng. 124, 38-50.

Tyler, H.H., Warren, S.L., Bilderback, T.E., 1996. Reduced leaching fractions improve irrigation use efficiency and nutrient efficiency. J. Environ. Hortic. 14, 199-204.

US EPA National Primary Drinking Water Regulations https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations (Accessed 23 September 2020)

Warsaw, A.L., Fernandez, R. T., Cregg, B.M., Andresen, J.A., 2009a. Water conservation, growth, and water use efficiency of container-grown woody ornamentals irrigated based on daily water use. HortScience. 44, 1308-1318.

Warsaw, A.L, Fernandez, R.T., Cregg, B.M, Andresen, J.A., 2009b. Container-grown ornamental plant growth and water runoff nutrient content and volume under four irrigation treatments. HortScience. 44, 1573-1580.

Weston, D.P., Holmes, R.W., Lydy, M.J., 2009. Residential runoff as a source of pyrethroid pesticides to urban creeks. Environ. Pollut. 157, 287-294.

CHAPTER ONE

Reducing Water and Pesticide Movement in Nursery Production

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1.1 Abstract

Ornamental nurseries produce a large number of plants in a concentrated area, and aesthetics are a key component of the product. To produce crops in this manner, high inputs of water, nutrients, and pesticides are typically used. Container nursery production further increases the inputs, especially water, because container substrates are designed to quickly drain, and the most effective method of irrigating large numbers of plants in containers (up to a certain size) is the use of overhead irrigation. Because irrigation and pesticides are broadcast over the crop, and because the crop is limited to the container, a large proportion of water or pesticides may land on nontarget areas, creating runoff contaminant issues. Water is the primary means of pesticide movement in nursery production. This review discusses water and pesticide dynamics and management strategies to conserve water and reduce pesticide and water movement during container nursery production.

CHAPTER TWO

Irrigation Return Flow and Nutrient Movement Mitigation By Irrigation Method for Container Plant Production

2.1 Abstract

The production of nursery crops demands substantial irrigation, with overhead irrigation the most common method of application; however, this method is inefficient with respect to water used and the precision with which it is applied, resulting in the generation of irrigation return flow and concomitant agrochemical export. Microirrigation systems such as individual container spray stakes provide water directly to crops thus applying water more efficiently than overhead systems but may be more costly in terms of installation (smaller pipes and components; however, a greater quantity of pipes and components) and maintenance. The study was conducted at the Michigan State University Research Nursery, where four ornamental shrub taxa were produced in #3 (11.3 L) containers using a control with 19 mm overhead irrigation per day and a conventional phosphorus fertilizer (19-2.16-6.64), compared with four treatments: a static, daily (2 L per container) spray stake irrigation and conventional phosphorus fertilizer; a static daily (2 L per container) spray stake irrigation and low phosphorus fertilizer (19-1.62-6.64); spray stake irrigation based on substrate volumetric water content (θ) (up to 2.4 L per container) and conventional fertilizer; and spray stake irrigation based on θ (up to 2.4 L per container) and low phosphorus fertilizer. Spray stakes reduced irrigation by 76-80% compared to the overhead control, and reduced the generation of both surface and subsurface irrigation return flow, mitigating the movement of both N and P. Plant growth index (GI) was measured on 12 June 2017 and 6 October 2017, followed by a destructive harvest to measure shoot dry weight, and shoot nutritional content. For all four taxa, microirrigation systems were capable of producing plants of equivalent GI and shoot nutritional concentration; however, the control typically produced more shoot biomass. Reducing the amount of phosphorus applied to crops did not reduce the amount of phosphorus lost to irrigation return flow relative to the conventional

formulation; however, crops typically yielded less shoot biomass under the low phosphorus formulation.

2.2 Introduction

The intensive nature of container crop production demands substantial water, fertilizer, and labor resources (Knight et al., 2019; Poudyal and Cregg, 2019; Ristvey et al., 2019; White et al., 2019). Agricultural production as a whole represents the majority of freshwater consumption worldwide (Döll, 2009; Pimentel et al., 2004), and as global water security concerns mount, it is expected that water will be preferentially allocated towards uses of direct human consumption, with ornamental and specialty crops likely to be one of the most scrutinized and regulated agricultural sectors with respect to water management (Fulcher et al., 2016; Godfray et al., 2010; Majsztrik et al., 2019; Rodell et al., 2018). Nurseries with access to ample, inexpensive water resources may not face the same immediate pressures to reduce their water use; however, inefficient and excessive irrigation is not without deleterious impact (Majsztrik et al., 2018). Irrigation return flow (IRF) results in the export of agrochemicals out of production areas, and with greater volumes generated more agrochemicals are exported (Mangiafico et al., 2008; Pershey et al., 2015; Tyler et al., 1996; Warsaw et al., 2009b). Extensive fertilizer use is common in container crop production, and in conjunction with the frequent irrigation typical in this production method, even when using controlled release fertilizers, the risk for nutrient export is increased (Agro and Zheng, 2014; Owen et al., 2008). Water leaching through containers can transport fertilizer, while un-intercepted irrigation water can also contribute to the generation of surface return flow and facilitate the movement of nutrients off-site (Pershey et al., 2015; Warsaw et al., 2009b; Hinz et al., 2019). In freshwater ecosystems phosphorus is often the nutrient which limits growth; therefore, garnering substantial attention in relation to

eutrophication (Abouali et al., 2017; Reddy et al., 1999). Concerns over pollutant movement to receiving water bodies has manifested in the implementation of total maximum daily loads (TMDLs), dictating acceptable thresholds for contaminant export to receiving water bodies from both rural and non-rural areas in the U.S. (Clean Water Act; https://www.epa.gov/laws-regulations/summary-clean-water-act), as well as the European Water Framework Directive and European Nitrate Directive (EWFD: https://ec.europa.eu/environment/water/water-framework/index_en.html ; END: https://ec.europa.eu/environment/water/water-nitrates/index_en.html), affecting a number of prominent ornamental production regions globally. Additionally, the proximity of many nursery operations to urban, suburban, and non-agricultural areas magnifies the attention paid to management practices used within this intensive industry by regulators and the surrounding public (Beeson et al., 2004; Berghage et al., 1999; Dennis et al., 2010; Fulcher et al., 2016). In light of the economic and ecological consequences of inefficient or excessive water and nutrient use, improving the management of these resources is critical in maintaining the sustainability of nursery crop production worldwide.

Frequent, often daily, irrigation is necessary in container crop production, as plant evapotranspiration demands, substrate hydraulic properties, and container size limit the amount of water available to the crop (Fernandez et al., 2019; Pershey et al., 2015). Typically, irrigation is applied via overhead systems, providing water to the entirety of the nursery production surface including both plants and inter-container spaces (Abdi and Fernandez, 2019; Beeson and Knox, 1991). The majority of overhead applied irrigation fails to reach the containerized plant, with 74-87% landing in the inter-container spaces (Davies et al., 2016; Million and Yeager, 2015; Pershey et al., 2015), with container spacing and crop canopy architecture further influencing application efficiency (Beeson and Yeager, 2003). Microirrigation systems such as in-container

spray stake irrigation are an alternative to overhead irrigation, and provide water directly to crop containers; however, this application method is often reserved for larger containers (typically over 19 L) since increased container spacing and canopy size for larger plants further reduces application efficiency and justifies the installation and maintenance investment required for microirrigation systems (Beeson and Knox, 1991; Incrocci et al., 2014; Incrocci et al., 2019; Majsztrik et al., 2017). Regardless of the irrigation method, substrate moisture sensors can be used to apply water more efficiently to meet crop needs (Fernandez et al., 2019; Sánchez-Blanco et al., 2019). Irrigating based on substrate moisture content is a management practice that may allow for improved water use efficiency through applying water on an as needed basis determined by measured substrate volumetric water content (θ) in substrates and reducing over irrigation (Bayer et al., 2015; Warsaw et al., 2009b). Irrigating based on θ can reduce the volume of water applied while maintaining crop growth and quality for a variety of ornamental species (Bayer et al., 2015; Fernandez et al., 2019; Niu et al., 2006; Pershey et al., 2015; Warsaw et al., 2009a,b). The benefits of irrigating certain ornamental species based on θ may extend beyond water savings. Sensor controlled irrigation has the ability to control crop growth and limit pruning requirements as well as reduce leaching of fertilizers from the container, potentially allowing reduced fertilizer application rates (Bayer et al., 2013; Burnett and van Iersel, 2008; Tyler et al., 1996; van Iersel et al., 2010).

In this study, we investigated irrigation practices and phosphorus fertilizer rates in the production of four common container species. We hypothesized that microirrigation would reduce the volume of water applied, as well as the volume of water lost to irrigation return flow. We hypothesized that reducing irrigation applied, especially when irrigating based on θ, would reduce nutrient loss to IRF, thus making nutrients more available for plant uptake. We

hypothesized that reducing the rate of P would have no effect on plant growth, but would lead to less loss in IRF. We hypothesized that limiting P leaching from containers by irrigating based on θ would compensate for the reduced application amount. Our objective for this study was to quantify the environmental and production impacts that microirrigation and reduced P application rate had in container production of four commonly grown woody ornamental taxa.

2.3 Materials and Methods

2.3.1 Research Nursery

A research nursery was constructed at the Michigan State University Horticulture and Teaching Research Center (HTRC) in Holt, MI (Latitude 42.67 N, Longitude -84.48), with sixteen raised beds serving as replicates where three irrigation practices and two fertilizer rates were compared. Treatments were initiated on 17 May 2017 and concluded on 22 September 2017, a typical production duration in Michigan. The experimental raised beds were arranged in two parallel rectangular blocks measuring 61 x 7.62 meters each with the length running north to south, and separated by a 1.8-m alley. Each rectangular block was divided into eight individual 7.62 x 7.62 x 0.6 m (LxWxH) beds for a total of 16 experimental beds. (Figure 2.1). Native soil was used to fill the bottom 0.3 m inside the walls of each individual bed and graded to achieve a 2% slope towards a center swale, and toward the outer edge of the individual beds in the two rectangular blocks. After the soil base was graded, a 9.1 x 9.1 m impermeable ethylene propylene diene monomer pondliner (Firestone Pondgard 45Mil (1.14 mm) Nashville, TN, USA) was placed over each bed and attached to the top of the side walls to create a basin in order to capture subsurface IRF. Over the top of the pond liner, 0.3 m of washed natural sand, free of clay, with a particle size range of 0.75-9.5 mm was placed and graded in the same manner as the soil sub-base and covered with a black woven polypropylene groundcover fabric (De Witt SBLT6300, Sikeston, MO, USA).

Bulkhead fittings (Banjo tf150 polypropylene bulkhead tank fitting, Banjo Corp, Crawfordsville, IN, USA) were installed at the lowest points of the soil sub-base through pondliner to collect subsurface IRF, and through the sand and above the groundcover fabric through the pondliner to collect surface IRF and each piped to 378 L polyethylene tanks (Duracast, manufacturer number 900100-1.2, Lake Wales,FL, USA) via 4.03 cm (inside diameter) schedule 40 PVC. Collection tanks were buried 15.2 cm below the soil level and anchored in place with concrete.

2.3.2 Irrigation Installation

Lateral irrigation lines to each of the raised beds were fitted with a 150 mesh inline filter (Toro T-ALFS75150-L, Bloomington MN, USA), a 30 psi pressure regulator (Senninger PRL303F3F, Clermont, FL), a flow meter (Badger Meter 62585-001 model 25, Milwaukee, WI, USA), and two solenoid valves (Rainbird CP075, Asuza, CA, USA). Irrigation was applied via either overhead sprinklers (Toro 961 P-120), or individual container spray stakes (Netafim 22500-002030, flow rate 12.1 LPH, Tel Aviv-Yafo, Israel). Overhead sprinklers were located at 0.3 m outside of the corners of the 6.1 x 6.1 m area to be irrigated for all beds, while spray stake irrigated beds also had a manifold consisting of four 6.1 m lengths of polyethylene tubing adjacent to distribute water in close enough proximity to the plant rows for installation of the spray stakes.

2.3.3 Irrigation Control and Sensor Installation

Irrigation was managed with a wireless sensor monitoring and control network using Sensorweb software (Mayim LLC, Pittsburgh, PA, USA), with the computer and communication devices installed in the main building of the HTRC. Solenoid valves were controlled via DC powered control nodes (model NC24, Decagon Devices, Inc., Pullman, WA, USA), with each node controlling 4 beds. Nodes were installed on the western raised beds, and oriented towards the communication devices in the HTRC building. θ was monitored using moisture sensors connected

to monitoring nodes (model 10HS and model EM50R, respectively, Decagon Devices, Inc., Pullman, WA, USA), where each bed had one monitoring node and four moisture sensors set to record at 5 minute intervals. Sensors were randomly assigned to one plant per taxa per bed and inserted halfway between the top and bottom of the container.

2.3.4 Plant Material and Substrate

Each individual raised bed (replicate) had a total of 81 plants, split between four taxa, and produced in 11.3 L containers (Nursery Supplies, Inc. model C1200, Chambersburg, PA, USA). Taxa used were *Cornus obliqua* 'Powell Gardens', *Hydrangea paniculata* 'Limelight', *Physocarpus opulifolius* 'Seward', and *Weigela florida* 'Elvera' (Spring Meadow Nursery, Grand Haven, MI, USA). Liners were received in June of 2016, and were potted up beginning on 14 June 2016. Plants were grouped by species, and the order in which they were placed on the beds was randomly assigned. A composted pine bark:peat moss (85:15 v/v) substrate was used (Renewed Earth, Otsego, MI, USA).

2.3.5 Irrigation and Fertilizer Treatments

An overhead control was compared to two microirrigation treatments. The overhead control applied 19 mm daily within each bed in a single application beginning at 8:00 A.M. and ending at 9:30 A.M. The two spray stake treatments were either 2 L per day per container, or a dynamic application rate based on sensor monitored θ. The daily 2 L per container treatment (SS2Lpd) was applied from 9:30 A.M. to 9:40 A.M. and was based on daily application rates of 1.4-1.9 L per #3 container reported by nursery producers (Garber et al., 2002). The sensor based treatment (SSθ) applied water based on θ with the activation threshold set at 35%, or 6% below the average container capacity measured during project setup (41.1% ± 0.61). The SSθ treatment applied irrigation based on the average θ of the four randomly assigned sensors in each bed.

Between 9:45 A.M. and 10:15 A.M., up to three 0.8 L cycles (0-2.4 L per day) per container were applied. Each 0.8 L cycle required a 4 minute irrigation run time and was followed by a 6 minute intermission to allow water distribution within the substrate and θ readings to reoccur between cycles to determine if θ had returned to container capacity, or else it would run for an additional cycle.

Fertilizer was applied to containers the preceding fall on September 27, 2016. Each bed for SS2Lpd or SSθ (3 replicates each) was randomly assigned one of two controlled release fertilizers with micronutrients, (5 months release at 26.7°C or 6 months release at 21.1°C, Polyon® Reactive Layers Coating, Harrell's Inc., Lakeland, FL, USA), receiving either 38 grams per container of a conventional P fertilizer formulation (conv) of 19% N - 2.16% P - 6.64% K (5.68% nitrate nitrogen, 6.79% ammoniacal nitrogen, 6.533% urea nitrogen; 2.16% Phosphate; and 6.64% Potassium) or a LowP fertilizer formulation (LowP) of 19% N - 1.62% P - 6.64% K (3.94% nitrate nitrogen, 4.72% ammoniacal nitrogen, 10.34 % urea nitrogen). The control irrigated beds (n=3) received the conv fertilizer formulation. One bed was left to serve as a blank, where 19 mm d^{-1} of overhead irrigation was applied to a bed without plants. Fertilizer was uniformly applied to each of the 81 containers per bed via topdressing, for a per bed application rate of 3,078 g.

2.3.6 Growth Measurements and Analysis

Three plants per taxa per bed were randomly selected for measuring growth index (GI), where the width of the plant in a north-south orientation, an east-west orientation, and height from the top of the container to highest shoot/leaf tip were averaged. GI was measured on 12 June 2017 and 6 October 2017. At the conclusion of the study, three randomly selected plants per taxa per bed were harvested for shoot dry weight and nutrient composition. Shoots were

defoliated, severed at the substrate surface, and oven dried at 60 °C for 7 days prior to weighing. Shoots were then ground in a Wiley Mill and sent for nutrient analysis to A&L Great Lakes Laboratories (Fort Wayne, IN, USA).

2.3.7 Water Sampling and Analysis

Surface and subsurface IRF volumes were assessed by measuring water height in collection tanks and converting to L based on tank dimensions. IRF samples were collected via a 473 mL sampling cup affixed to the end of a PVC sampling pole. An 8 mL sample was drawn into a 10 mL leur lock disposable polypropylene/polyethylene syringe, plunged through a 0.2 mm polyvinylidene fluoride filter into a 10 mL polystyrene Dionex vial (all ThermoScientific, Waltham, MA, USA) and stored at -18 °C until analysis.

The 8-mL samples were thawed and analyzed for nitrate (NO_3^-) and phosphate (PO_4^-) concentrations using dual ion chromatography. Anion concentrations were determined at 30 °C using an ICS-2100 gradient ion chromatograph (IC) system equipped with a hydroxide eluent generator cartridge, MFC-1 trap column, AG19 guard column, and an AS19 4 × 250 mm (i.d. × length) anion-exchange column (Thermo Fisher Scientific). Cation concentrations were determined via ICS-1600 at 35°C using a CG12A guard column and CS12A 4 × 250 mm (i.d. × length) cation-exchange column with sulfuric acid eluent (Thermo Fisher Scientific). Each system received the sample from an AS-AP autosampler to a 25 µL sample loop driven by an isocratic pump, with nutrients analyzed with a minimum detection limit of 0.0452 mg L^{-1} NO_3^- N and 0.0652 mg L^{-1} PO_4^-P.

2.3.8 Experimental Design and Statistical Analysis

This study was conducted as a split-plot design with factorial of 5 irrigation x fertilizer combinations as main plot and taxa as sub-plot using a completely randomized design, with

treatments, organization of plants on each bed, and sensors randomly assigned. The PROC GLM procedure of SAS (SAS Version 9.4, SAS Institute, Cary, NC, USA) was used to conduct analysis of variance for the volume of irrigation applied, GI, shoot dry weight, and shoot nutrient content. When treatment effects were significant ($p<0.05$) means were separated using Tukey tests in the LSMEANS prompt. Variable means and standard errors for volume of irrigation applied, shoot dry weight, shoot nutrient content and growth measurements were calculated using the PROC MEANS feature of SAS. The volumes of water lost to surface and subsurface return flow, nutrient concentration, and nutrient load were subject to analysis of variance using the PROC Mixed procedure with repeated measures. In cases where NO_3^--N or PO_4^--P concentrations were below detection, concentration was reported as the limit of detection (NO_3^--N: 0.0452 mg L^{-1}; PO_4^--P: 0.0652 mg L^{-1}) and loads were calculated as the limit of detection x IRF volume /2.

2.4 Results

2.4.1 Irrigation applied

The number of days irrigation was applied, as well as the daily liters applied per month is shown in Table 2.1 and Table 2.2, respectively, while precipitation and average temperature is shown in Figure 2.2. Irrigation equivalent to 24,571 kL ha^{-1} was applied to the control over the course of the 129 day period, which was greater ($p<0.0001$) than both the SS2Lpd (5,887 kL ha^{-1}) and the SSθ Conv (5,292 kL ha^{-1}) and SSθ LowP (4,942 kL ha^{-1}). There was no difference ($p>0.05$) in the total volume of water applied between the SS2Lpd and either SSθ treatment. For each month of the study, average daily irrigation volumes were greater in the control than either spray stake treatment / fertilizer combination (Table 2.2). Differences in application volume

between spray stake treatments occurred only during June where SSθ LowP applied less water than all other spray stake treatments.

Irrigating using SSθ applied irrigation on 96.7 (± 9.8) days for beds receiving the Conv fertilizer, while beds receiving the LowP fertilizer had irrigation applied on 90 (± 8.6) days, compared to the control and SS2Lpd fertilizer treatments, which both applied water on 129 days (Table 2.1). Irrigating using SSθ reduced the number of days irrigation was applied relative to the control and the SS2Lpd treatment ($p<0.0057$ for beds receiving 19-3-8; $p<0.0191$ for beds receiving 19-4-8).

2.4.2 Irrigation Return Flow

Surface and subsurface IRF volumes were collected on 13 sample dates throughout the course of the season in conjunction with nutrient samples, allowing load calculations. Nutrient samples were additionally collected from subsurface IRF on three more dates (total 16 dates); however, subsurface IRF volumes were not, thus allowing only concentration calculations on those days. Samples were only collected on days with less than 0.5 cm of precipitation in order to assess return flow reflective of irrigation events.

Of the 13 dates throughout the season where surface IRF volumes were collected, the control was greater than all treatments on 10 occasions (Table 2.3). For each date, a significant ($p < 0.05$) irrigation main effect on 12 of the 13 sample dates, while there were no significant ($p \geq 0.05$) fertilizer main effects or interactive effects on any date. Across all sample dates with less than 0.5 cm of precipitation for each month of the study, control irrigated beds averaged more surface IRF than the two spray stake treatments ($p<0.05$) (Table 2.4). The total volume of surface IRF was greater in the control than all treatments (which were no different from each other), and only an irrigation main effect was significant (Figure. 2.3).

Of the 13 dates throughout the season where subsurface IRF volumes were collected, the volume was equivalent between the control and all treatments on 6 occasions (Table 2.3). When differences were exhibited, the control was greater than one or both of the irrigation treatments. An irrigation main effect was significant on 7 of 13 dates, a fertilizer main effect on one date, and the interaction effect was not significant. There were no differences between treatments in the volume of water transported via subsurface IRF during May; however, for all months thereafter SSθ produced less subsurface IRF than overhead irrigated beds (Table 2.4). SS2Lpd had equivalent subsurface IRF volumes as the control irrigated beds in June and August, while in July and September SS2Lpd exported less subsurface IRF than the control but more than the SSθ. The total volume of subsurface IRF collected throughout the season was greater in the control than either SSθ treatment, while the SS2Lpd was no different from either the control or SSθ (Figure 2.3). Only an irrigation main effect was significant in total subsurface IRF.

2.4.3 Nitrate-N

Surface IRF samples were analyzed for NO_3^--N concentration on 13 sample dates (Table 2.5). The concentration of NO_3^--N was greater in the control than spray stake treatments on 7 of these dates, as surface IRF was typically eliminated using spray stakes. Of the 13 dates, an irrigation main effect was significant on 8 dates while neither fertilizer main effect nor irrigation x fertilizer interaction effect were significant on any date. The peak measured concentration in surface IRF from the control occurred on day 20 (3.28 mg L^{-1}) and for the SSθ Conv on day 97 (4.1 mg L^{-1}). All other treatments did not exceed 1 mg L^{-1} in surface IRF on any sample date.

The control exported a greater load of NO_3^--N in surface IRF compared to all treatments on 9 of the 13 dates (Table 2.5). Of these dates, an irrigation main effect was identified on 8 dates while neither fertilizer main effect nor interaction effect were significant. The total load of

NO_3^--N transported in surface IRF summed over the 13 sample dates was greater in the control versus all treatments (Figure 2.4). For the total load of NO_3^--N recovered in surface IRF, only irrigation had a main effect. The total load of NO_3^--N transported via surface IRF was reduced by 84-98% using spray stake irrigation compared to the control, as surface IRF was oftentimes eliminated.

Subsurface IRF samples were analyzed for NO_3^--N concentration on 16 sample dates (Table 2.6), with concentrations only differing on 2 dates. Of the 16 dates, an irrigation main effect was identified on 3 dates, a fertilizer main effect on 2 dates, and interaction effect was not significant. The highest measured concentration occurred on day 20 in the SS2Lpd conv treatment (13.2 mg L^{-1}) and the SSθ conv treatment (11.3 mg L^{-1}).

Of each of the 13 sample dates where load in subsurface IRF was measurable, only 3 sample dates exhibited differences (Table 2.6), twice where an SS2Lpd treatment transported a greater load than an SSθ treatment, and once where SS2Lpd was greater than the control. Of these sample dates, an irrigation main effect was identified on 3, a fertilizer main effect on 4, while the interaction effect was not significant. The total load of NO_3^--N transported in subsurface IRF summed over all sample dates was lowest in the SSθ LowP treatment relative to the SS2Lpd and SSθ conv fertilizer treatments (Figure 2.4); however, the control and SS2Lpd LowP were no different from any treatment. Irrigation and fertilizer main effects for total subsurface IRF were significant ($p<0.05$)

2.4.4 Phosphate-P

Surface IRF samples were analyzed for PO_4^--P on 13 sample dates (Table 2.7). Differences in concentration only occurred on 3 of these dates. The concentration of PO_4^--P did not exceed the limit of detection (0.065 mg L^{-1}) in the control or any treatment on any sample

date. Of the 13 sample dates, 11 exhibited an irrigation main effect while there were no significant fertilizer main effects or interaction effects.

The load of PO_4^--P transported in surface IRF was greater in the control than all treatments on 10 of the 13 sample dates (Table 2.7), as a result of the spray stake treatments oftentimes eliminating surface IRF generation. Of the 13 sample dates, 12 exhibited an irrigation main effect while there were no significant fertilizer main effect or interaction effect. The total load of PO_4^--P transported in surface IRF summed over all sample dates was greatest in the control versus all treatments, with only an irrigation main effect significant (Figure 2.5). The total load of PO_4^--P transported in surface IRF was reduced by 94-99% when using spray stakes compared to the control.

Subsurface IRF samples were analyzed for PO_4^--P on 16 sample dates (Table 2.8), with concentrations only differing on 2 dates; however, similarly to surface IRF, concentrations did not exceed the limit of detection and differences were based on whether IRF was in fact generated. Of the 16 sample dates, an irrigation main effect was significant on 2 dates and an interaction effect on 1 date, but no fertilizer main effects were significant.

The load of PO_4^--P transported in subsurface IRF was assessed on 13 sample dates (Table 2.8). Differences were exhibited on 6 sample dates, where the control transported more PO_4^--P than spray stake treatments. Of the 13 dates, an irrigation main effect was significant on 6 dates, a fertilizer main effect on 1 date, and no significant interaction effects. The total load of PO_4^--P transported in subsurface IRF summed over all sample dates was greatest in the control versus SSθ, while SS2Lpd was no different from either (Figure 2.5). Only an irrigation main effect was significant. Total PO_4^--P subsurface IRF loads were reduced only when using SSθ compared to

the control (by 59-79%), as a function of reduced subsurface IRF volumes when irrigating based on θ.

2.4.5 Crop growth

There were no differences due to treatments in GI of any of the four taxa on 12 June; however, by 6 October there were differences in GI all four taxa studied. Shoot growth was greatest in the control for two of four species (*C. obliqua* and *P. opulifolius*), but was equivalent to at least one irrigation x fertilizer treatment combination for *H. paniculata* and *W. florida*. With the exception of *P. opulifolius* N content, nutrient content in shoot biomass was universally equivalent.

2.4.5.1 Cornus obliqua 'Powell Gardens'

Differences were due only for the fertilizer main effect for GI. GI measured on 6 October was lower in plants receiving the LowP compared to the conventional formulation (Figure 2.6). Shoot dry biomass was greater in the control than all treatments (Figure 2.6). Irrigation and fertilizer main effects were significant for shoot dry biomass; however, the interaction effect was not. There were no differences in the percentage of N, P, or K within harvested shoots ($p>0.05$), with the average and standard error percent composition for all treatments and the control being 0.720 ± 0.008 % N, 0.071 ± 0.001 % P, and 0.287 ± 0.004 % K.

2.4.5.2 Hydrangea paniculata 'Limelight'

GI measured on 6 October was greater in the control versus the SSθ treatments (Figure 2.7), while SS2Lpd was no different from either. The irrigation main effect was significant, but the fertilizer main effect or interaction effect was not. Shoot dry biomass was greater for the control compared to all treatments with the exception of SS2Lpd conv (Figure

2.7). The LowP formulation for both SS2Lpd and SSθ yielded less shoot biomass than all treatments and the control, with the exception of SSθ conv. Main effects for both irrigation and fertilizer were significant; however, the interaction effect was not. There were no differences in the percentage of N, P, or K in the harvested shoots ($p>0.05$), with the average and standard error percent composition for all treatments and the control being 0.664 ± 0.018 % N, 0.076 ± 0.002 % P, and 0.582 ± 0.013 % K.

2.4.5.3 Physocarpus opulifolius 'Seward'

GI measured on 6 October was greatest in the SS2Lpd conv compared to the control and SSθ LowP treatment; whereas SS2Lpd LowP and SSθ Conv were no different from either the control or any other treatment (Figure 2.8). Both an irrigation and fertilizer main effect were significant; however, the interaction was not significant. Shoot dry biomass was greater in the control than all treatments; where within treatments, the two LowP formulation treatments yielded less biomass than the SS2Lpd conv (Figure 2.8). Both an irrigation and fertilizer main effect were significant, while the interaction was not. Plants grown under SSθ Conv had a higher percentage of nitrogen (0.963) ± standard error of 0.039 % than the overhead control (0.700 ± 0.039) and both daily spray stake treatments (SS2Lpd Conv: 0.810 % ± 0.031; SS2Lpd LowP: 0.673 % ± 0.025), while the SSθ LowP treatment had a greater percentage of N (0.839 % ± 0.043) than the SS2Lpd LowP treatment. There were no differences in P or K percentage in shoots between any treatment combination and the control ($P>.05$), with average (and standard error) percent composition for all treatments and the control being 0.072 (± 0.002) % P, and 0.574 (± 0.007) % K. The irrigation and fertilizer main effect for % N were significant but the interaction was not.

2.4.5.4 Weigela florida 'Elvera'

GI measured on 6 October was greater for the control than SS2Lpd LowP and SSθ LowP; whereas, the SS2Lpd conv, and SSθ conv treatments were no different from either the control or other treatments (Figure 2.9). Only irrigation main effect was significant. The control and SS2Lpd conv yielded the greatest shoot biomass compared to all LowP treatments, while SSθ conv was no different from the control or any other treatment (Figure 2.9). Both irrigation and fertilizer main effects were significant, but not the interaction. There were no differences in the % of N, P, or K within harvested shoots ($p>0.05$), with the average and standard error composition for all treatments and the control being 0.986 ± 0.016 % N, 0.107 ± 0.002 % P, and 1.45 ± 0.017 % K.

2.5 Discussion

2.5.1 Irrigation Applied

A survey of ornamental crop producers conducted by White et al. (2019) identified that after source water quality, irrigation return flow management and water availability were of greatest concern; considerations that can both be addressed through improving irrigation practices. Spray stake irrigation, regardless of whether θ sensors were employed, was consistently effective in reducing the volume of irrigation applied. The daily volume of irrigation applied was reduced by 74-77% using SS2Lpd and 75-88% using SSθ within each month of the study. The total volume applied throughout the season was reduced by 76% using SS2Lpd, and 78-80% using the SSθ. Microirrigation systems improve the application efficiency in which irrigation is applied relative to overhead systems, thus requiring less water, which is consistent with reports from Lamack and Niemera (1993), Mathers et al. (2005). While sensor based spray stake irrigation typically did not result in any more water savings than a static spray stake

regimen, irrigation was applied on fewer days throughout the study, potentially allowing more flexibility in irrigation management and reducing production costs by limiting pump operation energy usage (Lichtenberg et al., 2013).

2.5.2 Irrigation Return Flow

The greater volume of irrigation return flow, particularly surface return flow, generated by overhead irrigation produces more water that must be contained and/or treated before subsequent recycling or release. The precision with which spray stakes apply irrigation limits inter-container application of water, which oftentimes reduced or eliminated surface IRF. Across all months, surface IRF was reduced by 91-100% using SS2Lpd, and 98-100% using SSθ compared to the control. While spray stakes effectively reduced (and often eliminated) surface IRF due to the improved precision with which water is applied, the control and all treatments yielded subsurface IRF. Excessive leaching from containers may occur due to the rapid application rates of microirrigation emitters coupled with the hydraulic properties present in typical nursery substrates (Lamack and Niemera, 1993), providing the potential for container leachate to then infiltrate through the production surface and contribute to subsurface IRF. By month, SSθ consistently reduced subsurface IRF compared to the control, and at times compared to SS2Lpd. Burnett and van Iersel (2008) and Van Iersel et al. (2010) reported the use of θ sensors to control the irrigation volume to effectively reduce or eliminate container leachate, particularly if irrigating at a lower θ setpoint (10%-30% in production of *Gaura lindheimeri* eliminated container leachate in Burnett and van Iersel's study; and all θ setpoints (5% to 40%) in production of *Petunia x hybrida* eliminated container leachate in van Iersel et al.'s study). Using sensors with microirrigation systems can reduce the volume of IRF by minimizing container leachate, a best management practice suggested by Bilderback (2002). Furthermore,

days where θ is above the activation threshold and irrigation is not required neither surface or subsurface IRF is generated.

2.5.3 Nutrient Movement

Nutrient movement in surface IRF from container-production facilities has been extensively studied; however, the movement of nutrients in subsurface IRF has received less attention. Bilderback (2002) suggested the use of impervious liners in growing beds (particularly in regions with sandy soils) as a means of reducing subsurface IRF and concomitant nutrient movement.

NO_3^--N is mobile in a dissolved form based on its high solubility, allowing it to move with both surface and subsurface return flow; whereas phosphorus is more likely to adsorb and be transported via erosive detachment of soils via surface return flow (Hua et al., 2016; Heathwaite and Dils, 2000). NO_3^--N concentrations in surface IRF were never above the US EPA drinking water standard of 10 mg L^{-1} (EPA); however, peak concentrations in subsurface IRF were at times exceeding this threshold in spray stake irrigated beds. This is likely attributed to surface IRF being eliminated in spray stake irrigated beds; therefore, greater subsurface infiltration of NO_3^--N would be the prominent vector of movement. The concentrations of NO_3^--N in IRF were consistent with results from Warsaw et al. (2009b), where nursery IRF concentrations were typically below 5.5 mg L^{-1} and did not exceed 7.55 mg L^{-1}; as well as reports from Yeager et al. (1993) of average concentrations of 8 mg L^{-1}. The total load of NO_3^--N recovered in subsurface IRF was generally equivalent between the control and treatments; however, the SSθ LowP treatment reduced total subsurface NO_3^--N load by 73% compared to the SS2Lpd conv and SSθ conv treatments, suggesting that the nitrogen speciation in either fertilizer

formulation may have affected NO_3^--N movement, as the conventional formulation was comprised of a greater % of NO_3^--N.

PO_4^--P concentrations were almost universally below the limit of detection (0.0652 mg L^{-1}) and never exceeded 0.17 mg L^{-1} in both surface and subsurface IRF; however, phosphorus in aquatic systems is bioactive down to a concentration of 0.05 mg L^{-1} TP and capable of inducing eutrophic activity (Schindler et al., 2016). While the samples collected in this study were below detection, similar concentrations (below 1.5 mg L^{-1}) were reported by Warsaw et al (2009b). Heathwaite and Dils (2000) investigated subsurface movement of phosphate in a field system, considering both matrix/groundwater flow as well as macro-pore movement. Their results were similar to ours, where concentrations were consistently below 1 mg L^{-1} of total phosphate with the exception of two samples which were greater than 1.2 mg L^{-1}. The subsurface movement of phosphate in their study was largely attributed to macro-pore preferential flow and land management practices, while matrix movement of phosphate was unlikely to contribute to substantial loss. For both NO_3^--N and PO_4^--P, reducing/eliminating surface IRF limits nutrient movement, while in subsurface IRF only NO_3^--N was found above detection in our study.

2.5.4 Crop Growth

Irrigation method affected GI for three of the four taxa, while fertilizer formulation only affected the GI of *C. obliqua* and *P. opulifolius*; however, at least one irrigation x fertilizer treatment combination was capable of producing an equivalent or greater GI than the control. Applying irrigation based on θ thresholds has been shown to produce plants of equivalent size for 24 ornamental taxa when using a daily water use (DWU) based practice with overhead irrigation (Warsaw et al., 2009a), and a similar substrate θ threshold (35%) using microirrigation systems in the production of *Hibiscus acetosella* 'Panama Red' (Bayer et al., 2013). The effect of

P fertilizer rate on height and root collar width in production of *Acer mono* was investigated by Razaq et al. (2017), where increased P rates (from 0-8 g P per container) produced the greatest growth. This was similar to our results, where in the case of *C. obliqua* and *W. florida*, the LowP fertilizer reduced final GI by 37% and 45%, respectively, compared to plants grown under the control.

Increasing phosphorus application rate has been shown to increase shoot biomass in *Hydrangea quercifolia*, as well as two taxa used in this study (*P. opulifolius, C. obliqua*) (Poudyal et al., 2021); however, based on the tradeoff of increased growth versus the environmental impact of increased P leachate from containers, the optimum P application rate was not recommended to exceed 4 mg L^{-1} for the three taxa. Shoot dry biomass has also been reported to increase when providing greater volumes of irrigation and/or irrigating plants at a higher θ set point (Burnett and van Iersel, 2008; Fulcher et al., 2012; van Iersel et al., 2010); however, the benefits of increased shoot dry biomass relative to water savings may be minimal, as suggested by Bayer et al. (2015). It was the authors' observation that certain taxa (particularly *H. paniculata*), exhibited leggy growth habits as well as brittles stems which snapped under inflorescence weight when irrigated using the control, which was consistent with Fernández's (2020) observation that precision irrigation can be used to limit excessive growth in woody crops. Smaller, more compact plants are desirable in nursery production due to shipping considerations, where Burnett and van Iersel (2008) suggested using moisture sensors to maintain control over drought stress in order to slow growth.

For all four taxa, the LowP formulation produced less shoot dry biomass than the conventional fertilizer. This was consistent with reports on production of *Cotoneaster dammeri* 'Skogholm', where a 50% reduction in applied P reduced total biomass by 16% (Owen et al.,

2008) and shoot dry biomass by 26% (Tyler et al., 1996). Shoot tissue has been reported to be responsive to P application rate, where Parks et al. (2000) found greater P concentration of *Banksia ericifolia* shoot tissues under higher P application rates, but no difference in the amount of shoot biomass. This was converse to our results, where the concentration of P in shoot biomass was equivalent between the control and all treatments regardless of P application rate, in addition to shoot biomass being reduced with lower P application rates. Nitrogen concentrations in shoot biomass only exhibited differences in *P. opulifolius*, where the SSθ conv treatment was greatest. While the % N was equivalent for both fertilizer formulations, the N species composition varied. Differences in % N may be attributable to the conventional formulation having less urea than the LowP formulation, which is consistent with reports from Faustino et al (2015), where urea based fertilizers resulted in less growth of *Pinus taeda* relative to plants receiving ammonium based fertilizers.

2.6 Conclusion

Nursery growers prioritize producing a quality crop, which may come at the expense of increased water and fertilizer use; however, more efficient irrigation application methods capably produce an equivalent crop. Large reductions in the quantity of water extracted and applied can be accomplished by using either static or sensor controlled spray stake irrigation for container-grown woody ornamentals. Furthermore, using spray stake irrigation leads to similar reductions in the amount of surface IRF, and to a lesser extent, subsurface IRF along with the NO_3^--N and PO_4^--P moving in these channels. Container-grown woody ornamentals can also be produced more efficiently with respect to water use, and for some taxa, reduced fertilizer rates. Additionally, crop quality (particularly compactness) may be improved by using spray stake irrigation. Beyond water savings, the reduced volumes of irrigation return flow may facilitate

more efficient methods of capturing and treating irrigation return flow, prior to release to the surrounding environment.

Capture and reuse of IRF for recycled irrigation has been increasingly adopted by nursery growers to ensure water security and to satisfy water management and quality regulations (Lu et al., 2006; Poudyal et al., 2019). Reducing the volume of IRF via more efficient irrigation practices may allow less dedicated infrastructure for retention ponds and/or contaminant remediation systems. The use of microirrigation is effective in preventing the most critical vector in agrochemical movement (IRF); therefore, irrigating to minimize generation of IRF may be a more effective way to reduce the environmental impact of fertilizer loss to the environment versus reducing fertilizer rate at the point of application and potentially limiting crop growth. Furthermore, the environmental impact of fertilizer loss from production sites can effectively be addressed through improved irrigation practices rather than adjusting fertilizer application rate, where biomass reductions often occurred when fertilized with less P. Future research investigating irrigation and fertilizer rates on a wider range of woody-ornamental taxa may facilitate enhanced adoption of these technologies and practices.

APPENDIX

Table 2.1: The number of days irrigation was applied at the MSU experimental nursery throughout the 2017 season. Control and SS2Lpd irrigated every day throughout the study while SSθ irrigated only on days when substrate θ was below 35%.

Irrigation **Fertilizer**	**Control** **Conv**	**SS2Lpd** **Conv/LowP**	**SSθ** **Conv**	**SSθ** **LowP**
May	15 a[z]	15 a	11 (+/- 1) ab	6.67 (+/- 2.73) b
June	30 a	30 a	21 (+/- 2) b	13 (+/- 1.73) c
July	31 a	31 a	22.7 (+/- 3.71) a	26 (+/- 2.89) a
August	31 a	31 a	23.7 (+/- 1.76) b	25.3 (+/- 2.33) ab
September	22 a	22 a	18.3 (+/- 3.18) a	19 (+/- 1.73) a
TOTAL	129 a	129 a	96.7 (+/- 9.82) b	90 (+/- 8.62) b

[z]Means followed by different letters are significantly different at $p < 0.05$ by Tukey's HSD

Table 2.2: Average daily kL per ha^{-1} of irrigation applied by month at the MSU experimental nursery. Control and SS2Lpd all applied the same volume of irrigation per replicate while SSθ irrigation was applied to achieve 35% θ and varied between replicates.

Irrigation	**Control**	**SS2Lpd**	**SSθ**	**SSθ**
Fertilizer	**Conv**	**Conv/LowP**	**Conv**	**Low P**
May	190.5 a[z]	43.7 b	38.5 (+/- 3.5) b	23.3 (+/- 9.5) b
June	190.5 a	46.5 b	39.2 (+/- 3.5) b	25.2 (+/- 3.0) c
July	190.5 a	43.7 b	38.4 (+/- 6.3) b	44.0 (+/- 4.89) b
August	190.5 a	49.0 b	44.5 (+/- 3.0) b	47.6 (+/- 3.9) b
September	190.5 a	43.7 b	43.7 (+/- 7.6) b	45.3 (+/- 4.13) b
Total	24,570.7 a	5,886.9 b	5,292.2 (+/- 515.3) b	4,942.3 (+/- 452.4) b

[z]Means followed by different letters are significantly different at $p < 0.05$ by Tukey's HSD

Table 2.3: Irrigation Return Flow Volume: Surface and Subsurface irrigation return flow volume ha^{-1} collected throughout the season at the MSU experimental nursery.

Surface Irrigation Return Flow Volume													
Date (2017)	18-May	6-Jun	1-Aug	8-Aug	18-Aug	22-Aug	29-Aug	30-Aug	1-Sep	6-Sep	12-Sep	15-Sep	19-Sep
Days After Initiation	1	20	76	83	93	97	104	105	107	112	118	121	125
						Mean Volume (kl per ha^{-1})							
Control	21.5 a[z]	60.9 a	65.3 a	76.3 a	22.3 a	34.0 a	42.5 a	76.9 a	37.5 a	67.9 a	32.0 a	70.7 a	97.0 a
SS2Lpd Conv	0 b	0 b	0 b	6.0 b	0 a	0 a	0 b	0 b	0 b	0 a	0 b	0 b	0 b
SS2Lpd LowP	0 b	7.58 b	0 b	5.05 b	9.26 a	3.79 a	1.26 b	0 b	0 b	20.2 a	0 b	1.26 b	0 b
SSθ Conv	0 b	0 b	0 b	7.16 b	0 a	1.26 a	0 b	0 b	0 b	0 a	0 b	0 b	0 b
SSθ LowP	0 b	0 b	0 b	2.53 b	0 a	0 a	0 b	0 b	0 b	0 a	0 b	0 b	0 b
Subsurface Irrigation Return Flow Volume													
Date (2017)	18-May	6-Jun	1-Aug	8-Aug	18-Aug	22-Aug	29-Aug	30-Aug	1-Sep	6-Sep	12-Sep	15-Sep	19-Sep
Days After Initiation	1	20	76	83	93	97	104	105	107	112	118	121	125
						Mean Volume (kl per ha^{-1})							
Control	74.8 a	102 a	50.5 a	69.5 a	52.6 a	35.8 a	33.7 a	40.8 a	29.5 a	35.8 a	21.1 a	45.5 a	36.2 a
SS2Lpd Conv	55.4 a	72.8 ab	17.7 ab	62.3 a	47.6 a	18.1 a	28.6 a	29.1 ab	14.3 ab	37.9 a	11.8 a	23.6 ab	12.2 b
SS2Lpd LowP	32.8 a	69.9 ab	10.5 ab	22.7 ab	54.6 a	30.3 a	24.4 a	20.2 ab	16.4 ab	33.7 a	12.2 a	17.3 b	13.5 b
SSθ Conv	75.6 a	75.9 ab	6.32 b	37.9 ab	30.7 a	10.1 a	5.47 a	11.0 ab	1.26 b	7.16 a	19.8 a	2.11 b	0 b
SSθ LowP	12.6 a	23.2 b	1.26 b	6.83 b	19.8 a	19.4 a	10.9 a	2.95 b	1.68 b	20.6 a	13.1 a	6.74 b	4.63 b

[z]Means followed by different letters are significantly different at $p < 0.05$ by Tukey's HSD

Table 2.4: Monthly average of daily surface and subsurface irrigation return flow volume collected per ha^{-1} at the MSU experimental nursery.

Surface Return Flow	**May**	**June**	**July**	**August**	**September**
Control	21.5 (+/- 3.18) a[z]	69.4 (+/- 7.88) a	46.5 (+/- 10.3) a	48.5 (+/- 6.6) a	57.7 (+/- 8.73) a
SS2Lpd	0 (+/- 0) b	6.32 (+/- 2.36) b	0.44 (+/- 0.25) b	3.79 (+/- 1.65) b	1.79 (+/- 1.23) b
SSθ	0 (+/- 0) b	0.14 (+/- 0.14) b	0.18 (+/- 0.18) b	1.09 (+/- 0.56) b	0 (+/- 0) c
Subsurface Return Flow	**May**	**June**	**July**	**August**	**September**
Control	74.8 (+/- 16.3) a	79.3 (+/- 6.52) a	38.7 (+/- 7.33) a	42.5 (+/- 4.68) a	32.8 (+/- 2.44) a
SS2Lpd	44.1 (+/- 13.9) a	56.9 (+/- 5.45) a	22.2 (+/- 3.17) b	27 (+/- 2.97) ab	18.9 (+/- 2.15) b
SSθ	32.6 (+/- 14.8) a	30.3 (+/- 5.15) b	7.91 (+/- 1.78) c	16.7 (+/- 2.5) b	9.09 (+/- 1.63) c

[z]Means followed by different letters are significantly different at $p < 0.05$ by Tukey's HSD

Table 2.5: Concentration and load of nitrate-N collected in surface irrigation return flow at the MSU experimental nursery.

Date (2017)	18-May	6-Jun	1-Aug	8-Aug	18-Aug	22-Aug	29-Aug	30-Aug	1-Sep	6-Sep	12-Sep	15-Sep	19-Sep
Days after Initiation	1	20	76	83	93	97	104	105	107	112	118	121	125
					Mean Concentration (mg L^{-1})								
Control	0.29 a	3.28 a	0.28 a	0.21	0.26	0.06	0.24	0.2 a	0.15 a	0.06	0.24 a	0.11	0.13 a
SS2Lpd Conv	0 b	0 b	0 b	0.28	0	0	0	0 b	0 b	0	0 b	0	0 b
SS2Lpd LowP	0 b	0 b	0 b	0.23	0.55	0.08	0.41	0 b	0 b	0.48	0 b	0.21	0 b
SSθ Conv	0 b	0 b	0 b	3.35	0	4.1	0	0 b	0 b	0	0 b	0	0 b
SSθ LowP	0 b	0 b	0 b	0.62	0	0	0	0 b	0 b	0	0 b	0	0 b
					Mean Load (g ha^{-1})								
Control	5.71 a	168 a	16.1 a	11.3	8.58	6.4	9.2 a	13.3 a	4.88 a	5.74	6.21 a	6.6 a	12.7 a
SS2Lpd Conv	0 b	0 b	0 b	4.73	0	0	0 b	0 b	0 b	0	0 b	0 b	0 b
SS2Lpd LowP	0 b	0 b	0 b	3.52	7.8	0.87	1.55 b	0 b	0 b	12.8	0 b	0.81 b	0 b
SSθ Conv	0 b	0 b	0 b	29	0	15.5	0 b	0 b	0 b	0	0 b	0 b	0 b
SSθ LowP	0 b	0 b	0 b	4.68	0	0	0 b	0 b	0 b	0	0 b	0 b	0 b

[z]Means followed by different letters are significantly different at $p < 0.05$ by Tukey's HSD

Table 2.6: Concentration and load of nitrate-N collected in subsurface irrigation return flow at the MSU experimental nursery.

Date (2017)	18-May	6-Jun	18-Jul	25-Jul	28-Jul	1-Aug	8-Aug	18-Aug	22-Aug	29-Aug	30-Aug	1-Sep	6-Sep	12-Sep	15-Sep	19-Sep
Days after Initiation	1	20	62	69	72	76	83	93	97	104	105	107	112	118	121	125
							Mean Concentration (mg L^{-1})									
Control	1.81	1.95	1.13	0.84	0.73	0.41	0.29	0.55	0.49	0.34	0.29 b[z]	0.24 b	0.24	0.28	0.15	0.12
SS2Lpd Conv	1.63	13.2	2.68	2.17	2.23	1.37	1.34	1.74	1.28	1.09	1.03 a	0.87 a	1.05	0.72	0.66	0.54
SS2Lpd LowP	0.83	3.2	1.44	1.31	1.42	0.88	1.03	0.8	0.71	0.65	0.73 ab	0.67 ab	0.83	0.87	0.58	0.34
SSθ Conv	0.74	11.3	5.02	3.39	1.17	2.19	3.94	3.67	3.25	2.24	0.17 b	0 c	2.68	3.7	0.27	0
SSθ LowP	0.45	0.92	1.13	0.26	0.72	0.19	1.33	1.12	0.89	0.29	0.27 b	0.09 c	1.27	1.05	0.36	0.25
							Mean Load (g ha^{-1})									
Control	130	199	.	.	.	19.2	19.3	27.4	17	11.1	11.9 b	7.01 ab	7.73	5.15	6.59 ab	4.69
SS2Lpd Conv	130	1026	.	.	.	23.3	82.8	77.7	21.2	29.9	28.4 a	10.6 ab	36.8	7.29	14.7 a	6.16
SS2Lpd LowP	37.7	260	.	.	.	10	28.9	56.8	24.4	12.3	14.2 ab	11.1 a	25.4	9.19	8.82 ab	6.72
SSθ Conv	43.1	973	.	.	.	13.4	136	104	35.3	12.8	5.43 b	0 ab	13.5	116	1.72 b	0
SSθ LowP	5.92	29	.	.	.	0.73	4.01	21.9	18	6.28	1.25 b	0.44 b	26.1	13.7	4.75 ab	1.95

[z]Means followed by different letters are significantly different at $p < 0.05$ by Tukey's HSD

Table 2.7: Concentration and load of phosphate-P in surface irrigation return flow at the MSU experimental nursery.

Date 2017	18-May	6-Jun	1-Aug	8-Aug	18-Aug	22-Aug	29-Aug	30-Aug	1-Sep	6-Sep	12-Sep	15-Sep	19-Sep
Days after Initiation	1	20	76	83	93	97	104	105	107	112	118	121	125
						Mean Concentration (mg L^{-1})							
Control	0.065	0.065 a[z]	0.065	0.065	0.043	0.022	0.065 a	0.065	0.065	0.043	0.065	0.065 a	0.065
SS2Lpd Conv	0	0 b	0	0.043	0	0	0 b	0	0	0	0	0 b	0
SS2Lpd LowP	0	0 b	0	0.022	0.043	0.022	0.022 ab	0	0	0.043	0	0.022 ab	0
SSθ Conv	0	0 b	0	0.043	0	0.023	0 b	0	0	0	0	0 b	0
SSθ LowP	0	0 b	0	0.03	0	0	0 b	0	0	0	0	0 b	0
						Mean Load (g ha^{-1})							
Control	0.7 a	1.99 a	2.13 a	2.49 a	0.727	1.11	1.39 a	2.51 a	1.22 a	2.21	1.04 a	2.31 a	3.16 a
SS2Lpd Conv	0 b	0 b	0 b	0.195 b	0	0	0 b	0 b	0 b	0	0 b	0 b	0 b
$SS2Lp_d$ LowP	0 b	0 b	0 b	0.165 b	0.302	0.124	0.041 b	0 b	0 b	0.659	0 b	0.04 b	0 b
SSθ Conv	0 b	0 b	0 b	0.233 b	0	0.089	0 b	0 b	0 b	0	0 b	0 b	0 b
SSθ LowP	0 b	0 b	0 b	0.224 b	0	0	0 b	0 b	0 b	0	0 b	0 b	0 b

[z]Means followed by different letters are significantly different at $p < 0.05$ by Tukey's HSD

Table 2.8: Concentration and load of phosphate-P in subsurface irrigation return flow at the MSU experimental nursery.

Date 2017	18-May	6-Jun	18-Jul	25-Jul	28-Jul	1-Aug	8-Aug	18-Aug	22-Aug	29-Aug	30-Aug	1-Sep	6-Sep	12-Sep	15-Sep	19-Sep
Days after Initiation	1	20	62	69	72	76	83	93	97	104	105	107	112	118	121	125
							Mean Concentration (mg L^{-1})									
Control	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065 a[z]	0.065	0.065	0.065	0.065 a
SS2Lpd Conv	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065 a	0.065	0.065	0.065	0.065 a
SS2Lpd LowP	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065 a	0.065	0.065	0.065	0.043 ab
SSθ Conv	0.065	0.065	0.065	0.065	0.065	0.043	0.065	0.065	0.065	0.043	0.022	0 b	0.065	0.093	0.022	0 b
SSθ LowP	0.043	0.033	0.065	0.065	0.065	0.022	0.065	0.065	0.065	0.043	0.043	0.022 ab	0.065	0.065	0.043	0.043 ab
							Mean Load (g ha^{-1})									
Control	2.44	3.32	.	.	.	1.65 a	2.27 a	1.72	1.17	1.1	1.33 a	0.961 a	1.11	0.686	1.48 a	1.18 a
SS2Lpd Conv	1.81	2.37	.	.	.	0.576 ab	2.03 a	1.55	0.59	0.933	0.947 ab	0.466 ab	1.24	0.384	0.769 ab	0.398 b
SS2Lpd LowP	1.07	2.28	.	.	.	0.343 ab	0.741 ab	1.78	0.988	0.618	0.659 ab	0.532 ab	1.1	0.398	0.563 b	0.439 b
SSθ Conv	2.04	2.47	.	.	.	0.206 b	1.24 ab	1	0.329	0.178	0.357 ab	0 b	0.233	0.841	0.069 b	0 b
SSθ LowP	0.412	0.515	.	.	.	0.041 b	0.223 b	0.645	0.631	0.357	0.096 b	0.055 b	0.673	0.423	0.219 b	0.151 b

[z]Means followed by different letters are significantly different at $p < 0.05$ by Tukey's HSD

Figure 2.1: Diagram of MSU Research Nursery.

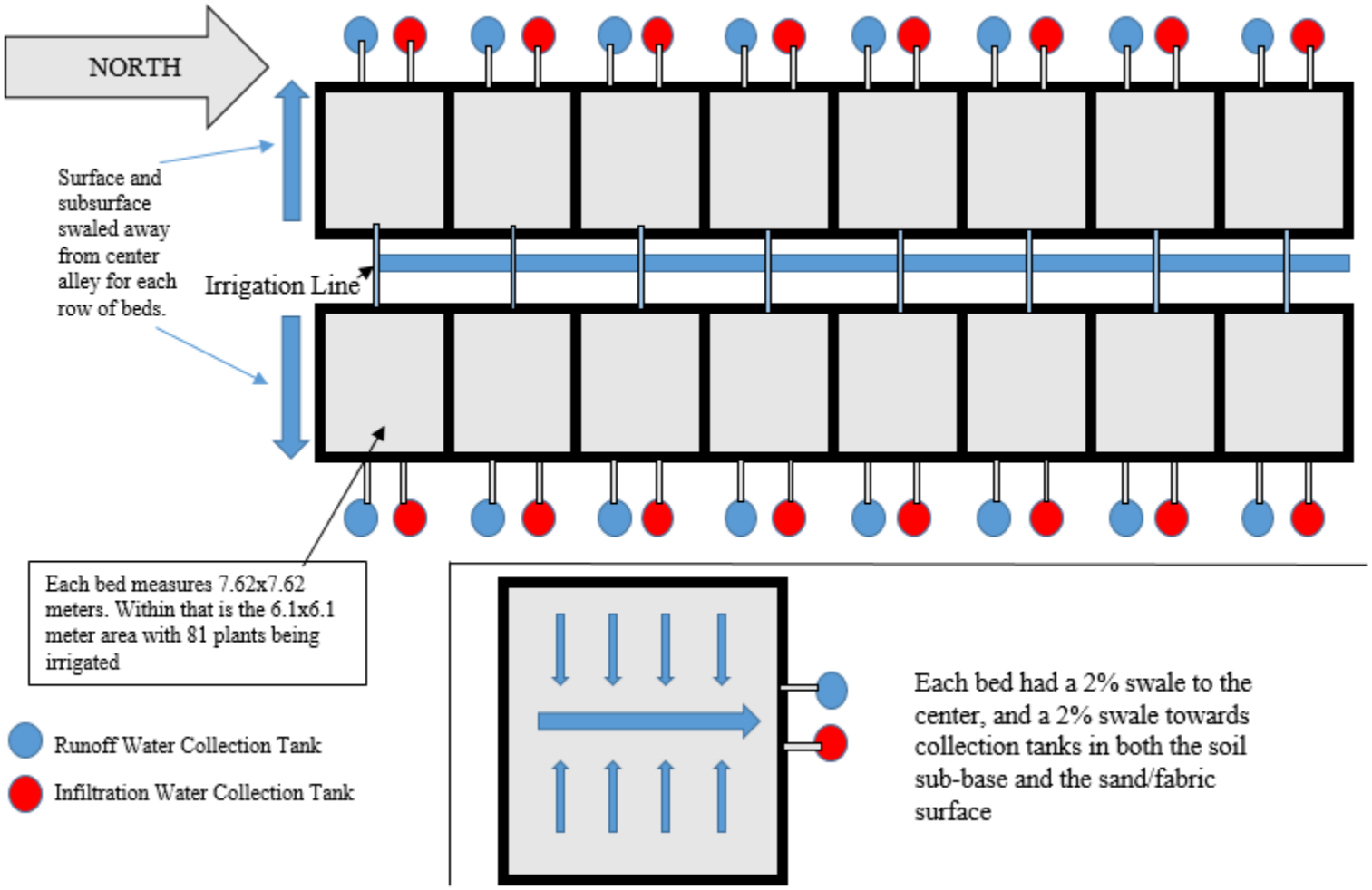


Figure 2.2**:** Precipitation (a) and temperature conditions (b) at the Michigan State University Research Nursery throughout the 2017 study.

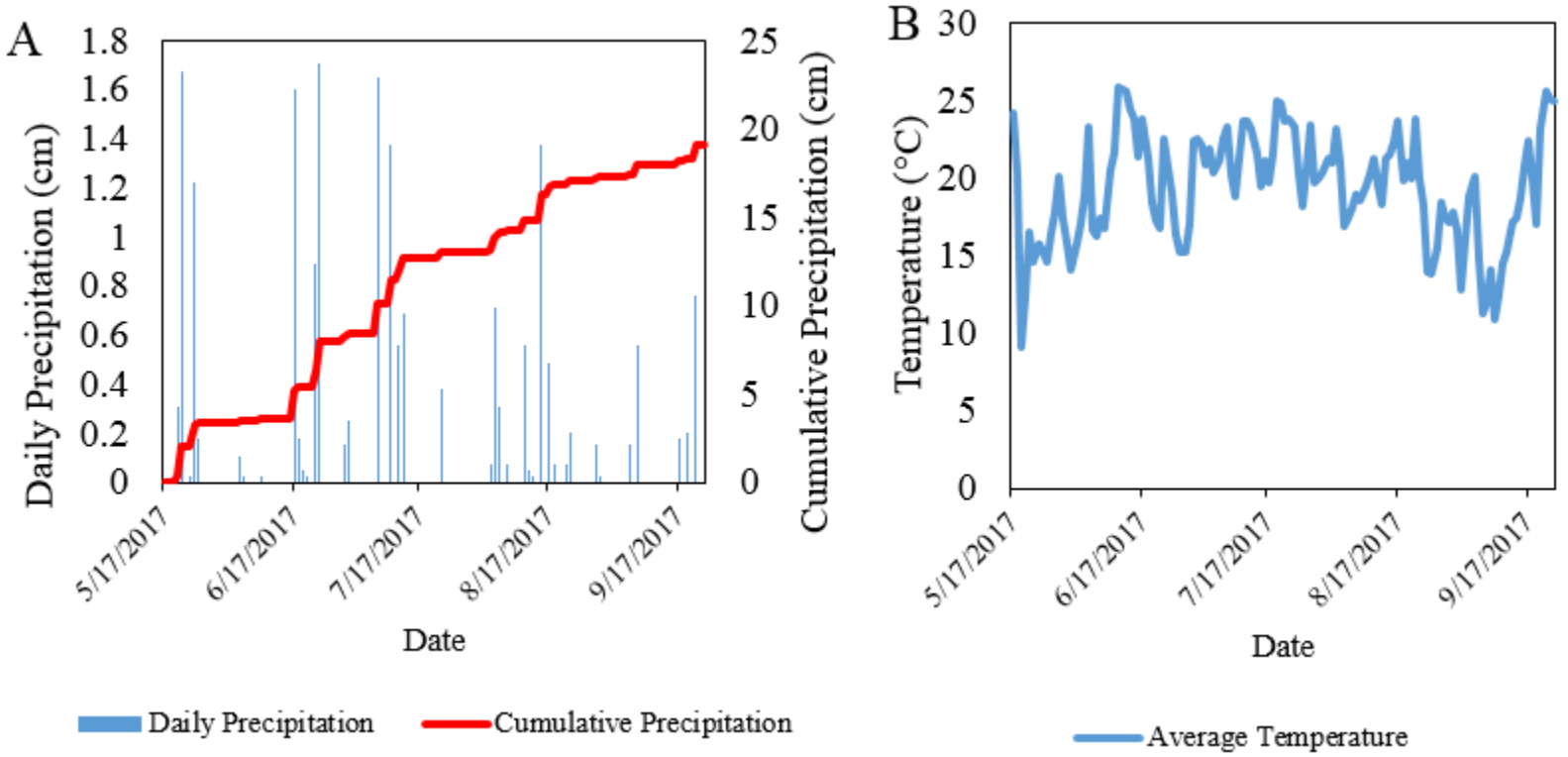


Figure 2.3**:** Total volume of surface (a) and subsurface (b) irrigation return flow volume per hectare collected over the season on dates with less than 0.5 cm of precipitation. Differences in means (separated using Tukey's test at $p<0.05$) are represented by lower case letters.

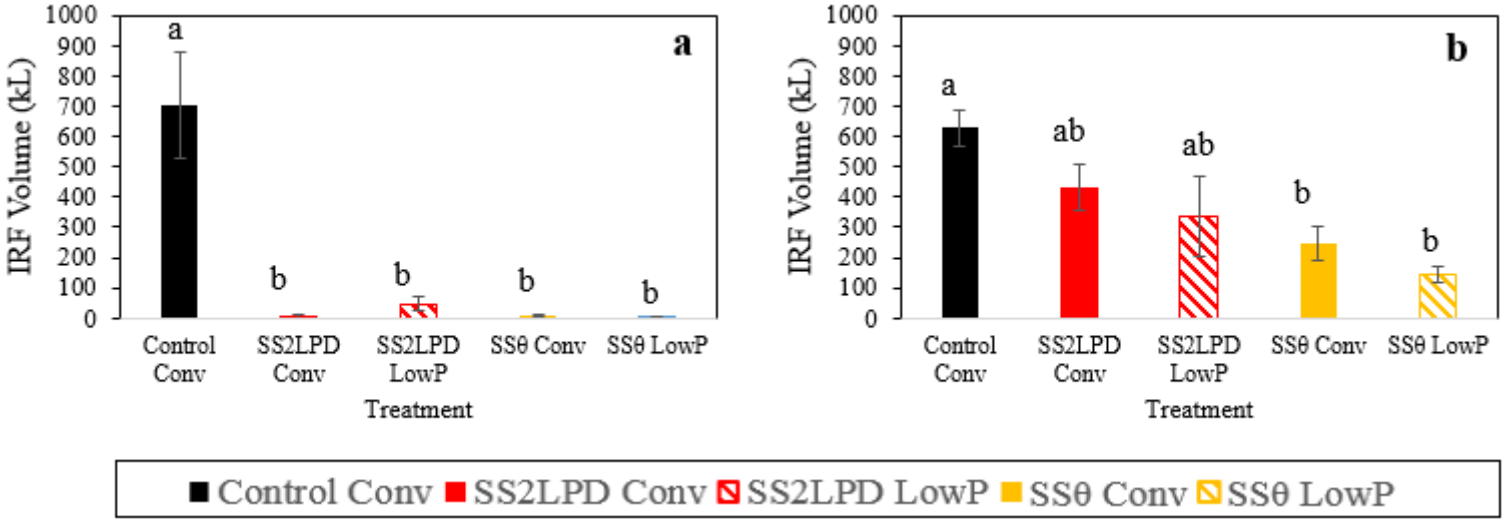


Figure 2.4**:** Total volume of surface (a) and subsurface (b) nitrate-N load per hectare collected over the season on dates with less than 0.5 cm of precipitation. Differences in means (separated using Tukey's test at $p<0.05$) are represented by lower case letters.

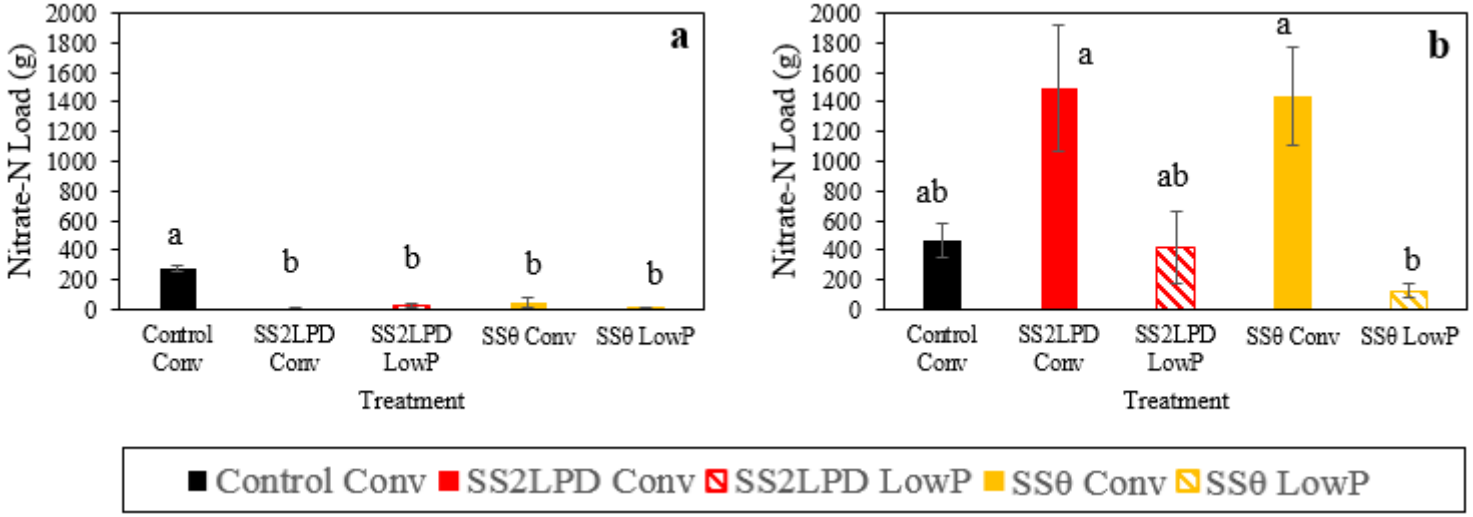


Figure 2.5: Total volume of surface (a) and subsurface (b) phosphate-P load per hectare collected over the season on dates with less than 0.5 cm of precipitation. Differences in means (separated using Tukey test at $p<0.05$) are represented by lower case letters.

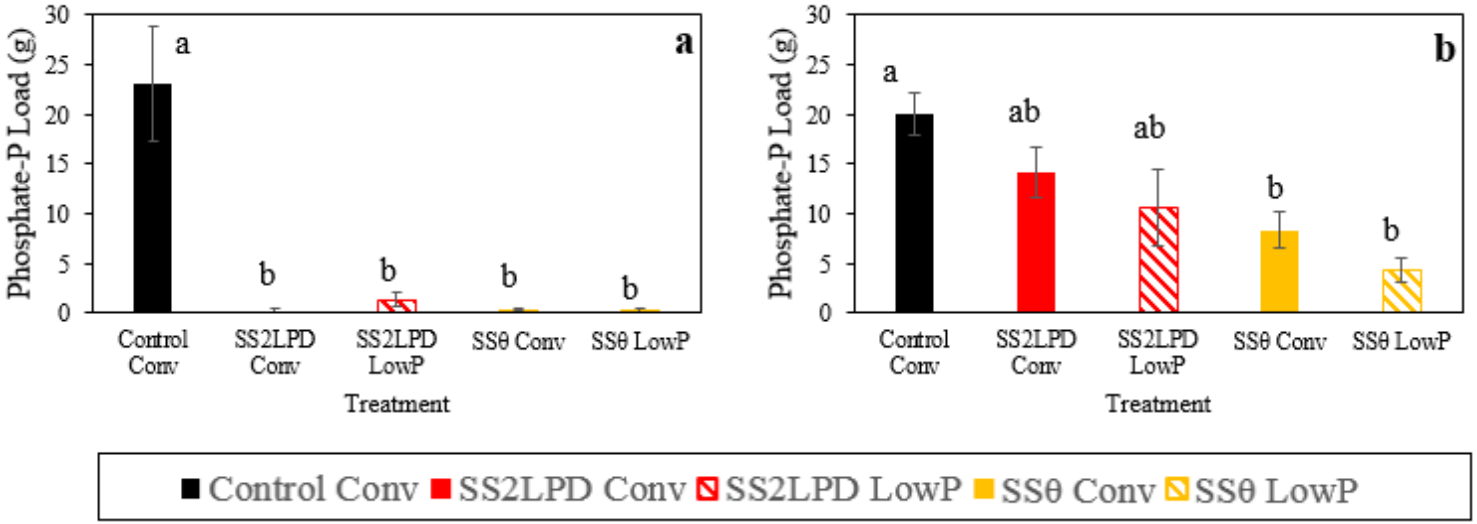


Figure 2.6**:** Final growth index (GI) (a) and shoot dry weight (b) of *Cornus obliqua* 'Powell Gardens'. Differences in means (separated using Tukey's test at $p<0.05$) are represented by lower case letters.

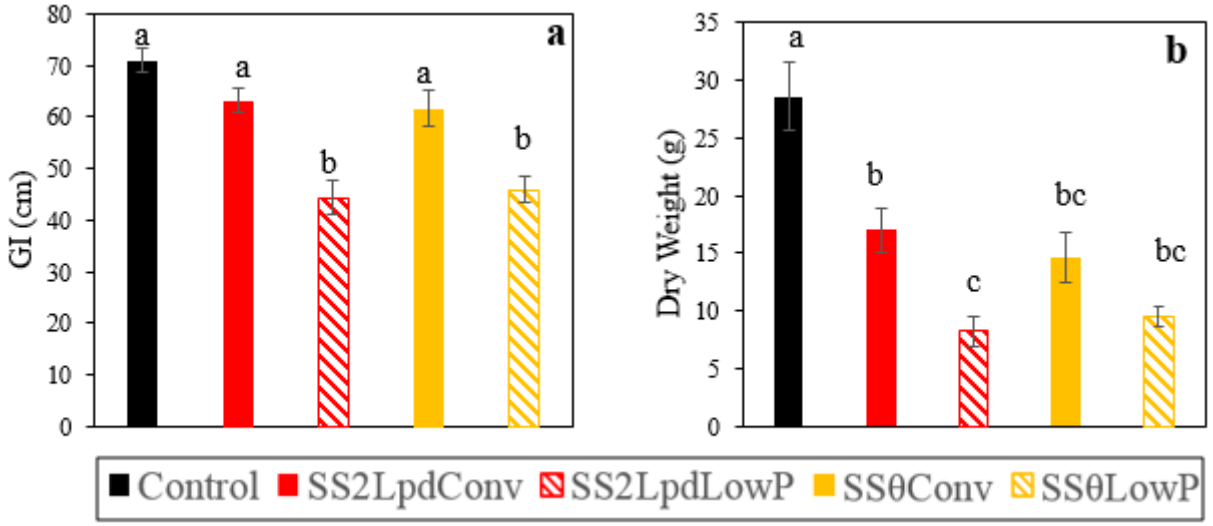


Figure 2.7: Final growth index (GI) (a) and shoot dry weight (b) of *Hydrangea paniculata* 'Limelight'. Differences in means (separated using Tukey's test at $p<0.05$) are represented by lower case letters.

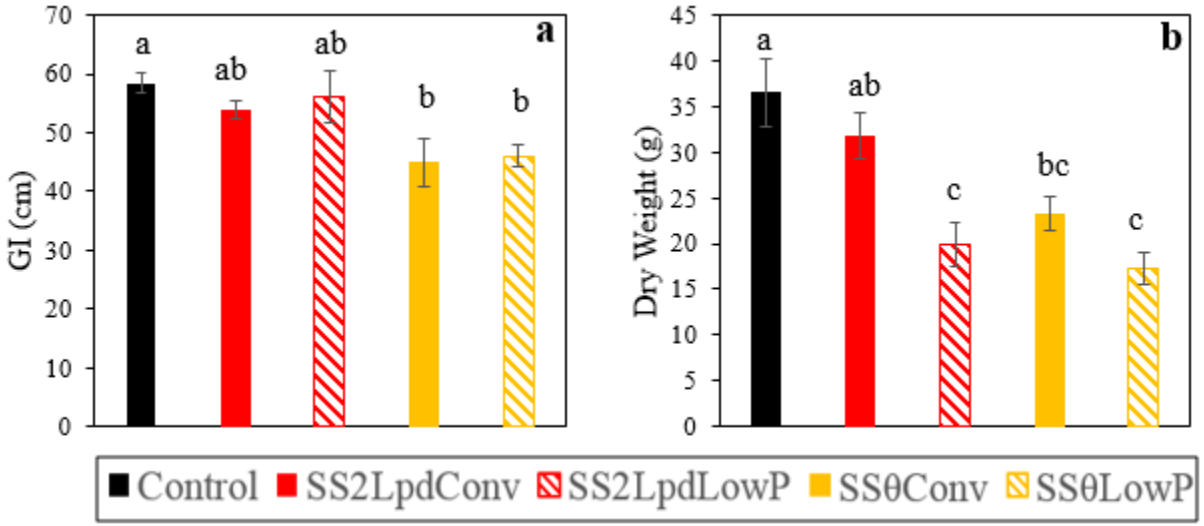


Figure 2.8: Final growth index (GI) (a) and shoot dry weight (b) of *Physocarpus opulifolius* 'Seward'. Differences in means (separated using Tukey's test at $p<0.05$) are represented by lower case letters.

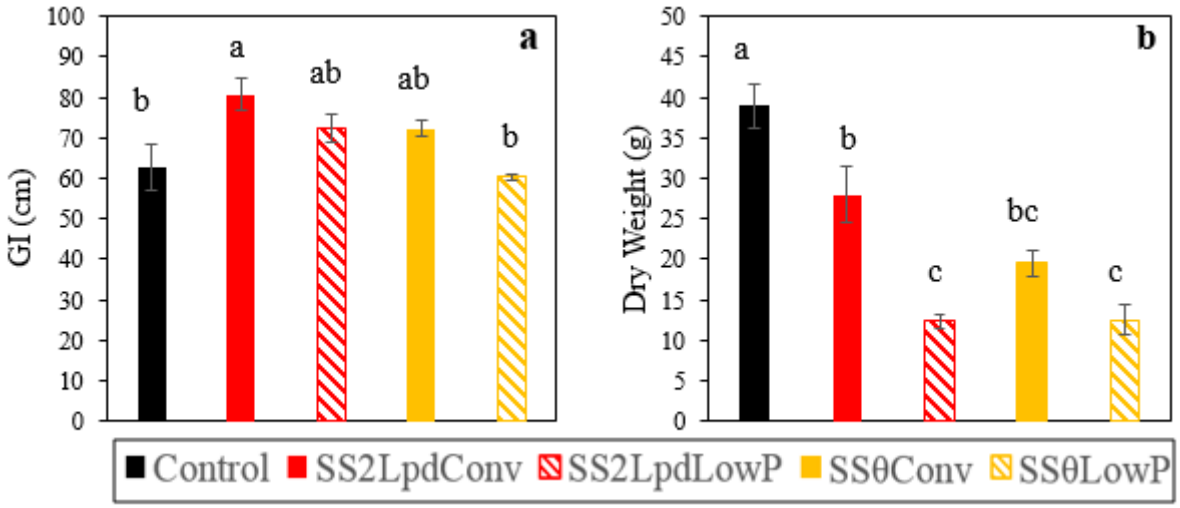
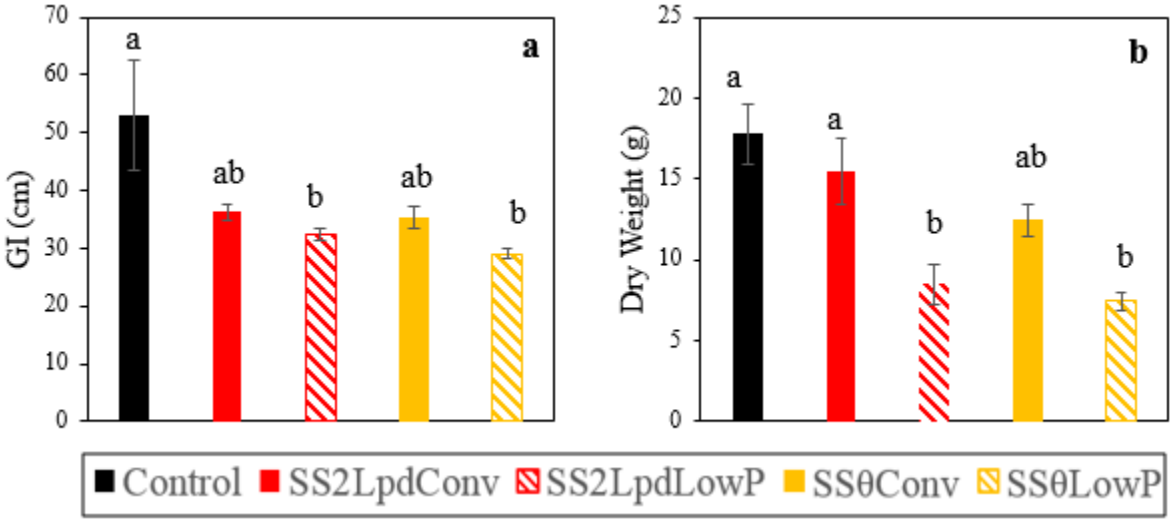


Figure 2.9: Final growth index (GI) (a) and shoot dry weight (b) of *Weigela florida* 'Elvera'. Differences in means (separated using Tukey's test at $p<0.05$) are represented by lower case letters.



LITERATURE CITED

LITERATURE CITED

Abdi, D.E., Fernandez, R.T., 2019. Reducing water and pesticide movement in nursery production. HortTechnology. 29, 730-735.

Abouali, M., Nejadhashemi, A.P., Daneshvar, F., Adhikari, U., Herman, M.R., Calappi, T.J., Rohn, B.G., 2017. Evaluation of wetland implementation strategies on phosphorus reduction at a watershed scale. J. of Hydrol. 552, 105-120.

Agro, E., Zheng, Y., 2014. Controlled-release fertilizer application rates for container nursery crop production in southwestern Ontario, Canada. HortScience. 49, 1414-1423.

Bayer, A., Mahbub, I., Chappell, M., Ruter, J., van Iersel, M.W., 2013. Water use and growth of Hibiscus acetosella 'Panama Red' grown with a soil moisture sensor-controlled irrigation system. HortScience. 48, 980-987.

Bayer, A., Ruter, J., van Iersel, M.W., 2015. Automated irrigation control for improved growth and quality of Gardenia jasminoides 'Radicans' and 'August Beauty'. HortScience. 50, 78-84.

Beeson, R.C., Arnold, M.A., Bilderback, T.E., Bolusky, B., Chandler, S., Gramling, H.M., Lea-Cox, J.D., Harris, J.R., Klinger, P.J., Mathers, H.M., Ruter, J.M., Yeager, T.H., 2004. Strategic vision of container nursery irrigation in the next ten years. J. Environ. Hortic. 22, 113-115.

Beeson, R.C. Jr., Yeager, T.H., 2003. Plant canopy affects sprinkler irrigation application efficiency of container-grown ornamentals. HortScience. 38, 1373-1377.

Beeson, R.C. Jr., Knox, G.W., 1991. Analysis of efficiency of overhead irrigation in container production. HortScience. 26, 848-850.

Berghage, R.D., MacNeal, E.P., Wheeler, E.F., Zachritz, W.H., 1999. "Green" water treatment for the green industries: opportunities for biofiltration of greenhouse and nursery irrigation water and runoff with constructed wetlands. HortScience 34, 50-54.

Bilderback, T.E., 2002. Water management is key in reducing nutrient runoff from container nurseries. HortTechnology. 12, 541-544.

Burnett, S.E., van Iersel, M.W., 2008. Morphology and irrigation efficiency of Gaura lindheimeri grown with capacitance sensor-controlled irrigation. HortScience. 43, 1555-1560.

Davies, M.J., R. Harrison-Murray, C.J. Atkinson, O.M. Grant., 2016. Application of deficit irrigation to container-grown hardy ornamental nursery stock via overhead irrigation, compared to drip irrigation. Agr. Water Manage. 163, 244-254.

Dennis, J.H., Lopez, R.G., Behe, B.K., Hall, C.R., Yue, C., Campbell, B.L., 2010. Sustainable production practices adopted by greenhouse and nursery plant growers. HortScience. 45, 1232-1237.

Döll, P., 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environ. Res. Lett. 4, 1-12.

Faustino, L.I., Moretti, A.P., Graciano, C., 2015. Fertilization with urea, ammonium, and nitrate produce different effects on growth, hydraulic traits and drought tolerance in Pinus taeda seedlings. Tree Physiol. 35, 1062-1074.

Fernandez, R.T., Pershey, N.A., Andresen, J.A., Cregg B.M., 2019. Water conserving irrigation practices, plant growth, seasonal crop coefficients, and nutrition of container-grown woody ornamentals. Water 11, 1-19.

Fernández, J.E., 2017. Plant-based methods for irrigation scheduling of woody crops. Horticulturae. 3, 1-137.

Fulcher, A.F., Buxton, J.W., Geneve, R.L., 2012. Developing a physiological-based, on demand irrigation system for container production. Scientia Horticulturae. 138, 221-226.

Fulcher, A., LeBude, A.V., Owen, J.S. Jr., White, S.A., Beeson, R.C., 2016. The next ten years: strategic vision of water resources for nursery producers. HortTechnology 26, 121-132.

Garber, M.P., Ruter, J.M., Midcap, J.T., Bondari, K., 2002. Survey of container nursery irrigation practices in Georgia. HortTechnology. 12, 727-731.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science. 327, 812-818.

Heathwaite, A.L., Dils, R.M., 2000. Characterising phosphorus loss in surface and subsurface hydrological pathways. Sci of the Total Environ. 251/252, 523-538.

Hinz, F.O., Albano, J.P., Wilson, P.C., 2019. Phosphate removal from nursery runoff water using an iron-based remediation system. Water. 11, 1-10.

Hua, G., Salo, M.W., Schmit, C.G., Hay, C.H., 2016. Nitrate and phosphate removal from agricultural subsurface drainage using laboratory woodchip bioreactors and recycled steel byproduct filters. Water Res. 102, 180-189.

Incrocci, L., Marzialetti, P., Incrocci, G., Di Vita, A., Balendonck, J., Bibbiani, C., Spagnol, S., Pardossi, A., 2014. Substrate water status and evapotranspiration irrigation scheduling in heterogenous container nursery crops. Agr. Water Mgmt. 131, 30-40.

Incrocci, L., Marzialetti, P., Incrocci, G., Di Vita, A., Balendonck, J., Bibbiani, C., Spagnol, S., Pardossi, A., 2019. Sensor-based management of container nursery crops irrigated with fresh or saline water. Agr. Water Mgmt. 213, 49-61.

Knight, J., Abdi, D.E., Ingram, D.L., Fernandez, R.T., 2019. Water scarcity footprint analysis of container-grown plants in a model research nursery as affected by irrigation and fertilization treatments. Water. 11, 1-16.

Lamack, W.F., Niemera, A.X., 1993. Application method affects water application efficiency of spray stake-irrigated containers. HortScience. 28, 625-627.

Lichtenberg, E., Majsztrik, J., Saavoss. M., 2013. Profitability of sensor-based irrigation in greenhouse and nursery crops. HortTechnology. 23, 770-774.

Lu, J., Wu, L., Newman, J., Faber, B., Gan, J., 2006. Degradation of pesticides in nursery recycling ponds. J. of Agr. Food Chem. 54, 2658-2663.

Majsztrik, J.C., Fernandez, R.T., Fisher, P.R., Hitchcock, D.R., Lea-Cox, J., Owen, J.S. Jr., Oki, L.R., White, S.A., 2017. Water use and treatment in container-grown specialty crop production: a review. Water Air and Soil Poll. 228, 1-27.

Majsztrik, J.C., Ristvey, A.G., Ross, D.S., Lea-Cox, J.D., 2018. Comparative water and nutrient application rates among ornamental operations in Maryland. HortScience. 53, 1364-1371

Majsztrik, J.C., Behe, B., Hall, C.R., Ingram, D.L., Lamm, A.J., Warner, L.A., White, S.A., 2019. Social and economic aspects of water use in specialty crop production in the USA: a review. Water. 11, 1-13.

Mangiafico, S.S., Gan, J., Wu, L., Lu, J., Newman, J.P., Faber, B., Merhaut, D.J., Evans, R., 2008. Detention and recycling basins for managing nutrient and pesticide runoff from nurseries. HortScience. 43, 393-398.

Mathers, H.M., Yeager, T.H., Case, L.T., 2005. Improving irrigation water use in container nurseries. HortTechnology. 15, 8-12.

Million, J.B. and T.H. Yeager., 2015. Capture of Sprinkler Irrigation Water by Container-grown Ornamental Plants. HortScience. 50, 442-446.

Niu, G., Rodriguez, D.S., Cabrera, R., McKenney, C., Mackay, W., 2006. Determining water use and crop coefficients of five woody landscape plants. J. Environ. Hortic. 24, 160-165.

Owen, J.S. Jr., Warren, S.L., Bilderback, T.E., Albano, J.P., 2008. Phosphorus rate, leaching fraction, and substrate influence on influent quantity, effluent nutrient content, and response of a containerized woody ornamental crop. HortScience. 43, 906-912.

Parks, S.E., Haigh, A.M., Cresswell, G.C., 2000. Stem tissue phosphorus as an index of the phosphorus status of Banksia ericifolia L. f. Plant and Soil. 227, 59-65.

Pershey, N.A., Cregg, B.M., Andresen, J.A., Fernandez, R.T., 2015. Irrigating based on daily water use reduces nursery runoff volume and nutrient load without reducing growth of four conifers. HortScience. 50, 1553-1561.

Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., Clark, S., Poon, E., Abbett, E., Nandagopal, S., 2004. Water resources: agricultural and environmental issues. Bioscience. 54, 909-918.

Poudyal, S., Cregg, B.M., 2019. Irrigating nursery crops with recycled run-off: a review on potential impact of pesticides on plant growth and physiology. HortTechnology. 29, 716-729.

Poudyal, S., Fernandez, R.T., Owen, J., Cregg, B., 2019. Dose-dependent phytotoxicity of pesticides in simulated nursery runoff on landscape nursery plants. Water. 11, 1-18.

Poudyal, S., Owen, J.S., Jr., Sharkey, T.D., Fernandez, R.T., Cregg, B., 2021. Phosphorus requirement for biomass accumulation is higher compared to photosynthetic biochemistry for three ornamental shrubs. Scientia Horticulturae. 275, 1-11.

Razaq, M., Zhang, P., Shen, H., Salahuddin., 2017. Influence of nitrogen and phosphorous on the growth and root morphology of Acer mono. PloS ONE. 12, 1-13.

Reddy, K.R., Kadlec, R.H., Flaig, E., Gale, P.M., 1999. Phosphorus retention in streams and wetlands: a review. Crit. Rev. in Environ. Sci. and Technol. 29, 83-146.

Ristvey, A.G., Belayneh, B.E., Lea-Cox, J.D., 2019. A comparison of irrigation-water containment methods and management strategies between two ornamental production systems to minimize water security threats. Water. 11, 1-14.

Rodell, M., Famigletti, J.S., Wiese, D.N., Reager, J.T., Beaudoing, H.K., Landerer, F.W., Lo, M.H., 2018. Emerging trends in global freshwater availability. Nature. 557, 651-659.

Sánchez-Blanco, M.J., Ortuño, M.F., Bañon, S., Álvarez, S., 2019. Deficit irrigation as a strategy to control growth in ornamental plants and enhance their ability to adapt to drought conditions. J. of Hortic. Sci. and Biotech. 94, 137-150.

Schindler, D.W., Carpenter, S.R., Chapra, S.C., Hecky, R.E., Orihel, D.M., 2016. Reducing phosphorus to curb lake eutrophication is a success. Environ. Sci. Technol. 50, 8923-8929.

Tyler, H.H., Warren, S.L., Bilderback, T.E., 1996. Reduced leaching fractions improve irrigation use efficiency and nutrient efficiency. J. Environ. Hortic. 14, 199-204.

Van Iersel, M.W., Dove, S., Kang, J.G., Burnett, S.E., 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience. 45, 277-282.

Warsaw, A.L., Fernandez, R. T., Cregg, B.M., Andresen, J.A., 2009a. Water conservation, growth, and water use efficiency of container-grown woody ornamentals irrigated based on daily water use. HortScience. 44, 1308-1318.

Warsaw, A.L, Fernandez, R.T., Cregg, B.M, Andresen, J.A., 2009b. Container-grown ornamental plant growth and water runoff nutrient content and volume under four irrigation treatments. HortScience. 44, 1573-1580.

White, S.A., Owen, J.S., Majsztrik, J.C., Oki, L.R., Fisher, P.R., Hall, C.R., Lea-Cox, J.D., Fernandez, R.T., 2019. Greenhouse and nursery water management characterization and research priorities in the USA. Water. 11, 1-19.

Yeager, T., Wright, R., Fare, D., Gilliam, C., Johnson, J., Bilderback, T., Zondag, R., 1993. Six state survey of container nursery nitrate nitrogen runoff. J. of Environ. Hortic. 11, 206-208.

Web References:

Clean Water Act (CWA); https://www.epa.gov/laws-regulations/summary-clean-water-act) (Accessed 23 September 2020). 33 U.S.C. §1251 et seq. (1972)

European Nitrate Directive (END): (https://ec.europa.eu/environment/water/water-nitrates/index_en.html) (Accessed 23 September 2020). Adopted 12 December 1991.

European Water Framework Directive (EWFD): (https://ec.europa.eu/environment/water/water-framework/index_en.html) (Accessed 23 September 2020). Adopted 23 October 2000.

US EPA National Primary Drinking Water Regulations https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations (Accessed 23 September 2020)

CHAPTER THREE

Pesticide Mobility in Surface and Subsurface Irrigation Return Flow in a Container-Plant Production System

3.1 Abstract

This study investigates the movement of ten pesticides in a container nursery production system using three irrigation methods: overhead irrigation applying 19 mm d^{-1}, spray stake microirrigation applying 2 L d^{-1}, and spray stake microirrigation controlled by substrate moisture sensors. Pesticides were selected to provide a range of water solubilities and adsorption coefficients. The research was conducted at an experimental nursery designed to collect surface and subsurface irrigation return flow in order to determine water and pesticide dynamics. Irrigation was applied daily except for the sensor controlled treatment. Irrigation volume was reduced when using microirrigation by more than 75% and surface return flow by up to 100% compared to overhead irrigation. Subsurface return flow was reduced by 23-47% with microirrigation compared to the overhead irrigation. Pesticides were applied three times during the year using standard practices at label rates. In general, as pesticide solubility decreased and adsorption coefficients increased, there was less occurrence of the particular pesticide in surface and, to a greater extent, subsurface return flow. Pesticides with high solubility and low adsorption coefficients generally exhibited a high and nearly equal degree of mobility in surface and subsurface return flow. Pesticides with high solubility were found in subsurface return flow across all irrigation methods; whereas, moderately soluble/ moderately sorptive pesticides were found in greater quantities for treatments receiving greater volumes of irrigation. Pesticides with low solubility and low adsorption coefficients were not found in subsurface return flow. Reducing or eliminating irrigation surface return flow with microirrigation reduced the movement of all pesticides through this vector by over 90%. Reductions in pesticide movement via subsurface flow was related more to physiochemical properties than water volume. This study demonstrates that pesticide movement in irrigation return flow can be reduced by selecting

pesticides with low solubility and high adsorption coefficients whenever possible and reducing irrigation volume applied and contact to non-target areas.

3.2 Introduction

Chemical movement from agricultural sites are an environmental concern, with high input intensive agriculture elevating risk of export. Container production of crops demands substantial water, fertilizer, and pesticide inputs to ensure a salable product (Warsaw et al., 2012). Pesticides are critical to maintaining a pest free, aesthetically appealing crop, with pesticides typically applied multiple times per year. Pesticides are commonly applied over the entirety of the production surfaces, covering the crop itself, as well as the container, substrate surface, and inter-container space between plants. Pesticides are subject to a variety of degradation mechanisms *in-situ*, including photolysis, bacterial metabolization, and vaporization among other pathways; however, pesticides may be mobile in production systems as water serves as the most common carrier of agrochemicals (Abdi and Fernandez, 2019; Vryzas, 2018). Pesticides vary with respect to their inherent chemical properties, such as solubility, sorption coefficients, and vapor pressure, all of which affect the likely fate of a particular compound (Von Merey, et al. 2016). Highly soluble pesticides are more likely to move in a dissolved phase in water; whereas pesticides with high sorption coefficients are more prone to binding to soils/organic matter, and instead are less mobile but may be transported via erosive detachment (Vryzas, 2018). The loss of pesticides from nursery production areas bears ecologic and economic consequences. Pesticides which are lost from production areas via surface and subsurface irrigation return flow contaminate water resources and may be toxic to biota in receiving water bodies. Additionally, pesticide loss from production areas may limit the

effectiveness with which applied compounds control target pests, thus bearing financial implications for growers, particularly if this comes at the expense of crop quality/mortality.

Production of crops in containers provides many advantages, such as homogeneity of growing conditions, ease with which plants can be moved, increased production per unit area, and faster growth (Agro and Zheng, 2014; Majsztrik et al., 2017). However, producing plants in this manner bears its own sets of challenges. Limitations dictated by the volume of the container, substrate hydraulic properties, and plant evapotranspiration requires frequent, oftentimes daily, irrigation. Irrigation is commonly applied via overhead sprinkler, providing water to the entirety of the production surface, encompassing both the plant and container as well as the inter-container spaces. Applied water which fails to reach the plant/container and lands in the inter-container spaces can contribute to irrigation return flow, where in the case of overhead irrigation typically 74-87% of applied water may be lost (Davies et al., 2016; Million and Yeager, 2015; Pershey et al., 2015). The inefficiencies of overhead irrigation have the capacity to generate substantial irrigation return flow, and result in the export of agrochemicals off-site (Briggs et al., 1998; Majsztrik et al., 2017; Warsaw et al., 2009). Alternative methods of irrigating container plants include using microirrigation systems which provide water directly to the container and the use of container substrate moisture sensors can be used to apply irrigation water more judiciously (Incrocci et al., 2019; Lea-Cox et al., 2013).

In this study, we investigated the movement of ten pesticides and their partitioning between irrigation surface return flow and subsurface return flow within a model nursery in response to overhead and microirrigation practices. With water serving as the most critical carrier of agrochemicals, we compared an overhead irrigation regiment to two treatments

applying water via individual container spray stakes in the production of four popular ornamental taxa. Microirrigation was selected as a means to provide irrigation directly to the substrate, thus avoiding washing residue from the plant canopy and non-target application. The ten pesticides were selected not only for their common use in nursery production, but also for a wide spectrum of physiochemical properties, chiefly solubility and sorption coefficients.

We hypothesized that the precision with which microirrigation applies water would result in reduced irrigation volumes and irrigation return flow. We hypothesized that more soluble and typically lower sorption coefficient compounds would be capable of infiltrating through the production surface and be mobile in subsurface return flow, while insoluble and typically higher sorption coefficient compounds would remain predominantly on production surfaces and be exported primarily via surface return flow. Considering the placement of water directly to containers with microirrigation, we hypothesized that surface return flow would be eliminated and subsurface return flow would be reduced for microirrigation methods compared to overhead irrigation. We hypothesized that the elimination of surface return flow would increase the partitioning of pesticides toward subsurface return flow moderated by physiochemical properties.

3.3 Materials and Methods

3.3.1 Research Nursery

A research nursery was constructed at the Michigan State University (MSU) Horticulture and Teaching Research Center (HTRC) in Holt, MI, USA (Latitude 42.67 N, Longitude 84.48 W), with sixteen raised beds serving as replicates where three irrigation treatments and two fertilizer rates were compared. Treatments were initiated on 17 May 2017 and concluded on 22 September 2017. The experimental raised beds were arranged in two parallel rectangular blocks

measuring 61 x 7.6 meters each with the long axis running north to south, and separated by a 1.8-m alley. Each rectangular block was divided into eight individual 7.6 x 7.6 x 0.6 m (LxWxH) beds for a total of 16 experimental beds (Figure 3.1). Native soil inside the walls of each individual bed was graded to achieve a 2% slope towards a center swale, funneling water to the edge opposite the alley. A 9.1 x 9.1 m impermeable ethylene propylene diene monomer pond liner (Firestone Pondgard 45Mil (1.14 mm) Nashville, TN, USA) was placed over each bed. Over the top of the pond liner, 0.3 m of washed natural sand, free of clay, with a particle size range of 0.75-9.5 mm was placed and graded in the same manner as the soil sub-base and covered with a black woven polypropylene landscape fabric (De Witt SBLT6300, Sikeston, MO, USA). Bulkhead fittings (Banjo tf150 polypropylene bulkhead tank fitting, Banjo Corp., Crawfordsville, IN, USA) were installed at the low points of the soil sub-base/pondliner and sand/fabric, respectively, and piped to separate 378 L polyethylene tanks (Duracast, manufacturer number 900100-1.2, Lake Wales, FL, USA) via 4.03 cm (inside diameter) schedule 40 polyvinly chloride pipe for the collection of surface return flow and subsurface return flow. Collection tanks were buried 15 cm below the soil level and anchored in place with concrete. Weather conditions were recorded throughout the season using an on-site MSU Enviro-weather station (MSU, 2020) and are shown for precipitation and temperature (Figure 3.2).

3.3.2 Irrigation Monitoring and Control System

Each of the raised beds was fitted with a 150 mesh inline filter (Toro T-ALFS75150-L, Bloomington MN, USA), a 30 psi pressure regulator (Senninger PRL303F3F, Clermont, FL, USA), a flow meter (Badger Meter 62585-001 model 25, Milwaukee, WI, USA), and two solenoid valves (Rainbird CP075, Asuza, CA, USA). Irrigation was applied via either overhead sprinklers (Toro 961 P-120), or individual container spray stakes (Netafim 22500-002030, flow

rate 12.1 Lph, Tel Aviv-Yafo, Israel). Overhead sprinklers were located at the corners of the 6.1 x 6.1 m area to be irrigated for all beds, while spray stake irrigated beds also had a manifold consisting of four 6.1-m sections of polyethylene tubing adjacent to plant rows providing water for the spray stakes.

Irrigation was managed with a wireless sensor and control network using Sensorweb software (Mayim LLC, Pittsburgh, PA, USA), with the computer and communication devices installed in the main building of the HTRC. Solenoid valves were controlled via DC powered control nodes (model NC24, Decagon Devices, Inc., Pullman, WA, USA), with each node controlling 4 beds. Nodes were installed on the western raised beds, and oriented towards the communication devices in the HTRC building. Substrate volumetric moisture content (θ) was monitored using moisture sensors connected to monitoring nodes (model 10HS and model EM50R, respectively, Decagon Devices, Inc., Pullman, WA, USA), where each bed had one monitoring node and four moisture sensors set to take measurements at 5 minute intervals. Sensors were randomly assigned to one plant per taxa per bed and inserted horizontally at an incision made halfway between the top and bottom of the container.

3.3.3 Irrigation Treatments

An overhead control was compared to two microirrigation treatments. The overhead control applied 19 mm daily, a common operational practice, within the 6.1 x 6.1 meter production area within each bed in a single application beginning at 8:00 A.M. and ending at 9:30 A.M. The two spray stake treatments were operated under a static, daily application rate and a dynamic application rate based on sensor monitored soil volumetric water content (θ), respectively. The static spray stake treatment applied 2L per container from 9:30 A.M. to 9:40

A.M. daily (SS2Lpd), based on daily application rates of 1.4-1.9 L per #3 container reported by nursery producers in a survey (Garber et al., 2002). The sensor based treatment (SSθ) applied water based on θ with the activation threshold set at 35%, or 6% below the average container capacity measured in containers during project setup (41.1% +/- 0.6). The SSθ treatment applied irrigation was based on the average θ of the four randomly assigned sensors in each bed. Between 9:45 A.M. and 10:15 A.M., up to three 0.8 L cycles (0-2.4 L per day) per container were applied as needed to bring containers back to container capacity. Each 4 minute cycle of irrigation was followed by a 6 minute intermission to allow water distribution within the substrate and θ readings to reoccur between cycles. Irrigation treatments were randomly assigned to each bed, with three beds serving as the control, six beds being used for the SS2Lpd, and six beds for the SSθ treatment. One bed was left to serve as a blank, where 19 mm d^{-1} of overhead irrigation was applied to a bed without plants.

3.3.4 Plant Material and Substrate

Each raised bed section (replicate) had a total of 81 plants, split between four taxa, and produced in 11.3 L containers (Nursery Supplies, Inc. model C1200, Chambersburg, PA). Taxa used were *Cornus obliqua* 'Powell Gardens', *Hydrangea paniculata* 'Limelight', *Physocarpus opulifolius* 'Seward', and *Weigela florida* 'Elvera' (Spring Meadow Nursery, Grand Haven, MI, USA). Plants were grouped by species, and the order in which they were placed on the beds was randomly assigned. All containers were spaced 0.3 meters from container edge to edge. A composted pine bark:peat moss (85:15 v/v) substrate was used (Renewed Earth, Otsego, MI, USA). Fertilizer was applied the preceding fall on 27 September 2016. Each bed for either the SS2Lpd or SSθ was randomly assigned one of two controlled release fertilizers with micronutrients, (5 months release at 26.7°C or 6 months release at 21.1°C, Polyon® Reactive

Layers Coating, Harrell's Inc., Lakeland, FL, USA), receiving either 38 g per container of a 19-2.16-6.64 or a 19-1.62-6.64 of % nitrogen, % phosphorus, and % potassium. The three control irrigated beds all received 19-2.16-6.64 fertilizer, while three of the six beds for both the daily and sensor based spray stake treatments received either the 19-2.16-6.64 or the 19-1.62-6.64 fertilizer. Fertilizer was uniformly applied to each of the 81 containers per bed via topdressing, for a per bed application rate of 3,078 g. The control irrigated beds (n=3) received only conventional P fertilizer, while three of the six beds for both the daily and sensor based spray stake treatments received either the conventional P (Conv) or the low P fertilizer (LowP), thus irrigation x fertilizer treatments would respectively be SS2LpdConv (n=3), SS2LpdLowP (n=3), SSθConv (n=3), and SSθLowP (n=3).

3.3.5 Pesticide Application and Sampling

A total of 10 pesticides were applied over the course of three monitoring periods with herbicides applied separately while the insecticides and fungicides were applied as a tank mix (Table 3.1). Pesticides were selected based on their physiochemical properties and common use in nursery production, and were organized based on McCall's Koc class and FAO mobility classifications into three groups (Table 3.2). Pesticides were applied at ornamental crop label rate with a wagon mounted sprayer connected by hose to a four nozzle boom, measuring 1.52 meters across with a 1.83 meter spray width. The boom width allowed the 6.1 x 6.1 meter area to be divided into thirds, with passes made starting at the low point and moving uphill (West to East for the western block of raised beds, vice verse for the eastern block). Herbicide applications required one pass over each third in order to achieve desired application rates, while the tank mix required two passes. The herbicides isoxaben, oxyfluorfen, and prodiamine were applied first in each of their respective monitoring periods using nozzles with an 80° angle and 0.76 L min^{-1}

application rate per nozzle (Teejet model 8002, Wheaton, IL, USA) on the spray boom, followed by overhead irrigation for watering-in per label recommendations, with the control treatment beds receiving their daily 19 mm while the spray stake treatments received the recommended 12.6 mm following isoxaben and prodiamine application, and 6.33 mm after oxyfluorfen. Following herbicide application and watering-in, the insecticide/fungicide tank mix was applied using an 80° angle and 2.27 L min^{-1} application rate per nozzle (Teejet model 8006). Nozzles were tested prior to each spray event to ensure uniformity in spray output, and applicator walking speed was calibrated to provide desired application rates (Teejet 8002 average flow per nozzle 1,110 mL min^{-1}; Teejet 8006 average flow per nozzle 2,165 mL min^{-1}; applicator walking speed 3.93 km hr^{-1}). The first application of pesticides was 27 June 2017, with 69 g of isoxaben (Gallery 75DF, Corteva Agriscience, Wilmington, DE, USA) mixed in 15.1 L of water, followed by 39.8 g of acephate (Acephate 97UP, United Phosphorus Inc., King of Prussia, PA, USA), 9.1 mL of bifenthrin (Talstar P, FMC Corp., Philadelphia, PA, USA), and 1.2 mL of mefenoxam (Mefenoxam 2AQ, Makhteshim Agan of North America, Inc., Raleigh, NC, USA) applied simultaneously as a tank mix in 68.1 L of water. The second application of pesticides was 7 August 2017, with 48 mL of the herbicide oxyfluorfen (Goaltender, Corteva Agriscience) mixed in 15.1 L water, followed by the requisite watering in before a tank mix comprised of 77 mL of chlorpyrifos (Lorsban 4E, Corteva Agriscience), and 18 mL of triflumizole (Terraguard SC, McDermid Agricultural Solutions, Inc. Waterbury, CT, USA) were mixed with 68.1 L of water. Following the tank mix, glyphosate (Roundup PowerMax, Bayer AG, Monheim am Rhein, Germany) at a concentration of 5 mL L^{-1} was applied via a backpack sprayer in equivalent volume (750 mL per bed) to the inter-container spaces for each bed. The third and final pesticide application occurred on 28 August, 2017. The herbicide prodiamine (Barricade 65WG,

Syngenta, Greensboro, NC, USA) at 135 g in 15.1 L of water. After the watering-in event, the fungicide thiophanate-methyl (Thiophanate Methyl 85 WDG, Makhteshim Agan of North America) was applied at 35 g in 68.1 L of water, after which glyphosate was applied in the same manner as in the second application.

Collection tanks were emptied 24 hours prior to collection times to allow the accumulation of subsurface return flow over a full day. The height of the water in the collection tanks was measured using a meter stick, and converted to liters based on tank dimensions in order to quantify the amount of surface and subsurface return flow per bed. A sample of 750 mL from each tank was collected, provided there was adequate surface or subsurface return flow water, for pesticide concentration analysis. A submersible pump with a hose attachment was inserted into the tank, and allowed to run for 10 seconds prior to sample collection in a glass amber bottle (Qorpak, Clinton, PA, USA). Each sample was spiked with 75 µL of acetic acid to acidify the sample and prevent pesticide disassociation prior to storage in a -4 degree C freezer.

3.3.6 Pesticide Analysis

Samples were analyzed at the Organic Contaminants Analytical Research Laboratory in the Soil and Water Sciences Department, University of Florida, Gainesville, FL, USA using the sample preparation, extraction technique, and instrument conditions described by Hinz et al. (2019) and Leiva et al. (2019). Due to matrix effects determined in preliminary work for this study, non-treated control water from surface and subsurface IRF were provided to prepare corresponding matrix matched calibration standards and quality assurance/quality control (QA/QC) samples.

3.3.6.1 Direct Injection Procedure

PESTANAL grade standards of acephate (P/N: 45315-250MG) and AMPA (P/N: 324817-250MG) were from Sigma-Aldrich (St. Louis, MO, USA). The glyphosate (P/N: N-12133-250MG) standard was from ChemService (West Chester, PA, USA). ^{13}C-AMPA (P/N: CDNLM-6786-1.2) and ^{13}C-glyphosate (P/N: CNLM-4666-1.2) were from Cambridge Isotope Laboratories, Inc. (Tewksbury, MA, USA). Calibration standards ranging from 5-1000 µg L^{-1} were prepared by serial dilution. The non-matrix matched calibration standards for each pesticide was prepared in Optima Grade water (Fisher Scientific, Waltham, MA, USA). Matrix matched calibration standards were prepared in surface and subsurface IRF sites and non-treated control water in the same manner. One mL aliquots of each experimental sample were transferred into 2 mL amber gas chromatography (GC) vials (Fisher Scientific) for direct injection analysis. Pesticide concentrations were quantified using an external calibration method for acephate and an internal calibration method for AMPA and glyphosate. Calibration standards were analyzed prior to sample analysis and again after every batch of twenty samples. Passing criteria for the calibrations was a linear slope with a $R^2 \geq 0.9900$. Any sample batches not bracketed with passing calibrations were reanalyzed after performing corrective actions.

QA/QC samples were analyzed along with experimental samples. Method blanks (reagent-grade water) were analyzed to verify that methods utilized did not cross contaminate samples. Spiked QA/QC samples consisting of reagent-grade water spiked with 100 µL of a 1 mg L^{-1} solution containing each pesticide dissolved in the respective site control water were also analyzed for method validation. Passing criteria was 80-120% recovery of the added pesticide. One randomly selected sample per twenty samples collected during the experiment was used for matrix spikes (MS) and duplicate matrix spikes (MSD). Samples selected for MS/MSD analysis

were divided into three 1 mL aliquots, with two aliquots receiving 100 µL of a 1 mg L^{-1} solution of each pesticide. Each sample was vortexed then analyzed by LCMS using the respective method. Passing criteria was 80-120% recovery of the added pesticides in spiked samples and ≤10% difference in concentrations between the duplicates. The minimum method quantitation limits for all chemicals of interest was 5 µg L^{-1}.

3.3.6.2 Extraction Procedure

PESTENAL standards of bifenthrin (P/N: 34314-100MG), chlorpyrifos (P/N: 45395-100MG), isoxaben (P/N: 36138-100MG), metalaxyl-m (P/N: 32808-100MG), oxyflurofen (P/N: 35031-100MG), thiophanate-methyl (P/N: 45688-250MG), and triflumizole (P/N: 32611-100MG), were purchased from Sigma-Aldrich (St. Louis, MO). The prodiamine (P/N: N-13096-100MG) standard (99.5% purity) was purchased from ChemService.

All samples were extracted according to a modified version of US EPA Method 3510C (1996). Briefly, 500 mL of sample water were added to a 1000 mL teflon separatory funnel and extracted with 30 mL methylene chloride. The procedure was repeated two additional times using a total of 90 mL of methylene chloride. The methylene chloride extracts were combined after each extraction, placed in a water bath at 35°C, and concentrated to a final volume of 0.5 mL using a gentle flow of nitrogen gas. A solvent exchange with methanol was performed by adding approximately 1-2 mL of methanol to the concentrated extract, re-concentrating it to 0.5 mL, then repeating this step an additional two times or until all methylene chloride was evaporated. The final 1 mL extracts were transferred into individual 2 mL amber glass vials for analysis on the respective instrument. Matrix matched calibration standards were prepared by adding known amounts of pesticide solution then extracting 500 mL aliquots of each non-treated control water as previously described. Target pesticide concentrations in the final 1 mL

calibration extracts were 25, 100, 500, and 750 µg L^{-1}. Respective samples were quantitated under the paired matrix matched calibration series.

3.3.6.3 LCMS Analysis

Acephate, isoxaben, metalaxyl-m, triflumizole, and thiophante-methyl were analyzed by high pressure liquid chromatography-mass spectrometry (HPLC-MS). Pesticide concentrations were quantified using a Waters Alliance 2695 HPLC (Waters Corp., Milford, MA, USA) equipped with a C_{18} reversed phase LC column (Phenomenex Synergi Hydro-RP; 80 Å, 50 x 2 mm, 4 µm; P/N 00B-4375-B0) with a C_{18} guard column (Waters Nova-Pak; 4 µm; P/N: WAT044380), coupled to a Micromass Quattro Ultima MS (Micromass UK Limited, Wythenshawe, England). Fifty µL of each sample were injected onto the LC column and pesticides were separated and concentrated using a gradient mobile phase consisting of solution A (Optima LC-MS water with 0.1% Optima formic acid, 0.9% 1M ammonium formate (NH_4COOH), and 5% Optima methanol) and solution B (Optima methanol with 0.1% Optima formic acid, 0.9% 1 M NH_4COOH, and 9% Optima water). The gradient started with a 60:40 (A:B) ratio from 0 to 6 min., changing linearly to 5:95 (A:B) from 6 to 8 min. where it was held from 8 to 15 min., and then returned to initial conditions at 15 min. (total run time of 15 min.). The flow rate was constant at 0.50 mL min^{-1} and the column was held at ambient temperature (~22 °C). All chemicals for the mobile phases A and B were purchased from Thermo Fisher Scientific. The MS/MS was operated in heated electrospray ionization (ESI) positive mode with a capillary voltage of 2.96 kV. Source and desolvation temperatures were 150 °C and 350 °C, respectively. Cone and desolvation gas flow rates were 50 and 500 L hr^{-1}, respectively, with nitrogen used as the carrier gas. The data were acquired in multiple-reaction monitoring (MRM) mode. Conditions used to perform m/z transitions are summarized in Table 3.3.

AMPA and glyphosate were also analyzed by HPLC-MS. Pesticide concentrations were quantified using a Waters Alliance 2695 HPLC equipped with an anion exchange LC column (Supelcosil LC-SAX1; 25 cm x 4.6 mm, 5 µm; P/N: 59138; Supelco, Bellefonte, PA, USA) with a guard column (Supelguard SAX1; 2 cm x 4 mm; 5 µm; P/N: 59536-U), coupled to a Micromass Quattro Ultima MS (Micromass UK Limited). One hundred µL of each sample were injected onto the LC column and pesticides were separated and concentrated using a gradient mobile phase consisting of solution A (Optima LC-MS water with1 mM ammonium acetate ($C_2H_7NO_2$) at pH 9) and solution B (acetonitrile at pH 7). The gradient started with a 60:40 (A:B) ratio from 0 to 0.25 min., changing linearly to 80:20 (A:B) from 0.25 to 9.50 min., then changed to 100% solution A at 9.50 and held to 15 min. The flow rate was constant at 0.50 mL min^{-1} and the column was held at ambient temperature (~22 °C). All chemicals for the mobile phases A and B were purchased from Thermo Fisher Scientific. The MS/MS was operated in heated ESI- mode with a capillary voltage of 2.8 kV. Source and desolvation temperatures were 120 °C and 200 °C, respectively. Cone and desolvation gas flow rates were 50 and 500 L hr^{-1}, respectively, with nitrogen used as the carrier gas. The data were acquired in multiple-reaction monitoring (MRM) mode. Conditions used to perform m/z transitions are summarized in Table 3.

3.3.6.4 GC-MS Analysis

For samples collected, bifenthrin, chlorpyrifos, oxyfluorfen, and prodiamine were analyzed using an Agilent 7890B gas chromatograph (GC) coupled to an Agilent 7010A triple quadruple mass spectrometer (MS) with an electron ionization (EI) high efficiency source (HES; Santa Clara, CA, USA). The GC was equipped with two 15 m HP-5MS-UI (0.25 mm id x 0.25 µn film; P/N: 19091S-431UI; Agilent Technologies) columns joined by a pressure-controlled-tee

to provide backflushing capabilities. Extracts (1 µL) were injected in splitless mode into the inlet equipped with a Siltek gooseneck splitless liner with deactivated glass wool (Restek Corp., Bellefonte, PA, USA; 4 mm x 6.5 mm x 78.5; P/N 22406-213.5) set at 280°C. The oven temperature program began at an initial 70°C (held for 1.5 min.), then ramped to 200°C at 10°C min^{-1}, followed by an increase to 320°C at 7°C min^{-1} (held for 3 min.), for a total run time of 34.64 min with a post run parameters at 310°C for 2.04 min for backflushing. The solvent delay was set to 3.0 min and the EI-HES temperature was set to 280°C. Relative retention times and the ratio of precursor and product ions for each pesticide were used for identification and quantitation using multiple reaction monitoring (MRM) mode (Table 4). QA/QC samples were extracted and analyzed along with experimental samples. Method blanks using reagent-grade water were extracted and analyzed to verify that the extraction/analysis methods did not cross contaminate samples. Spiked QA/QC samples consisting of reagent-grade water spiked with 100 µL of a 1 mg L^{-1} solution of bifenthrin, chlorpyrifos, oxyfluorfen, and prodiamine in methanol were also extracted and analyzed for method validation. Passing criteria was 80-120% recovery. One randomly selected sample per twenty samples was used for matrix spikes and matrix spike duplicates. These samples were randomly selected and divided into three 500 mL aliquots, with two aliquots receiving 100 µL of a 1 mg L^{-1} solution of target pesticides in methanol. Each sample was extracted and analyzed as previously described. Passing criteria were 80-120% recovery of the added pesticides in spiked samples and ≤10% concentration differences between duplicate samples. The minimum method quantitation limit for each pesticide was 0.125 µg L^{-1} at sample level.

3.3.7 Experimental Design and Statistical Analysis

A completely randomized design was used for this study, with irrigation treatment, fertilizer treatment, and plant order for individual beds randomly assigned. Data was analyzed using SAS v 9.4 (Cary, NC, USA). The volume of irrigation applied was evaluated using analysis of variance with the PROC GLM procedure, when treatment effects were significant ($P<0.05$) means were separated using Tukey tests in the LSMEANS prompt. Assessment of average surface and subsurface return flow volumes throughout the season used only sample days in which less than 0.5 cm of precipitation occurred. The volumes of water transported via surface and subsurface return flow, pesticide concentration, and pesticide load were subject to analysis of variance using the PROC Mixed procedure with repeated measures. When treatment effects were significant ($P<0.05$) means were separated using Tukey tests in the LSMEANS prompt. Variable means and standard errors for irrigation applied, volume of water transported via surface and subsurface return flow, pesticide concentration, and pesticide load were calculated using the PROC MEANS feature. Regression models, when significant ($P<0.05$), were used to estimate pesticide load as a function of time over the entire 16 day period, using the PROC GLM procedure. Analysis of variance by date for surface and subsurface IRF showed no fertilizer by irrigation interaction, main effect due to fertilizer for 1 out of 28 tables but main effect due to irrigation for 17 out of 28 tables, therefore, only irrigation main effects are presented. Similarly, analysis of variance by date for pesticide load in IRF showed a fertilizer by irrigation interaction for only 2 out of 95 tables, main effect due to fertilizer for only 4 out of 95 tables but main effect due to irrigation for 50 out of 95 tables, therefore, only irrigation main effects are presented.

3.4 Results

3.4.1 Irrigation and Irrigation Return Flow

3.4.1.1. Monitoring Period 1

A total of 3,238 kL ha^{-1} of water was applied from the watering-in of the herbicides and day 16 of the monitoring period to the control, which was greater than that applied to either spray stake treatment (Table 3.5). Irrigation was applied on all 17 dates during the first monitoring period for the control and SS2Lpd, compared to 11.5 days of irrigation on average for the SSθ treatment. Across all 5 sample dates, with the exception of day 16, a greater volume of surface return flow was generated by the control than either treatment (Figure 3.3). The control generated more subsurface return flow than SSθ on day 1 and day 4; however, there were no other differences between treatments or the control on any other sample date (Figure 3.3).

3.4.1.2. Monitoring Period 2

A total of 3,238 kl ha^{-1} were applied between the watering-in of the herbicides and day 16 of the monitoring period in the control, which was greater than the 763 kl ha^{-1} for SS2Lpd (Table 3.5). The 641 total kl ha^{-1} applied in the SSθ was equivalent to SS2Lpd, and also lower than the control. Both the control and SS2Lpd applied irrigation 17 times during the second monitoring period, which was greater than the 12.6 average days irrigated for SSθ.

Across all 5 sample dates, a greater volume of surface return flow was generated by the control than either treatment (Figure 3.4). The control generated a greater volume of subsurface return flow than the SSθ treatment on day 1 and 2; however, all subsequent days exhibited no differences between the control and treatments (Figure 3.4).

3.4.1.3. Monitoring period 3

A total of 3,238 kl ha^{-1} were applied between the watering-in of the herbicides and day 16 of the monitoring period in the control, which was greater than the 827 kl ha^{-1} for SS2Lpd (Table 3.5). The 935 total kl ha^{-1} applied in the SSθ was equivalent to SS2Lpd, and also lower than the control. There were no differences in the number of days irrigation was applied, where for both the control and SS2Lpd it was 17 days, and the SSθ was 15 days. The control generated more surface return flow than either treatment on day 1, 2, 4, and 16; however, there were no differences on day 11 (Figure 3.5). The control generated more subsurface return flow than the SSθ on day 1, 2, and 4, and SS2Lpd on day 4 but no differences on day 16 (Figure 3.5).

3.4.2 Pesticide Dynamics

3.4.2.1. Acephate

Acephate load recovered in surface return flow samples was greater in the control than either treatment on day 4 and 8; whereas there were no differences on day 16 (Figure 3.3). Comparisons for day 1 were unable to be made due to control sample replicate damage. The control exhibited a quadratic decrease in surface return flow acephate load when the x axis was log transformed (Table 3.6). Since both SS treatments substantially reduced, and oftentimes eliminated surface return flow, there was no significant model for surface return flow acephate movement in either treatment. Over the four sample dates, the control exported 77.7 g of acephate per hectare in surface return flow, while the SS2Lpd and SSθ treatments totaled 6.56 g and 3.4 g ha^{-1} (Table 3.7). This corresponded to 14% of the 553 g of acephate applied per hectare for the control, 1.2% for SS2Lpd, and 0.6% for SSθ. Acephate concentrations in surface return flow were generally equivalent, with the exception of day 4, where the control was greater than SSθ but no different from SS2Lpd (Table 3.8).

The load and concentration of acephate recovered in subsurface return flow samples was equivalent across all four sample dates (Figure 3.3; Table 3.8). Both spray stake treatments exhibited a linear increase in acephate load exported over time when the x axis was log transformed; however, there was no relationship identified in the control. Total subsurface acephate load recovered over the 4 sample dates was 94.9 g from the control, 89.4 g from SS2LPD, and 34.8 g from SSθ; respectively corresponding to 17.2%, 16.1%, and 6.2% of applied acephate.

Combining surface and subsurface acephate load across the 4 sample dates, a total of 173 g, 96 g, and 38.2 g were recovered from the control, SS2Lpd, and SSθ, respectively, corresponding to 31.2%, 17.4%, and 6.9% of applied acephate.

3.4.2.2. Bifenthrin

Bifenthrin load recovered in surface return flow samples was greater in the control than either treatment on day 4, and 8; however, was equivalent on day 16 (Figure 3.3). Comparisons for day 1 were unable to be made due to control sample replicate damage. The control exhibited a quadratic decrease in bifenthrin load when both axes were log transformed; where no relationships were found for either spray stake treatments, considering surface return flow was substantially reduced or eliminated (Table 3.6). Over the four sample dates, a total of 454 g of bifenthrin was recovered in surface return flow from the control, while SS2Lpd and SSθ totaled 35.4 g and 17.9 g; corresponding to 0.3% of applied bifenthrin for the control, and less than 0.1% for either treatment (Table 3.7). Surface return flow samples collected from the control on day 1 had the highest concentration at 6.69 µg L^{-1}; whereas, all subsequent sample dates never exceeded 0.6 µg L^{-1} (Table 3.8). There were no differences in surface return flow concentrations

between the control and treatments on day 1, 4, and 16; however, on day 8 the control was greater than both treatments.

Bifenthrin load recovered in subsurface return flow was greater in the control than SSθ on day 1 and 4 (Figure 3.3); however, there were no differences between the control or treatments on any day thereafter. Concentrations of bifenthrin in subsurface return flow were universally below 0.2 µg L^{-1}, and often times below the limit of detection (Table 3.8). A total of 29 g, 23.6 g, and 15.9 g were recovered in subsurface return flow over the four sample dates from the control, SS2Lpd, and SSθ; corresponding to less than 0.1% of applied bifenthrin for both control and treatments.

Combining surface and subsurface bifenthrin load across the 4 sample dates, a total of 484 g, 59.1 g, and 33.9 g were recovered from the control, SS2Lpd, and SSθ; corresponding to 0.4% of applied bifenthrin for the control, and less than 0.1% for either treatment.

3.4.2.3. Isoxaben

Isoxaben load recovered in surface return flow samples was greater in the control than SSθ on day 0, following the watering in event, as well as day 4, and 8 (Figure 3.3). While SS2Lpd was equivalent to both the control and SSθ following the watering in sample collected on day 0, it was less than the control on day 4 and 8. There were no differences between the control or treatments on day 16. A quadratic equation modeling surface return flow isoxaben load in the control from day 1 through 16 was identified when the x axis was log transformed (Table 3.6). As surface return flow was often eliminated, no models were significant for either treatment. Over the 5 sample dates, a total of 69.5 g, 5.95 g, and 0.53 g were recovered in the control, SS2Lpd, and SSθ; corresponding to 8%, 0.7%, and less than 0.1% of applied isoxaben (Table 3.7). Concentrations were equivalent in surface return flow from the watering-in event;

however, the control had a higher concentration than the SSθ on day 4, and 8, and the SS2Lpd only on day 8 (Table 3.8).

Isoxaben load recovered in subsurface return flow samples was greater in the control than either treatment on day 1, 4 and 8; however, there were no differences on day 16 (Figure 3.3). The control exhibited a linear decrease in isoxaben load over time when the x axis was transformed, while neither spray stake treatment had a significant model. The total isoxaben load recovered across the 4 sample dates was 37.4 g, 6.86 g, and 0.87 g for the control, SS2Lpd, and SSθ; respectively, corresponding to 4.3%, 0.8%, and 0.2% of applied isoxaben. Concentration of isoxaben in subsurface IRF was greater in the control than either treatment on day 1, 4, and 8, but no different on day 16 (Table 3.8).

Combining surface and subsurface isoxaben load across the 5 sample dates, a total of 107 g, 12.8 g, and 2.1 g were recovered from the control, SS2Lpd, and SSθ; corresponding to 12.3% of applied isoxaben for the control, 1.5% for SS2Lpd, less than 0.2% for SSθ.

3.4.2.4. Mefenoxam

Mefenoxam load recovered in surface return flow was greater in the control than either treatment on day 4 and 8, but was equivalent on day 16 (Figure 3.3). Comparisons for day 1 were unable to be made due to control sample replicate damage. The control exhibited a quadratic decrease in surface load exported over time when log transforming both axes (Table 3.6). There was no significant model for either spray stake treatment, as they reduced and often eliminated surface return flow. A total of 2,942 mg was recovered from the control over the four sample dates, compared to 68.7 mg for SS2Lpd and 46.1 mg for SSθ; corresponding to 16.1%, 0.4%, and 0.3% of applied mefenoxam, respectively (Table 3.7). Surface concentrations were greater in the control than both treatments on day 4, but equivalent on day 1, 8, and 16 (Table 3.8).

Mefenoxam load recovered in subsurface return flow was equivalent for all four sample dates except for day 4, where the control exported more mefenoxam than SSθ, while SS2Lpd was equivalent to both (Figure 3.3). There was no relationship between the mefenoxam load exported in subsurface return flow over time for the control; however, both treatments exhibited a linear increase when both axes were log transformed. The total mefenoxam load recovered in subsurface return flow was 979 mg, 429 mg, and 166 mg for the control, SS2Lpd, and SSθ, respectively; corresponding to 5.4%, 2.4%, and 0.1% of applied mefenoxam. Concentrations were equivalent between control and treatments on all days except for day 4, where the control was higher than SSθ but SS2Lpd was no different from either (Table 3.8).

Combining surface and subsurface mefenoxam load across the 4 sample dates, a total of 3,921 mg, 498 mg, and 213 mg were recovered from the control, SS2Lpd, and SSθ; corresponding to 21.5% of applied mefenoxam for the control, 2.7% for SS2Lpd, 1.2% for SSθ.

3.4.2.5. Chlorpyrifos

Chlorpyrifos load recovered in surface return flow was greater in the control than either treatment on 5 sample dates (Figure 3.4). A linear decrease in chlorpyrifos load over time in surface return flow was exhibited for the control when log transforming both axes (Table 3.6). The total chlorpyrifos load recovered over the 5 sample dates was 14461 mg for the control, 237 mg for SS2Lpd, and 1 mg for the SSθ; corresponding to 1.3% of applied chlorpyrifos for the control, and less than 0.01% for either treatment (Table 3.7). Concentrations of chlorpyrifos in surface return flow was greater in the control than the SSθ treatment on all sample dates except day 4, and greater than SS2Lpd on day 1, 2, and 16 (Table 3.8).

Chlorpyrifos load recovered in subsurface return flow was greater in the control than both treatments on day 1 and day 4; however, there were no differences on any other sample date

(Figure 3.4). There were no relationships between chlorpyrifos load export in subsurface return flow over time identified for the control or either treatment. Total chlorpyrifos load recovered over the 5 sample days was 413 mg, 41.1 mg, 44.7 mg for the control, SS2Lpd and SSθ respectively, all corresponding to less than 0.1% of applied chlorpyrifos. Concentrations of chlorpyrifos in subsurface return flow were greater in the control on day 2 and 4 relative to all other treatments; however, on all other days there were no differences (Table 3.8). Combining surface and subsurface return flow over all 5 sample dates, 14,875 mg, 278 mg, and 45.7 mg of chlorpyrifos were recovered from the control, SS2Lpd, and SSθ, respectively, corresponding to 1.3%, and less than 0.01% for either treatment.

3.4.2.6. Triflumizole

Triflumizole load recovered in surface return flow was greater in the control than the SSθ on all 5 sample dates; while it was also greater than the SS2Lpd on day 1, 2, and 16 (Figure 3.4). Export of triflumizole in surface return flow from the control exhibited a linear decrease when both axes were log transformed; whereas, no models for either spray stake treatment were significant considering they typically reduced or eliminated surface return flow (Table 3.6). The total triflumizole load recovered in surface return flow load was 3,747 mg in the control, 135.1 mg in SS2Lpd, and 0.43 mg in SSθ; corresponding to 1.3% of applied triflumizole, and less than 0.01% for both treatments (Table 3.7). Triflumizole concentrations were greater in the control than both treatments on day 1, 2, and 16, but no different on day 4 and 8 (Table 3.8).

Triflumizole load recovered in subsurface return flow was greater in the control versus both treatments on day 1, 2, and 4; however, there were no differences on day 8 and 16 (Figure 3.4). A quadratic increase then decrease was observed in triflumizole subsurface movement in the control when log transforming both axes, while no relationships were identified for either

treatment. A total of 861 mg were recovered over the 5 sample dates for the control, versus 28.2 mg and 51 mg for SS2Lpd and SSθ; corresponding to 0.3% of total applied triflumizole for the control, and less than 0.01% for either treatment. Subsurface concentrations were greatest in the control on days 1, 2, and 4; however, there were no differences on day 8 and 16 (Table 3.8).

Combining surface and subsurface return flow, triflumizole recovered over the 5 sample dates, a total of 4,608 mg, 163 mg, and 51.4 mg were recovered in the control, SS2Lpd, and SSθ, respectively; corresponding to 1.6 % of total triflumizole applied and less than 0.01% for both treatments.

3.4.2.7. Oxyfluorfen

Oxyfluorfen load recovered in surface return flow was greater in the control than either treatment on all 5 sample dates (Figure 3.4). Oxyfluorfen load exported in surface return flow from the control exhibited a linear decrease when both axes were log transformed (Table 3.6). The total oxyfluorfen load recovered in surface return flow across the five sample dates was 4,706 mg in the control, 273 mg for SS2Lpd, and 78.2 mg for SSθ; corresponding to 0.4% of applied oxyfluorfen for the control, and less than 0.1% for either treatment (Table 3.7). Oxyfluorfen concentrations in surface return flow samples collected following the watering-in event on day 0 were equivalent between the control and both treatments, as was samples taken on day 4 (Table 3.8). The control had a greater concentration than both spray stake treatments on day 1, 2 and 16, but was no different from SS2Lpd on day 8.

Oxyfluorfen load recovered in subsurface return flow was equivalent across all 5 sample dates (Figure 3.4). Neither the control nor treatments exhibited a relationship between time and oxyfluorfen load exported in subsurface return flow. The total oxyfluorfen load recovered in subsurface return flow across the five sample dates was 78.1 mg for the control, 37.2 for

SS2Lpd, and 17.2 for SSθ, respectively, corresponding to less than 0.001% of applied oxyfluorfen. Concentrations in subsurface return flow were universally below 1 µg L^{-1}, and were equivalent across all dates (Table 3.8).

Combining surface and subsurface return flow, the total oxyfluorfen load recovered over the 5 sample dates was 4,784 mg from the control, 310 mg for SS2Lpd, and 95 mg from SSθ, respectively, corresponding to 0.4% of applied oxyfluorfen 0.03% for SS2lpd, and less than 0.001% for SSθ.

3.4.2.8. Prodiamine

Prodiamine load recovered in surface return flow was greater than both treatments on all days except day 11 (Figure 3.5). There was no relationship between the load exported over time identified for the control or either treatment. The total load recovered over the 5 surface return flow sample dates was 3,996 mg for the control, 1,254 mg for SS2Lpd, and 61.4 mg for SSθ; corresponding to 0.2% of applied Prodiamine for the control, and less than 0.1% for either spray stake treatment (Table 3.7). Surface return flow concentrations were greater in the control than either treatment on day 2, 4, and 16; however, they were equivalent on day 11 (Table 3.8).

Prodiamine load recovered in subsurface return flow was greater in the control on day 2, 4, and 16 than either spray stake treatment (Figure 3.5). Comparisons were unable to be made for day 1. Samples were not collected from subsurface return flow on day 11. There were no relationships identified in subsurface prodiamine movement over time. The total load collected for the control on days 2, 4, and 16 was 144 mg for the control, 10 mg for SS2Lpd, and 4 mg for SSθ, universally corresponding to less than 0.001%. Subsurface Prodiamine concentrations were greater in the control than SSθ on day 2, 4, 11, and 16, and also greater than the SS2lpd on day 4, 11, and 16 (Table 3.8).

Combining surface and subsurface return flow total loads, 4,110 mg of Prodiamine was recovered from the control, 1,264 mg from SS2Lpd, and 65.5 mg from SSθ, respectively, corresponding to 0.2%, less than 0.1%, and less than 0.001% of applied Prodiamine.

3.4.2.9. Thiophanate-Methyl

The TPM load recovered in surface return flow across the 5 sample dates was greater in the control than both spray stake treatments on all days, with the exception of day 11 (Figure 3.5). A quadratic relationship was identified in TPM load in surface return flow over time from the control, whereas no relationship was identified for either treatment (Table 3.6). Total TPM load exported in surface return flow across all 5 sample dates was 32.4 g in the control, 0.05 g for SS2Lpd, and 0.02 g for SSθ; corresponding to 6.7% of applied TPM for the control, and less than 0.001% for either spray stake treatment (Table 3.7). The concentration of TPM in surface IRF was greater in the control than either treatment on day 1, 2, and 16; however, was equivalent on day 11 (Table 3.8).

TPM load recovered in subsurface return flow was greater in the control on day 2 versus both treatments, and on day 4 versus SSθ (Figure 3.5). There were no differences on day 16. Comparisons were unable to be made for day 1. Load samples were not collected from subsurface return flow on day 11. There were no relationships identified in subsurface TPM movement over time for either treatment; however, the control exhibited a quadratic decrease then increase in the control when both axes were log transformed. The total load collected for the control on days 2, 4, and 16 was 1.11 g for the control, 0.006 g for SS2Lpd, and 0.002 g for SSθ, corresponding to 0.2% of applied TPM for the control, and less than 0.01% for either treatment. TPM concentration in subsurface return flow from the control were greater on day 2 than all

other treatments, and on day 4 versus SSθ; however, it was equivalent on all other dates (Table 3.8).

Combining total surface and subsurface return flow collected over the monitoring period, 33.5 g, 0.05 g, and 0.02 g were collected from the control, SS2Lpd, and SSθ; corresponding to 6.9%, 0.01%, and less than 0.01% of applied TPM, respectively.

3.4.2.10. Glyphosate Monitoring Period 2

Glyphosate load recovered in surface return flow during the second monitoring period was equivalent on all sample dates, with the exception of day 16, where it was greater in the control than both treatments (Figure 3.4). Glyphosate export in surface return flow over time from the control exhibited an increasing then decreasing quadratic relationship when both axes were log transformed (Table 3.6). No relationships were identified for either treatment. The total glyphosate load recovered over the 5 sample dates was 80.2 g, 1.42 g, and 1.39 g for the control, SS2Lpd, and SSθ treatment, respectively, which corresponded to 3.9% of applied glyphosate for the control, and less than 0.1% for either spray stake treatment (Table 3.7). With the exception of day 16, where the control had a higher surface return flow glyphosate concentration than either treatment, there were no differences in glyphosate concentration on any other sample date (Table 3.8).

Glyphosate load recovered in subsurface return flow during the second monitoring period was equivalent on all sample dates (Figure 3.4). No relationship between glyphosate load exported in subsurface return flow over time was identified for the control or either treatment. The total glyphosate load recovered in subsurface return flow samples was 1.76 g, 4.38 g, and 3.78 g for the control, SS2Lpd, and SSθ, respectively, corresponding to less than 0.1%, 0.2%,

and 0.2% of applied glyphosate. There were no differences in subsurface return flow glyphosate concentration on any sample date (Table 3.8).

Combining surface and subsurface return flow total loads over the sample period, 81.9 g, 5.8g, and 5.2 g were recovered from the control, SS2Lpd, and SSθ, respectively, corresponding to 4%, 0.3%, and 0.2% of the applied glyphosate.

3.4.2.11. Glyphosate Monitoring Period 3

Glyphosate load exported in surface return flow was greater in the control than any treatment on day 1, 2, 4, and 16, but was equivalent on day 11 (Figure 3.5). The control exhibited a quadratic decrease in glyphosate load exported over time, when both axes were log transformed; however, there was no relationship identified for either treatment (Table 3.6). The total glyphosate load recovered over the 5 sample dates was 104 g, 11g, and 0.58 g for the control, SS2Lpd, and SSθ; corresponding to 5%, 0.5%, and less than 0.1% of applied glyphosate, respectively (Table 3.7). Glyphosate concentration was greater in surface return flow samples collected from the control on day 1, 2, 4, and 16 versus all treatments; however, there were no differences on day 11 (Table 3.8).

Glyphosate load recovered in subsurface return flow was assessed on day 2, 4, and 16. The control was greater than both treatments on day 2 and 4; however, there were no differences on day 16 (Figure 3.5). SS2Lpd was also greater than SSθ on day 4. The control exhibited a quadratic decrease in glyphosate load exported over time, when both axes were log transformed; however, there was no relationship identified for either treatment. The total glyphosate load recovered in subsurface return flow over day 2, 4, and 16 totaled 5.24 g, 0.25 g, and 0.09 g for the control, SS2Lpd, and SSθ, respectively, corresponding to 0.2%, less than 0.01% and less than 0.001% of applied glyphosate. Glyphosate concentrations on these sample dates were greatest in

the control relative to both treatments on day 2 and day 4, while equivalent on day 11 and 16 (Table 3.8).

Combining surface and subsurface return flow totals, 109 g, 11.2 g, and 0.67 g were recovered from the control, SS2Lpd, and SSθ treatments, respectively, corresponding to 5.2%, 0.5%, and less than 0.1% of applied glyphosate.

3.5. Discussion

3.5.1. Irrigation and Irrigation Return Flow

The volume of irrigation applied by the two spray stake treatments was consistently lower than the control for each monitoring period (74-76% reduction for SS2Lpd and 71-80% for SSθ). Spray stake irrigation, regardless of method, was consistently capable of reducing and often eliminating surface IRF compared to the control due to the precision with which irrigation was applied (directly to the container versus to the entire production surface). The total volume of surface IRF measured on all sample dates following the post-herbicide watering-in event for each monitoring period was reduced by 69-94% when irrigated using SS2Lpd and 81-98% using SSθ compared to the control. Subsurface IRF volumes were generally equivalent on a per day basis; however, the SSθ treatment was at times capable of reducing individual day subsurface IRF volume compared to the control. The total volume of subsurface IRF recovered during each monitoring period in the SS2Lpd treatment was reduced by 14-37% and SSθ treatment by 39-75% compared to the control. Excessive leaching from containers irrigated using microirrigation may occur due to the rapid application rates of microirrigation emitters coupled with the hydraulic properties present in typical nursery substrates (Lamack and Niemera, 1993), providing the potential for container leachate to then infiltrate through the production surface and contribute to subsurface IRF. Burnett and Van Iersel (2008) and Van Iersel et al. (2010) reported

the use of substrate moisture sensors to apply irrigation volume that reduced or eliminated container leachate, particularly if irrigating at a lower θ. This suggests that using sensors with microirrigation systems can reduce the volume of IRF by minimizing container leachate, a best management practice suggested by Bilderback (2002). Furthermore, days where θ is above the activation threshold and irrigation is not required would result in elimination of subsurface IRF. In summation, irrigating using in container spray stakes oftentimes prevents surface IRF, and when used in conjunction with substrate moisture sensors, may reduce subsurface IRF generation as well.

3.5.2. Pesticide Dynamics

Relevant pesticide properties are presented in Table 3.2.

3.5.2.1. Acephate

Acephate is an insecticide within the organophosphate class which acts as an acetylcholinesterase inhibitor within nervous systems (http://npic.orst.edu/factsheets/archive/acephatech.html). Acephate is a highly soluble compound, where coupled with its low Koc coefficient, is expected to exhibit a high degree of mobility, particularly in a dissolved phase. Aerobic degradation is considered the primary method of breakdown, as the low vapor pressure and high solubility suggest volatilization is unlikely in either a dry or wet environment, and the compound is considered photostable (https://pubchem.ncbi.nlm.nih.gov/compound/Acephate). As such, it was hypothesized to be present in surface return flow as well as water which infiltrates through the sand layer. Acephate mobility in water has been reported by Sun et al. (2018), where of pesticide residues investigated in the Yangtze River, acephate was measured in the highest concentrations. Similarly to our results, acephate was the pesticide recovered in the greatest percentage of the amount applied of

the 10 investigated compounds. While surface return flow (and concomitant acephate) was largely eliminated using spray stake irrigation treatments, subsurface IRF transported acephate for the control and both treatments; however, the SSθ treatment yielded 63% less total acephate over the sample period than the control and 61% less than SS2Lpd. The increase over time in acephate load transported in both spray stake treatments suggests that acephate movement through subsurface profiles exhibited a lag effect as repeated irrigation events would transport acephate residues through the profile. Considering the high potential for mobility in both surface and subsurface IRF, reducing IRF shortly after application can limit the movement of acephate.

3.5.2.2. Bifenthrin

Bifenthrin is an insecticide within the pyrethroid class, which acts by delaying closure of the axon sodium channel gates within the nervous system (http://npic.orst.edu/factsheets/archive/biftech.html). Bifenthrin exhibits a very low solubility, and a high Koc coefficient, suggesting that it will preferentially sorb to soils/organic matter and pose little threat to infiltrate through soils in a dissolved phase. Given the extremely low solubility of bifenthrin it may be expected to volatilize from moist soils or surface water; however, the sorptive strength of this compound may limit the extent that this pathway of degradation occurs (https://pubchem.ncbi.nlm.nih.gov/compound/5281872). Bifenthrin is not likely to undergo photodegradation (Jin et al. 2009); however, bifenthrin is subject to microbial degradation by species such as *Pseudomonas* sp. CB2 and *Stenotrophomonas acidaminiphila* (Lee et al., 2004; Zhang et al., 2018). Bifenthrin was primarily hypothesized to move via surface return flow, most likely via erosive detachment of sediments/particles rather than in a dissolved phase. Bifenthrin is unlikely to move in a dissolved phase; however, the potential for it to harm receiving water bodies may occur based on its environmental persistence and widespread use

(Sardiña et al., 2019), and toxic bioactivity at low concentrations to sensitive aquatic life (Bertotto et al., 2019; Brander et al., 2016). On the first irrigation event following application, the control transported a concentration of 6.69 µg L^{-1} in surface IRF; however, samples collected on subsequent dates did not exceed 1 µg L^{-1} and oftentimes was below the limit of detection. Similarly, subsurface concentrations were nearly universally below the limit of detection. The low concentrations in our study were consistent with Weston et al.'s (2009) reported concentrations of 0.073 µg L^{-1} and 1.2 µg g^{-1} of bifenthrin in water and suspended sediments collected from a Californian urban creek. As such, eliminating or at least mitigating the generation of surface IRF would be expected to maintain bifenthrin in place and allow it to degrade before it can be transported.

3.5.2.3. Isoxaben

Isoxaben is a pre-emergent herbicide within the benzamide class capable of inhibiting cell wall biosynthesis in susceptible plants, effectively preventing germination and/or growth (Dow Form No. 233-00845-MM-1111). Isoxaben is a slightly soluble compound with a Koc coefficient, suggesting that it is likely sorbed to sediments and other materials but may still be capable of moving in water (https://pubchem.ncbi.nlm.nih.gov/compound/Isoxaben). Based on the vapor pressure and Henry's Law constant of this compound, volatilization is not expected to be a major pathway of degradation from dry soils, or moist soils / water surfaces, respectively, nor is it expected to hydrolyze based on its functional group composition; however, this compound may degrade via photolysis (https://pubchem.ncbi.nlm.nih.gov/compound/Isoxaben). Microbial degradation has also been reported to be a major pathway in isoxaben dissipation, particularly in aerobic and moist soils (Camper et al., 2001; Walker, 1987). Briggs et al. (1998) reported isoxaben movement in nursery IRF was greatest on the days following application,

which was similar to our results, where samples collected on the first four sample dates following application exhibited a quadratic increase then decrease. The slight solubility of isoxaben suggested that it may be mobile in subsurface IRF; however, 1% or less of the total amount applied was recovered in the control or either treatment, with no identified increases over time.

3.5.2.4. Mefenoxam

Mefenoxam is a fungicide within the phenylamide class, which acts through inhibiting mycelium growth and sporulation through disrupting RNA polymerases (Hu et al., 2008). Mefenoxam exhibits a high solubility, low Koc, and is not expected to volatilize based on a Henry's Law constant of $3.5x10^{-5}$, nor is it expected to degrade via photo-chemically induced reactions or hydrolyze in water (Triantafyllidis et al., 2012). Gardner and Branham (2001) investigated the mobility of mefenoxam through turf covered or barren soil plots under a static irrigation (10 mm, 5 times per week), and an estimated evapotranspiration based regime, observing rapid infiltration of mefenoxam through the soil profile regardless of irrigation method, and suggesting aerobic microbial activity were the primary pathway of degradation. Based on the high solubility and low Koc, it was hypothesized that mefenoxam would be capable of infiltrating through the sand layer as well as be mobile in surface return flow. Similarly to Gardner and Branham's results, mefenoxam was rapidly exported in IRF in the control, considering both the quadratic decrease in surface IRF and the peak load exported in subsurface IRF on day 1, which was nearly three times greater than day 4 and ten times greater than day 8 and 16. While the spray stake treatments were effective in eliminating or reducing surface IRF and associated mefenoxam residues, subsurface IRF mefenoxam content represented the majority of mefenoxam movement in the two treatments, accounting for nearly 3-6 times as

much recovered mefenoxam in subsurface than surface IRF. Additionally, the increase in mefenoxam load recovered over time in subsurface IRF in the two treatments indicated the potential for a lag effect, as repeated irrigation events transported mefenoxam through the subsurface profile.

3.5.2.5. Oxyfluorfen

Oxyfluorfen is a pre-emergent herbicide within the diphenyl-ether class bearing a mode of action which inhibits the protoporphyrinogen oxidase enzyme within the chlorophyll biosynthesis pathway (Stagg et al., 2012). Oxyfluorfen is not expected to move in water considering its low solubility, and high Koc coefficient, nor is it expected to volatilize based on Henry's Law constant (8.2×10^{-7}) (https://pubchem.ncbi.nlm.nih.gov/compound/Oxyfluorfen). Oxyfluorfen movement was predominantly mobile in surface IRF, where nearly 60 times more oxyfluorfen was recovered in the control surface IRF than subsurface IRF, and 7.5 and 4.7 times as much in the SS2Lpd and SSθ treatments. Concentrations of oxyfluorfen in subsurface IRF were universally below 1 µg L^{-1}. The low concentrations of oxyfluorfen detected subsurface IRF, were consistent with both Riley et al's. (1994) report of water samples analyzed for oxyfluorfen being below the level of solubility, as well as Alister et al's. (2009) report that over 74% of oxyfluorfen recovered in soil samples was found in the top 2.5 cm after 90 and 340 days following application in a vineyard production site, indicating that oxyfluorfen is unlikely to move through subsurface profiles.

3.5.2.6. Chloryprifos

Chlorpyrifos, an insecticide within the organophosphate class acting as an acetyl cholinesterase inhibitor, has a moderate solubility and a high Koc range. Prominent degradation mechanisms for chlorpyrifos include volatilization, as suggested by a vapor pressure of 2.02 x

10^{-5} and Henry's Law constant of 3.55 x 10^{-5}, as well as photodecomposition, and microbial degradation. (https://pubchem.ncbi.nlm.nih.gov/compound/2730). Surface IRF represented the most prominent vector for the movement of chlorpyrifos, where in the control nearly 35 times as much chlorpyrifos was recovered in surface IRF versus subsurface IRF. In our study, chlorpyrifos concentrations were consistently lower in subsurface IRF than surface IRF, which was similar to results from Milhome et al (2015) where chlorpyrifos was below detection in groundwater samples.

3.5.2.7. Triflumizole

Triflumizole is a fungicide within the sterol-demethylation inhibiting class (DMI) which disrupts the biosynthesis of ergosterol within fungal cells (Hashimoto et al., 1990; Rosenberger et al., 2003). Triflumizole is slightly soluble with a high Koc is primarily expected to adsorb to soils. Volatilization is not expected to be a major pathway of degradation considering a vapor pressure of 1.4 x 10-6 mm Hg and Henry's Law constant of 6.2 x 10^{-8} atm-cu m/mole; however triflumizole is susceptible to photodegradation (https://pubchem.ncbi.nlm.nih.gov/compound/91699). The widespread use of triflumizole across numerous agricultural sectors increases surface water contamination risk, where it has been reported to be detrimental towards freshwater algal species, such *Chlorella vulgaris* (Xi et al., 2019). Considering the slight solubility of triflumizole, we hypothesized that it would be mobile in both surface and subsurface IRF; however, nearly 4.5 times as much triflumizole residue was recovered in surface IRF than subsurface IRF in the control. In either case this represented a small fraction of the applied triflumizole, with 1% in control surface IRF and less than 1% in control subsurface IRF, while both treatments recovered less than 1%.

3.5.2.8. Glyphosate

Glyphosate is the most widely used herbicide in modern agriculture, acting by disrupting the synthesis of aromatic amino acids through inhibition of the enolpyruvate shikimate 3-phosphate synthase enzyme within the shikimic acid pathway (Pollegioni et al., 2011). Glyphosate is an unusual compound with both a high solubility and a high Koc, with limited likelihood of volatilizing (Vapor Pressure: 9.8×10^{-8}) or photochemically degrading (https://pubchem.ncbi.nlm.nih.gov/compound/3496). Glyphosate has been shown to adsorb within soils, particularly those with a high clay fraction, in a similar manner to phosphorus, as well as be mobile in surface return flow and soil infiltrating water (Dion et al., 2001; Lupi et al., 2019; Sasal et al., 2015). Given the high solubility of glyphosate, it was hypothesized that it could be mobile in surface return flow in both a dissolved phase as well as a sorbed phase upon transported sediments. Subsurface movement of glyphosate has typically been reported to be limited, with concentrations seldom above detection (Saunders et al., 2015). Glyphosate exhibited the most mobility in surface IRF, where nearly 46 times as much total glyphosate was recovered in surface IRF as subsurface IRF in the control in monitoring period 2 and nearly 20 times as much in monitoring period 3. The peak concentration in monitoring period 2 occurred 2 days after application, where 1,403 µg L^{-1} were recovered in surface IRF, and in monitoring period 3 on the first day after application (2,090 µg L^{-1}), which while greater than the peak concentration (8.7 µg L^{-1} in Midwestern streams) measured by Battaglin et al. (2005), was less than the maximum concentration found in runoff from agricultural fields by Saunders et al. (2015) (5,153 µg L^{-1}). Concentrations recovered in subsurface IRF reached peak concentrations in monitoring period 2 on day 8 (134 µg L^{-1}) and monitoring period 3 on day 2 (92.3 µg L^{-1});

however the increased subsurface movement in our model nursery is likely attributed to the subsurface sand layer being free of clay particles for which glyphosate can adsorb to.

3.5.2.9. Thiophanate-Methyl

Thiophanate-Methyl (TPM) is a fungicide within the benzimidazole class, which acts through disrupting the mitotic process via inhibiting nuclear division in susceptible fungi (Cycon et al., 2011). TPM has a high solubility and a moderate Koc coefficient, suggesting that it will be mobile within soil/water systems and may be transported via irrigation return flow or precipitation events shortly following application (Briggs et al., 1998; https://pubchem.ncbi.nlm.nih.gov/compound/Thiophanate-methyl). Thiophanate-methyl is unlikely to volatilize or photochemically degrade; however, microbial degradation is considered a likely pathway (Briggs et al., 2002; Cycon et al., 2011). TPM in movement in irrigation IRF from container nurseries has been reported to be greatest shortly following application, where Briggs et al. (2002) reported that between 3.5% and 7% of applied TPM was recovered in the first irrigation event post-application. Similarly to our results, the amount of applied TPM recovered in surface IRF on the first irrigation event post-application represented 6% of the total amount applied, and the highest concentrations of TPM were recovered in surface IRF from the control on the first two sample dates post application (625 µg L^{-1} on day 1 and 38.8 µg L^{-1} on day 2 before remaining below 1 µg L^{-1} on subsequent sample dates). TPM load recovered over the first two sample dates represented over 99% of the total recovered TPM in surface IRF over the sample period, highlighting the potential for greatest export to occur shortly following application.

3.5.2.10. Prodiamine

Prodiamine is an herbicide within the dinitroaniline class, which acts through inhibiting polymerization of cell microtubules (Breeden et al., 2017; Briggs et al., 2003). A low solubility and a high Koc coefficient suggests prodiamine is not mobile in water (http://npic.orst.edu/HPT/# CAS #: 29091-21-2). In a study assessing Prodiamine removal via subsurface constructed wetland, Stearman et al. (2012) reported nursery irrigation IRF concentrations of 500-3,200 $\mu g\ L^{-1}$; however, these concentrations were substantially higher than the peak concentration measured in surface IRF in our model nursery (23.2 $\mu g\ L^{-1}$). Subsurface IRF was typically below 1 $\mu g\ L^{-1}$; however, samples collected on day 11 and day 16 were 12.3 $\mu g\ L^{-1}$ and 3.34 $\mu g\ L^{-1}$, respectively.

3.5.3 Ecological Considerations

Daphnia magna (water flea) and *Oncorhynchus mykiss* (rainbow trout) are frequently used as an indicator species to evaluate the negative impacts that pesticide residues may have on aquatic ecosystems in relation to the lethal concentration that kills 50% of a test population (LC50). The reported LC50 values of each compound for *Daphnia magna* and *Oncorhynchus mykiss* are shown in Table 3.9. Of the ten compounds used in this study, only three (bifenthrin, chlorpyrifos, oxyfluorfen) had a peak concentration that exceeded one or both of the LC50 values for the two indicator species. Considering the greatest concentrations of these (and all other) pesticides occurred in the surface IRF generated the day following pesticide application, delaying or reducing irrigation (and by extension IRF) when possible following pesticide application may allow degradation mechanisms to reduce the bioactivity of these compounds before transport to aquatic ecosystems.

Pesticide persistence in the environment can be assessed using reported half-lives of each compound in aquatic and soil systems (Table 3.10). For the three compounds that were present in concentrations exceeding the LC50 values for *Daphnia magna* and *Oncorhynchus mykiss*, the respective persistence in aqueous environments span from one month (oxyfluorfen) to over a year (bifenthrin), similar to their persistence in soil environments. Considering the sorption coefficients of these compounds, minimizing transport to surface waters shortly after application may allow enhanced adsorption to soils; therefore, reducing the aquatic impact and allowing degradation processes in the soil to occur.

The pesticide with the shortest half-life in both soil and water systems was TPM, where the majority was exported on the day following application before sharply declining. Acephate, the second most rapidly dissipating compound in both soils and water, exhibited the greatest amount of mobility in both surface and subsurface IRF, as well as the highest percentage recovered of amount applied. In both cases, minimizing IRF in the days immediately following application may substantially reduce the overall movement of these two compounds.

For all other investigated compounds, the respective half-lives in water are less than in soils. Every pesticide in this study exhibited greater overall movement in surface IRF than subsurface IRF, particularly in days immediately following pesticide application. Reducing surface IRF movement may allow these pesticides to adsorb to soil, organic matter and production surfaces instead of moving towards receiving water bodies. The benefit of this is two-fold, limiting downstream aquatic risk to the environment as well as increasing retention within production areas to protect crops.

3.6 Conclusions

Considering that IRF is the most prominent vector in the transport of agrochemicals, irrigation application methods which reduce IRF effectively reduce the movement of pesticides. As we hypothesized, microirrigation delivery methods consistently reduced the volume of water applied for each monitoring period while also reducing the volume of IRF. Surface IRF was oftentimes eliminated when applying irrigation using microirrigation systems, regardless of whether sensors were employed, as the water was applied directly within the containers; whereas, overhead irrigation consistently generated surface IRF. As we hypothesized, the partitioning of pesticide residues between surface and subsurface IRF was reflective of the physiochemical properties of each compound, chiefly solubility and Koc. The most soluble pesticides (acephate and mefenoxam) were recovered in the highest percentage of amount applied of all studied compounds, with subsurface IRF movement comprising a substantial portion of the transported amount. Conversely, the least soluble pesticides (oxyfluorfen, prodiamine, and bifenthrin) were often below the limit of detection and typically below 1 µg L^{-1} in subsurface IRF, with less than 1% of the applied compound recovered. We hypothesized that reducing and/or eliminating surface IRF with spray stake irrigation would provide only one pathway for movement (subsurface IRF). This was the case for the mobile and most of the moderately mobile pesticides while the low mobile pesticides were often undetectable in subsurface IRF. For the moderately mobile to relatively immobile compounds, this resulted in less than 1% of the total amount of applied pesticide recovered in combined IRF from the two spray stake treatments. For some of the moderately mobile pesticides a lag effect in subsurface IRF was observed where increases in the load exported over time reflected the compound moving through the subsurface profile in response to repeated irrigation events.

The results suggest that the benefits of irrigating using microirrigation systems extend beyond water savings, and can be used to limit IRF generation and influence the movement of pesticides. Surface IRF was the predominant vector of movement for all pesticides, regardless of physiochemical properties, and pesticides were transported in the greatest quantities on days immediately following application. While the more soluble compounds exhibited mobility in subsurface IRF, regardless of irrigation application method, less soluble compounds were unlikely to infiltrate and percolate through the subsurface; therefore, selection of pesticides with physiochemical properties that limit mobility can be considered a best management practice when possible, acknowledging there are other factors to consider in regard to pesticide selection. Retention of pesticides upon the nursery production surface may offer greater pest control and treatment efficacy, while also allowing preferable degradation mechanisms to occur, such as volatilization or photolysis. The use of microirrigation in container nursery production is an effective tool to reduce water use, reduce IRF and concomitant pesticide movement, and limit the economic and ecologic concerns of agrochemical transport. . Despite microirrigation systems such as spray stakes encompassing more labor considerations, the volume of water saved (regardless of applying based on static regiment or θ), and the mitigation of agrochemical export that accompany this technology can enhance the sustainability of nursery crop production amidst mounting concerns over water availability and quality.

APPENDIX

Table 3.1: Pesticides were applied in three rounds at the MSU research nursery during the 2017 season using label recommendations for ornamental crops. Following application of pre-emergent herbicides Isoxaben and Prodiamine, the overhead control irrigated beds received 19 mm of irrigation and the spray stake treatments received 12.6 mm of overhead irrigation for the recommended watering-in, while following Oxyfluorfen application the controls again received 19 mm, but the treatments received the recommended 6.33 mm.

Round 1 (Applied 27 June 2017)	***Active Ingredient***	***Trade Name***	***Grams A.I. Applied per Hectare***
Herbicide	Isoxaben	Gallery 75DF	866.5
Insecticide	Acephate	Acephate 97UP	553
Insecticide	Bifenthrin	Talstar P	130
Fungicide	Mefenoxam	Mefenoxam 2AQ	18.2
Round 2 (Applied 7 August 2017)	***Active Ingredient***	***Trade Name***	***Grams A.I. Applied per Hectare***
Herbicide	Oxyfluorfen	Goaltender	1142.2
Herbicide	Glyphosate	Roundup PowerMax	2,078
Insecticide	Chlorpyrifos	Lorsban 4E	1145.8
Fungicide	Triflumizole	Terraguard SC	288.5
Round 3 (Applied 28 August, 2017)	***Active Ingredient***	***Trade Name***	***Grams A.I. Applied per Hectare***
Herbicide	Prodiamine	Barricade 65WG	1697.9
Herbicide	Glyphosate	Roundup PowerMax	2,078
Fungicide	Thiophanate-Methyl	Thiophanate-Methyl 85WDG	482.5

Table 3.2**:** Pesticide mobility groups, chemical class, solubility, and Koc for each active ingredient. Pesticides were categorized based on solubility and Koc Mccalls and FAO classifications. [1]https://www.chemsafetypro.com/Topics/CRA/Mobility_Classification_of_Chemicals_in_Soil.html (Accessed 18 September 2020). [2]http://www.fao.org/3/x2570e/X2570E06.htm (Accessed 18 September 2020).

Group	*Active Ingredient:*	*Pesticide Class:*	*Solubility in mg/L*	*Koc*	*Mccalls (Koc Class)[1]*	*FAO Classification of mobility (Koc)[1]*	*FAO Classification of mobility (solubility)[2]*
High Solubility / Low Koc	**Acephate**	Insecticide	818,000 mg L^{-1}	4.7	Very High	Highly Mobile	Highly Soluble
	Mefenoxam	Fungicide	26,000 mg L^{-1}	660	Low	Moderately Mobile	Highly Soluble
	Glyphosate	Herbicide	10,500 mg L^{-1}	2,600 - 4,900	Slightly	Slightly Mobile	Highly Soluble
Moderate Solubility / Moderate Koc	**Thiophanate-Methyl**	Fungicide	26.6 mg L^{-1}	330	Medium	Moderately Mobile	Readily Soluble
	Triflumizole	Fungicide	10.2 mg L^{-1}	1400	Low	Slightly Mobile	Readily Soluble
	Isoxaben	Herbicide	1.42 mg L^{-1}	3,300	Slightly	Slightly Mobile	Moderately Soluble
	Chlorpyrifos	Insecticide	1.4 mg L^{-1}	995 - 31,000	Low to Immobile	Moderately to Hardly Mobile	Moderately Soluble

Table 3.3: Retention times, precursor and product ions, and MS parameters used for identification and quantification of target pesticides by LCMS.

Compound	Retention time (min)	Precursor ion	Product ions	Dwell (ms)	Cone (V)	CE (V)
Acephate	1.27	184	125, 143	0.5	25	17
Isoxaben	8.86	333	165	0.5	22	17
Metalaxyl-m	8.44	280	192, 220	0.5	17	17
Thiophanate-methyl	0.85	343	151, 226	0.5	20	17
Triflumizole	9.8	346	73, 278	0.5	22	17
AMPA	6.59	110	63, 79	0.5	20	21
^{13}C-AMPA	6.59	114	63.2, 79	0.5	23	19
Glyphosate	4.35	168	63, 79	0.5	20	20
^{13}C-Glyphosate	4.35	169.7	63.2, 79.1	0.5	23	17

Table 3.4: Retention times, precursor and product ions, and MS parameters used for identification and quantification of target pesticides by GCMS.

Compound	Retention time (min)	Precursor ion	Product ions	Dwell (ms)	CE (eV)
Bifenthrin	22.02	181.2	165.2	10	25
		181.2	166.2	10	10
Chlorpyrifos	16.74	198.9	171	10	15
		196.6	169	10	15
Oxyfluorfen	19.14	299.9	222.8	10	15
		252	146	10	30
Prodiamine	16.11	321	279	10	5
		321	203	10	10

Table 3.5: Irrigation volume applied per ha^{-1} over the three monitoring periods. All control and SS2Lpd replicates received an identical, static volume every day throughout the course of the study (respectively); whereas, the SSθ treatment varied between replicates based on in-container substrate θ.

	Total kL ha^{-1} Applied								
	Monitoring Period 1			Monitoring Period 2			Monitoring Period 3		
	Mean	Standard Error			Mean	Standard Error		Mean	Standard Error	
Control	3,238	0	a[z]	Control	3,238	0	a	Control	3,238	0	a
SS2Lpd	827	0	b	SS2Lpd	763	0	b	SS2Lpd	827	0	b
SSθ	733	111	b	SSθ	641	124	b	SSθ	935	54	b
	Total Days Irrigation Applied								
	Mean	Standard Error			Mean	Standard Error		Mean	Standard Error	
Control	17	0	a	Control	17	0	a	Control	17	0	a
SS2Lpd	17	0	a	SS2Lpd	17	0	a	SS2Lpd	17	0	a
SSθ	11.5	1.9	a	SSθ	12.6	0.84	b	SSθ	15	0.93	a

[z]Means followed by different letters are significantly different at $p \leq 0.05$ by Tukey's HSD

Table 3.6: Regression Equations for Pesticide Load: Equation, F Value, and R Squared Value for pesticides estimating load over a 16 day period. Y (grams ha^{-1}) was modeled based on day of sampling (DOS), or the natural log of DOS using either a linear or quadratic equation.

Regression Equations for Pesticide Load over Monitoring Period					
Pesticide	**Irrigation**	**Surface/Subsurface**	**Equation**	**F Value**	**R Squared**
Acephate	Control	Surface	Y= (-42.4 (LogDOS)) + (8.41 (LogDOS*LogDOS)) + 56.2	53.2	0.95
Acephate	SS2Lpd	Subsurface	LogY= (1.50 (LogDOS)) + -0.85	24.2	0.62
Acephate	SSθ	Subsurface	LogY= (1.55 (LogDOS)) + -1.33	32.8	0.72
Bifenthrin	Control	Surface	LogY= (-5.05 (LogDOS)) + (1.50 (LogDOS*LogDOS)) + 1.06	11.4	0.79
Isoxaben	Control	Surface	Y= (-19.6 (LogDOS)) + (2.67 (LogDOS*LogDOS)) + 35	16.7	0.85
Isoxaben	Control	Subsurface	Y= (-6.99 (LogDOS)) + 20.3	18.5	0.65
Mefenoxam	Control	Surface	LogY= (-4.12 (LogDOS)) + (0.92 (LogDOS*LogDOS)) + 0.99	51.8	0.95
Mefenoxam	SS2Lpd	Subsurface	LogY= (1.20 (LogDOS)) + - 5.24	19.2	0.55
Mefenoxam	SSθ	Subsurface	LogY= (1.13 (LogDOS)) + -5.78	23.9	0.63
Chlorpyrifos	Control	Surface	LogY= (-1.69 (LogDOS)) + 2.37	136	0.94

Table 3.6 (cont'd)

Triflumizole	Control	Surface	LogY= (-1.67 (LogDOS)) + 0.96	36.3	0.82
Triflumizole	Control	Subsurface	LogY= (1.25 (LogDOS)) + (- 1.01 (LogDOS*LogDOS)) + -1.53	20.3	0.87
Oxyfluorfen	Control	Surface	LogY= (-0.82 (LogDOS)) + 0.80	20.3	0.72
TPM	Control	Surface	LogY= (-8.10 (LogDOS)) + (1.83 (LogDOS*LogDOS)) + 3.69	29.9	0.86
TPM	Control	Subsurface	LogY= (-12.7 (LogDOS)) + (3.02 (LogDOS*LogDOS)) + 6.76	19.6	0.85
Glyphosate Rd 2	Control	Surface	LogY= (3.68 (LogDOS)) + (-1.8 (LogDOS*LogDOS)) + 0.71	6.12	0.64
Glyphosate Rd 3	Control	Surface	LogY= (3.31 (LogDOS)) + (0.47 (LogDOS*LogDOS)) + 4.32	27.1	0.84
Glyphosate Rd 3	Control	Subsurface	LogY= (-3.42 (LogDOS)) + (0.51 (LogDOS*LogDOS)) + 3.57	128	0.98

Table 3.7: Amount of pesticide applied, recovered in irrigation return flow, and percent of applied pesticide recovered per hectare.

Pesticide	Amount Applied per ha^{-1} (grams)	Treatment	Total Grams Recovered in Surface IRF ha^{-1}	% of Applied Pesticide	Total Grams Recovered in Subsurface IRF ha^{-1}	% of Applied Pesticide	Total Grams in Combined IRF ha^{-1}	% of Applied Pesticide
Acephate	553	Control	77.7	14%	94.9	17%	173	31%
		SS2Lpd	6.56	1%	89.4	16%	96	17%
		SSθ	3.41	<1%	34.8	6%	38.2	7%
Mefenoxam	18.2	Control	2.94	16%	0.98	5%	3.92	22%
		SS2Lpd	0.07	<1%	0.43	2%	0.5	3%
		SSθ	0.05	<1%	0.17	1%	0.21	1%
Thiophanate-Methyl	482	Control	32.4	7%	1.11	<1%	33.5	7%
		SS2Lpd	0.05	<1%	0.006	<1%	0.05	<1%
		SSθ	0.02	<1%	0.002	<1%	0.02	<1%
Triflumizole	288	Control	3.75	1%	0.862	<1%	4.61	2%
		SS2Lpd	0.14	<1%	0.028	<1%	0.16	<1%
		SSθ	0.0004	<1%	0.051	<1%	0.05	<1%

Table 3.7 (cont'd)

Isoxaben	867	Control	69.5	8%	37.4	4%	107	12%
		SS2Lpd	5.95	<1%	6.86	<1%	12.8	1%
		SSθ	0.53	<1%	1.54	<1%	2.07	<1%
Chlorpyrifos	1,146	Control	14.5	1%	0.413	<1%	14.9	1%
		SS2Lpd	0.24	<1%	0.041	<1%	0.28	<1%
		SSθ	0.001	<1%	0.045	<1%	0.05	<1%
Oxyfluorfen	1,142	Control	4.71	<1%	0.078	<1%	4.78	<1%
		SS2Lpd	0.278	<1%	0.037	<1%	0.31	<1%
		SSθ	0.08	<1%	0.017	<1%	0.1	<1%
Prodiamine	1,698	Control	3.97	<1%	0.144	<1%	4.11	<1%
		SS2Lpd	1.25	<1%	0.01	<1%	1.26	<1%
		SSθ	0.06	<1%	0.004	<1%	0.07	<1%

Table 3.7 (cont'd)

Bifenthrin	130	Control	0.45	<1%	0.029	<1%	0.48	<1%
		SS2Lpd	0.04	<1%	0.024	<1%	0.06	<1%
		SSθ	0.02	<1%	0.016	<1%	0.03	<1%
Glyphosate Monitoring Period 2	2,078	Control	80.2	4%	1.76	<1%	81.9	4%
		SS2Lpd	1.42	<1%	4.38	<1%	5.8	<1%
		SSθ	1.39	<1%	3.78	<1%	5.18	<1%
Glyphosate Monitoring Period 3	2,078	Control	104	5%	5.24	<1%	109	5%
		SS2Lpd	11	<1%	0.25	<1%	11.2	<1%
		SSθ	0.58	<1%	0.09	<1%	0.67	<1%

Table 3.8: Pesticide concentration in samples collected from irrigation return flow over a 16 day period over the course of three monitoring periods.

	Sample Day					
	0	1	2	4	8	16
			Acephate Concentration (µg L^{-1}) Monitoring Period 1			
Treatment			Surface Return Flow			
Control		936.00		373.25 a[z]	155.50	33.17
SS2Lpd		0.00		116.23 ab	248.43	70.87
SSθ		0.00		6.33 b	0.00	53.27
			Subsurface Return Flow			
Control		328.87		772.80	642.83	117.00
SS2Lpd		29.25		926.10	945.18	307.83
SSθ		29.00		233.10	648.73	327.48
			Bifenthrin (µg L^{-1}) Monitoring Period 1			
			Surface Return Flow			
Control		6.69		0.13	0.30 a	0.38
SS2Lpd		0.00		0.03	0.02 b	0.60
SSθ		0.00		0.02	0.00 b	0.29
			Suburface Return Flow			
Control		0.15		0.13	0.13	0.13
SS2Lpd		0.13		0.13	0.13	0.13
SSθ		0.13		0.04	0.10	0.13
			Isoxaben (µg L^{-1}) Monitoring Period 1			
			Surface Return Flow			
Control	506.40	595.13		277.44 a	225.12 a	1.95
SS2Lpd	475.49	0.00		81.90 ab	32.62 b	9.38
SSθ	78.60	0.00		0.11 b	0 b	5.53

Table 3.8 (cont'd)

			Subsurface Return Flow		
Control	271.17 a		277.27 a	181.87 a	3.32
SS2Lpd	69.83 b		50.50 b	67.53 b	9.48
SSθ	46.92 b		2.08 b	6.24 b	10.74
		Mefenoxam (µg L^{-1}) Monitoring Period 1			
			Surface Return Flow		
Control	46.6		1.74 a	0.84	0.38
SS2Lpd	0.00		0.16 b	1.4	0.95
SSθ	0.00		0.02 b	0	0.75
			Subsurface Return Flow		
Control	7.74		4.93 a	2.03	0.76
SS2Lpd	0.17		3.4 ab	3.67	2.49
SSθ	0.22		0.32 b	1.00	1.75
		Chlorpyrifos (µg L^{-1}) Monitoring Period 2			
			Surface Return Flow		
Control	270.80 a	39.59 a	11.69	6.84 a	3.75 a
SS2Lpd	6.91 b	0.00 b	5.26	1.32 ab	0.00 b
SSθ	0.07 b	0.00 b	0.00	0.00 b	0.00 b
			Subsurface Return Flow		
Control	1.30	2.43 a	3.97 a	3.50	0.89
SS2Lpd	0.65	0.50 b	0.14 b	0.41	0.09
SSθ	0.18	0.20 b	0.20 b	1.84	1.03
		Triflumizole (µg L^{-1}) Monitoring Period 2			
			Surface Return Flow		
Control	44.28 a	15.18 a	4.68	1.17	1.19 a
SS2Lpd	5.96 b	0.00 b	1.72	0.71	0.00 b
SSθ	0.03 b	0.00 b	0.00	0.00	0.00 b

Table 3.8 (cont'd)

			Subsurface Return Flow			
Control		1.96 a	12.87 a	7.14 a	1.74	0.34
SS2Lpd		0.26 b	0.23 b	0.11 b	0.45	0.13
SSθ		0.08 b	0.08 b	0.13 b	2.94	1.00
			Oxyfluorfen (µg L^{-1}) Monitoring Period 2			
			Surface Return Flow			
Control	72.50	61.98 a	10.38 a	9.93	10.16 a	8.16 a
SS2Lpd	144.51	12.73 b	0.00 b	2.19	1.19 a	0.00 b
SSθ	402.69	5.63 b	0.00 b	0.00	0.00 b	0.00 b
			Subsurface Return Flow			
Control		0.19	0.74	0.69	0.47	0.17
SS2Lpd		0.29	0.76	0.12	0.48	0.10
SSθ		0.06	0.55	0.10	0.51	0.38
			Glyphosate (µg L^{-1}) Monitoring Period 2			
			Surface Return Flow			
Control		34.74	1403.02	104.26	32.92	3.33 a
SS2Lpd		11.88	0.00	49.96	1.67	0.00 b
SSθ		10.73	0.00	0.00	.	0.00 b
			Subsurface Return Flow			
Control		5.00	21.27	14.65	7.82	5.00
SS2Lpd		5.56	39.04	41.92	118.92	19.48
SSθ		3.33	3.75	129.88	134.03	23.26

Table 3.8 (cont'd)

	Sample Day				
	1	2	4	11	16
	Thiophanate-Methyl (µg L^{-1}) Monitoring Period 3				
	Surface Return Flow				
Control	624.53 a	38.78 a	0.125	0.08	0.08 a
SS2Lpd	1.92 b	0.00 b	0.00	0.78	0.00 b
SSθ	0.00 b	0.00 b	0.00	0.68	0.00 b
	Subsurface Return Flow				
Control	.	24.91 a	0.10 a	0.13	0.13
SS2Lpd	0.13	0.13 b	0.13 b	0.13	0.13
SSθ	0.06	0.05 b	0.03 b	0.99	0.13
	Prodiamine (µg L^{-1}) Monitoring Period 3				
	Surface Return Flow				
Control	9.80 a	10.60 a	7.10 a	22.60	3.93 a
SS2Lpd	2.30 ab	0.00 b	0.00 b	23.23	0.00 b
SSθ	0.00 b	0.00 b	0.00 b	2.32	0.00 b
	Subsurface Return Flow				
Control	.	0.56 a	0.88 a	12.29 a	3.39 a
SS2Lpd	0.14	0.22 ab	0.15 b	0.37 b	0.20 b
SSθ	0.06	0.04 b	0.03 b	0.60 b	0.29 b

Table 3.8 (cont'd)

		Glyphosate (µg L^{-1}) Monitoring Period 3			
		Surface Return Flow			
Control	2090.23 a	240.51 a	57.66 a	3.33	3.33 a
SS2Lpd	51.86 b	0.00 b	0.00 b	340.48	0.00 b
SSθ	0.00 b	0.00 b	0.00 b	22.04	0.00 b
		Subsurface Return Flow			
Control	.	92.57 a	37.67 a	7.60	5.00
SS2Lpd	6.36	5.00 b	8.78 b	21.71	5.00
SSθ	2.5	2.00 b	1.00 b	5.00	5.00

[z]Means followed by different letters are significantly different at $p \leq 0.05$ by Tukey's HSD

Table 3.9: Concentrations of pesticides for 50% mortality (LC50) of two common aquatic ecotoxicity indicator species.

	LC 50 Concentrations for *Daphnia magna* and *Oncorhynchus mykiss* (µg L^{-1})		
	Daphnia magna **Water Flea**	***Oncorhynchus mykiss*** **Rainbow Trout**	Source(s)[1]
Acephate	1,110-71,800	1,000-880,000	https://pubchem.ncbi.nlm.nih.gov/compound/Acephate https://www.amleo.com/images/art/Acephate-97UP-SDS-ACP97.pdf https://www3.epa.gov/pesticides/endanger/litstatus/effects/redleg-frog/acephate/analysis_acephate.pdf
Mefenoxam	900	470	http://www.syngentacropprotection.com/pdf/msds/03_177322262007.pdf
Glyphosate	4,100-234,000	77,600-134,000	https://pubchem.ncbi.nlm.nih.gov/compound/3496
TPM	16,000	7,800-25,200	https://pubchem.ncbi.nlm.nih.gov/compound/Thiophanate-methyl#section=Ecotoxicity-Values
Triflumizole	1,420	580	https://pubchem.ncbi.nlm.nih.gov/compound/91699#section=Ecotoxicity-Values https://www.ohp.com/Labels_MSDS/PDF/terraguard_sds.pdf

Table 3.9 (cont'd)

Isoxaben	1,300	1,100	http://triangleturf.net/labels/dow/DOW-Gallery%2075%20DF%20MSDS.pdf https://www3.epa.gov/pesticides/chem_search/cleared_reviews/csr_PC-125851_23-May-88_029.pdf
Chlorpyrifos	1-3.7	8-550	https://pubchem.ncbi.nlm.nih.gov/compound/2730#section=Ecotoxicity-Values
Oxyfluorfen	80	410	https://pubchem.ncbi.nlm.nih.gov/compound/Oxyfluorfen#section=Ecotoxicity-Values https://archive.epa.gov/pesticides/reregistration/web/pdf/oxyfluorfen_red.pdf
Prodiamine	660	830	http://www.fluoridealert.org/wp-content/pesticides/msds/prodiamine.barricade.65wg.syngenta.pdf
Bifenthrin	0.86-12.4	0.15	https://pubchem.ncbi.nlm.nih.gov/compound/5281872#section=Ecotoxicity-Values

[1]All links were accessed on 18 September 2020

Table 3.10: Time (in days) for 50% of an active ingredient to degrade in aquatic and terrestrial environments.

Half Life of Pesticides in Water and Soils

Active Ingredient:	**Water**	**Soil**	**Reference(s)[1]**
Acephate	6-20 days	4.5-32 days	NPIC.orst.edu/factsheets
Mefenoxam	7-27 days	70 days	pmep.cce.cornell/edu
Glyphosate	3-91 days	47 days	NPIC.orst.edu/factsheets
Thiophanate-Methyl	5 days	7 days	archive.epa.gov
Triflumizole	4 days	18 days	pmep.cce.cornell/edu
Isoxaben	14 days	100 days	wsdot.wa.gov ; Jameson, G.L., Briggs, J.A., Whitwell, T., Fernandez, R.T., Riley, M.B. 2004. Influence of pine bark and gravel on degradation of isoxaben in retention basins. Weed Science 52:158-165
Chlorpyrifos	35-78 days	7-120 days	NPIC.orst.edu/factsheets
Oxyfluorfen	17-28 days	30-70 days	pmep.cce.cornell/edu

Table 3.10 (cont'd)

Prodiamine	1.4-5.1 days	69-120	https://apvma.gov.au/sites/default/files/publication/13916-prs-prodiamine.pdf ; Stearman, G.K., George, D.B., Hutchings, L.D. 2012. Removal of nitrogen, phosphorus and prodiamine from a container nursery by a subsurface flow constructed wetland
Bifenthrin	276-416	122-345 days	NPIC.orst.edu/factsheets

[1] All links were accessed on 18 September 2020

Figure 3.1. Diagram of MSU Research Nursery.

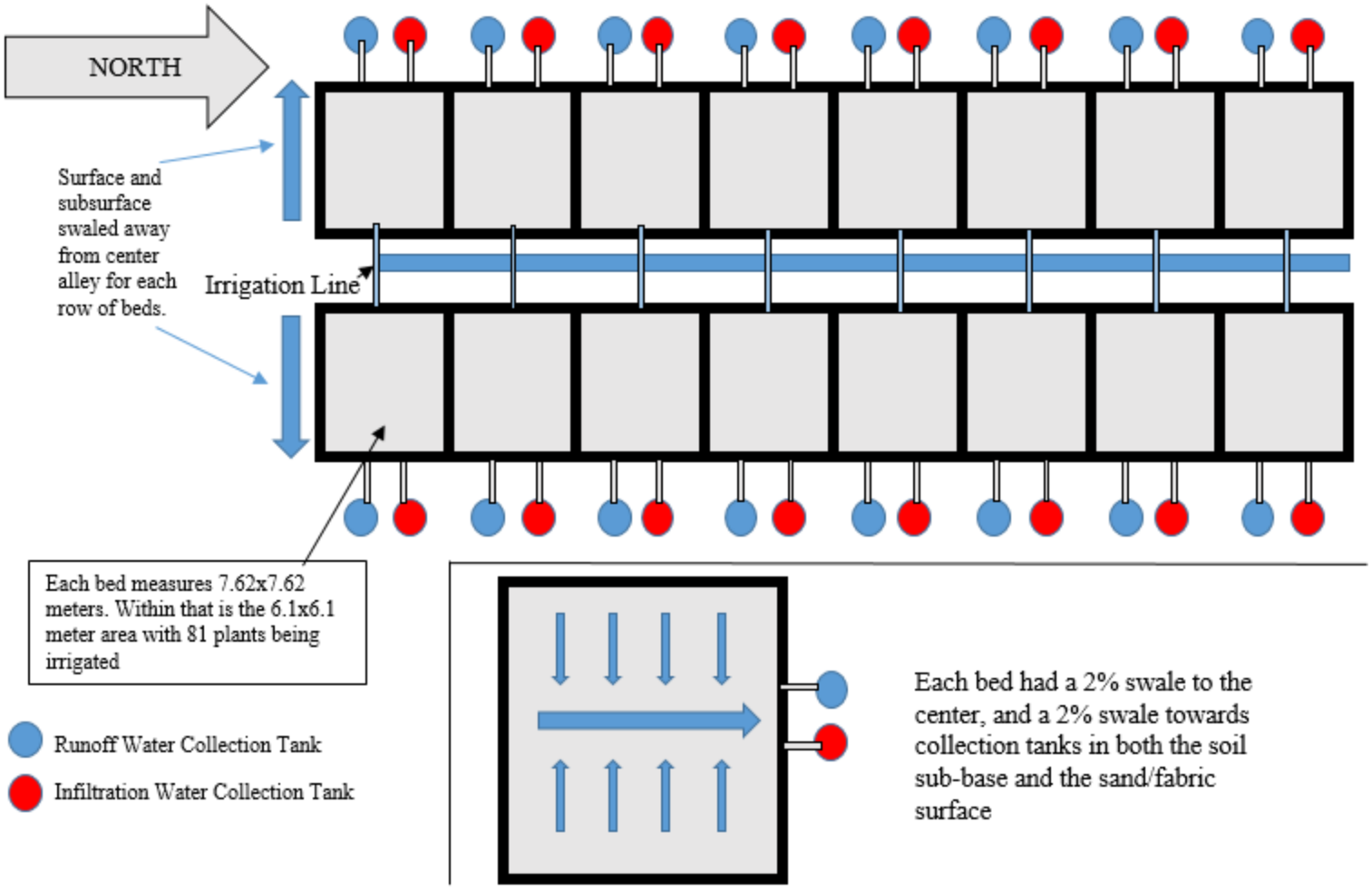


Figure 3.2. Precipitation (A) and temperature conditions (B) at the Michigan State University Research Nursery throughout the 2017 study.

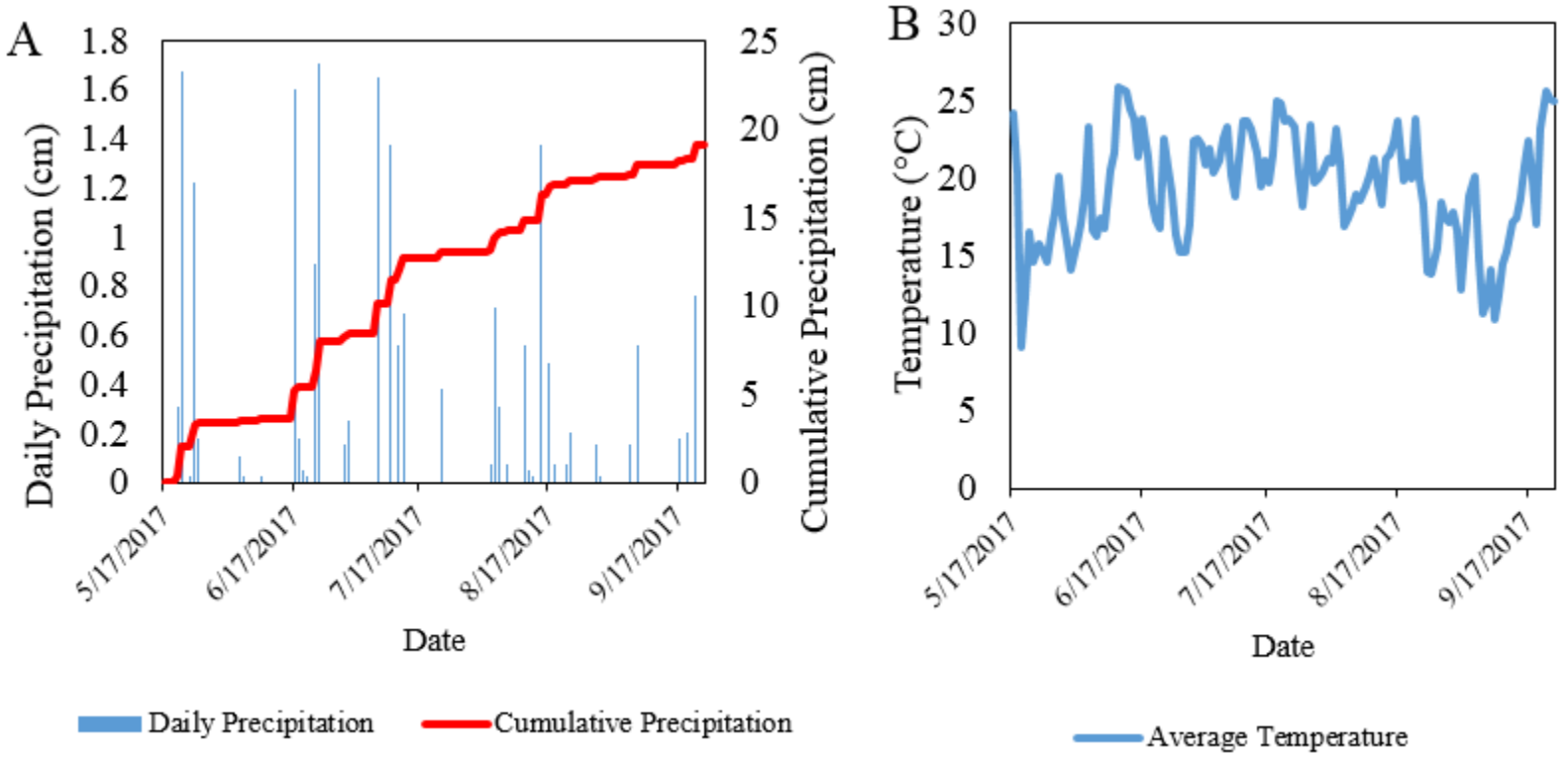


Figure 3.3: Pesticides were applied on 27 June 2017, with Isoxaben applied on Day 0, followed by the requisite watering in (12.6 mm via overhead for treatments, 19 mm via overhead for control).The volume of irrigation applied was recorded over the ensuing 16 days at the MSU Research Nursery (**a**), in addition to measuring the volume of surface (**b**) and subsurface (**c**) return flow and associated load of pesticide content (Acephate **d**, **e**; Bifenthrin **f**, **g**; Isoxaben **h**, **i**; and Mefenoxam **j**, **k**) exported 1, 4, 8, and 16 days after application. Means followed by respective color-coded letters are significantly different at $p < 0.05$ by Tukey's HSD.

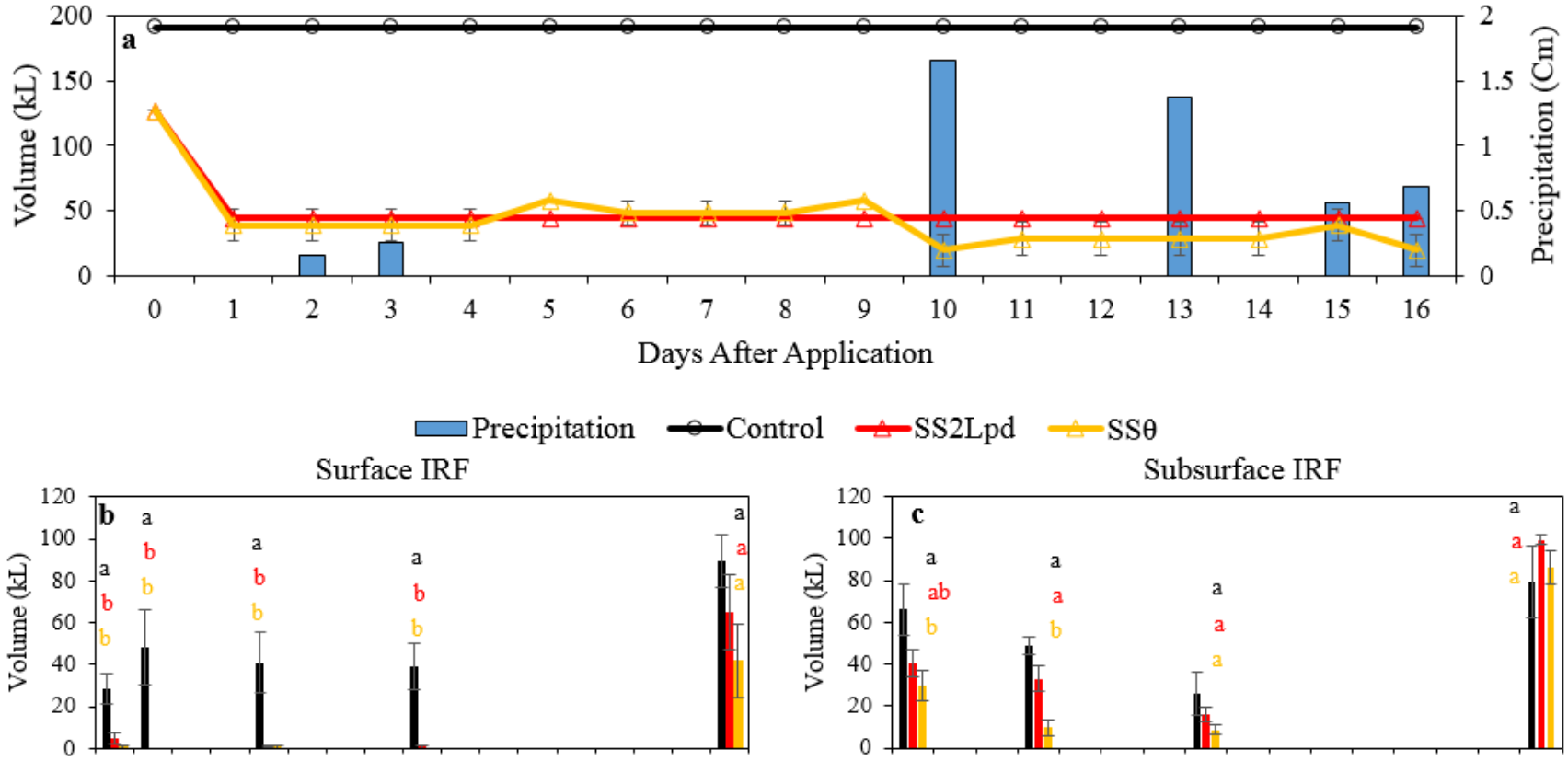


Figure 3.3 (cont'd)

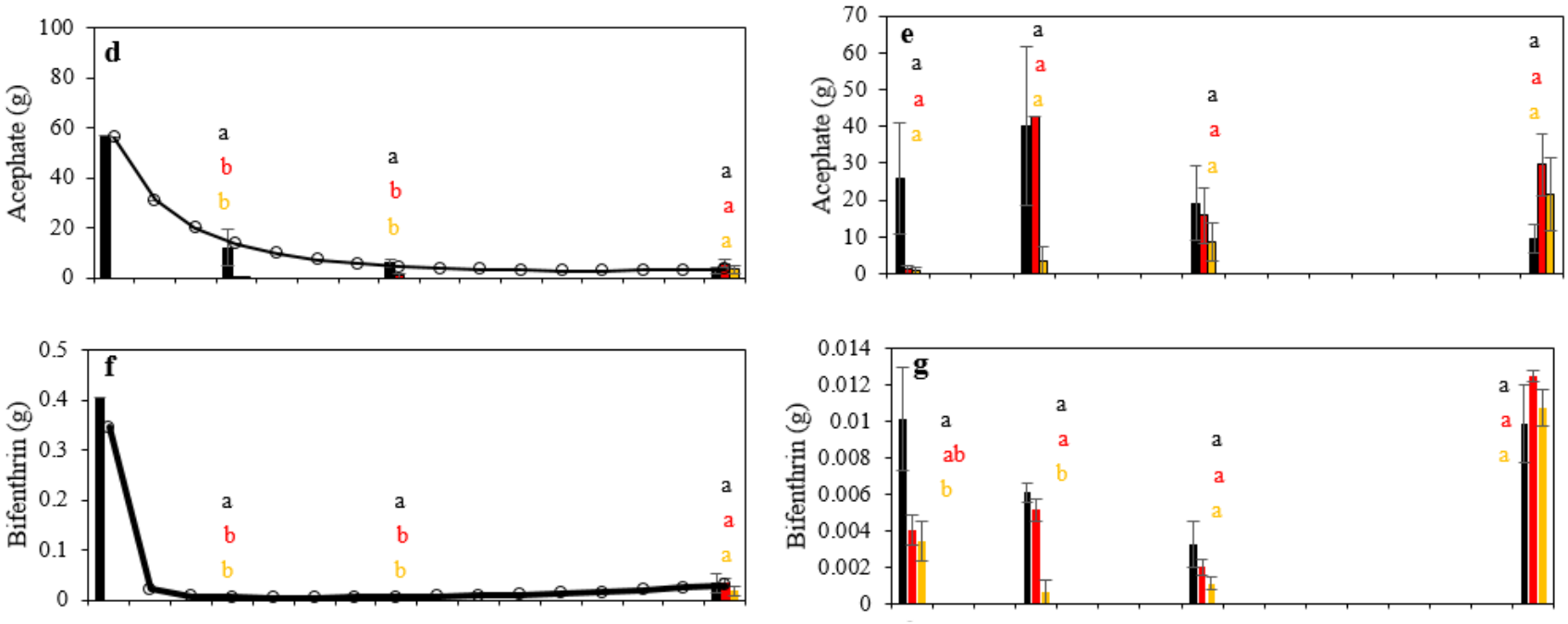


Figure 3.3 (cont'd)

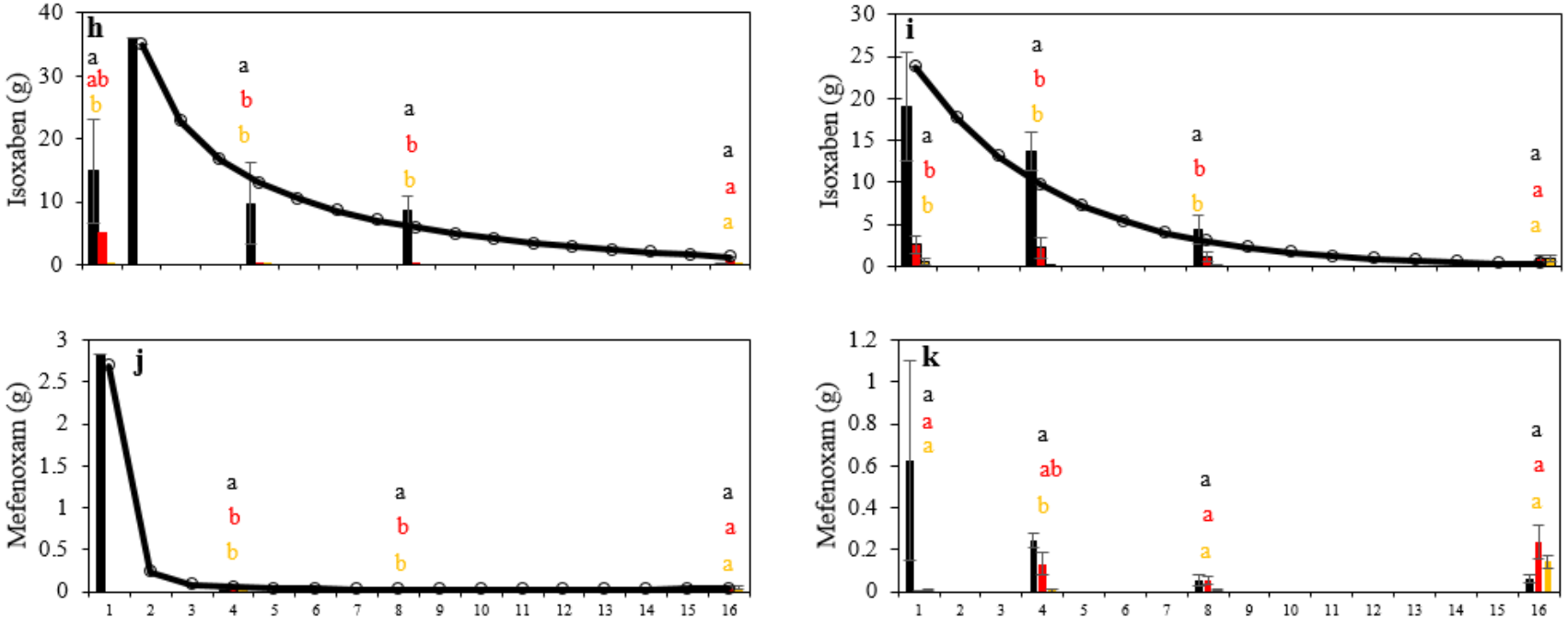


Figure 3.4: Pesticides were applied on 7 August 2017, with Oxyfluorfen applied on Day 0, followed by the requisite watering in (6.33 mm via overhead for treatments, 19 mm via overhead for control), followed by triflumizole, chlorpyrifos, and glyphosate application. The volume of irrigation applied was recorded over the ensuing 16 days at the MSU Research Nursery (**a**), in addition to measuring the volume of surface (**b**) and subsurface (**c**) return flow and associated load of pesticide content (Chlorpyrifos **d**, **e**; Oxyfluorfen **f**, **g**; Triflumizole **h**, **i**; and Glyphosate **j**, **k**) exported 1, 2, 4, 8, and 16 days after application. Means followed by respective color-coded letters are significantly different at $p < 0.05$ by Tukey's HSD.

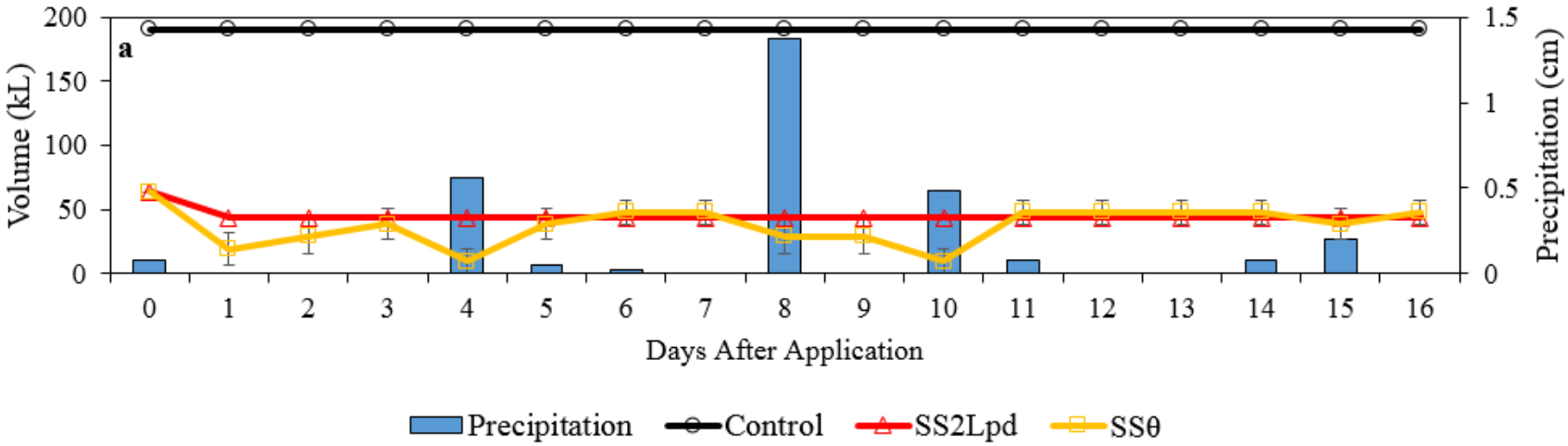


Figure 3.4 (cont'd)

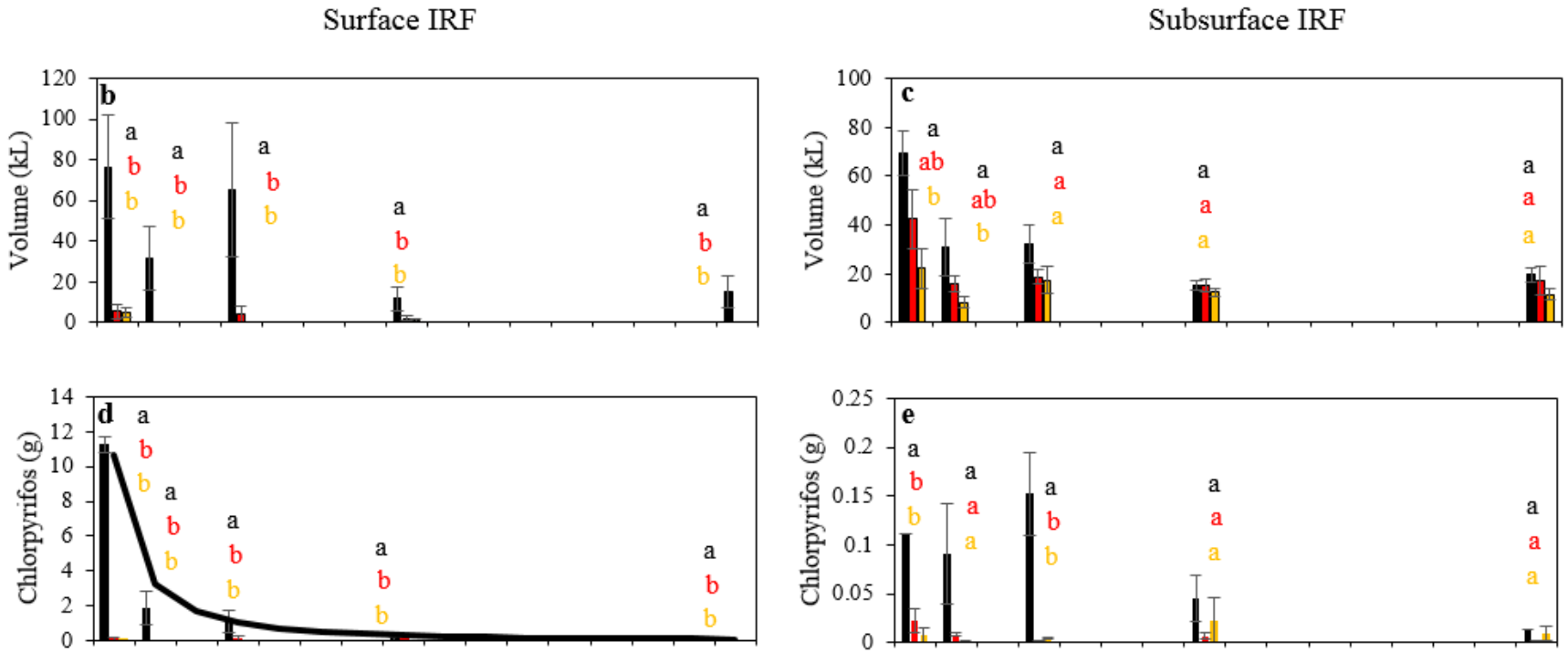


Figure 3.4 (cont'd)

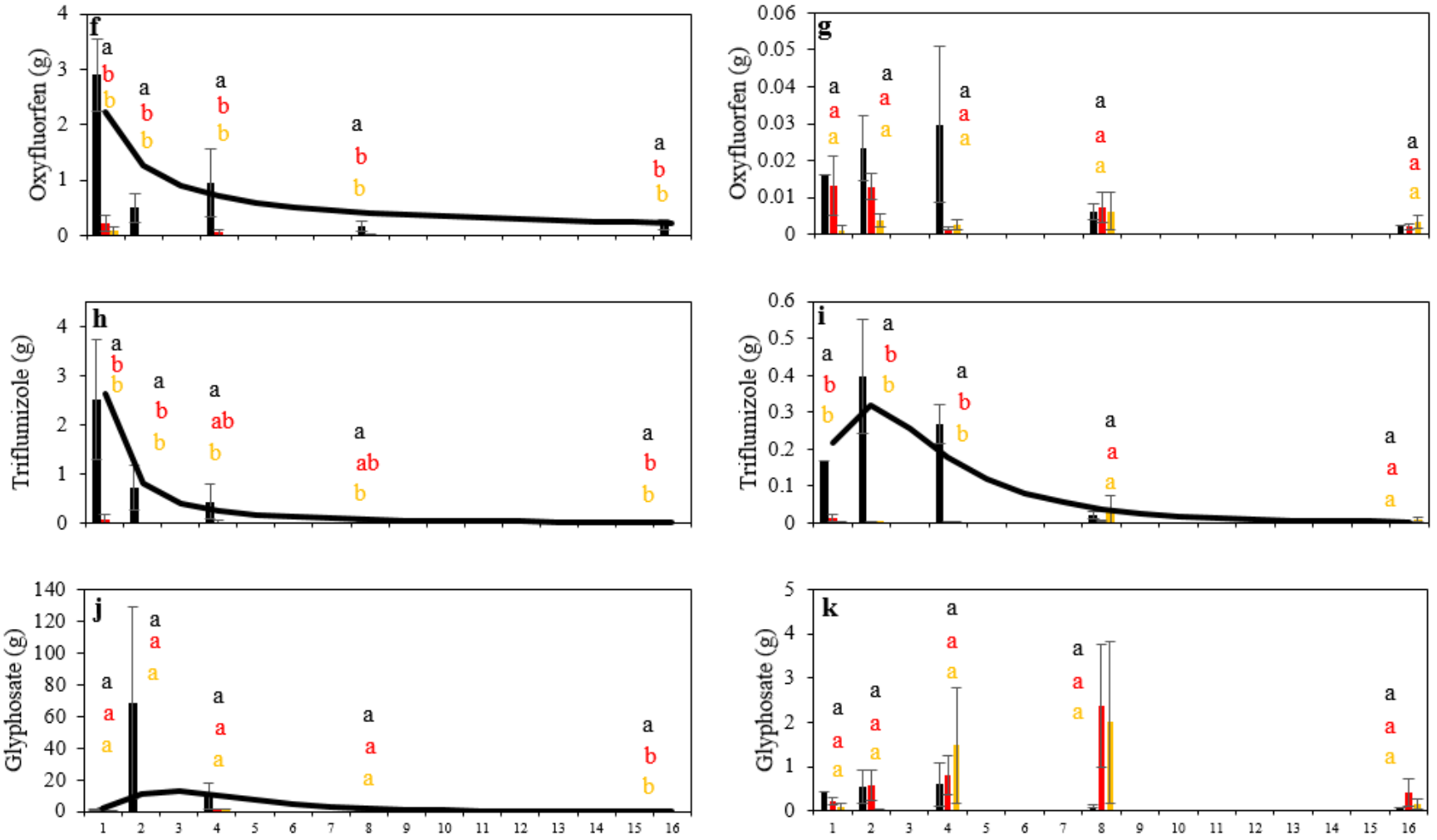


Figure 3.5: Pesticides were applied on 28 August 2017, with prodiamine applied on Day 0, followed by the requisite watering in (12.6 mm via overhead for treatments, 19 mm via overhead for control) before thiophanate-methyl and glyphosate were applied. The volume of irrigation applied **(a)** was recorded over the ensuing 16 days at the MSU Research Nursery, in addition to measuring the volume of surface **(b)** and subsurface **(c)** return flow and associated load of pesticide content (Prodiamine **d**, **e**; Thiophanate-Methyl (TPM) **f, g**; and Glyphosate **h**, **i**) exported in surface return flow on 1, 2, 11, and 16 days after application, and subsurface return flow 1, 2, 4, and 16 days after application. Means followed by respective color-coded letters are significantly different at $p < 0.05$ by Tukey's HSD.

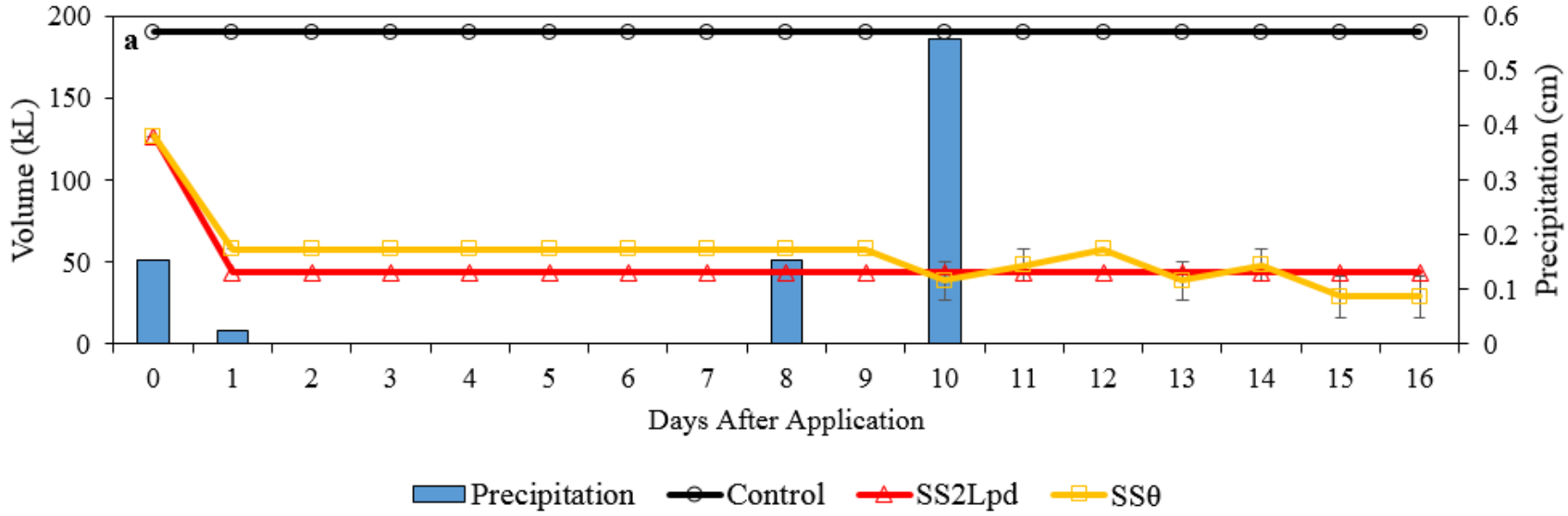


Figure 3.5 (cont'd)

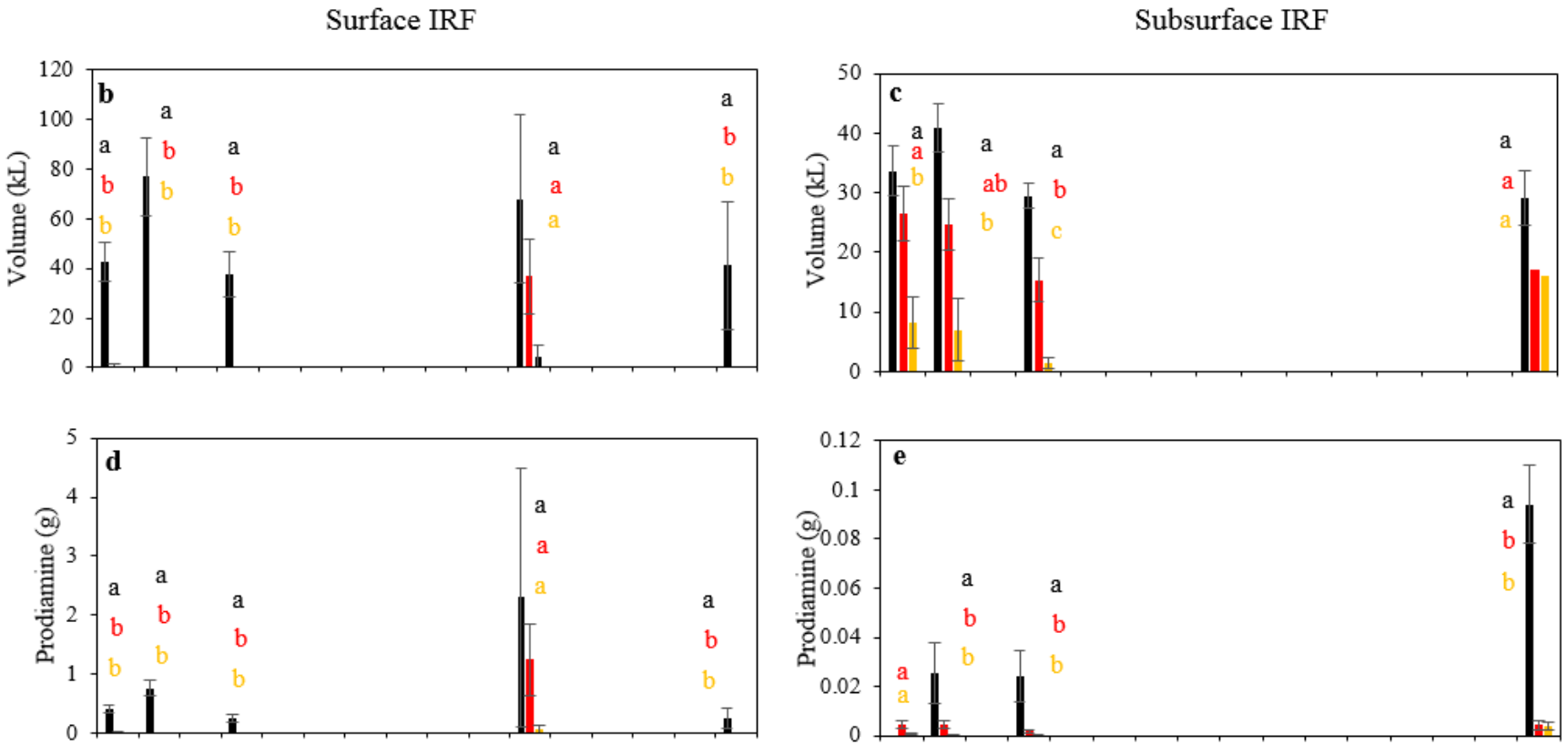
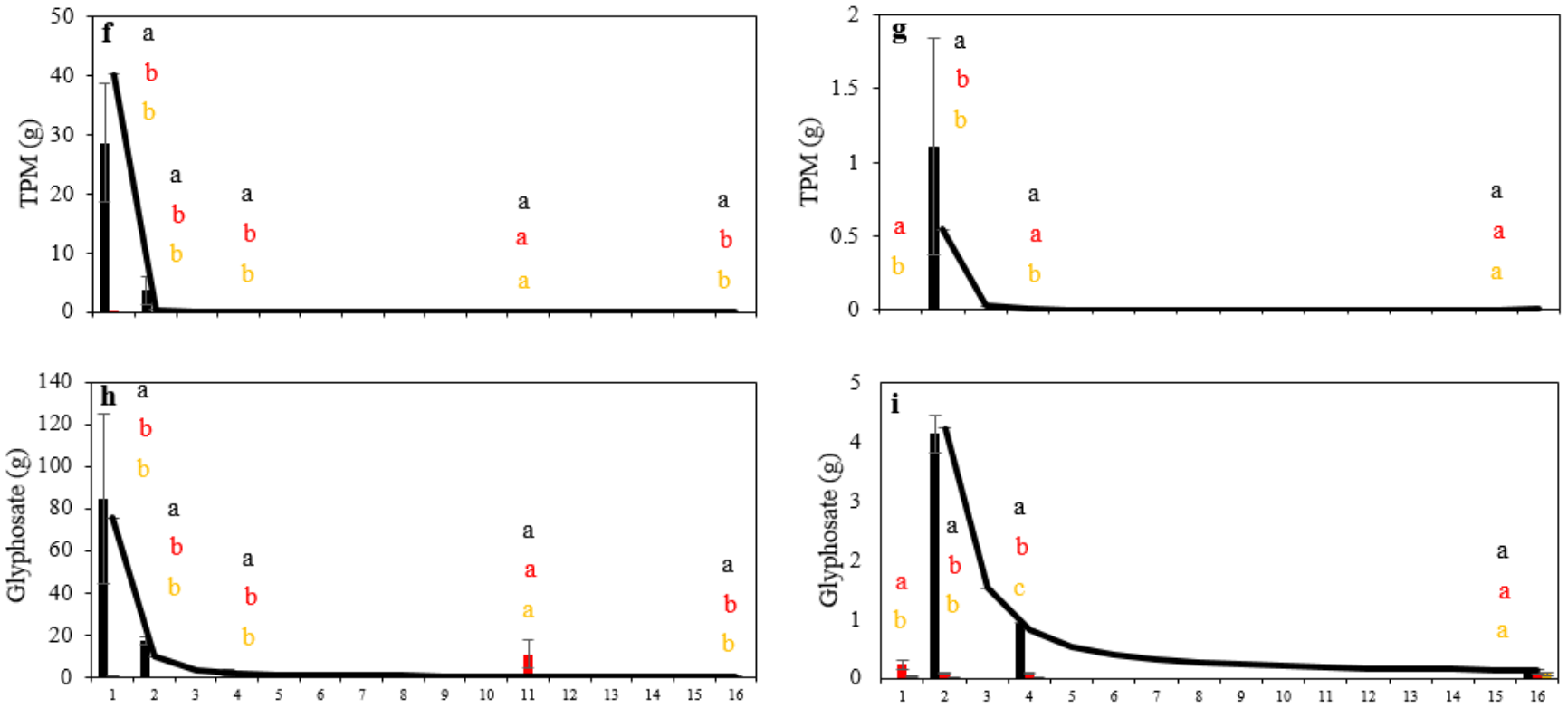


Figure 3.5 (cont'd)



LITERATURE CITED

LITERATURE CITED

Abdi, D.E.; Fernandez, R.T., 2019. Reducing water and pesticide movement in nursery production. HortTechnology. 04298, 1-6.

Abdi, D.E., Owen, J.S. Jr., Brindley, J.C., Birnbaum, A.C., Wilson, P.C., Hinz, F.O., Reguera, G., Lee, J.Y., Cregg, B.M., Kort, D.R., Fernandez, R.T., 2020. Nutrient and pesticide remediation using a two-stage bioreactor-adsorptive system under two hydraulic retention times. Water Res. 170, 1-14.

Agro, E., Zheng, Y., 2014. Controlled-release fertilizer application rates for container nursery crop production in southwestern Ontario, Canada. HortScience. 49, 1414-1423.

Alister, C.A., Gomez, P.A., Rojas, S., Kogan, M., 2009. Pendimethalin and oxyfluorfen degradation under two irrigation conditions over four years application. J. of Environ. Sci. and Health part B. 44, 337-343.

Battagin, W.A., Kolpin, D.W., Scribner, E.A., Kuivila, K.M., Sandstrom, M.W., 2005. Glyphosate, other herbicides, and transformation products in Midwestern streams. J. of Am. Water Resour. Assoc. 41, 323-332.

Beeson, R.C. Jr., Knox, G.W., 1991. Analysis of efficiency of overhead irrigation in container production. HortScience. 26, 848-850.

Bertotto, L.B., Dasgupta, S., Vliet, S., Dudley, S., Gan, J., Volz, D.C., Schlenk, D., 2019. Evaluation of the estrogen receptor alpha as a possible target of bifenthrin effects in the estrogenic and dopaminergic signaling pathways in zebrafish embryos. Sci. of the Total Environ. 651, 2424-2431.

Bilderback, T.E., 2002. Water management is key in reducing nutrient runoff from container nurseries. HortTechnology. 12, 541-544.

Brander, S.M., Gabler, M.K., Fowler, N.L., Connon, R.E., Schlenk, D., 2016. Pyrethroid pesticides as endocrine disruptors: molecular mechanisms in vertebrates with a focus on fishes. Environ. Sci. and Technol. 50, 8977-8992.

Breeden, S.M., Brosnan, J.T., Breeden, G.K., Vargas, J.J., Eichberger, G., Tresch, S., Laforest, M., 2017. Controlling dinitroaniline-resistant goosegrass (Eleusine indica) in turfgrass. Weed Technol. 31, 883-889.

Briggs, J.A., Riley, M.B., Whitwell, T., 1998. Quantification and remediation of pesticides in runoff water from containerized plant production. J. of Environ. Qual. 27, 814-820.

Briggs, J., Whitwell, T., Fernandez, R.T., Riley, M.B., 2002. Effect of integrated pest management strategies on chlorothalonil, metalaxyl, and thiophanate-methyl runoff at a container nursery. J. of Am. Hortic. Sci. 127, 1018-1024.

Briggs, J.A., Whitwell, T., Riley, M.B., 2003. Effect of delayed irrigation on isoxaben and oryzalin runoff from a container nursery. Weed Sci. 51, 463-470.

Burnett, S.E., van Iersel, M.W., 2008. Morphology and irrigation efficiency of Gaura lindheimeri grown with capacitance sensor-controlled irrigation. HortScience. 43, 1555-1560.

Camper, N.D., Kim, J.H., Riley, M.B., 2001. Degradation of isoxaben in soils and an aqueous system. J. of Environ. Sci. and Health part B. 36, 729-739.

Cycon, M., M. Wojcik, Piotrowska-Seget Z., 2011. Biodegradation kinetics of the benzimidazole fungicide thiophanate-methyl by bacteria isolated from loamy sand soil. Biodegradation. 22, 573-583.

Davies, M.J., R. Harrison-Murray, C.J. Atkinson, O.M. Grant., 2016. Application of deficit irrigation to container-grown hardy ornamentalnursery stock via overhead irrigation, compared to drip irrigation. Agr. Water Manage. 163, 244-254.

Dion, H.M., Harsh, J.B., Hill, H.H. Jr., 2001. Competitive sorption between glyphosate and inorganic phosphate on clay minerals and low organic matter soils. J. of Radioanal. and Nucl. Chem. 249, 385-390.

Dow Form No. 233-00845-MM-1111

Garber, M.P., Ruter, J.M., Midcap, J.T., Bondari, K., 2002. Survey of container nursery irrigation practices in Georgia. HortTechnology. 12, 727-731.

Gardner, D.S., Branham, B.E., 2001. Effect of turfgrass cover and irrigation on soil mobility and dissipation of mefenoxam and propiconazole. J. of Environ. Qual. 30, 1612-1618.

Hashimoto, Y., Sugimoto, S., Soeda, Y., Sano, S., Nakata, A., Hashimoto, S., 1990. Absorption, translocation, and metabolism of the fungicide triflumizole in cucumber plants. J. of Pestic. Sci. 15, 375-383.

Hinz, F.O., Fisher, P.R., Wilson, P.C., 2019. Losses of Selected Pesticides in Drainage Water from Containerized Ornamental Plants. J. Environ. Qual. In Review.

Hu, J.H., Hong, C.X., Stromberg, E.L., Moorman, G.W., 2008. Mefenoxam sensitivity and fitness analysis of Phytophtora nicotianae isolates from nurseries in Virginia, USA. Plant Pathol. 57, 728-736.

Incrocci, L., Marzialetti, P., Incrocci, G., Di Vita, A., Balendonck, J., Bibbiani, C., Spagnol, S., Pardossi, A., 2019. Sensor-based management of container nursery crops irrigated with fresh or saline water. Agr. Water Manage. 213, 49-61.

Jin, M., Zhang, X., Wang, L., Huang, C., Zhang, Y., Zhao, M., 2009. Developmental toxicity of bifenthrin in embryo-larval stages of zebrafish. Aquat. Toxicol. 95, 347-354.

Lamack, W.F., Niemera, A.X., 1993. Application method affects water application efficiency of spray stake-irrigated containers. HortScience. 28, 625-627.

Lea-Cox, J.D., Bauerle, W.L., van Iersel, M.W., Kantor, G.F., Bauerle, T.L., Lichtenberg, E., King, D.M., Crawford, L., 2013. Advancing Wireless Sensor Networks for Irrigation Management of Ornamental Crops: an Overview. HortTechnology. 23, 717-724.

Lee, S., Gan, J., Kim, JS, Kabashima, J.N., Crowley, D.E., 2004. Microbial transformation of pyrethroid insecticides in aqueous and sediment phases. Environ. Toxicol. and Chem. 23, 1-6.

Leiva, J.A., Wilson, P.C., Albano, J.P, Nkedi-Kizza, P., O'Conner, G.A., 2019. Pesticide Sorption to Soilless Media Components Used for Ornamental Plant Production and Aluminum Water Treatment Residuals. ACS Omega. https://doi.org/10.1021/acsomega.9b02296

Lupi, L., Bedmar, F., Puricelli, M., Marino, D., Aparicio, V.C., Wunderlin, D., Miglioranza, K. S.B., 2019. Glyphosate runoff and its occurrence in rainwater and subsurface soil in the nearby area of agricultural fields in Argentina. Chemosphere. 225, 906-914.

Majsztrik, J.C., Fernandez, R.T., Fisher, P.R., Hitchcock, D.R., Lea-Cox, J., Owen Jr., J.S., Oki, L.R., White, S.A., 2017. Water Use and Treatment in Container-grown specialty crop production: a review. Water Air Soil Pollut. 228, 1-27.

Milhome, M.A.L., Sousa, P.L.R., Lima, F.A.F., Nascimento, R.F., 2015. Influence the use of pesticides in the quality of surface and groundwater located in irrigated areas of Jaguaribe, Ceara, Brazil. Int. J. of Environ. Res. 9, 255-262

Million, J.B. and T.H. Yeager., 2015. Capture of Sprinkler Irrigation Water by Container-grown Ornamental Plants. HortScience. 50, 442-446.

MSU, 2020. https://enviroweather.msu.edu/weather.php?stn=msu. (18 September 2020)

NCBI https://pubchem.ncbi.nlm.nih.gov/ (18 September 2020).

http://npic.orst.edu/factsheets.html (18 September 2020).

Pershey, N.A., R.T. Fernandez, B.M. Cregg and J.A. Andresen., 2015. Irrigating based on daily water use reduces nursery effluent volume and nutrient load without reducing growth of

four conifers. HortScience. 50, 1553-1561. https://doi.org/10.21273/HORTSCI.50.10.1553

Pollegioni, L., Schonbrunn, E., Siehl, D., 2011. Molecular basis of glyphosate resistance – different approaches through protein engineering. FEBS Journal. 278, 2753-2766.

Riley, M.B., Keese, R.J., Camper, N.D., Whitwell, T., Wilson, P.C., 1994. Pendimethalin and oxyfluorfen residues in pond water and sediment from container plant nurseries. Weed Technol. 8, 299-303.

Rosenberger, D.A., Robinson, T.L., Schupp, J.R., Engle-Ahlers, C.A., F.W. Meyer., 2003. Effect of sterol-demethylation inhibiting fungicides on apple fruit set, fruit size, total yield, and gross returns. HortScience. 38, 601-604.

Sardiña, P., Leahy, P., Metzeling, L., Stevenson, G., Hinwood, A., 2019. Emerging and legacy contaminants across land-use gradients and the risk to aquatic ecosystems. Sci. of the Total Environ. 695, 1-13.

Sasal, M.C., Demonte, L., Cislaghi, A., Gabioud, E.A., Oszust, J.D., Wilson, M.G., Michlig, N., Beldoménico, H.R., Repetti, M.R., 2015. Glyphosate loss by runoff and its relationship with phosphorus fertilization. J. of Agr. Food Chem. 63, 4444-4448.

Saunders, L.E., Pezeshki, R., 2015. Glyphosate in runoff waters and in the root-zone: a review. Toxics. 3, 462-480.

Stagg, N.J., LeBaron, M.J., Eisenbrandt, D.L., Gollapudi, B.B., Klaunig, J.E., 2012. Assessment of possible carcinogenicity of oxyfluorfen to humans using mode of action analysis of rodent liver effects. Toxicol. Sci. 128, 334-345.

Stearman, G.K., George, D.B. Hutchings, L.D., 2012. Removal of nitrogen, phosphorus, and Prodiamine from a container nursery by a subsurface flow constructed wetland. J. of Bioremediation and Biodegrad. S7, 1-5.

Sun, S., Chen, Y., Lin, Y., An, D., 2018. Occurrence, spatial distribution, and seasonal variation of emerging trace organic pollutants in source water for Shanghai, C. Sci. of the Total Environ. 639, 1-7.

Triantafyllidis, V., Hela, D., Papadaki, M., Bilalis, D., Konstantinou, I., 2012. Evaluation of mobility and dissipation of mefenoxam and pendimethalin by application of CSTR model and field experiments using bare and tobacco tilled soil columns. Water Air Soil Pollut. 223, 1625-1637.

US Environmental Protection Agency., 1996. Test Methods. EPA Methods 3510C. Revision 3. [CD-ROM].

Van Iersel, M.W., Dove, S., Kang, J.G., Burnett, S.E., 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience. 45, 277-282.

Von Merey, G., Manson, P.S., Mehrsheikh, A., Sutton, P., Levine, S.L., 2016. Glyphosate and Aminomethylphosphonic acid chronic risk assessment for soil biota. Environ. Toxicol and Chem. 35, 2742-2752.

Vryzas, Z., 2018. Pesticide fate in soil-sediment-water environment in relation to contamination preventing actions. Curr. Opin. Environ. Sci. Health. 4, 5e9.

Walker, A., 1987. Evaluation of a simulation model for prediction of herbicide movement and persistence in soil. Weed Res. 27, 143-152.

Warsaw, A.L., Fernandez, R.T., Cregg, B.M., Andresen, J.A., 2009. Container-grown ornamental plant growth and water runoff nutrient content and volume under four irrigation treatments. HortScience 44, 1573-1580.

Warsaw, A.L., Fernandez, R.T., Kort, D.R., Cregg, B.M., Rowe, B., Vandervoort, C., 2012. Remediation of metalaxyl, trifluralin, and nitrate from nursery runoff using container-grown woody ornamentals and phytoremediation areas. Ecol. Eng. 47, 254-263.

Weston, D.P., Holmes, R.W., You, J., Lydy, M.J., 2005. Aquatic toxicity due to residential use of pyrethroid insecticides. Environ. Sci. and Technol. 39, 9778-9784.

Xi, J., Shao, J., Wang, Y., Wang, X., Yang, H., Zhang, X., Xiong, D., 2019. Acute toxicity of triflumizole to freshwater green algae Chlorella vulgaris. Pesticide Biochem. and Physiol. 158, 135-142.

Zhang, Q., Li, S., Ma, C., Wu, N., Li, C., Yang, X., 2018. Simultaneous degradation of bifenthrin and chlorpyrifos by Pseudomonas sp. CB2. J. of Environ. Sci. and Health part B. 53, 304-312.

CHAPTER FOUR

Reducing Water Use, Irrigation Return Flow, and Nutrient Transport Using Sensor-Based Irrigation Management for Nursery Container Production

4.1 Abstract

Irrigation is commonly applied daily in container crop production, oftentimes at a static volume in excess of crop needs generating substantial irrigation return flow. Combined with the intensive fertilizer use common in container production, risk for nutrient export in irrigation return flow to receiving water bodies is of chief concern. Irrigating based on substrate moisture content (θ) allows more judicious applications of water to meet container crop needs, and can reduce irrigation return flow volumes. Sixteen raised beds were constructed, where four ornamental taxa were produced under three irrigation practices: a control, applying 19 mm daily via overhead irrigation, a θ guided overhead irrigation treatment applying up to 19 mm, and an individual container spray stake treatment applying up to 3 L per container. For each treatment, a pine bark/peat moss substrate was compared to a pine bark/coconut coir substrate. Raised beds were designed to allow collection of surface and subsurface return flow, with water volumes measured and samples analyzed for nitrate and phosphate content throughout the season. Irrigating based on θ reduced the volume of water applied between 49% and 77% compared to the control. For all four of the taxa studied, equivalent growth index was achieved after 99 days; however, shoot dry biomass was often times reduced in the sensor-based treatments relative to the control. Reductions in applied water associated with sensor based irrigation also reduced total irrigation return flow (up to 86%), particularly surface return flow (up to 99%), while also reducing the total load of nitrate and phosphate exported in surface return flow by up to 98%. Applying irrigation based on θ regardless of irrigation delivery method reduced the volume of water applied, as well as the volume of water and concomitant nutrient load lost to irrigation return flow compared to a static control, without

4.2 Introduction

The majority of freshwater extraction and consumption worldwide is used for agricultural production (Döll, 2009; Parsinejad et al., 2013; Pimentel et al., 2004). As global concerns mount over impending water security issues, water resources are likely to be preferentially allocated towards crops with direct human interest, considering that food production may need to be doubled by 2050 (Godfray et al., 2010; Rodell et al., 2018), thus relegating the needs of ornamental and specialty crops as a less critical consideration. Container crop production is an intensive industry, demanding substantial irrigation and agrochemical inputs to produce a salable crop. With respect to both the resources that container nurseries use, as well as the proximity of these nurseries to urban, suburban, and non-agricultural areas, management practices employed by container nurseries face magnified scrutiny from both regulators and the surrounding public (Berghage et al., 1999; Dennis et al., 2010; Fulcher et al., 2016). Nurseries that have access to ample, inexpensive water resources may not face the same pressure to limit water use; however, inefficient and excessively applied irrigation can also have negative consequences (Majsztrik et al., 2018). Irrigation return flow (IRF) can transport agrochemicals from production areas, with increased IRF volume enhancing mobility (Mangiafico et al., 2008; Pershey et al., 2015; Tyler et al., 1996; Warsaw et al., 2009b). Intensive fertilizer use is typical in container crop production as to not limit growth, where in conjunction with daily irrigation, the potential for nutrient movement in IRF is increased (Agro and Zheng, 2014; Owen et al., 2008). Container leachate can transport fertilizers, and irrigation water which fails to reach the crop contributes to IRF generation and facilitates the off-site movement of fertilizers (Pershey et al., 2015; Warsaw et al., 2009b; Yazdi et al., 2019). Concerns over pollutant transport to receiving water bodies have led to the implementation of total maximum daily loads (TMDLs) for impaired water bodies in the

U.S. (Clean Water Act; https://www.epa.gov/laws-regulations/summary-clean-water-act) and Europe (European Water Framework Directive EWFD: https://ec.europa.eu/environment/water/water-framework/index_en.html ; European Nitrate directive END: https://ec.europa.eu/environment/water/water-nitrates/index_en.html), affecting numerous prominent nursery crop production regions.

Frequent, typically daily, irrigation applications are necessary for producing container crops, as the evapotranspirative demands of the plant, the hydraulic properties of the substrate, and the container volume may provide limitations to the amount of available water for the crop. Irrigation is typically applied using overhead application systems, which applies water to the entire of production surface including both the containerized plant as well as the space between containers (Beeson and Knox, 1991; Paudel et al., 2016). Most of the overhead applied irrigation water is not captured in the plant container, where typically 74-87% reaches the inter-container spaces (Davies et al., 2016; Million and Yeager, 2015; Pershey et al., 2015), with inter-container space and crop canopy morphology affecting application efficiency (Beeson and Yeager, 2003). Micro-irrigation systems apply water directly to crops thus eliminating irrigation applied to the inter-container spaces; however, these systems require a greater infrastructure and maintenance investment. In-container spray stake irrigation provides a more efficient alternative to overhead irrigation; however, this irrigation practice is often employed only for larger sized containers (typically greater than 19 L), as the reduced application efficiency of overhead irrigation due to the greater crop size and inter-container spacing justifies the cost of implementing these systems (Beeson and Knox, 1991; Incrocci et al., 2014; Incrocci et al., 2019; Majsztrik et al., 2017).

Incorporating in-container substrate moisture sensors may allow for irrigation systems to apply water based on crop needs, either with an automated system or as a manual decision

support tool, allowing reductions in water usage and improving water use efficiency (Bayer et al., 2013, 2015; Burnett and van Iersel, 2008; Fernandez et al., 2019; Incrocci et al., 2019; Pershey et al., 2015; Warsaw et al., 2009a,b). Irrigating based on container substrate volumetric water content (θ) can reduce the volume of water applied while producing an equivalent or better plant for a wide range of ornamental taxa in nursery production environments (Bayer et al., 2015; Fernandez et al., 2019; Pershey et al., 2015; Warsaw et al., 2009a,b). The benefits of irrigating ornamental taxa based on θ may extend beyond water savings. In addition to reducing water use, θ directed irrigation practices can offer more control over crop growth, reduce pruning requirements, and limit fertilizer loss in container leachate, offering the potential to reduce the amount of fertilizer used (Bayer et al., 2013; Burnett and van Iersel, 2008; Pershey et al., 2015; van Iersel et al., 2010; Warsaw et al., 2009b).

In this study, we investigated irrigation practices and substrate blends in the production of four common container species. We compared a control that applied 19 mm daily via overhead irrigation with two irrigation treatments both applying irrigation based on θ, one applying up to 19 mm via overhead, and one applying up to 3 L per container via spray stake. For each of the two irrigation treatments, a pine bark:peat moss substrate was compared to a pine bark:coconut coir substrate. We hypothesized that irrigation practices applying water based on θ would reduce the volume of water applied, as well as the volume of water lost to irrigation return flow when compared to an overhead control. We hypothesized that coconut coir incorporation into substrate blends would increase water holding capacity based on reports of increased water retention from Abad et al. (2005) and Kukal et al. (2012) in substrates incorporating this material, and would reduce the volume of irrigation needed to achieve target θ. We hypothesized that limiting or reducing irrigation return flow would minimize nutrient export, particularly

nitrate. Finally, we hypothesized that irrigating to meet target θ would produce crops of equivalent growth (growth index, shoot dry weight, root dry weight) when compared to the control. Our objective for this study was to quantify the environmental and production impacts that irrigating based on θ and using different substrate blends may have in the production of four common container taxa.

4.3 Materials and Methods

4.3.1 Research Nursery

A research nursery was constructed at the Michigan State University Horticulture and Teaching Research Center (HTRC) in Holt, MI, USA (Latitude 42.67 N, Longitude -84.48), with sixteen raised beds serving as replicates where three irrigation treatments and two substrates were compared. Treatments were initiated on 11 June, 2018 and concluded on 11 October, 2018. The experimental raised beds were arranged in two parallel rectangular blocks measuring 61 x 7.62 meters each with the length running north to south, and separated by a 1.8-m alley. Each rectangular block was divided into eight individual 7.62 x 7.62 x 0.6 m (LxWxH) beds for a total of 16 experimental beds. Native soil inside the walls of each individual bed was graded to achieve a 2% slope towards a center swale, funneling water to the outer eastern or western edge, respectively, of the individual beds in the two rectangular blocks. After the soil base was graded, a 9.1 x 9.1 m impermeable ethylene propylene diene monomer pondliner (Firestone Pondgard 45Mil (1.14 mm) Nashville, TN) was placed over each bed. Over the top of the pond liner, 0.3 m of washed natural sand, free of clay, with a particle size range of 0.75-9.5 mm was placed and graded in the same manner as the soil sub-base and covered with a black woven polypropylene landscape fabric (De Witt SBLT6300, Sikeston, MO). Bulkhead fittings were installed at the low points of the soil sub-base/pondliner and sand/fabric, respectively, and piped to 378 L polyethylene

tanks (Duracast, manufacturer number 900100-1.2, Lake Wales,FL) via 4.03 cm (inside diameter) schedule 40 PVC for the collection of surface return flow and subsurface return flow. Collection tanks were buried 15.2 cm below the soil level and anchored in place with concrete.

4.3.2 Irrigation Installation

Each of the raised beds was fitted with a 150 mesh inline filter (Toro T-ALFS75150-L, Bloomington MN), a 30 psi pressure regulator (Senninger PRL303F3F, Clermont, FL), a flow meter (Badger Meter 62585-001 model 25, Milwaukee, WI), and two solenoid valves (Rainbird CP075, Asuza, CA). Irrigation was applied via either overhead sprinklers K-Rain RN300-Adj (Riviera Beach, FL), or individual container spray stakes (Netafim 22500-002030, flow rate 12.1 Lph, Tel Aviv-Yafo, Israel). Overhead sprinklers were located at the corners of the 6.1 x 6.1 m area to be irrigated for all beds, while spray stake irrigated beds also had a manifold consisting of four 6.1-m sections of polyethylene tubing adjacent to plant rows providing water for the spray stakes.

4.3.3 Irrigation Control and Sensor Installation

Irrigation was managed with a wireless sensor and control network using Sensorweb software (Mayim LLC, Pittsburgh, PA, USA), with the computer and communication devices installed in the main building of the HTRC. Solenoid valves were controlled via DC powered control nodes (model NC24, Decagon Devices, Inc., Pullman, WA, USA), with each node controlling 4 beds. Nodes were installed on the western raised beds, and oriented towards the communication devices in the HTRC building. Substrate volumetric moisture content (θ) was monitored using moisture sensors connected to monitoring nodes (model 10HS and model EM50R, respectively, Decagon Devices, Inc.), where each bed had one monitoring node and four

moisture sensors set to take measurements at 5 minute intervals. Sensors were randomly assigned to one plant per taxa per bed and placed halfway between the top and bottom of the container.

4.3.4 Irrigation Treatments

A control of 19 mm applied daily via overhead irrigation was compared to two treatments irrigating based on substrate moisture content, one applying water via overhead application and the other using spray stakes. Container capacity was assessed for each of the beds prior to treatment initiation in 2018, with beds irrigated via the overhead sprinkler treatment intended to reach 100% of container capacity, and beds irrigated via the spray stake treatment to return to 100% of container capacity. Measured container capacities of the pine bark:peat moss (85:15 v/v) substrate was 38%; whereas it was 37% for the pine bark:coconut coir (80:20). For the overhead irrigated beds based on container capacity (hereafter referred to as OH), up to 19 mm was applied over three 6.33 mm cycles, with five minutes elapsing between each cycle to allow for moisture sensor readings. Similarly, the spray stake based on container capacity treatment (hereafter referred to as SS) provided up to three 1 L cycles, with five minutes between each cycle for moisture sensor readings. Irrigation commenced at 9:00 A.M. for control treatments, with both container capacity treatments beginning at 10:00 A.M. The sensor in the *H. paniculata* was used as the sole basis for the OH and spray stake treatments. Irrigation treatments were randomly assigned to each bed, with three beds serving as the control, six beds being used for the overhead OH treatment, and six beds for the spray stake sensor based treatment. One bed was left to serve as a blank, where 19 mm d^{-1} of overhead irrigation was applied to a bed without plants.

4.3.5 Plant Material, Substrate, and Fertilizer

Each individual raised bed (replicate) had a total of 81 plants, split between four taxa, and produced in 11.3 L containers. *Cornus sericea* 'Farrow', *Hydrangea paniculata* 'Limelight', *Rosa*

x'Meipeporia', and *Spiraea japonica* 'SMNSJMFP' (Spring Meadow Nursery, Grand Haven, MI) were grouped by taxa, with the order of placement randomly assigned. A pine bark:peat moss blend (85:15 v/v) substrate was compared with a pine bark:coconut coir mix (80:20 v/v) (Renewed Earth, Otsego, MI). The three control replicates used the pine bark/peat moss substrate, while three of the six OH and three of the six SS treatments were randomly assigned either the pine bark/peat moss or the pine bark/coconut coir substrate. One fertilizer rate for all beds, a 17-3.24-9.96 formulation (8.17% Nitrate Nitrogen, 8.83% Ammoniacal Nitrogen; 3.24% Phosphate, 9.96% Potassium) with micronutrients and a 5-6-month longevity at 27° Celsius (Harrell's, Lakeland, FL, USA). Each of the 81 plants per bed received 61.4 grams of fertilizer applied via top-dressing, for a per bed application rate of 4,973 g. Fertilizer was applied on June 11th, 2018. In total, the replications for each irrigation and substrate combinations were Control (19 mm via overhead / pine bark substrate; n=3), OH / pine bark (OH PB) (n=3), OH / pine bark + coir (OH PBC) (n=3), SS / pine bark (SS PB) (n=3), SS / pine bark + coir (SS PBC) (n=3).

4.3.6 Growth Index, Shoot and Root Dry Biomass Protocol

Growth index (GI) was measured on six sample dates, where measurements were taken on an X Y Z plane. For each taxa, three plants were randomly selected for growth index (GI) measurements, or the average width of the plant in a north-south orientation, an east-west orientation, and height from the top of the container to highest shoot/leaf tip. At the termination of the study, 3 plants for each species and for each bed were randomly selected for biomass assessment. Shoots were defoliated and severed at the substrate level prior to oven drying, while substrate was removed from root systems by hand initially, prior to using an air compressor to remove remaining substrate.

4.3.7 Nutrient Sampling Protocol

Collection tanks were emptied 24 hours prior to collection dates to allow the accumulation of subsurface return flow over a full day, and for surface return flow generated in response to a single irrigation event. The height of the water in the collection tanks was measured using a meter stick and converted to liters based on tank dimensions in order to quantify the amount of surface and subsurface return flow volume per bed. A 473 mL sampling cup was used to extract a water sample from each tank, provided there was surface or subsurface return flow generated. From there, an 8 mL sample was drawn into a 10 mL leur lock disposable polypropylene/polyethylene syringe, plunged through a 0.2 μm polyvinylidene fluoride filter into a 10 mL polystyrene Dionex vial (all ThermoScientific) and stored at −18 °C until analysis. Following sample collection, 5 ul of acetic acid was added to reduce pH and minimize phosphorus precipitation.

The 8-mL samples were thawed and analyzed for ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), phosphate (PO_4), potassium (K), calcium (Ca) and magnesium (Mg) concentrations using dual ion chromatography. Anion concentrations were determined at 30°C using an ICS-2100 gradient ion chromatograph (IC) system equipped with a hydroxide eluent generator cartridge, MFC-1 trap column, AG19 guard column, and an AS19 4 × 250 mm (i.d. × length) anion-exchange column (Thermo Fisher Scientific). Cation concentrations were determined via ICS-1600 at 35°C using a CG12A guard column and CS12A 4 × 250 mm (i.d. × length) cation-exchange column with sulfuric acid eluent (Thermo Fisher Scientific). Each system received the sample from an AS-AP autosampler to a 25-μL sample loop driven by an isocratic pump, with nutrients analyzed with a minimum detection limit of 0.19 mg L^{-1}.

4.3.8 Experimental Design and Statistical Analysis

A three way factorial completely randomized design was used for this study, with irrigation treatment, substrate treatment, and plant placement for individual beds randomly assigned. Data was analyzed using SAS v 9.4 (Cary, NC). Irrigation applied was subjected to analysis of variance using the PROC GLM procedure, when treatment effects were significant ($p<0.05$) means were separated using Tukey's test in the LSMEANS prompt. Assessment of average surface and subsurface return flow volumes throughout the season used only sample days in which less than 0.6 cm of precipitation occurred. The volumes of water lost to surface and subsurface return flow, nutrient concentration, and nutrient load were subjected to analysis of variance using the PROC Mixed procedure with repeated measures, again when treatment effects were significant ($p<0.05$) means were separated using Tukey's tests in the LSMEANS prompt. Shoot dry biomass and root dry biomass were subject to analysis of variance using the PROC GLM procedure, when treatment effects were significant ($p<0.05$) means were separated using Tukey's test in the LSMEANS prompt. Variable means and standard errors for irrigation applied, volume of water lost to surface and subsurface return flow, growth index, shoot dry biomass, root dry biomass, nutrient concentration, and nutrient load were calculated using the PROC MEANS feature.

4.4. Results

4.4.1 Water Applied

Between 11 June, 2018 and 11 October, 2018, the control applied 16,765 (+/- 173.6) kiloliters per hectare, which was greater than both OH treatments (OH PB: 8,872 +/- 983; OH PBC: 8201 +/- 745) and both SS treatments (SS PB: 3,992 +/- 746; SS PBC: 3885 +/- 517) (Figure 4.2). Both SS treatments were also effective in reducing the volume of water applied

compared to the two OH treatments. There were no differences in the volume of irrigation applied between the two substrates within in each irrigation treatment. Combining the two substrates for each irrigation treatment, the OH treatment and the SS treatment reduced the volume of irrigation applied when compared to the control by 49.1% and 76.5%; while the SS treatment reduced the volume of irrigation applied relative to the OH treatment by 53.8%. ANOVA identified an irrigation main effect in assessing total irrigation applied, while there were no substrate main effects or interactive effects.

In comparing the OH treatment and SS treatment with the control, the number of days irrigated was no different between treatments but consistently lower than the number of days the control irrigated across the months of June, July, August, September, and October, as well as the total days irrigated throughout the season ($p<.05$). When dividing irrigation treatments between the two substrates, the number of days irrigated was reduced ($p<.05$) compared to the control across all irrigation x substrate combinations during the months of August and September; however, during June and July the number of days irrigation was applied was no different between the control and irrigation treatments using a PB+C substrate, while the control remained greater than irrigation treatments using PB substrate during these months. ANOVA for the number of days irrigation was applied identified an irrigation main effect for every month throughout the study, a substrate main effect for July and October, and an interactive effect only during the month of September. The total amount of days irrigated when comparing the control versus the four irrigation x substrate combinations was greatest in the control versus any irrigation x substrate combination, while there were no differences between any of the treatments. The total number of days applied varied among irrigation treatments and substrates but there was no interaction between irrigation and substrate.

4.4.2 Irrigation Return Flow

4.4.2.1 Surface Irrigation Return Flow

Across all 15 sample dates, the control irrigation resulted in a greater volume of surface return flow than the SS irrigation (Figure 4.2). On 7 of these dates, the control irrigation also generated a greater volume of surface return flow than both OH treatments. OH irrigation exported equivalent volumes of surface return flow compared to both the control and the two SS treatments on 3 of the sample dates. Irrigation affected surface return flow on all 15 days on which it was measured but there was no effect of substrate or irrigation x substrate interaction effect. The total volume of water collected per hectare in surface return flow samples was greater in the control than all other treatments (figure 4.3).

4.4.2.2 Subsurface Irrigation Return Flow

Across all 15 sample dates there were only three dates where differences in subsurface return flow volume were identified (Figure 4.2). On day 2, the OH PB exported a greater volume of subsurface return flow than the SS PB, while all other treatments and the control were equivalent to both and each other. On day 36, the volume of subsurface return flow was greater in the OH PB than all other treatments. Finally, on day 52, the OH PB was greater than both the control and the SSPB, while the OH PBC and SSPBC were equivalent to both and each other. Of the 15 ANOVA tables from each sample date, only 3 exhibited an irrigation main effect, 1 exhibited a substrate main effect, and 4 exhibited an interaction effect. The total volume of subsurface return flow samples collected over the course of the season was equivalent across all treatments and the control (Figure 4.3); however, an irrigation main effect and an irrigation x substrate interactive effect were identified.

4.4.2.3 Irrigation Return Flow Totals

Combining surface and subsurface return flow volumes, the control exported a greater irrigation return flow volume than all treatments (Figure 4.3). OH PB was greater than SS PB; however, OH PBC and SS PBC were no different from either. Only an irrigation main effect was identified in ANOVA modeling the total irrigation return flow volume.

4.4.3 Cornus sericea 'Arctic Fire'

4.4.3.1 Growth Index

Measurements taken on the final two dates reflected no difference in growth index between the controls and the treatments (Figure 4.4). The control had a greater growth index than the SS and pbc combination over the first four measurement dates, greater growth than the SS PB treatment on days 39 and 59, as well as greater growth than the OH PB combination on day 15. ANOVA tables assessing the main and interactive effects of irrigation and substrate on growth index across the 6 sample dates identified that irrigation had a main effect on GI on each sample date. While there were no substrate main effects, an interaction effect was identified on day 15.

In assessing changes in growth index within the control over time, GI increased sequentially from day 15 to 39, and from day 39 to day 59; however, the GI measured on day 59 was no different from any subsequent measurement date. The control GI measured on day 73 was however greater than the GI measured on day 122. For all four treatments, GI increased sequentially from day 15 to 39, and from day 39 to day 59; however, the GI measured on day 59 was no different from any subsequent measurement date.

4.4.3.2 Shoot Dry Biomass

The control had greater shoot dry biomass than all treatments with the exception of the OH PBC treatment. The OH PBC treatment had greater shoot biomass than either of the SS treatments; but was no different from either the control or the OH PB treatment. ANOVA tables assessing the main and interactive effects of irrigation and substrate on shoot dry biomass identified a significant irrigation main effect, but no substrate or interactive effects.

4.4.3.3 Container Leachate pH

There were no differences in pH between the control and treatments on days 39, 99, and 122. On day 59, the SS PBC treatment had a higher pH than the SS PB treatment, while the control and two OH treatments were no different from either. On day 59, a substrate main effect, and a substrate and irrigation interactive effect were identified through ANOVA. There were no other main or interactive effects identified on other sample dates. Regression equations modelling pH over time indicated there was no change over time in pH for the control and all treatments, with the exception of the SS PB treatment exhibiting a linear increase over time (F value:7.62; R Squared: 0.43).

4.4.3.4 Container Leachate Electrical Conductivity

There were no differences in EC between the control and any treatments on any individual sample day. Regression equations modelling EC over time identified decreasing linear models for all treatments (OH PB: F value 7.76; R squared 0.46; OH PBC: F value 11.54; R squared 0.56; SS PB: F value 6.39; R squared 0.38; SS PBC: F value 20.37; R squared 0.69;); however, there was no relationship between EC and sample date for the control. ANOVA for EC exhibited no irrigation or substrate main effects or interactions on any sample date.

4.4.4 Hydrangea paniculata ‘Limelight’

4.4.4.1 Growth Index

There were no differences in growth index measurements on any sample date when comparing the control, OH PB, OH PBC, and SS PB treatments (Figure 4.5). SS PBC treatments were lower than the control on day 39, 59, 73, and 122, while also lower than the both the OH PB and the SS PB treatment on day 39. ANOVA tables assessing the main and interactive effects of irrigation and substrate on growth index identified a significant irrigation main effect on day 39, 59, 73, and 122; however, there were no substrate or interactive effects on any sample date.

In assessing changes in growth index within treatment over time, GI increased in the control from day 15 to day 39, day 39 to day 59, and day 59 to day 73; however, growth decreased from day 73 to day 99, before increasing again from day 99 to day 122, where it achieved peak GI. Similarly the OH PB treatment exhibited an increase in GI from day 15 to day 39, day 39 to day 59, and day 59 to day 73, prior to decreasing from day 73 to day 99, before again increasing to day 122, where it achieved peak GI. The OH PBC treatment exhibited increase in GI from day 15 to day 39, and day 39 to day 59. There were no changes in growth index between day 59 and day 73; however, between day 73 and 99 GI decreased, prior to increasing again from day 99 to day 122. The final growth index (day 122) of *Hydrangea* grown under the OH PBC treatment was no different from the growth index measured on day 73. GI of *Hydrangea* grown under the SS PB treatment increased from day 15 to day 39, day 39 to day 59, and day 59 to 73 prior to decreasing from day 73 to day 99, and finally increasing from day 99 to day 122 where it achieved its peak GI. GI of *Hydrangea* grown under a SS and PBC treatment increased from day 15 to day 39. Day 39 to day 59, and day 59 to 73; however, contrary to the control and the other

treatments, there were no changes (increasing or decreasing) between day 73 and 99. GI increased in SS PBC treatment from day 99 to day 122.

4.4.4.2 Shoot Dry Biomass

There were no differences in shoot dry biomass between the control and treatments. ANOVA identified only an irrigation main effect when modeling shoot dry biomass.

4.4.4.3 Root Dry Biomass

There were no differences in root dry biomass between the control and any of the treatments. ANOVA identified only a substrate main effect when modeling root dry biomass.

4.4.4.4 Container Leachate pH

There were no differences in pH between the control and treatments on sample days 99 and 122. On day 39, the control and OH PB treatment had a higher pH than the SS PBC treatment, while the OH PBC and SS PB treatments were no different from either. On day 59, the SS PB treatment had a higher pH than the SS PBC treatment, while both OH treatments and the control were no different from either. Regression equations modelling pH over time identified no change over time for the control or the OH PB treatment; whereas a linear increase was identified for the OH PBC (F value: 10.29; R squared 0.23), and both SS treatments (SS PB F value: 4.61; R squared 0.12; SS PBC F value: 22.22; R squared 0.40).

4.4.4.5 Container Leachate Electrical Conductivity

There were no differences in EC between the control and treatments on sample days 99 and 122. On sample day 39, the SS PBC treatment had a greater EC than either the control or OH PB treatment, while the OH PBC and SS PB treatment were no different from either. On day 59, the SS PBC treatment had a greater EC than the control or the SSPB treatment, while the two

OH treatments were no different from either. Regression equations modelling EC over the sample period identified a linear decrease for the control (F value 39.73; R squared 0.54) and all treatments (OH PB: F value 13.14; R squared 0.28; OH PBC: F value 24.59; R squared 0.42; SS PB: F value 16.52; R squared 0.33; SS PBC: F value 32.19; R squared 0.49).

4.4.5 Rosa x

4.4.5.1 Growth Index

Measurements over the last two sample dates (Day 99, Day 122), as well as over the first two sample dates (Day 15, Day 39) reflected no difference between the control and treatments (Figure 4.6). However, the GI of *Rosa* grown under the SS PBC treatment was lower than the control and all other treatments on day 59, and lower than the control and OH PBC treatment on day 73, while no different from the OH PB and SS PB treatment. ANOVA assessing GI identified an irrigation main effect as well as an interactive effect between irrigation and substrate on days 59 and 73.

In assessing changes in growth index within treatment over time, GI increased in the control from day 15 to day 39, and day 39 to day 59. Between day 59 and day 73 there was no increase in growth. GI increased in the control from day 73 to 99, but was no greater on the final sample date. The OH PB treatment increased from day 15 to day 39, and day 39 to day 59, but did not increase from day 59 to day 73. From day 73 through sample dates 99 and 122, GI increased. The OH PBC treatment increased from day 15 through sample days 39 and 59, but did not increase from day 59 to day 73. GI was greater on day 99 than day 73, but no different from the final measurement on day 122. The SS PB treatment increased from days 15 through days 39 and 59, but exhibited no sequential increases from day 59 to day 73, or day 73 to day 99; however, the GI on day 99 was greater than day 59. GI increased from day 99 to day 122. SS

PBC did not exhibit increases in GI over sequential measurement dates until growth increased from day 73 to day 99. There was no change in GI from day 122 and day 99. Despite there being only one instance where GI increased in sequential sample dates for SSPBC, growth was consistently greater on every measurement date versus the second most recent measurement under this treatment.

4.4.5.2 Shoot Dry Biomass

The control had greater shoot biomass than the SS PBC treatment; however, all other treatments had growth equivalent to both the control and the SS PBC treatment. ANOVA assessing shoot dry biomass identified no main or interactive effects for either irrigation or substrate.

4.4.5.3 Root Dry Biomass

There were no differences in root dry biomass between the control and treatments. ANOVA identified an interactive effect between irrigation and substrate, but no individual main effects of either.

4.4.5.4 Container Leachate pH

There were no differences in pH between the control and treatments on days 59, 99, and 122. On day 39, the SS PB treatment had a higher pH than the SS PBC treatment, while the control and two OH treatments were no different from either. ANOVA identified no main or interactive effects for irrigation or substrate on any given sample date. Regression equations modeling pH over the sample period identified a linear increase over time for the control (F value: 5.01; R squared 0.33), while no models were significant for any of the treatments.

4.4.5.5 Container Leachate Electrical Conductivity

There were no differences in EC between the control and treatments on any sample date. ANOVA identified no main or interactive effects for irrigation or substrate on any given sample date. Regression equations modeling EC over the sample period identified a linear decrease in EC over time for the control and all treatments, with the exception of SS PB treatment which exhibited no change over time (Control: F value: 16.4 R squared 0.62; OH PB: F value 20.11; R squared 0.67; OH PBC: F value 41.34; R squared 0.81; SS PBC: F value 11.88; R squared 0.54).

4.4.6 Spiraea japonica 'Double Play Pink'

4.4.6.1 Growth Index

GI measured on days 15 and 99 were equivalent between the control and all treatments (Figure 4.7). Final GI, measured on day 122, was greater in the control than either of the SS treatments, while the OH treatments were both equivalent to the control and SS treatments. Measurements taken on day 39 were greater in the control than either of the PBC treatments, while the PB treatments were no different from either. On days 59 and 73, the control had a greater GI than any other treatment. ANOVA for GI identified an irrigation main effect on all sample days post day 15, and no substrate main effects or interactive effects on any date.

In assessing changes in growth index within treatment over time, GI increased sequentially in the control from day 15 through day 39 and day 59; however did not increase from day 59 to day 73 or day 73 through 99. The final growth index was greater than the GI on day 99, but no different from day 73. In the OH PB treatment, GI increased sequentially in the control from day 15 through day 39 and day 59; however did not increase from day 59 to day 73 or day 73 through day 99. The final growth index was greater than all other days. In the OH PBC treatment, GI increased sequentially in the control from day 15 through day 39 and day 59;

however did not increase in sequential sample dates from day 59 through day 122. The final GI was greater than all prior measurement days, with the exception of day 99. In the SS PB treatment, there was only an increase in GI on sequential sample dates from day 15 to day 39. The final GI on day 122 was greater than all prior measurement dates, with the exception of day 99. In the SS PBC treatment, GI increased in sequential sample dates from day 15 through day 39 and day 59; however, there were no increases in sequential sample dates from day 59 through day 122. Final GI was greater on day 122 than day 15 through 59, but no different from days 73 and 99.

4.4.6.2 Shoot Growth

Shoot dry biomass was greater in the control than all other treatments, which were no different from each other. ANOVA identified a main effect from irrigation, but no substrate main effects or interactive effects were significant.

4.4.6.3 Root Growth

Root dry biomass was greater in the control than all other treatments, which were no different from each other. ANOVA identified a main effect from irrigation, but no substrate main effects or interactive effects were significant.

4.4.6.4 Container Leachate pH

There were no differences in pH between the control and treatments on days 25, 45, and 108. On day 85, both the control and OH PB treatment were greater than the SS PB treatment, while the OH PBC and SS PBC treatments were no different from either. ANOVA identified no main or interactive effects for irrigation or substrate on any given sample date. Regression equations modeling pH over the sample period identified no change over time for the control and

all treatments, with the exception of the SS PBC treatment exhibiting a linear increase (F value: 6.06; R squared 0.38).

4.4.6.5 Container Leachate Electrical Conductivity

There were no differences in EC between the control and treatments on any sample date. ANOVA identified a main effect for both irrigation and substrate on day 85, but no interactive effects. No other main or interactive effects were significant on any other sample date. Regression equations modeling EC over the sample period identified a linear decrease for the control and all treatments, with the exception of the OH PB treatment which exhibited no change over time. (Control: F value 13.9; R squared 0.58; OH PBC: F value 11.59; R squared 0.54; SS PB: F value 10.44; R squared 0.51; SS PBC: F value 31.85; R squared 0.76)

4.4.7 Nitrate Concentration in Irrigation Return Flow

The concentration of nitrate in surface return flow was equivalent across all 15 sample dates, with the exception of day 2 and day 8 (Figure 4.8). Average surface return flow concentrations did not exceed 2 mg L^{-1} Nitrate-N across the control or treatments. Of the 15 ANOVA tables, 7 had a significant irrigation main effect, 1 had a substrate main effect, and none of them had an interactive main effect.

An increasing then decreasing quadratic relationship between surface return flow nitrate concentration and day of sampling was identified in the control (F value: 7.85 R squared 0.37), OH PB (F value: 10.58 R squared 0.54) and OH PBC (F value: 9.07 R squared 0.36) treatment when log transforming both axes. SS surface return flow nitrate concentrations were not modeled, considering most sample dates there was zero surface return flow generated via this treatment.

The concentration of Nitrate-N in subsurface return flow was equivalent on 11 of the 15 sample dates, where the SS PBC treatment had greater concentrations than either some of the treatments (OH PB on day 4; OH PB and OH PBC on day 29; and OH PBC and SS PBC on day 36), or all treatments and the control (day 107). Of the 15 ANOVA tables, 2 had a significant irrigation main effect, 2 had a substrate main effect, and 3 of them had an interactive main effect. The control and all treatments exhibited an increasing then decreasing quadratic relationship between concentration and time (Control: F value: 8.25 R squared 0.38; OH PB: F value: 15.77 R squared 0.43; OH PBC: F value: 5.13 R squared 0.20; SS PB: F value: 6.88 R squared 0.25; SSPBC: F value: 9.09 R squared 0.31).

4.4.8 Nitrate Load in Irrigation Return Flow

The load of Nitrate-N exported in surface return flow over the 15 sample dates were different between treatments on 8 occasions, 4 of which the control exported a greater quantity than all treatments, and 4 of which the control exported a greater load than both SS treatments; however, both OH treatments were equivalent to both the control and SS treatments (Figure 4.8). Of the 15 ANOVA tables, 10 had a significant irrigation main effect, while there were no substrate main effects or interactive effects between the two. When log transforming both axes, the control (F value: 7.09; R squared 0.34) and the OH PB treatment (F value:4.53; R squared 0.33) exhibited a quadratic increase then decrease in nitrate load in surface return flow, while the OH PBC treatment exhibited a decreasing quadratic relationship (F value: 3.33; R squared 0.17). Per hectare, the control exported a greater total amount of Nitrate-N in surface return flow (817 +/- 29.5 grams), than the OH PB (226 +/- 125), SS PB (45.7 +/- 27.2), and SS PBC (15.1 +/- 10.4); while the OH PBC (400 +/- 283) was equivalent to the control and other treatments

(Figure 4.3). The total load recovered in surface return flow exhibited an irrigation main effect based on ANOVA.

The load of Nitrate-N exported in subsurface return flow over the 15 sample dates were different on only three occasions, day 8 where the SS PBC was greater than the OH PBC, while nothing else was different from each other; day 36, where OH PB was greater than the control, OH PBC, and SS PB, with SS PBC equivalent to everything; and finally 107 where SS PBC was greater than the control and all other treatments. Of the 15 ANOVA tables, main effects only occurred once for either irrigation or substrate; however, interactive effects were significant for 5 of the tables. The control exhibited a linear decrease (F value: 31.97: R squared 0.53) in nitrate load over time while both OH PB (F value: 8.05; R squared 0.28) and SSPBC (F value: 4.79; R squared 0.19) exhibited a quadratic increase then decrease in subsurface return flow. There were no differences between the total load of Nitrate-N exported between the control and treatments (Figure 4.3). The total irrigation return flow Nitrate-N load exported was greater in the control than SSPB; however, the OH PB, OH PBC, and SS PBC treatments were no different from any treatment or the control (Figure 4.3). ANOVA identified an irrigation main effect, but no substrate or interactive effects.

4.4.9 Phosphate-P Concentration in Irrigation Return Flow

The concentration of nitrate in surface return flow was equivalent across all 15 sample dates, with the exception of day 30, day 36, day 74, and day 107 (Figure 4.9). Average surface return flow concentrations did not exceed 0.15 mg L^{-1} Phosphate-P across the control or treatments. Of the 14 ANOVA tables, 5 had a significant irrigation main effect, 0 had a substrate main effect, and 1 of them had an interactive main effect.

The concentration of Phosphate-P in subsurface return flow was equivalent across all 15 sample dates, and often times at the limit of detection. The average concentration across any sample date for any treatment did not exceed 0.14 mg L^{-1}. Of the 11 ANOVA tables, 0 had a significant irrigation main effect, 1 had a substrate main effect, and 0 of them had an interactive main effect.

4.4.10 Phosphate Load in Irrigation Return Flow

The load of Phosphate-P exported in surface return flow over the 15 sample dates were different between the control and treatments on 11 occasions, 8 of which the control exported a greater quantity than all treatments, 2 of which where the control exported a greater load than both SS treatments; however, both OH treatments were equivalent to both the control and SS treatments, and finally one date where the control was greater than all treatments with the exception of the OH PBC treatment (Figure 4.9). Of the 15 ANOVA tables, 12 had a significant irrigation main effect, while there were no substrate main effects or interactive effects. The control exported a greater total amount of Phosphate-P in surface return flow (50.7 +/- 4.38 grams/hectare) than the OH PB (12.2 grams +/- 5.94), the SS PB treatment (2.76 +/- 1.78), and the SS PBC treatment (1.08 grams +/- 0.63). The OH PBC treatment exported 23.1 grams (+/- 15.2) over the entire season, which was no different from any other treatment or the control (Figure 4.3). The total load recovered in surface return flow exhibited an irrigation main effect based on ANOVA, while there was no substrate or interactive effects.

The load of Phosphate-P exported in subsurface return flow over the 15 sample dates was different between the control and treatments on 2 occasions, day 36 where the OH PB exported a greater load than the control and all treatments, and day 52 where OH PB was again greater than the control and SS PB, but the OH PBC and SSPBC treatments were no different from either. Of the 15 ANOVA tables, 2 had a significant irrigation main effect, 1 had a substrate main effect,

and 2 exhibited an interactive effect. There was no difference in the total load of phosphate recovered in subsurface return flow between the control and treatments (Figure 4.3), and there were no main or interactive effects identified via ANOVA.

Load of phosphate-P recovered per hectare in total irrigation return flow was greatest in the control (57 grams +/- 30.6) relative to the OH PB (25.4 grams +/- 5.45), SS PB (8.44 +/- 0.95), and SSPBC (9.44 grams +/- 1.03). OH PBC (34.2 +/- 5.45 grams) was no different from the control or any treatment (Figure 4.3). ANOVA identified an irrigation main effect, but no substrate main effect or interactive effects.

4.5 Discussion

4.5.1 Irrigation Applied

Irrigating container crops based on substrate θ reduced water usage compared to the common practice of a daily, static volume of irrigation applied via overhead, regardless of whether the same overhead system is utilized, or a micro-irrigation system is utilized. Irrigating based on θ reduced the volume of water applied by 49% and 77% for overhead systems and spray stake systems, when compared to the control. This was consistent with Warsaw (2009a) et al report of water savings of 6-75% when using soil moisture sensors to direct irrigation volumes when compared to a similar 19 mm overhead application, as well as Fernandez et al.'s (2019) reported water savings of up to 23% in production *Hydrangea*, and 57% for *Itea virginica* 'Morton', again when using soil moisture sensors to direct irrigation when compared to a 19 mm control. SS treatments were even more effective than the OH treatments in reducing water usage; however, spray stakes are typically more common in larger containers, considering the additional labor required for spray stake implementation and maintenance. In addition to reducing the total volume of irrigation applied, the need to apply irrigation was eliminated on

certain days when irrigating based on θ. The reduction in irrigation volume applied when using soil moisture sensors, as well as energy required for pump operation, etc., was stated by Lichtenberg et al. (2013), providing more benefits to growers who employ θ driven irrigation practices.

4.5.2 Irrigation Return Flow

Irrigation return flow, particularly surface return flow, was heavily influenced by irrigation practice. The reduced volume of irrigation applied when using θ, regardless of irrigation delivery method, contributed to substantial reduction in surface return flow, where the total volume generated was 68-80% lower when using the OH treatments, and 97-99% lower when using the SS treatments in comparison to the control. This was consistent with both Pershey et al.'s (2015) and Warsaw et al.'s (2009b) report of both reduced water applied and water lost to return flow when irrigating using θ to dictate the volume applied. Total subsurface return flow did not vary between the control and treatments. Total combined return flow was greatest in the control. Surface return flow contributed to 89% of the total irrigation return flow generated in the control, 39-67% for the OH treatments, and 5-20% for the SS treatments.

4.5.3 Crop Growth

For all four taxa studied, equivalent GI was achieved under all treatment combinations and the control on day 99. For *Cornus* and *Rosa*, the final growth index was also equivalent. This was consistent with Warsaw et al. (2009a, 2009b), and Pershey et al. (2015) reporting no differences (and at times greater) growth index between substrate θ based treatments and a similar 19 mm control. Differences between treatments were exhibited in shoot dry biomass for every species outside of *Hydrangea*, with the control producing a greater shoot biomass than some or all treatments. The increase in shoot biomass with greater irrigation volumes applied, or

maintaining substrate θ at a higher level, was consistent with results from Bayer et al. (2013, 2015), and Burnett and Van Iersel (2008), as well as Tyler et al.'s (1996) report that irrigating to achieve a lower leaching fraction reduced shoot growth by 8%.

Root dry biomass was equivalent in *Hydrangea* and *Rosa*, while *Spiraea* had the greatest root dry biomass from the control. Tyler et al. (1996) reported no difference in root growth in *Cotoneaster dammeri* 'Skogholm' between irrigation practices targeting a certain leaching fraction; however, Bayer et al. 2015 found that for *Gardenia jasminoides* cultivars 'August beauty' and 'Radicans', root growth increased when substrates were maintained at a higher θ threshold.

4.5.3.1 Cornus

Cornus grown under all treatments and the control exhibited the same growth pattern, where after day 59 there was no increase in growth index, effectively plateauing thereafter. Shoot dry biomass was greatest in the control, relative to all treatments except the OH PBC treatment. For the two metrics used in assessing the growth of *Cornus* (GI, Shoot Dry Biomass), there were no differences on any date between the control and the OH PBC treatment.

4.5.3.2 Hydrangea

By all three metrics assessing crop growth (GI, Shoot Dry Biomass, Root Dry Biomass), *Hydrangea* was equivalent between the control and all treatments. For the control and 3 of the four treatments (excluding SS PBC), a decrease in growth index was identified between day 73 and day 99. This was attributed to the inflorescence weighing down shoots, reducing GI and at times resulting in snapping of stems. Fernandez et al. (2019) reported that *Hydrangea* required the greatest amount of irrigation of all taxa in their study; however, in this study all four treatments and the control grew to equivalent size while reducing water use by nearly 50-75%.

Consistent with their observations, limited differences were observed in growth index of *Hydrangea*.

4.5.3.3 Rosa

Rosa was capable of being produced to equivalent size (GI) across all treatments and the control over the final two measurement dates, as well as equivalent final root dry biomass. Differences were only exhibited between the control and SSPBC treatment, where reduced GI on day 59 and 73 were identified, and final shoot dry biomass was lower. Producing *Rosa* under SSPBC slowed growth, as evidenced by the lack of increase between sequential sample dates; however, by day 99 there were no differences. The other treatments and the control exhibited sequential increases in GI; however, growth plateaued between days 59 and 73, prior to increasing on later sample dates.

4.5.3.4 Spiraea japonica

Equivalent GI was achieved across all treatments relative to the control on day 99. Based on the increase in GI on sequential sample dates, as well as the greater growth exhibited on day 59 and 73, the control grew faster than all other treatments; however as it plateaued temporarily in growth, all treatments were able to reach equivalent size by day 99. Dry biomass of both shoots and roots was greater in the control than any of the treatments.

4.5.4 Nitrate Movement

The concentration of nitrate in surface return flow samples seldom differed across the fifteen sample dates. Concentrations of nitrate in subsurface return flow were generally equivalent. The EPA water quality standard for nitrate-N is 10 mg L^{-1}, and across all sample dates surface or subsurface concentrations did not exceed this threshold (EPA Nitrate Drinking Water https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-

regulations). This was consistent with Warsaw et al.'s (2009b) average nitrate concentrations in irrigation return flow often times less than 5.5 mg L^{-1} NO3 (1.2 mg L^{-1} Nitrate-N).

The load exported in surface return flow was oftentimes greatest in the control, as a result of greater surface return flow volumes generated. The total load of nitrate exported in surface return flow was reduced by 72%, 94%, and 98% when using the OH PB treatment and SS PB treatment, and SSPBC treatments, respectively. This was consistent with the Warsaw et al.'s (2009b) report of 38-59% reduction in nitrate load exported in irrigation return flow when irrigating using θ directed practices. Considering that the control generated more surface return flow than the θ based treatments, reducing or eliminating this vector is an effective way to limit Nitrate export.

4.5.5 Phosphate Movement

Phosphate-P concentrations were typically at or just above the limit of detection in surface return flow samples, and never averaged greater than 0.15 mg L^{-1}. Phosphate-P concentrations in surface return flow were similar to those reported by Warsaw et al. (2009b), where the peak concentration as 0.7 mg L^{-1}. Differences in surface return flow concentrations was largely dictated by whether surface return flow was in fact generated. Subsurface return flow concentrations of phosphate were typically at the limit of detection, consistent with Schipper et al.'s (2010) statement that phosphate is typically in low concentrations in groundwater.

Despite the lack of differences in phosphate concentration in surface return flow samples, the load exported was almost always greatest in the control, and oftentimes greater than the OH treatments. This was consistent with Warsaw et al.'s (2009b). Report of phosphate load reductions between 46 and 74% when irrigating using θ directed practices.

Considering that the concentrations of phosphate in subsurface return flow were almost universally below detection, the volume of subsurface return flow water produced serves as the best estimator of phosphate movement via this vector.

4.6 Conclusions

Irrigating using θ to determine the volume applied reduces water use by 49 to 77% when using overhead or individual container spray stake delivery methods; with no differences between the two substrates studied. In addition to reducing the volume of water applied, the number of days and/or the duration for which irrigation had to be applied was reduced when using θ driven irrigation practices. The reduced volume of irrigation applied when using the two θ driven treatments produced crops of equivalent GI for all four of the studied taxa 99 days after treatment initiation, if not sooner. It was observed that greater growth occurred early on under the control regiment; however, growth often slowed or plateaued, allowing treatments to reach equivalent size. Shoot growth was oftentimes greatest in control irrigated plants; however, all treatments produced equivalent shoot biomass for *Hydrangea*. Root growth was no different between control and treatments for *Hydrangea* or *Rosa*, but *Spiraea* again exhibited more growth when provided the control irrigation.

Concentrations of nitrate and phosphate were generally equivalent, indicating that the bioactivity of either nitrate or phosphate did not vary much between the control or treatment; however, the reduced volume of irrigation applied in the OH treatment, and the precision with which SS treatments applied water resulted in vast reductions in surface return flow generation, thus reducing the daily and total loads of nitrate and phosphate lost via this vector.

Irrigating based on θ is an effective tool that can effectively reduce the volume of irrigation applied, water lost to irrigation return flow (particularly surface return flow), and the

load of nitrate and phosphate exported from production. Irrigating based on θ can produce crops of equivalent size, and at times biomass, when compared to a standard practice of daily overhead irrigation. This study highlights the opportunities growers have to reduce water use and mitigate nutrient export by irrigating based on θ without sacrificing crop quality.

APPENDIX

Figure 4.1: Precipitation (A) and temperature (B) throughout the 2018 season at the MSU Research Nursery.

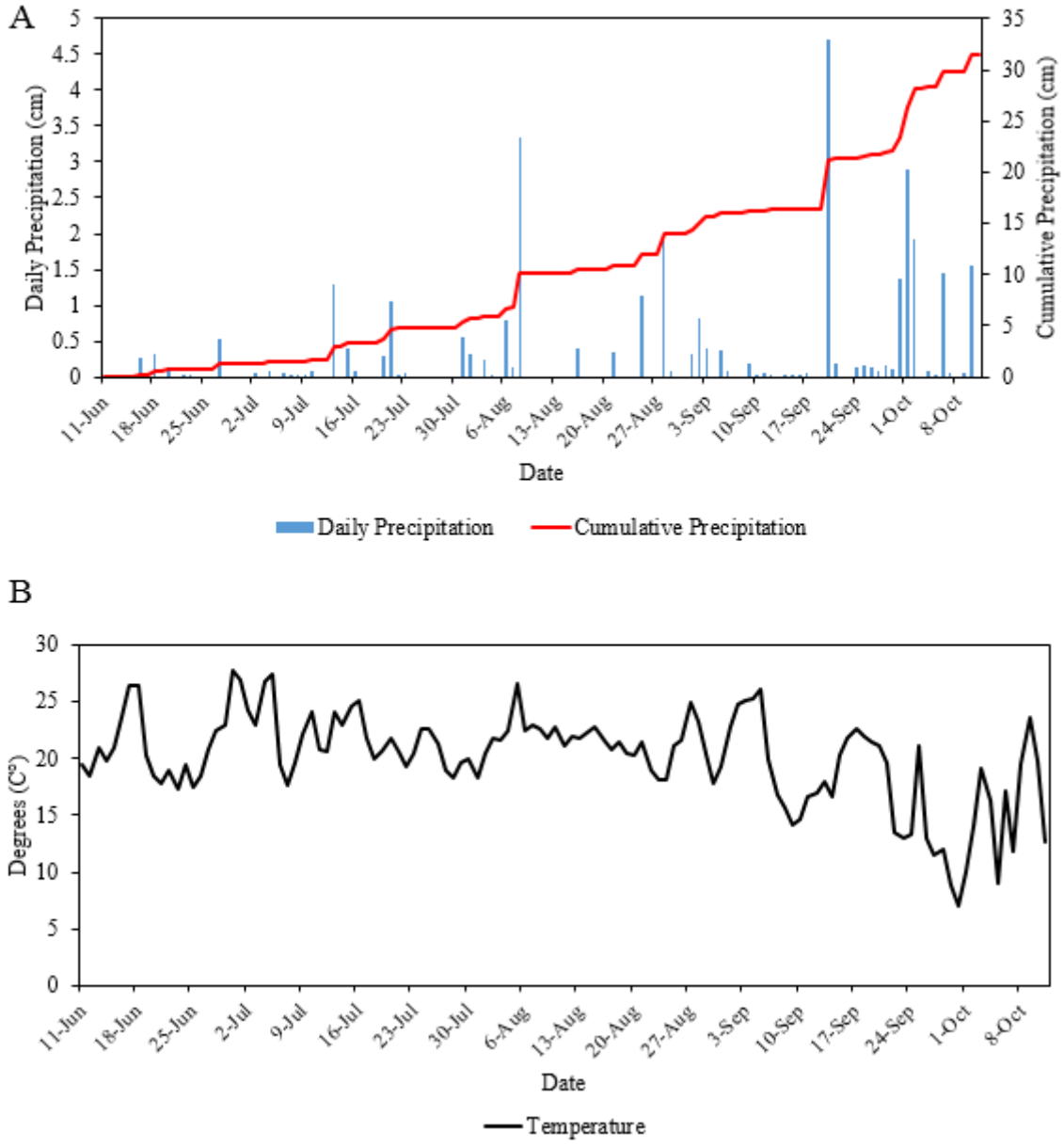


Figure 4.2: Cumulative irrigation applied per hectare (A), daily surface return flow volume per hectare (B), and daily subsurface return flow volume per hectare (C). Means were separated based on Tukey test at <.05 significance, indicated by color coded letters corresponding to irrigation treatment and underlined letters representing the PBC substrate. If there were no differences on a given date, letters were not displayed.

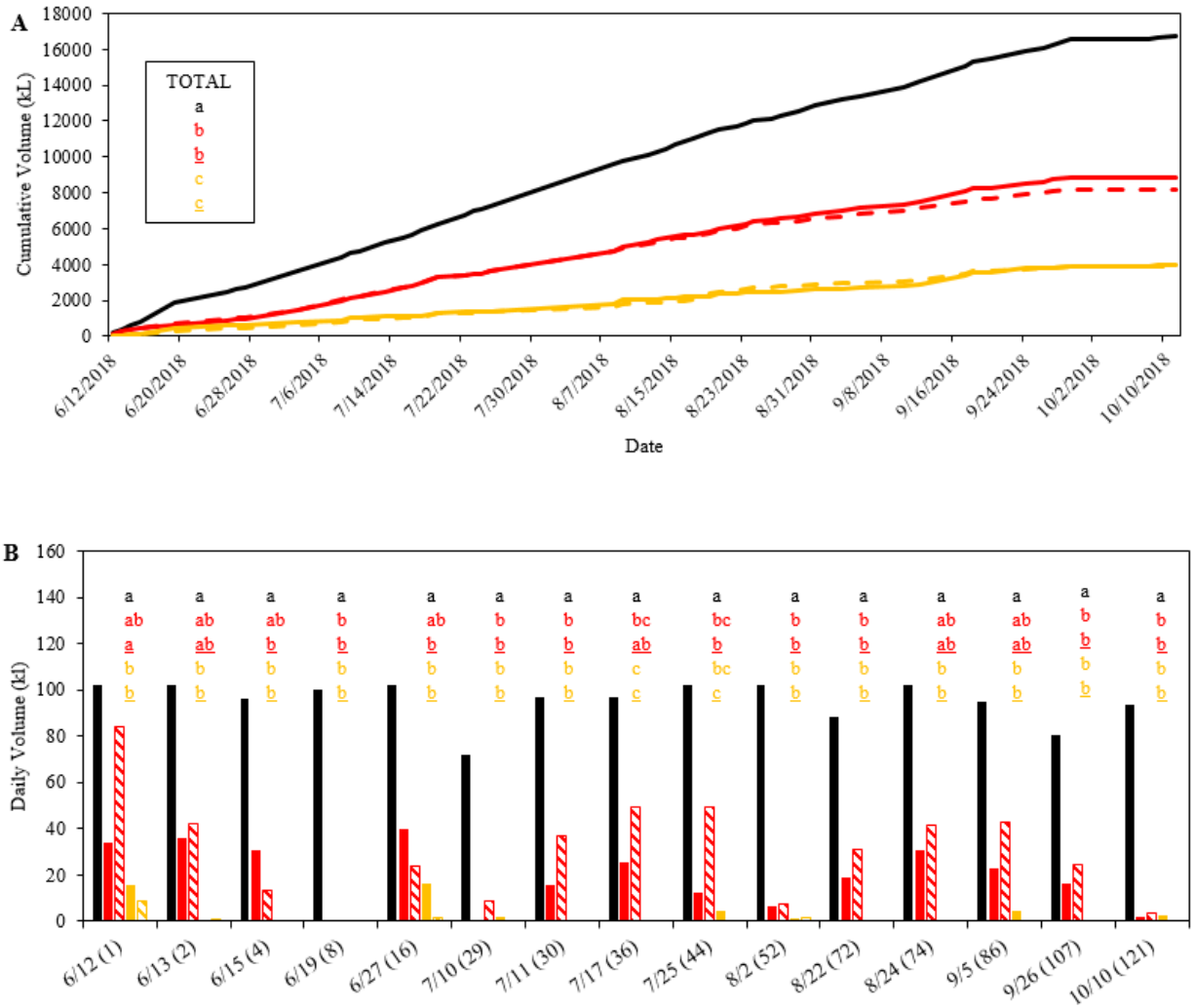


Figure 4.2 (cont'd)

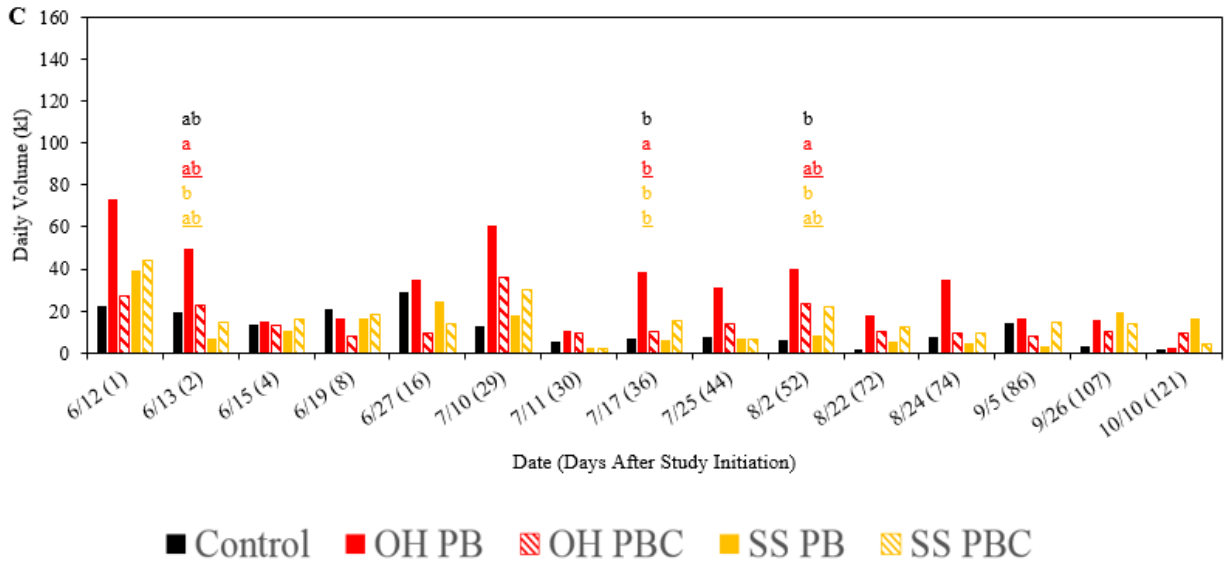
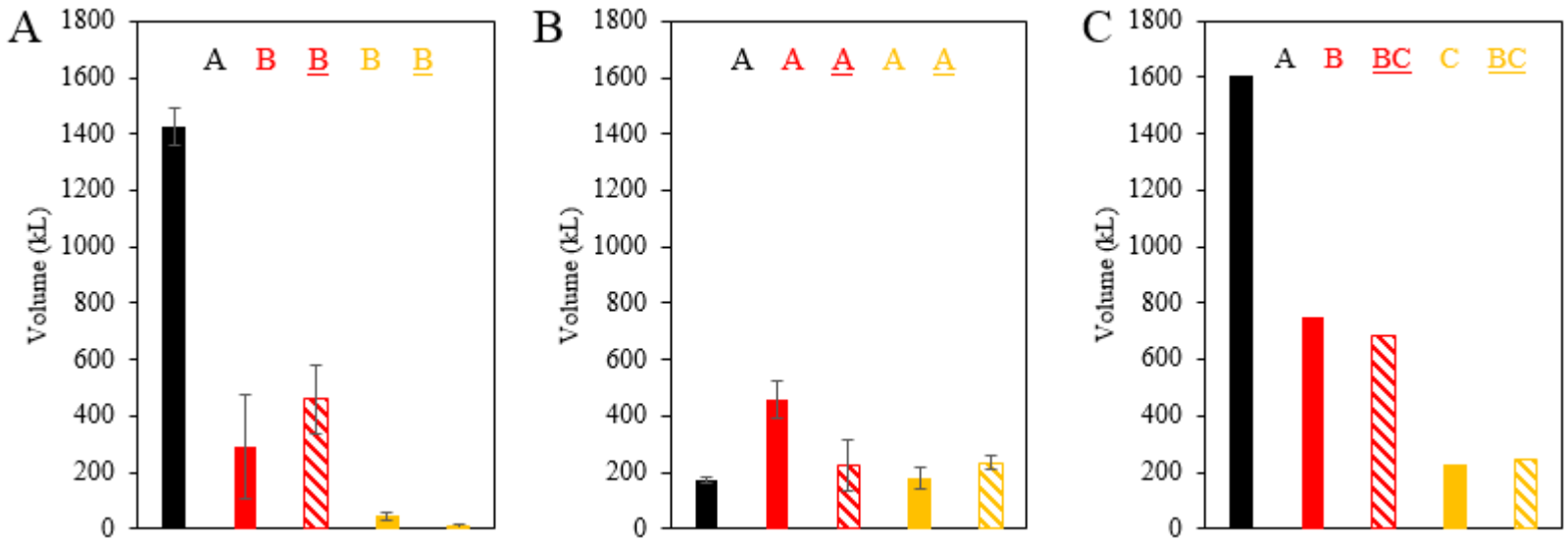


Figure 4.3: Total surface (A), subsurface (B), and combined irrigation return flow water volumes (C), Nitrate-N Load (Surface: D; Subsurface E; Combined: F), and Phosphate-P Load (Surface: G; Subsurface H; Combined: I) during the 2018 season (per hectare) over fifteen sample dates. Means, when significantly (<.05) different based on a Tukey test were separated by color coded letters corresponding to irrigation treatment, with the PBC substrate letters underlined.



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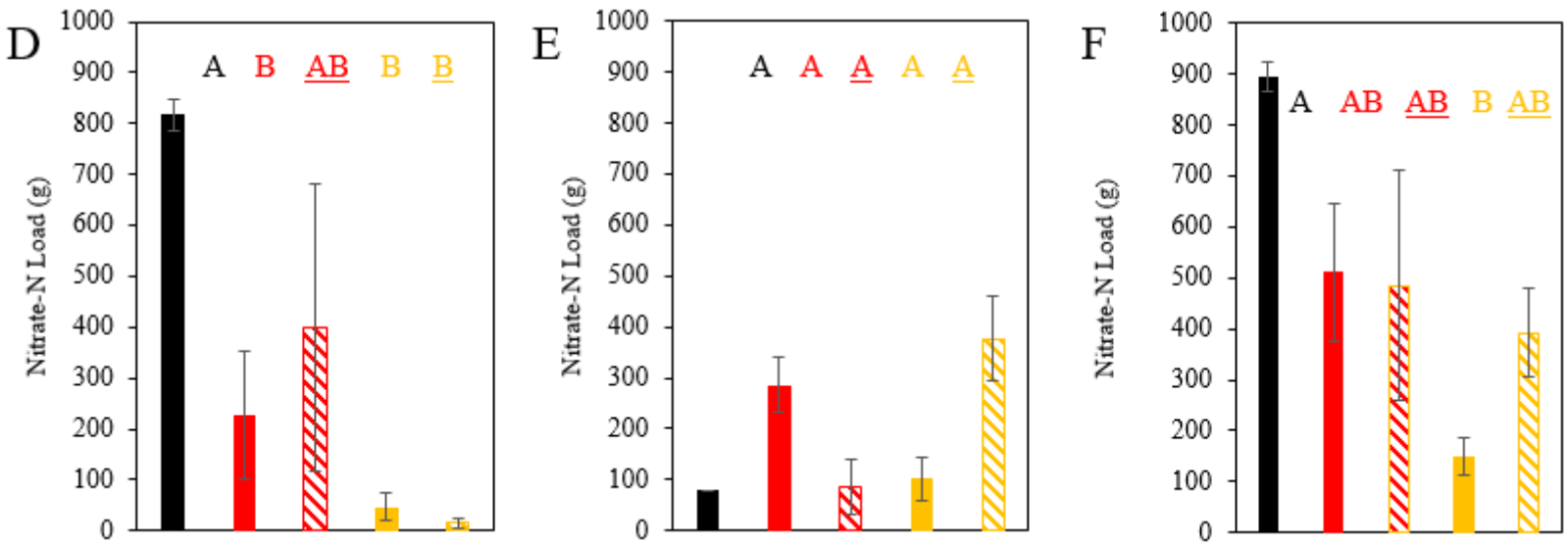

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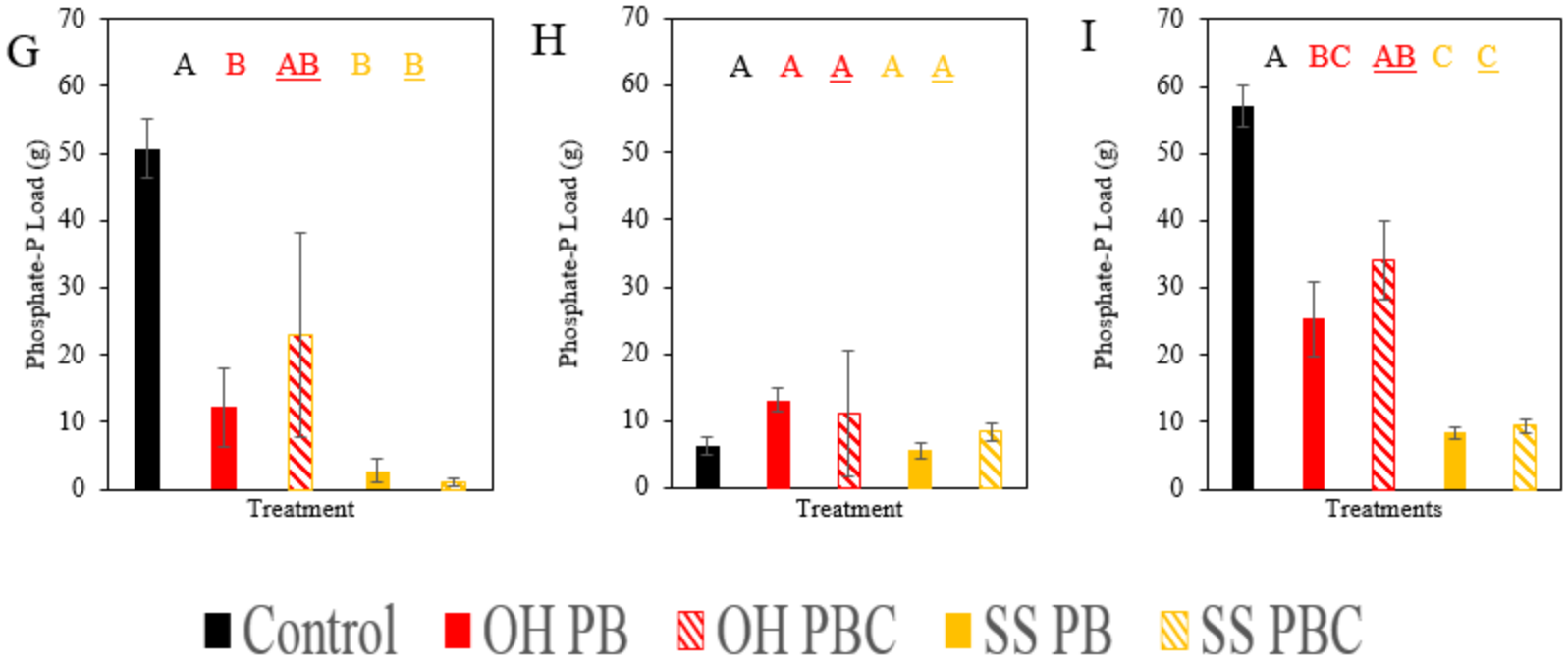
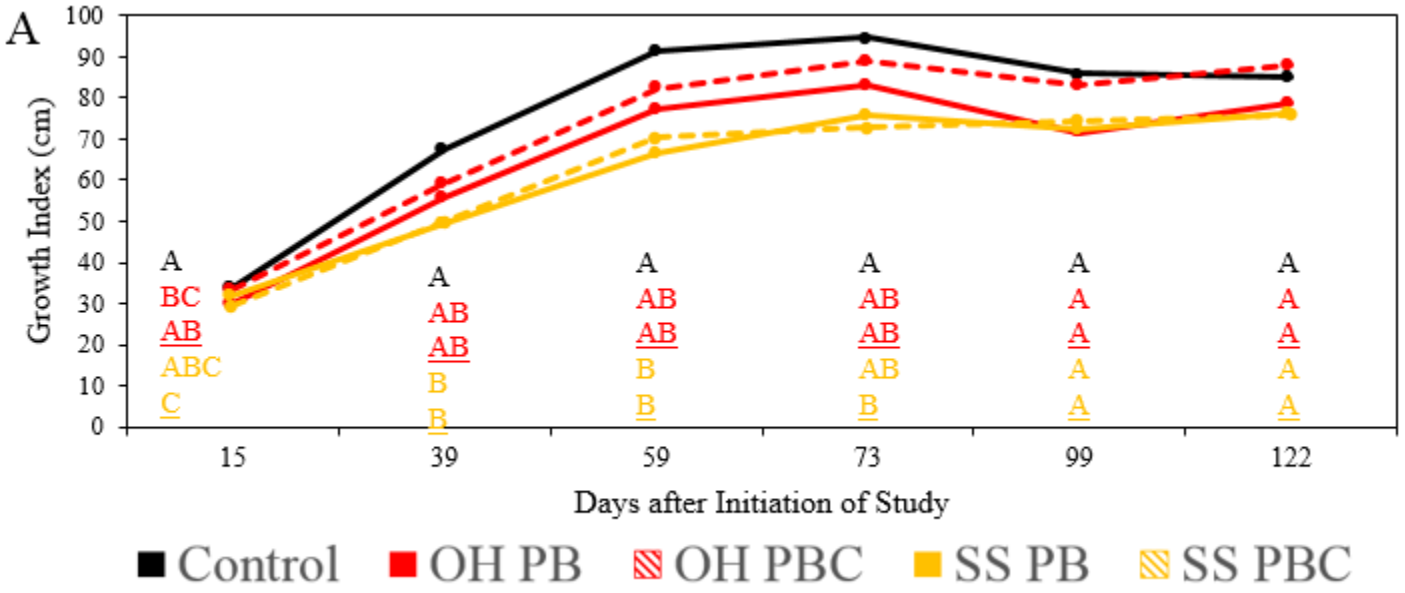


Figure 4.4: Cornus sericea Growth index was measured on 6 occasions throughout the study (A), as well as shoot dry biomass at the termination of the study (B). Container leachate pH (C) and electrical conductivity (D) was measured 4 times throughout the study. Means separations are displayed conforming to irrigation color coding, with the pine bark + coir substrates underlined.



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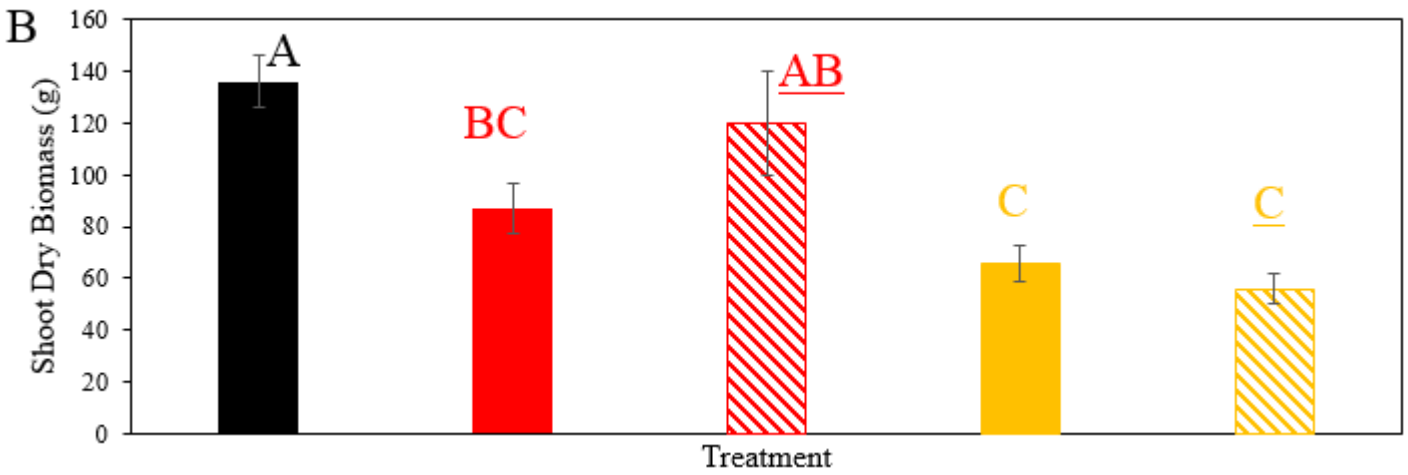

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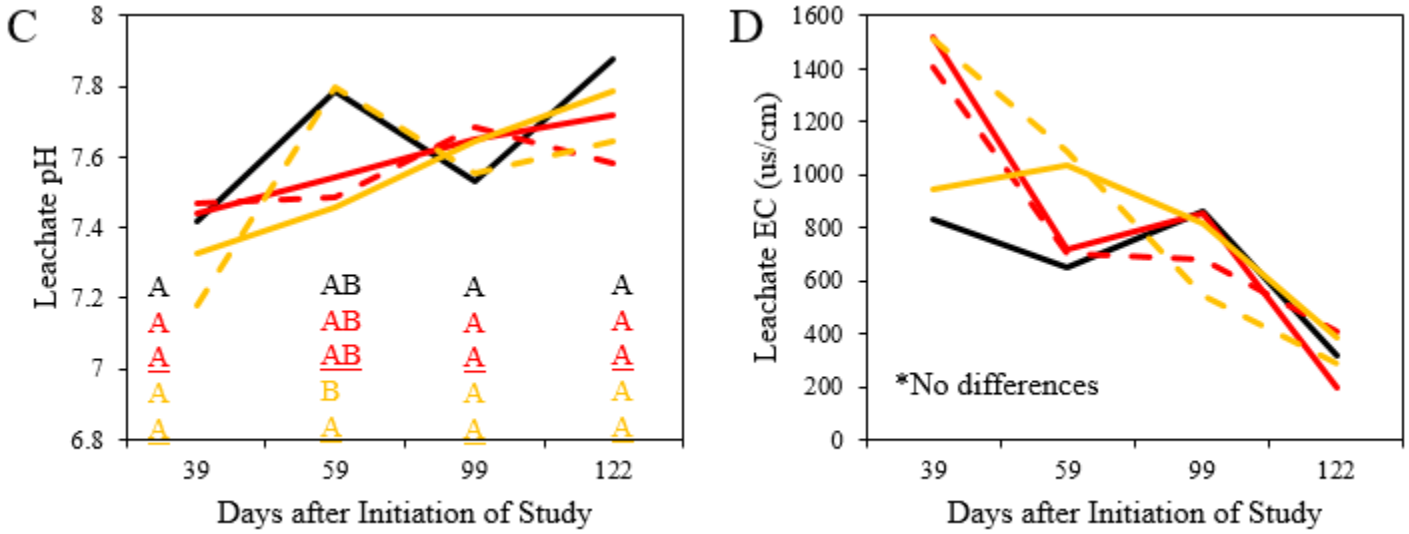
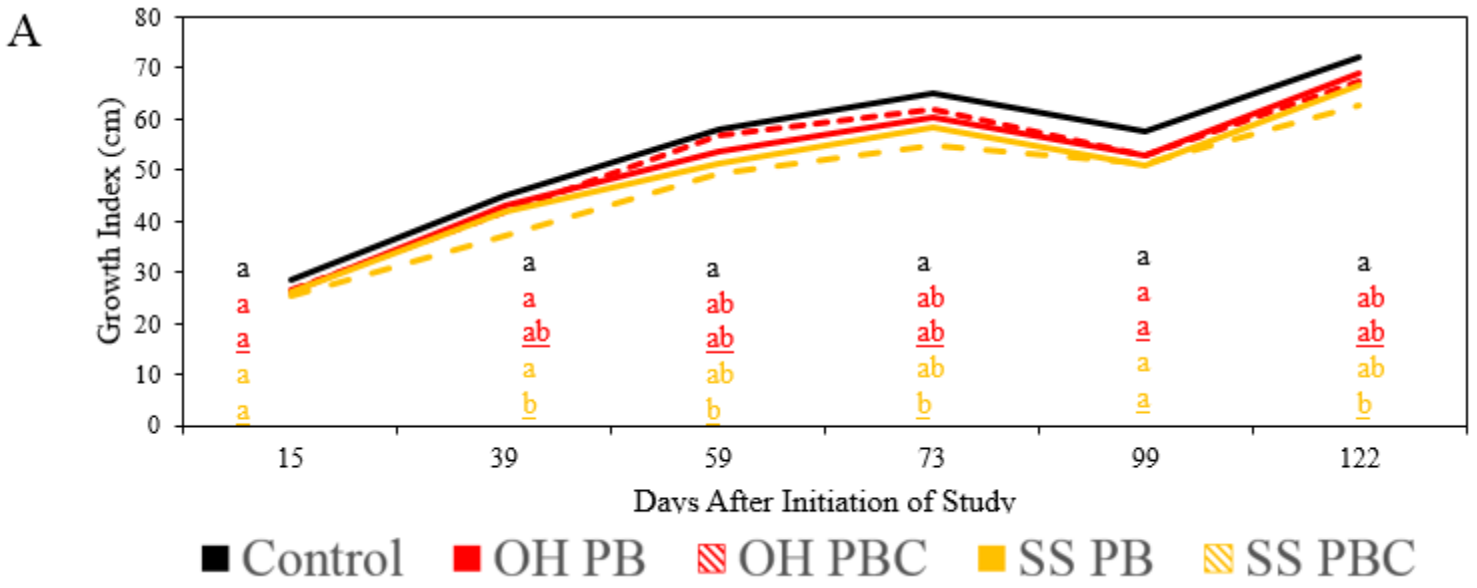


Figure 4.5: Hydrangea paniculata Growth index was measured on 6 occasions throughout the study (A), as well as shoot (B) and root dry biomass (C) at the termination of the study. Container leachate pH (D) and electrical conductivity (E) was measured 4 times throughout the study. Means separations are displayed conforming to irrigation color coding, with the pine bark + coir substrates underlined.



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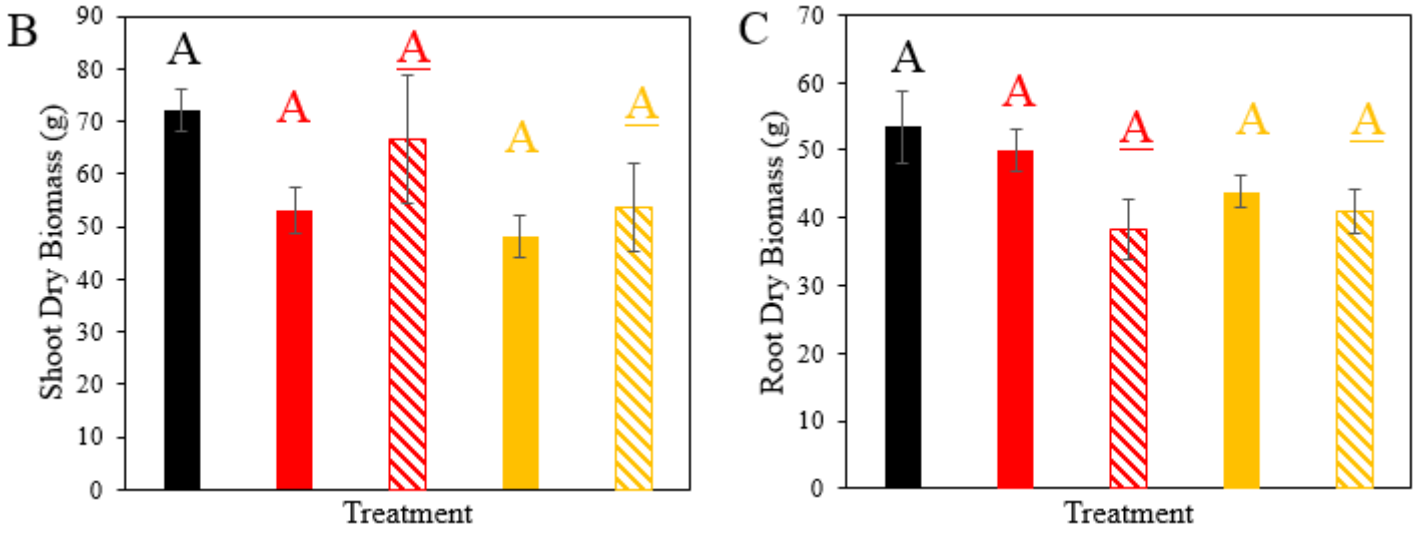

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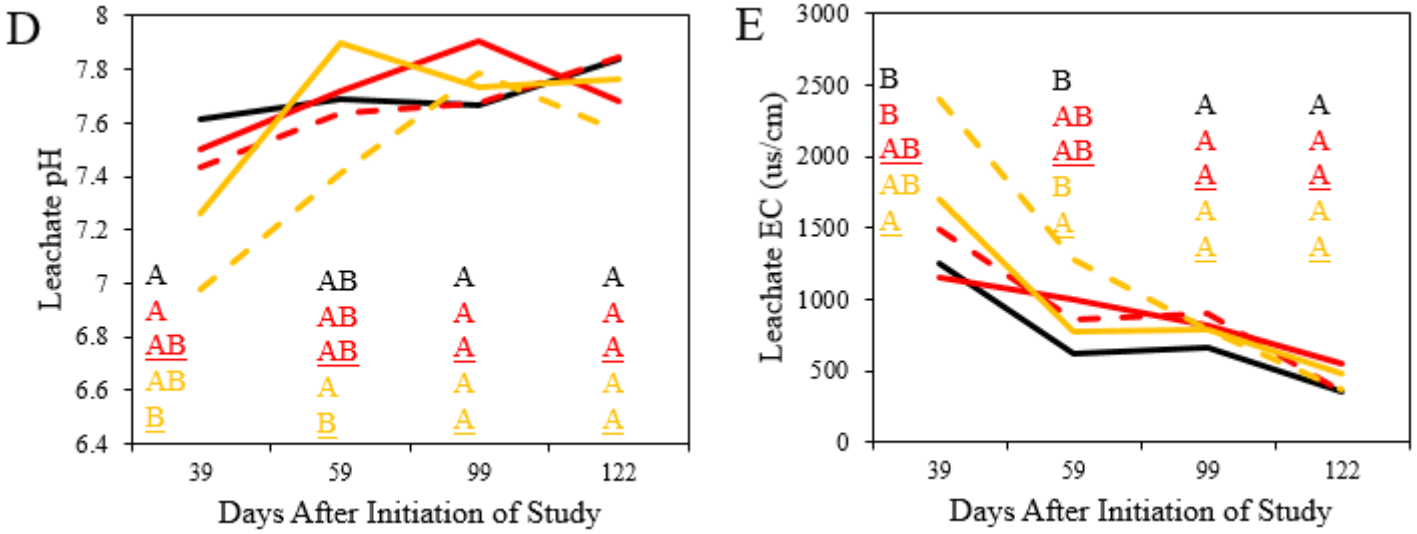
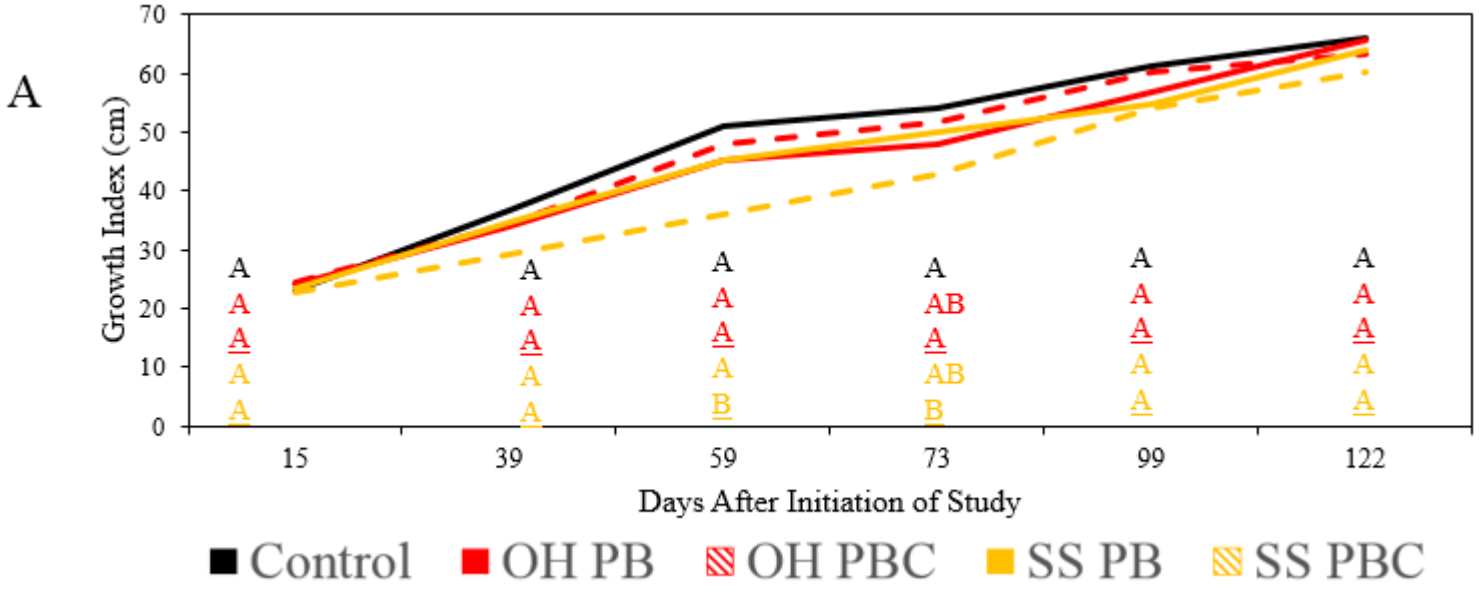


Figure 4.6: Rosa x Growth index was measured on 6 occasions throughout the study (A), as well as shoot (B) and root dry biomass (C) at the termination of the study. Container leachate pH (D) and electrical conductivity E) was measured 4 times throughout the study. Means separations are displayed conforming to irrigation color coding, with the pine bark + coir substrates underlined.



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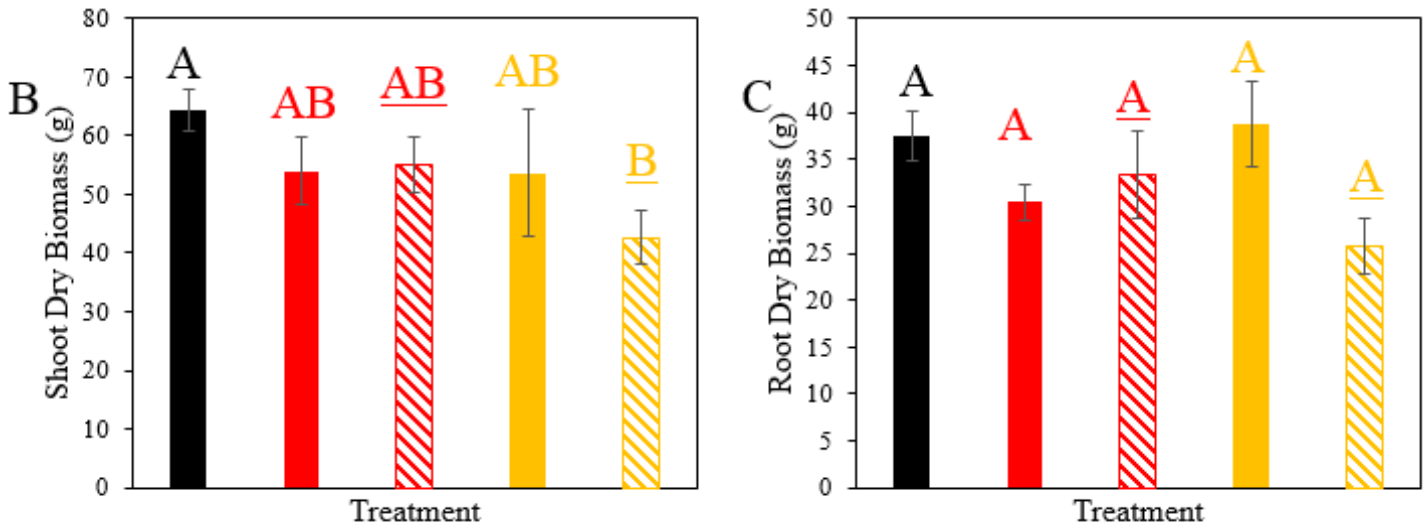

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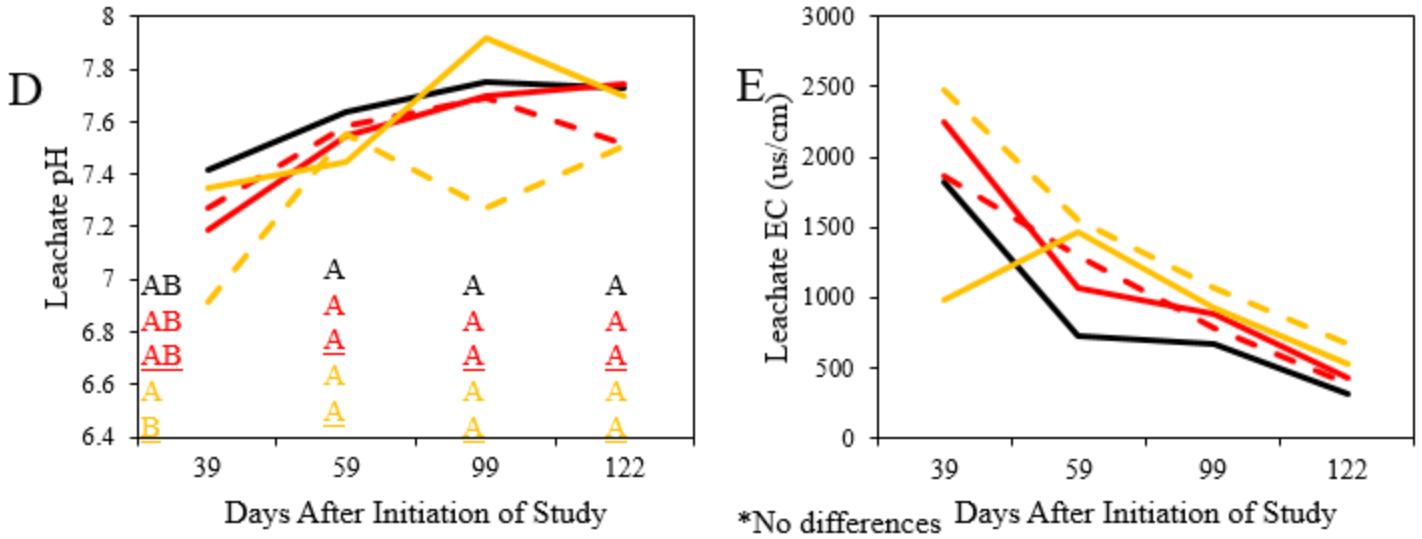
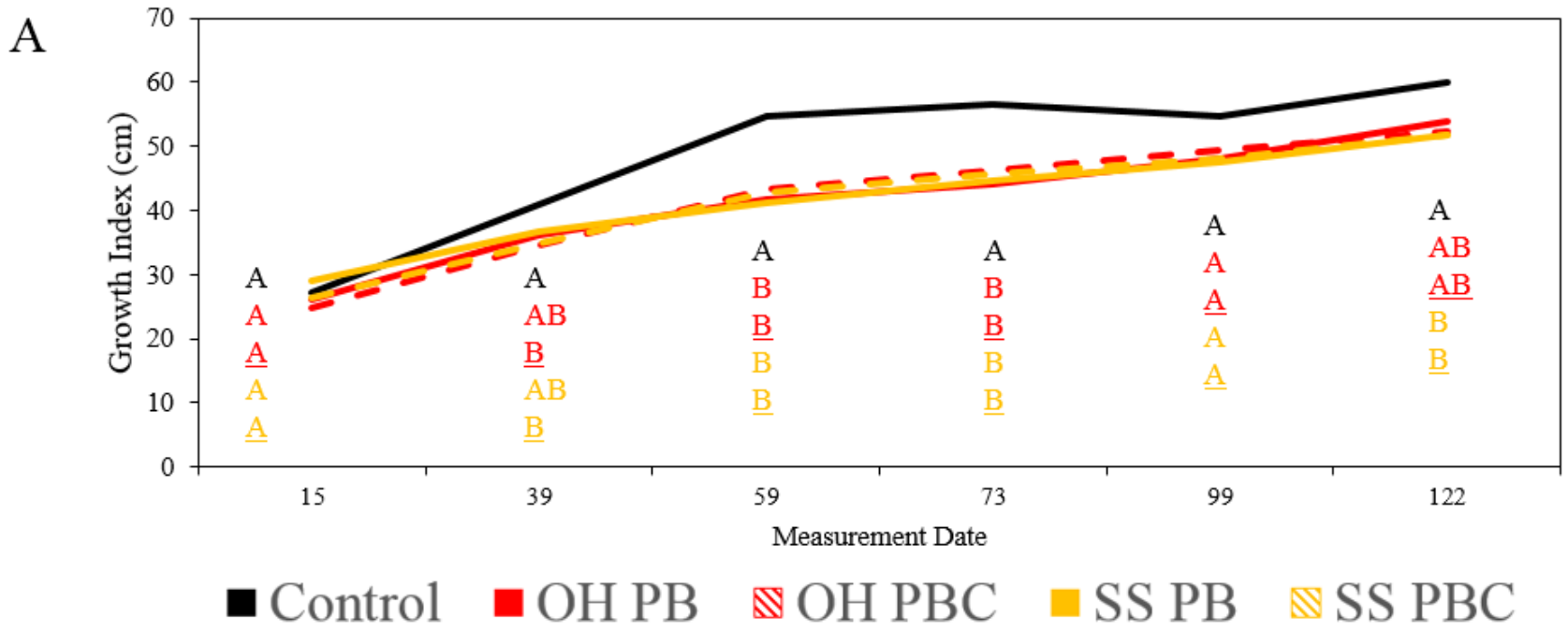


Figure 4.7: Spiraea growth index was measured on 6 occasions throughout the study (A), as well as shoot (B) and root (C) dry biomass at the termination of the study. Container leachate pH (D) and electrical conductivity (E) was measured 4 times throughout the study. Means separations are displayed conforming to irrigation color coding, with the pine bark + coir substrates underlined.



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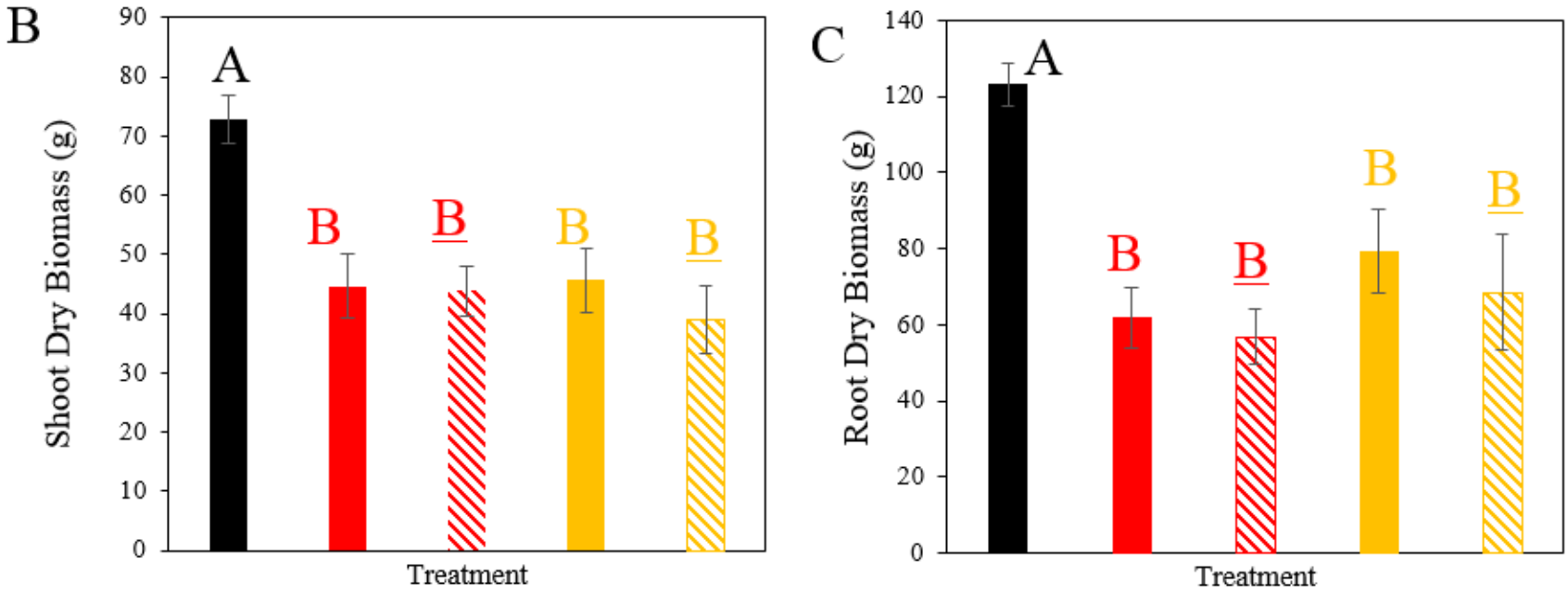

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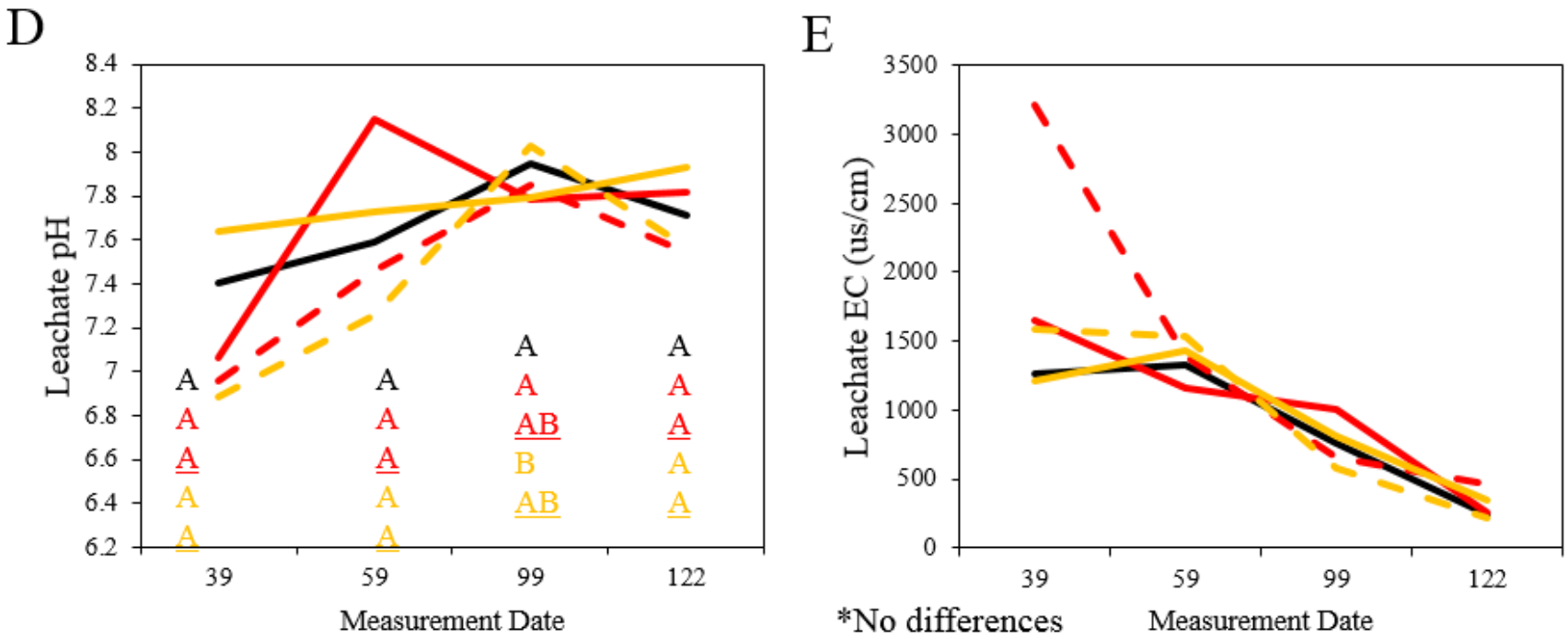


Figure 4.8: Surface and subsurface irrigation return flow samples collected on days without precipitation over 0.6 cm were analyzed for Nitrate-N concentration, which was then multiplied by the volume of water collected to calculate load on each date. Samples below detection were reported at detection limit (0.0452 mg/L Nitrate –N), with load estimates calculated by multiplying half of the collected water volume by the limit of detection. A repeated measures analysis of variance was conducted, with means separated when significant (<0.05) based on a Tukey Test with respective color coded letters indicating irrigation treatment, and underlined letters indicating substrate. If there were no differences within a particular date, no letters are displayed. Surface concentration: A; subsurface concentration (B); surface load (C); subsurface load (D).

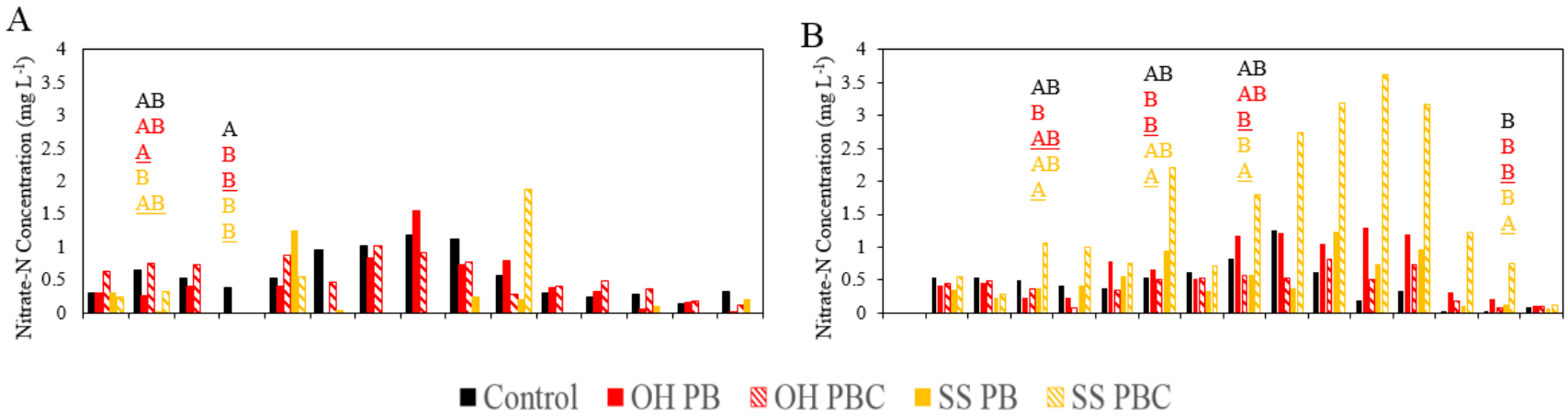


Figure 4.8 (cont'd)

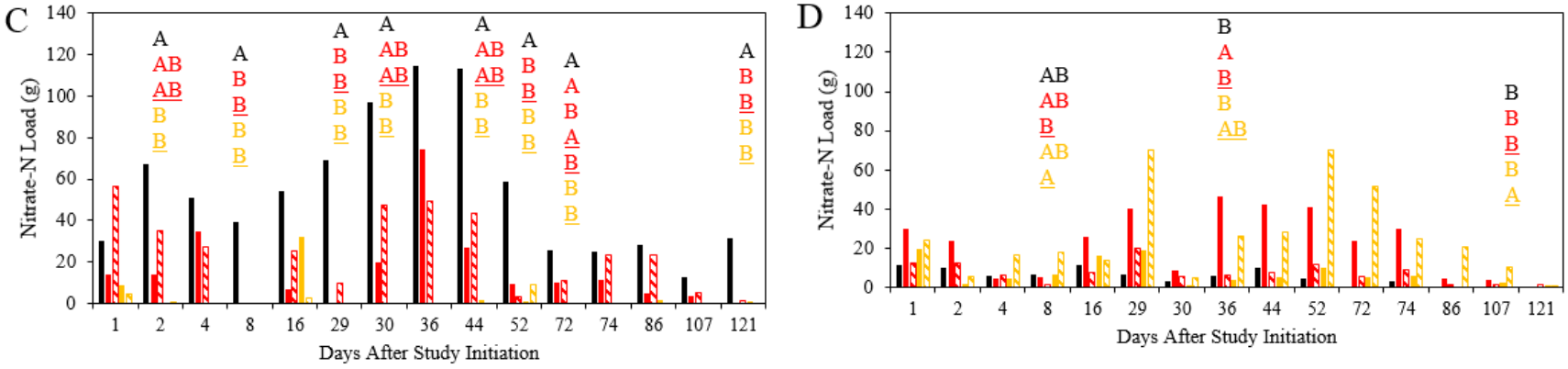


Figure 4.9: Surface and subsurface irrigation return flow samples collected on days without precipitation over 0.6 cm were analyzed for Phosphate-P concentration, which was then multiplied by the volume of water collected to calculate load on each date. Samples below detection were reported at detection limit (0.0652 mg/L Phosphate-P), with load estimates calculated by multiplying half of the collected water volume by the limit of detection. A repeated measures analysis of variance was conducted, with means separated when significant (<0.05) based on a Tukey Test with respective color coded letters indicating irrigation treatment, and underlined letters indicating substrate. If there were no differences within a particular date, no letters are shown. Surface concentration: A; subsurface concentration (B); surface load (C); subsurface load (D).

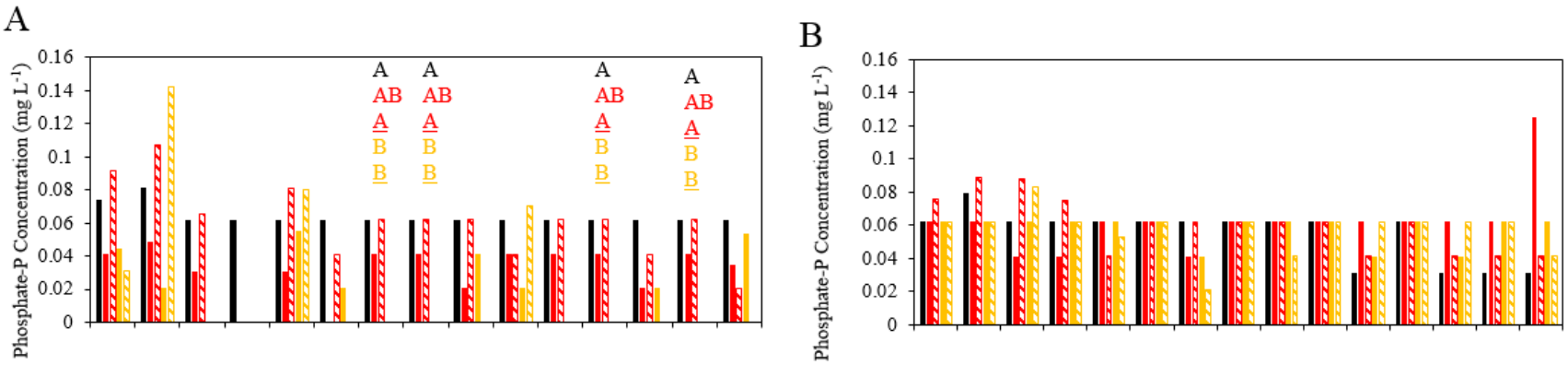
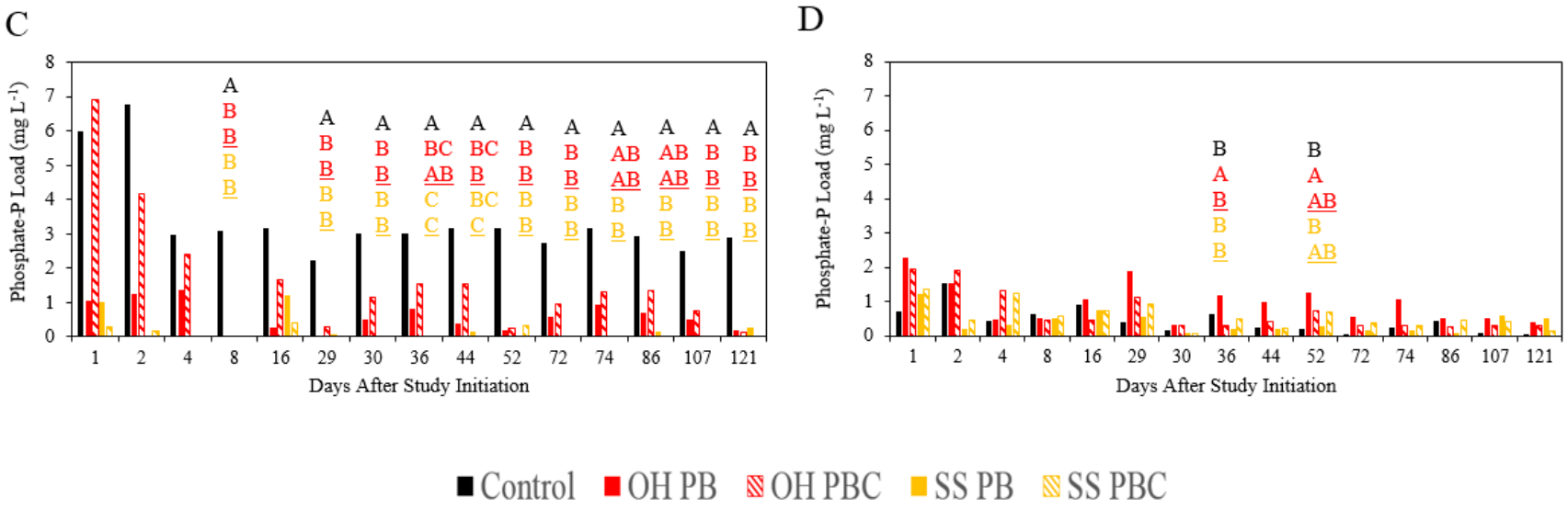


Figure 4.9 (cont'd)



LITERATURE CITED

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Abad, M., Fornes, F., Carrión, C., Noguera, V., Noguera, P., Maquieira, A., Puchades, R., 2005. Physical properties of various coconut coir dusts compared to peat. HortScience. 40, 2138-2177.

Agro, E., Zheng, Y., 2014. Controlled-release fertilizer application rates for container nursery crop production in southwestern Ontario, Canada. HortScience. 49, 1414-1423.

Bayer, A., Mahbub, I., Chappell, M., Ruter, J., van Iersel, M.W., 2013. Water use and growth of Hibiscus acetosella 'Panama Red' grown with a soil moisture sensor-controlled irrigation system. HortScience. 48, 980-987.

Bayer, A., Ruter, J., van Iersel, M.W., 2015. Automated irrigation control for improved growth and quality of Gardenia jasminoides 'Radicans' and 'August Beauty'. HortScience. 50, 78-84.

Beeson, R.C. Jr., Knox, G.W., 1991. Analysis of efficiency of overhead irrigation in container production. HortScience. 26, 848-850.

Beeson, R.C. Jr., Yeager, T.H., 2003. Plant canopy affects sprinkler irrigation application efficiency of container-grown ornamentals. HortScience. 38, 1373-1377.

Berghage, R.D., MacNeal, E.P., Wheeler, E.F., Zachritz, W.H., 1999. "Green" water treatment for the green industries: opportunities for biofiltration of greenhouse and nursery irrigation water and runoff with constructed wetlands. HortScience. 34, 50-54.

Burnett, S.E., van Iersel, M.W., 2008. Morphology and irrigation efficiency of Gaura lindheimeri grown with capacitance sensor-controlled irrigation. HortScience. 43, 1555-1560.

Davies, M.J., Harrison-Murray, R., Atkinson, C.J., Grant, O.M., 2016. Application of deficit irrigation to container-grown hardy ornamental nursery stock via overhead irrigation, compared to drip irrigation. Agr. Water Manage. 163, 244-254.

Dennis, J.H., Lopez, R.G., Behe, B.K., Hall, C.R., Yue, C., Campbell, B.L., 2010. Sustainable production practices adopted by greenhouse and nursery plant growers. HortScience 45, 1232-1237.

Döll, P. 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environ. Res. Lett. 4, 1-12.

Fernandez, R.T., Pershey, N.A., Andresen, J.A., Cregg B.M., 2019. Water conserving irrigation practices, plant growth, seasonal crop coefficients, and nutrition of container-grown woody ornamentals. Water. 11, 1-19.

Fulcher, A., LeBude, A.V., Owen, J.S. Jr., White, S.A., Beeson, R.C., 2016. The next ten years: strategic vision of water resources for nursery producers. HortTechnology. 26, 121-132.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science. 327, 812-818.

Incrocci, L., Marzialetti, P., Incrocci, G., Di Vita, A., Balendonck, J., Bibbiani, C., Spagnol, S., Pardossi, A., 2014. Substrate water status and evapotranspiration irrigation scheduling in heterogenous container nursery crops. Agr. Water Manage. 131, 30-40.

Incrocci, L., Marzialetti, P., Incrocci, G., Di Vita, A., Balendonck, J., Bibbiani, C., Spagnol, S., Pardossi, A. 2019. Sensor-based management of container nursery crops irrigated with fresh or saline water. Agr. Water Manage. 213, 49-61.

Kukal, S., Saha, D., Bhowmik, A., Dubey, R.K. 2012. Water retention characteristics of soil bio-amendments used as growing media in pot culture. J. of Appl. Hortic. 14, 92-97.

Lichtenberg, E., Majsztrik, J., Saavoss, M., 2013. Profitability of sensor-based irrigation in greenhouse and nursery crops. HortTechnology. 23, 770-774.

Majsztrik, J.C., Fernandez, R.T., Fisher, P.R., Hitchcock, D.R., Lea-Cox, J., Owen, J.S. Jr., Oki, L.R., White, S.A., 2017. Water use and treatment in container-grown specialty crop production: a review. Water Air and Soil Poll. 228, 1-27.

Majsztrik, J.C., Ristvey, A.G., Ross, D.S., Lea-Cox, J.D., 2018. Comparative water and nutrient application rates among ornamental operations in Maryland. HortScience. 53, 1364-1371.

Mangiafico, S.S., Gan, J., Wu, L., Lu, J., Newman, J.P., Faber, B., Merhaut, D.J., Evans, R., 2008. Detention and recycling basins for managing nutrient and pesticide runoff from nurseries. HortScience. 43, 393-398.

Million, J.B. and T.H. Yeager., 2015. Capture of Sprinkler Irrigation Water by Container-grown Ornamental Plants. HortScience. 50, 442-446.

Owen, J.S. Jr., Warren, S.L., Bilderback, T.E., Albano, J.P., 2008. Phosphorus rate, leaching fraction, and substrate influence on influent quantity, effluent nutrient content, and response of a containerized woody ornamental crop. HortScience. 43, 906-912.

Parsinejad, M., Yazdi, A.B., Araghinejad, S., Nejadhashemi, A.P., Tabrizi, M.S., 2013. Optimal water allocation in irrigation networks based on real time climatic data. Agr. Water Manage. 117, 1-8.

Paudel, K.P., Pandit, M., Hinson, R., 2016. Irrigation water sources and irrigation application methods used by U.S. plant nursery producers. Water Resour. Res. 52, 698-712

Pershey, N.A., Cregg, B.M., Andresen, J.A., Fernandez, R.T., 2015. Irrigating based on daily water use reduces nursery runoff volume and nutrient load without reducing growth of four conifers. HortScience. 50, 1553-1561.

Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., Clark, S., Poon, E., Abbett, E., Nandagopal, S., 2004. Water resources: agricultural and environmental issues. Bioscience. 54, 909-918.

Rodell, M., Famigletti, J.S., Wiese, D.N., Reager, J.T., Beaudoing, H.K., Landerer, F.W., Lo, M.H., 2018. Emerging trends in global freshwater availability. Nature. 557, 651-659.

Schipper, L.A., Robertson, W.D., Gold, A.J., Jaynes, D.B., Cameron, S.C., 2010. Denitrifying bioreactors – an approach for reducing nitrate loads to receiving waters. Ecol. Eng. 36, 1532-1543.

Tyler, H.H., Warren, S.L., Bilderback, T.E., 1996. Reduced leaching fractions improve irrigation use efficiency and nutrient efficiency. J. Environ. Hortic. 14, 199-204.

Van Iersel, M.W., Dove, S., Kang, J.G., Burnett, S.E., 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience. 45, 277-282.

Warsaw, A.L., Fernandez, R. T., Cregg, B.M., Andresen, J.A., 2009a. Water conservation, growth, and water use efficiency of container-grown woody ornamentals irrigated based on daily water use. HortScience. 44, 1308-1318.

Warsaw, A.L, Fernandez, R.T., Cregg, B.M, Andresen, J.A., 2009b. Container-grown ornamental plant growth and water runoff nutrient content and volume under four irrigation treatments. HortScience. 44, 1573-1580.

Yazdi, M.N., Sample, D.J., Scott, D., Owen, J.S., Ketabchy, M., Alamradi, N., 2019. Water quality characterization of storm and irrigation runoff from a container nursery. Sci. of the Total Environ. 667, 166-178.

Web References:

Clean Water Act (CWA); https://www.epa.gov/laws-regulations/summary-clean-water-act) (Accessed 23 September 2020). 33 U.S.C. §1251 et seq. (1972)

European Nitrate Directive (END): (https://ec.europa.eu/environment/water/water-nitrates/index_en.html) (Accessed 23 September 2020). Adopted 12 December 1991.

European Water Framework Directive (EWFD): (https://ec.europa.eu/environment/water/water-framework/index_en.html) (Accessed 23 September 2020). Adopted 23 October 2000.

US EPA National Primary Drinking Water Regulations https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations (Accessed 23 September 2020)

CHAPTER FIVE

Reducing Pesticide Mobility in Surface and Subsurface Irrigation Return Flow Using Sensor-based Irrigation Management for Nursery Container Production

5.1 Abstract

This study investigates the movement of 9 pesticides in a container-plant production system using a control overhead irrigation of 190 kl ha^{-1} d^{-1} and two treatments irrigating based on substrate volumetric moisture content (θ), one via overhead irrigation and one via spray stake irrigation. The research was conducted at an experimental nursery designed to collect surface and subsurface irrigation return flow in order to determine water and pesticide dynamics. Pesticides were applied at 3 times during the year and were selected to provide a range of water solubilities and adsorption coefficients. For the range of pesticides investigated, as the solubility decreased and adsorption coefficients increased, there was less occurrence of the particular pesticide in surface and, to a greater extent, subsurface return flow. Irrigating based on θ reduced total irrigation volume applied by 49% or 77% compared to the control when using overhead irrigation or spray stake treatments. The reduced irrigation volume in the θ overhead treatment, and the precision in which spray stake apply water (directly to containers) reduced the volume of surface return flow by 71% and 92%. Combining surface and subsurface return flow, the θ overhead and spray stake treatments reduced the total volume of irrigation return flow by 52% and 78% versus the control. Nearly universally, the movement of pesticides in surface return flow exhibited a linear or quadratic decrease for the control, while pesticide movement via subsurface flow was related more to physiochemical properties limiting mobility rather than subsurface return volume or irrigation practice. This study demonstrates that pesticide movement in irrigation return flow can be substantially reduced by selecting pesticides with low solubility and high adsorption coefficients whenever possible, and reducing the volume and/or application of irrigation to non-target areas.

5.2 Introduction

Chemical movement from agricultural sites are an environmental concern, with particularly input intensive forms of agriculture, such as container nursery crop production, elevating risk of export. Pesticides are critical to maintaining a pest-free, aesthetically appealing crop, with herbicides, insecticides, and fungicides typically applied multiple times per year. Pesticide degradation encompasses a range of processes, including photolysis, microbial metabolization and volatilization; however, pesticides may exhibit high degrees of mobility in nursery crop production as water is the most frequent transporter of agrochemicals (Abdi and Fernandez, 2019; Vryzas, 2018). Coupled with the frequent, oftentimes daily, irrigation common in container-crop production, pesticides can be transported in irrigation return flow (IRF), both via surface and subsurface IRF, and subsequently transported off site.

Pesticides represent a critical component in modern agriculture; however, their widespread use across a range of agricultural sectors increases the risk for export to water bodies (Martins et al., 2020; Nie et al., 2020). Within the ornamental crop industry, 350 different modes of action, spanning several pesticide and chemical classes, were used in 2009 (USDA, 2011). Pesticide contamination of surface and ground water resources can deleteriously affect ecological systems, both aquatic and terrestrial, where their presence in toxic or sub lethal concentrations may elicit undesirable effects in susceptible organisms (Beggel et al., 2011; Graves et al., 2014; Ilhan et al., 2012; Weston et al., 2005). Certain pesticides, such as the pyrethroid insecticide bifenthrin, may act as endocrine disruptors in susceptible organisms, even at concentrations in the low parts per billion, while pesticide metabolites generated via transformation processes may be bioactive as well (Brander et al., 2016; Giroux et al., 2019). Pesticides in other classes, such as the organophosphate insecticide chlorpyrifos, pose a threat to

receiving water bodies as the bacterial metabolization of this compound yields the toxic, persistent metabolite trichloropyridinol with subsequent breakdown releasing free chlorine which effectively acts as a local sanitizer of microorganisms (Singh and Walker, 2006).

Pesticides vary within and between classes with respect to their inherent chemical properties, such as solubility, sorption coefficients, half-life and vapor pressure, all of which determine the likely environmental fate of a particular compound (Von Merey et al., 2016). Highly soluble pesticides are likely to move in a dissolved phase in water; whereas, pesticides with high sorption coefficients are more prone to binding to soils/organic matter, and instead may be transported via erosive detachment. Sorptive processes are dependent on the properties of a particular compound, or the adsorbate, and the composition of the organic and inorganic components within the soil, or adsorbent (Yen et al., 2000). Pesticides which are lost from production areas via IRF can contaminate water resources, and may be toxic to local biota in receiving water bodies. Additionally, pesticide loss from production areas may limit the effectiveness with which applied compounds control for target pests, thus bearing financial implications for growers, particularly if this results in crop loss due to reduced quality or mortality. In agricultural operations collecting IRF for recycled irrigation use, pesticide residues, particularly herbicides, may be present in bioactive levels that may cause damage to crops (Poudyal and Cregg, 2019).

Production of crops in containers provides many advantages, such as improved homogeneity of growing conditions, ease with which plants can be moved, increased production per unit area, and faster growth (Agro and Zheng, 2014; Majsztrik et al., 2017). However, producing plants in containers has unique challenges. Limitations dictated by the volume of the container, substrate hydraulic properties, and plant evapotranspiration can rapidly deplete

substrate stored water, thus necessitating frequent, oftentimes daily, irrigation. Irrigation of container-plants grown in containers less than 19 L is commonly applied via overhead delivery systems, providing water to the entirety of the production area, encompassing the plant canopy, containers surfaces, and the inter-container spaces (Beeson and Knox, 1991; Majsztrik et al., 2017). Applied water that is shed by the plant canopy outside of the containers or that lands in the inter-container spaces, typically 74-87% for overhead irrigation, contributes to IRF (Davies et al., 2016; Million and Yeager, 2015; Pershey et al., 2015). The inefficiencies common to overhead delivery within container crop production is capable of producing considerable volumes of IRF, increasing agrochemical mobility (Majsztrik et al., 2017; Pershey et al., 2015; Warsaw et al., 2009). Micro-irrigation systems provide an alternative to overhead systems, delivering water directly within the container below the plant canopy; however, this practice is often used for crops produced in larger containers or crops spaced in a low density per area (Garber et al., 2002). The use of substrate moisture (θ) sensors can also be used to apply irrigation more precisely (Incrocci et al., 2019; Lea-Cox et al., 2013). Warsaw et al. (2009) demonstrated that applying overhead irrigation based on replenishing 100% and 75% of crop water use reduced the volume of irrigation applied by 45% and 59% when compared to a control of 190 kl ha^{-1} d^{-1} per application, in addition to reducing surface IRF generation by 66% and 79%.

This study investigated the mobility of nine pesticides, varying in physiochemical properties and mobility classes, and their partitioning between irrigation surface IRF and subsurface IRF when irrigated using either an overhead system or a micro-irrigation system applying water based on θ compared to a typical 190 kL ha^{-1} d^{-1} practice within a model nursery. We hypothesized that 1: reducing water application volume would reduce IRF and pesticide

movement, 2: reducing or eliminating non-target water interception would further reduce IRF and pesticide movement, 3: that surface IRF would be affected more than subsurface IRF, 4: that more water and pesticides would move in surface than subsurface IRF, and 5: that early reductions IRF and pesticide movement would result in overall reductions in total pesticide movement.

5.3 Materials and Methods

5.3.1 Research Nursery

A research nursery was constructed at the Michigan State University Horticulture and Teaching Research Center (HTRC) in Holt, MI (Latitude 42.67, Longitude -84.48), with sixteen raised beds serving as replicates where three irrigation methods and two substrate blends were compared. Treatments were initiated on 11 June, 2018 and concluded on 11 October, 2018. The experimental raised beds were arranged in two parallel rectangular blocks measuring 61 x 7.62 meters each with the length running north to south, and separated by a 1.8-m alley. Each rectangular block was divided into eight individual 7.62 x 7.62 x 0.6 m (LxWxH) beds for a total of 16 experimental beds. (Figure 5.1). Native soil inside the walls of each individual bed was graded to achieve a 2% slope towards a center swale and to the side opposite the center alley, funneling water to the outer eastern or western edge of the individual beds in the two rectangular blocks. After the soil base was graded, a 9.1 x 9.1 m impermeable ethylene propylene diene monomer pondliner (Firestone Pondgard 45Mil (1.14 mm) Nashville, TN) was placed over each bed and up the remaining exposed side walls. Over the top of the pond liner, 0.3 m of washed natural sand, free of clay, with a particle size range of 0.75-9.5 mm was placed and graded in the same manner as the soil sub-base and covered with a black woven polypropylene landscape fabric (De Witt SBLT6300, Sikeston, MO). Bulkhead fittings were installed at the low points of the soil

sub-base/pondliner and sand/fabric, respectively, and piped to 378 L polyethylene tanks (Duracast, manufacturer number 900100-1.2, Lake Wales, FL) via 4.03 cm (inside diameter) schedule 40 PVC for the collection of surface and subsurface IRF. Collection tanks were buried 15.2 cm below the soil level and anchored in place with concrete.

5.3.2 Irrigation Installation

The irrigation system to each of the raised beds was fitted with a 150 mesh inline filter (Toro T-ALFS75150-L, Bloomington MN), a 30 psi pressure regulator (Senninger PRL303F3F, Clermont, FL), a flow meter (Badger Meter 62585-001 model 25, Milwaukee, WI), and two solenoid valves (Rainbird CP075, Asuza, CA). Irrigation was applied via either overhead sprinklers (K-Rain RN300-Adj, Riviera Beach, FL), or individual container spray stakes (Netafim 22500-002030, flow rate 12.1 Lph, Tel Aviv-Yafo, Israel). Overhead sprinklers were located at the corners of the 6.1 x 6.1 m area to be irrigated for all beds, while spray stake irrigated beds also had a manifold consisting of four 6.1-m sections of polyethylene tubing adjacent to plant rows providing water for the spray stakes.

5.3.3 Irrigation Control and Sensor Installation

Irrigation was managed with a wireless sensor and control network using Sensorweb software (Mayim LLC, Pittsburgh, PA, USA), with the computer and communication devices installed in the main building of the HTRC. Solenoid valves were controlled via direct current battery powered control nodes (model NC24, Decagon Devices, Inc., Pullman, WA, USA), with each node controlling 4 beds. Nodes were installed on the side wall of the western raised beds, and oriented towards the communication devices in the HTRC building. Substrate volumetric moisture content (θ) was monitored using moisture sensors connected to monitoring nodes (model 10HS and model EM50R, respectively, Decagon Devices, Inc., Pullman, WA), where each bed had four

moisture sensors and one monitoring node set to take measurements at 5 minute intervals. Sensors were randomly assigned to one plant per taxa per bed and inserted horizontally into the substrate halfway between the top and bottom of the container.

5.3.4 Irrigation Treatments

A control overhead irrigation at a rate of 190 kl ha^{-1} d^{-1} was compared to two treatments irrigating based on θ, one via overhead application (OH) and the other using spray stakes (SS). Container capacity was assessed for each of the beds prior to treatment initiation in 2018, with irrigation treatments intended to return container θ to container capacity. Measured container capacities of both substrates were 38%. For the overhead irrigated beds based on container capacity (OH), up to 190 kl ha^{-1} d^{-1} was applied over three 63.3 kl ha^{-1} cycles, with five minutes elapsing between each cycle to allow for moisture sensor readings. Similarly, the spray stake beds irrigated based on container capacity would irrigate up to three 1 L (per container) cycles, with five minutes between each cycle for moisture sensor readings. Irrigation commenced at 9:00 A.M. for control replicates, with both the OH and SS treatments beginning at 10:00 A.M.

The sensor in the *H. paniculata* replicate for each bed was used as the sole basis for the OH and SS treatments. Irrigation treatments were randomly assigned to each bed, with three beds serving as the control, six beds being used for the OH treatment, and six beds for the SS treatment. One bed was left to serve as a blank, where 190 kl ha^{-1} d^{-1} of overhead irrigation was applied to a bed without plants.

5.3.5 Plant Material, Substrate, and Fertilizer

Each individual raised bed (replicate) had a total of 81 plants, split between four taxa, and produced in 11.3 L containers. *Cornus sericea* L. 'Farrow', *Hydrangea paniculata* Sieb. 'Limelight', *Rosa* x Lindl 'Meipeporia', and *Spiraea japonica* L. 'SMNSJMFP' received from a

commercial propagation nursery (Spring Meadow Nursery, Grand Haven, MI) were grouped by taxa, with the order of placement in each bed randomly assigned. A pine bark:peat moss blend (85:15 v/v) substrate was compared with a pine bark:coconut coir mix (80:20 v/v) (Renewed Earth, Otsego, MI). The three control replicates used the pine bark/peat moss substrate, while three of the six OH and three of the six spray stake treatments were randomly assigned either the pine bark/peat moss or the pine bark/coconut coir substrate. A fertilizer rate of 61.4 g per container of a 17-3.24-9.96 formulation (Nitrogen 17%; 3.24% Phosphate, 9.96% Potassium) with micronutrients and a 5-6-month longevity at 27 Celsius (Harrell's, Lakeland, FL USA) was used for a per bed application rate of 4,973 g. Fertilizer was applied on 11 June 2018.

5.3.6 Pesticide Applications

A total of 9 pesticides were applied over the course of three monitoring periods with herbicides applied separately while the insecticides and fungicides were applied as a tank mix (Table 5.1). Pesticides were selected based on their physiochemical properties and common use in nursery production, and were organized based on McCall's Koc class and FAO mobility classifications into three groups (Table 5.2). On each date the pre-emergent herbicide was applied first followed by watering-in using overhead irrigation as recommended by the pesticide label. After surface IRF from watering-in ceased, the insecticides and fungicides were applied as a tank mix. As a result, herbicides have one more day of sampling than other pesticides. All pesticides were applied as liquids according to the ornamental crop label rate with a wagon mounted sprayer connected by hose to a four nozzle boom, measuring 1.52 meters across with a 1.83 meter spray width. The boom width allowed the 6.1 x 6.1 meter area to be divided into thirds, with passes made starting at the low point and moving uphill (West to East for the western block of raised beds, vice verse for the eastern block). Herbicide applications required one pass

over each third in order to achieve desired application rates, while the tank mix required two passes. Prior to each application event, spray boom nozzles were tested to ensure a minimum of 95% uniformity in spray output and applicator walking speed was calibrated to provide the desired application rates. The herbicides isoxaben, oxyfluorfen, and prodiamine were applied first in each of their respective monitoring periods using nozzles with an 80° angle and 0.76 L min^{-1} application rate per nozzle (Teejet model 8002, Wheaton, IL, USA) on the spray boom, followed by overhead irrigation for watering-in per label recommendations. Following herbicide application and watering-in, the insecticide/fungicide tank mix was applied using an 80° angle and 2.27 L min^{-1} application rate per nozzle (Teejet model 8006). Nozzles were tested prior to each spray event to ensure uniformity in spray output, and applicator walking speed was calibrated to provide desired application rates (Teejet 8002 average flow per nozzle 1,110 mL min^{-1}; Teejet 8006 average flow per nozzle 2,165 mL min^{-1}; applicator walking speed 3.93 km hr^{-1}).

The first date of application was 11 June 2018, consisting of isoxaben, acephate, bifenthrin, and mefenoxam. Following isoxaben application, all beds received 190 kl ha^{-1} of overhead irrigation to water in the herbicide, no other irrigation was applied on this date. The second date of application was 9 July 2018, consisting of oxyfluorfen, acephate, chlorpyrifos, and triflumizole. Following oxyfluorfen application, the control received 190 kl per hectare of overhead irrigation, while the two treatments received the label minimum recommended watering-in rate of 63.3 kl per hectare, no other irrigation was applied on this date. The third date of application was 20 August 2018, consisting of prodiamine, acephate, and thiophanate-methyl. Following prodiamine application, the control received 190 kl ha^{-1} of overhead irrigation and the

two treatments received the label minimum watering-in rate of 126.6 kl hectare, no other irrigation was applied on this date.

5.3.7 Sampling Protocol

Collection tanks were emptied 24 hours prior to collection dates to allow the accumulation of infiltration water over a full day, and for runoff generated in response to an irrigation event. Samples were collected following herbicide application (Day 0) from surface IRF tanks, and from surface and subsurface IRF tanks on Days 1, 2, 4, 8, and 16 days after application for each monitoring period. The height of the water in the collection tanks was measured using a meter stick and converted to liters based on tank dimensions in order to quantify the amount of surface and subsurface IRF water per bed. A sump pump with a hose attachment was inserted into the tank and allowed to run for 10 sec prior to sample collection in a 950 mL glass amber bottle (Qorpak GLC02164, Clinton, PA). Following sample collection, 75 ul of acetic acid was added to stabilize the sample.

5.3.8 Pesticide Chemical Analysis

Water samples were analyzed at the Organic Contaminants Analytical Research Laboratory in the Soil and Water Sciences Department, University of Florida, Gainesville, FL using the sample preparation, extraction technique, and instrument conditions described by Hinz et al. (2019) and Leiva et al. (2019). Due to matrix effects determined in preliminary work for this study, non-treated control sample waters from a surface and subsurface return flow collection tank were provided to prepare corresponding matrix matched calibration standard series and quality assurance/quality control (QA/QC) samples.

5.3.8.1 Extraction Procedure

PESTENAL grade standards of acephate (P/N: 45315-250MG), bifenthrin (P/N: 34314-100MG), chlorpyrifos (P/N: 45395-100MG), isoxaben (P/N: 36138-100MG), metalaxyl-m (P/N: 32808-100MG), oxyfluorfen (P/N: 35031-100MG), thiophanate-methyl (P/N: 45688-250MG), and triflumizole (P/N: 32611-100MG), were purchased from Sigma-Aldrich (St. Louis, MO). The prodiamine (P/N: N-13096-100MG) standard (99.5% purity) was purchased from ChemService (West Chester, PA).

All samples were extracted according to a modified version of US EPA Method 3510C. Briefly, 500 mL of sample water were added to a 1000 mL teflon separatory funnel and extracted with 30 mL methylene chloride. The procedure was repeated two additional times using a total of 90 mL of methylene chloride. The methylene chloride extracts were combined after each extraction, placed in a water bath at 35°C, and concentrated to a final volume of 0.5 mL using a gentle flow of nitrogen gas. A solvent exchange with methanol was performed by adding approximately 1-2 mL of methanol to the concentrated extract, re-concentrating it to 0.5 mL, then repeating this step an additional two times or until all methylene chloride was evaporated. The final 1 mL extracts were transferred into individual 2 mL amber glass vials for analysis on the respective instrument. Matrix matched calibration standards were prepared by adding known amounts of pesticide solution then extracting 500 mL aliquots of each non-treated control water as previously described. Target pesticide concentrations in the final 1 mL calibration extracts were 25, 100, 500, and 750 µg L^{-1}. Respective samples were quantitated under the paired matrix matched calibration series.

5.3.8.2 LCMS Analysis

Acephate, isoxaben, metalaxyl-m, triflumizole, and thiophante-methyl were analyzed by high pressure liquid chromatography-mass spectrometry (HPLC-MS). Pesticide concentrations were quantified using a Waters Alliance 2695 HPLC (Waters Corp., Milford, MA) equipped with a C_{18} reversed phase LC column (Phenomenex Synergi Hydro-RP; 80 Å, 50 x 2 mm, 4 µm; P/N 00B-4375-B0) with a C_{18} guard column (Waters Nova-Pak; 4 µm; P/N: WAT044380), coupled to a Micromass Quattro Ultima MS (Micromass UK Limited, Wythenshawe, England). Fifty µL of each sample were injected onto the LC column and pesticides were separated and concentrated using a gradient mobile phase consisting of solution A (Optima LC-MS water with 0.1% Optima formic acid, 0.9% 1M ammonium formate (NH_4COOH), and 5% Optima methanol) and solution B (Optima methanol with 0.1% Optima formic acid, 0.9% 1 M NH_4COOH, and 9% Optima water). The gradient started with a 60:40 (A:B) ratio from 0 to 6 min., changing linearly to 5:95 (A:B) from 6 to 8 min. where it was held from 8 to 15 min., and then returned to initial conditions at 15 min. (total run time of 15 min.). The flow rate was constant at 0.50 mL min^{-1} and the column was held at ambient temperature (~22 °C). All chemicals for the mobile phases A and B were purchased from Thermo Fisher Scientific, Waltham, MA. The MS/MS was operated in heated electrospray ionization (ESI) positive mode with a capillary voltage of 2.96 kV. Source and desolvation temperatures were 150 °C and 350 °C, respectively. Cone and desolvation gas flow rates were 50 and 500 L hr^{-1}, respectively, with nitrogen used as the carrier gas. The data were acquired in multiple-reaction monitoring (MRM) mode. Conditions used to perform m/z transitions are summarized in Table 5.3.

5.3.8.3 GC-ECD Analysis

Bifenthrin, chlorpyrifos, oxyfluorfen, and prodiamine were analyzed using an HP 5890 Series II GC (Agilent Technologies, Santa Clara, CA) equipped with dual electron capture detectors (ECD) and fitted with DB-5MS + DG and DB-35MS columns (30 m x 0.250 mm; Agilent technologies, Santa Clara, CA). Extracts (1 μL) were injected into the injection port operating in splitless mode (1 min.) and equipped with a Siltek gooseneck splitless liner with deactivated glass wool (Restek Corp., Bellefonte, PA; 4 mm x 6.5 mm x 78.5; P/N 22406-213.5). The injector and detector temperatures were held at 225 °C and 300 °C, respectively, and the head pressure was held at 20 psi continuously. The oven program began with an initial temperature of 60 °C. After an initial hold time of 1.5 min, the temperature was increased to 280 °C at a rate of 65 °C min^{-1} with a final hold time of 5.2 min (total run time 10.08 min). The retention times of each pesticide on the respective column is provided in Table 5.4. Pesticides needed to be detected on both columns in order to confirm its presence. Between the two columns, analyzed concentrations were generally within ±10% of one another. Calibration series were run before and after each batch of 20 samples as described earlier.

Quality control/assurance

QA/QC samples were extracted and analyzed along with experimental samples. Method blanks (reagent-grade water) were extracted and analyzed to verify that the extraction/analysis methods did not cross contaminate samples. Spiked QA/QC samples consisting of reagent-grade water spiked with 100 μL of a 1 mg L^{-1} solution of pesticides in methanol were also extracted and analyzed for method validation. Passing criteria was 80-120% recovery. One randomly selected sample per twenty samples collected was used for matrix spikes and matrix spike duplicates. These samples were randomly selected and divided into three 500 mL aliquots, with

two aliquots receiving 100 µL of a 1 mg L^{-1} solution of pesticides in methanol. Each sample was extracted and analyzed as previously described. Passing criteria were 80-120% recovery of the added pesticide in spiked samples and ≤10% concentration differences between duplicate samples. The minimum method quantitation limit for all pesticides was 0.125 µg L^{-1}.

5.3.9 Experimental Design and Statistical Analysis

A completely randomized design was used for this study, with irrigation treatment, substrate treatment, and plant placement for individual beds randomly assigned. Data was analyzed using SAS v 9.4 (Cary, NC). Irrigation applied was subjected to analysis of variance using the PROC GLM procedure. When irrigation treatment effects were significant ($p \leq 0.05$) means were separated using Tukey's test in the LSMEANS prompt. Assessment of average surface and subsurface IRF volumes throughout the season used only sample days on which less than 0.5 cm of precipitation occurred. The volumes of water lost to surface and subsurface IRF, pesticide concentration, and pesticide load were subjected to analysis of variance using the PROC Mixed procedure with repeated measures, again when treatment effects were significant ($p<0.05$) means were separated using Tukey's tests in the LSMEANS prompt. Variable means and standard errors for irrigation applied, volume of water lost to surface and subsurface IRF, pesticide concentration, and pesticide load were calculated using the PROC MEANS feature. Regression models, when F values were significant ($p<0.05$), were used to model pesticide load over the entire 16 day period using the PROC GLM procedure.

5.4 Results

Analysis of variance by date for surface and subsurface IRF showed a substrate by irrigation interaction for only 6 out of 33 dates, main effect due to substrate type for only 2 out of 33 dates but main effect due to irrigation for 21 out of 33 dates, therefore, only irrigation main

effects are presented. Analysis of variance by date for pesticide load in IRF showed a substrate by irrigation interaction for only 7 out of 110 dates, main effect due to substrate type for only 3 out of 110 dates but main effect due to irrigation for 39 out of 110 dates, therefore, only irrigation main effects are presented. All values were converted to a per hectare equivalence for ease of comparison.

5.4.1 Water Applied and Irrigation Return Flow

Three monitoring periods were observed throughout the study, encompassing the 16 days following pesticide applications, with the daily application volume measured for day 0, 1, 2, 3, 4, 7, 8, 15, and 16.

5.4.1.1 Monitoring Period 1

During the first monitoring period, a total of 2,734 kl of irrigation per hectare was applied in the control, which was greater than the OH (1,025 kl per hectare), and the SS (531 kl per hectare). There was no difference in the total amount of irrigation applied between the OH and SS during the first monitoring period (Figure 5.2). There were no differences in the volume applied on day 0, where an equivalent volume was applied to each bed following isoxaben application for watering-in. With the exception of day 4, a greater volume of irrigation was applied to the control versus the SS. The OH applied an equivalent amount of irrigation to the control on day 1 and day 4; however, was less than the control on all other measured days in the monitoring period. A greater volume of irrigation was applied to the OH than the SS on day 1, 2, and 15. The control applied irrigation on all 16 dates post pesticide application, which was greater than the average days for OH (10.33), while SS (11.5) was no different from either the control or the treatment. Following the Day 0 watering in event (where the control was greater than the OH treatment, while SS was equivalent to both control and OH), the volume of surface

IRF collected in the first monitoring period was greater in the control than the spray stake treatment on all sample dates (Figure 5.2). The control also exported a greater volume of surface IRF than the OH treatment on all sample dates, with the exception of day 1. Surface IRF volumes from OH and SS were equivalent on all days following day 1. There were no differences in the volume of subsurface IRF between the control and the treatments on any sample date (Figure 5.2).

5.4.1.2 Monitoring Period 2

During the second monitoring period, a total of 2,852 kl per hectare were applied to the control, 1,601 kl to the OH, and 529 kl to the SS. The control was greater than both the OH and SS treatments, while the OH was also greater than the SS treatment. The watering in event following oxyfluorfen application in the second monitoring period applied the standard control application rate, while 63.3 kl ha^{-1} were applied to the two treatments to meet the minimum watering-in requirements, where the control applied a greater volume than either treatment. Across all measured dates, the control applied a greater volume of irrigation than the SS treatment (Figure 5.3). Post day 0, the OH applied less irrigation than the control on 5 of 8 measurement dates, while also applying more than the SS on 3 sample dates. The control applied irrigation on all 16 dates post pesticide application, which was equivalent to the average days for OH (11.6), while SS (9.5) was less than the control but equivalent to OH. Irrigating with the minimum watering-in rate recommended for oxyfluorfen in monitoring period 2 led to reduced surface IRF on Day 0 for both treatments when compared to the control (Figure 5.3). The volume of surface IRF collected over the rest of the second monitoring period was greater in the control than the spray stake treatment on all sample dates. The control also exported a greater volume of surface IRF than the OH treatment on all sample dates, with the exception of day 4. OH and SS

were equivalent on all days, with the exception of day 8, where the SS was lower than the control. There were no differences in the volume of subsurface IRF, with the exception of day 2, where the OH generated more subsurface IRF than SS, while the control was equivalent to both treatments (Figure 5.3).

5.4.1.3 Monitoring Period 3

During the third monitoring period, a total of 2,062 kl per hectare were applied to the control, which was greater than the OH (1,120 kl), and the SS (550 kl). The OH was also greater than SS. Similarly to the second monitoring period, the control received its standard application rate while the two treatments received the minimum watering-in rate recommended for prodiamine. The volume of water applied on day 0 was greatest in the control, while it was no different between the two treatments (Figure 5.4). Irrigation was not applied to the control or treatments on day 1 or day 8; however, the control received more irrigation than the SS on all other sample dates. The OH applied an equivalent volume of water as the control on day 2, 3, 4, and 16. The control applied irrigation on 14 dates post application, with no irrigation applied on day 1 or 8 for the control or all treatments in response to precipitation. The OH treatment applied irrigation on 9.33 days, which was less than the control, but equivalent to the SS (10.5 days). Control and SS applied irrigation on an equivalent number of dates. Irrigating using the minimum recommended watering-in rate for prodiamine reduced the volume of surface IRF in the treatments compared to the control standard daily rate (Figure 5.4). A greater volume of surface IRF was generated in the control than the SS on all sample dates. OH was equivalent to both the control and SS on day 1 and 4. While on day 2 OH generated more surface IRF than SS, there were no differences between the two treatments on any other sample date. There were no

differences in the volume of subsurface IRF generated between the controls and treatments on any date (Figure 5.4).

5.4.2 Pesticide Dynamics

5.4.2.1 Acephate Monitoring Period 1

The load of acephate recovered in surface IRF samples was greater in the control than the spray stake treatment on 4 of 5 sample dates, with the exception being day 4 where the control was equivalent to both treatments (Figure 5.2). The load of acephate recovered in surface IRF from OH irrigated beds was equivalent to both the control and spray stake irrigated beds on all sample dates, with the exception of day 8, where both treatments were less than the control but equivalent to each other. Both the control and the OH treatment exhibited a linear decrease in surface IRF acephate load when both axes were log transformed (Table 5.5). The control exported 591 g of acephate in surface IRF over the 5 sample dates (Table 5.6). The load recovered in surface IRF over the 5 sampling dates in the OH and spray stake treatment was 256 g and 0.51 g, or 46% and less than 1% of applied acephate. Higher acephate concentrations were measured in surface IRF of the control versus the spray stake treatment on day 1 and 8, and versus the OH treatment on day 8 (Table 5.7).

The load of acephate recovered in subsurface IRF was equivalent between the control and both treatments on all sample dates throughout the monitoring period (Figure 5.2). Subsurface IRF samples collected over the 5 sampling dates yielded 22 g, 79 g, and 39 g in the control, OH treatment, and spray stake treatment, respectively, corresponding to 4%, 14%, and 7% of applied acephate (Table 5.6). There were no changes over the duration of the monitoring period in subsurface IRF load of acephate in either the control or the OH treatment; however, the spray stake treatment exhibited a quadratic relationship between the log transformed acephate load and

log transformed day after application (Table 5.5), suggesting that a lag effect occurred in the percolation of acephate through the sand profile of spray stake irrigated beds. There were no differences in the concentration of acephate in subsurface IRF between the control and treatments (Table 5.2).

Combining surface and subsurface acephate load across the 5 sample dates, a total of 613 g, 335 g, and 39.2 g were recovered in the control, OH and spray stake treatments, respectively, corresponding to 110%, 61% and 7% of applied acephate (Table 5.6).

5.4.2.2 Mefenoxam

A greater load of mefenoxam was recovered in surface IRF from the control than the spray stake treatment on days 1, 4, and 8 (Figure 5.2). With the exception of day 8, the control and the OH treatment exported an equivalent load of mefenoxam. A linear decrease was observed in the surface IRF load of both the control and OH treatment when both axes were log transformed (Table 5.5). In surface IRF samples collected across the 5 sample dates, 1.68 g were recovered from the control, 0.95 g in the OH treatment, and less than 0.02 g in the spray stake treatment, corresponding to 9.2 %, 5.2 %, and less than 0.1% total amount applied recovered by irrigation practice (Table 5.6). Concentrations of mefenoxam in surface IRF peaked on day 1 for the control and OH at 9.98 and 8.22 µg L^{-1}; however, SS often eliminated surface IRF movement and the concentration never exceeded 1 µg L^{-1} (Table 5.7).

The load of mefenoxam recovered in subsurface IRF was equivalent between the control and treatments on each sample date in the monitoring period (Figure 5.2). Total mefenoxam recovered in subsurface IRF over these 5 sample dates was 0.086 g for the control, 0.49 g for the OH treatment, and 0.31 g for the spray stake treatment, or less than 1% of applied mefenoxam in the control, and less than 3% and 2% for the OH and spray stake treatment, respectively (Table

5.6). There was no relationship between mefenoxam load and days after application in subsurface IRF for either the control or the OH treatment; however, a quadratic equation modeling the log transformed mefenoxam load and log transformed days after application (Table 5.5) was significant when assessing mefenoxam load in subsurface IRF from SS. The load of mefenoxam recovered in subsurface IRF from SS was greater on day 4 than the load recovered 1 and 2 days after application, suggesting a lag effect occurred; whereas, samples collected 8 and 16 days after application were no different from day 4. The total load of mefenoxam recovered across these 5 sample dates in combined IRF was 1.77 g, 1.45 g, and 0.33 g for the control, OH treatment and spray stake treatments, respectively, corresponding to 9.7%, 7.9%, and 1.8% of applied mefenoxam (Table 5.6). While subsurface concentrations did not differ between the control or treatment on any day, the control and OH peaked on day 2 at 2.73 and 8.32 µg L^{-1}. SS peaked on day 4 at 11.39 µg L^{-1}, furthering the notion that a lag-effect was occurring in subsurface IRF from this treatment (Table 5.7).

5.4.2.3 Bifenthrin

The load of bifenthrin recovered in surface IRF from the control was greater than the spray stake treatment across all sample dates (Figure 5.2). For all sample dates after day 1, a reduced load of bifenthrin was recovered in surface IRF from the OH treatment versus the control. Both the control and OH treatment exhibited a linear decrease in bifenthrin load exported over time via surface IRF when both x and y axes were log transformed (Table 5.5). Across the 5 sample dates, the load of bifenthrin recovered in surface IRF was 319 mg ha^{-1}, 126 mg ha^{-1}, and 2.84 mg ha^{-1} in the control, OH treatment, and spray stake treatment, respectively (Table 5.6). With the exception of day 1, where the control and OH treatment exported

concentrations of 1.9 µg L^{-1} and 1.41 µg L^{-1}, all concentrations were below 0.7 µg L^{-1} in surface IRF (Table 5.7).

There were no differences in subsurface load of bifenthrin between the control and treatments on any sample date (Figure 5.2). Subsurface IRF load of bifenthrin in spray stake irrigated beds exhibited a linear increase when both axes were log transformed, whereas the control also exhibited a linear increase under these same conditions (Table 5.5); however, this is more reflective of estimates based upon volumes of subsurface IRF generated. Total bifenthrin load recovered across the 5 sample dates in subsurface IRF was 16.7 mg ha^{-1}, 12.8 mg ha^{-1}, and 8.44 mg ha^{-1} in the control, OH treatment, and spray stake treatment, respectively (Table 5.6). The concentration of bifenthrin in subsurface IRF was typically below the limit of detection, and did not exceed 0.23 µg L^{-1} across any sample date for the control and treatments (Table 5.7).

Combining surface and subsurface IRF, the control, OH treatment, and spray stake treatment exported 336, 139, and 11.3 mg, respectively, across these sample dates. Of the 130,000 mg applied per hectare, less than 0.3% was recovered across the control and the treatments in the total IRF (Table 5.6).

5.4.2.4 Isoxaben

An equivalent load of isoxaben was recovered in surface IRF from the control and both treatments following the watering-in event (day 0) (Figure 5.2). A greater load of isoxaben was recovered in surface IRF from the control than the spray stake treatment on day 1, 2, and 8. Isoxaben load exported in surface IRF exhibited a linear decrease when both axes were log transformed for the control and the OH treatment (Table 5.5). The load of isoxaben recovered from the OH treatment was equivalent to both the control and the spray stake treatment on days 1, 2, 4, and 16. Across the 6 sample dates post application, the load of isoxaben recovered per

hectare in surface IRF was 86.4 g, 44.3 g, and 19.1 g in the control, OH treatment, and SS treatment, respectively, representing 10%, 5% and 2% of applied Isoxaben (Table 5.6). Surface IRF concentrations were generally equivalent, with the greatest concentrations occurring on the watering-in event and the first day after application (Table 5.7).

The load of isoxaben recovered in subsurface IRF was equivalent between the control and both treatments on every sample date within the monitoring period (Figure 5.2). A linear decrease was identified in subsurface IRF for the control when both axes were log transformed, while the spray stake treatment exhibited an increasing then decreasing quadratic relationship (Table 5.5), indicating a lag effect occurred. Total isoxaben load recovered per hectare across these 5 sample dates in subsurface IRF was 1.41 g, 6.07 g, and 2.34 g in the control, OH treatment, and spray stake treatment, respectively, representing less than 1% of applied isoxaben in all cases (Table 5.6). Isoxaben concentrations were no different between the control and treatments in subsurface IRF, with averages of 96 µg L^{-1}, 74 µg L^{-1}, 38.8 µg L^{-1}, 4.38 µg L^{-1}, and finally 1.05 µg L^{-1} in samples collected on day 1, 2, 4, 8, and 16, respectively (Table 5.7).

Combined, the control, OH treatment, and spray stake treatment exported 87.8 g, 50.4 g, and 21.5 g, respectively, across these sample dates. Of the 867 g applied per hectare, 10% was recovered in total IRF for the control, while the OH treatment and spray stake treatment recovered 6% and 2% (Table 5.6).

5.4.2.5 Acephate monitoring period 2

During the second monitoring period, the load of acephate recovered in surface IRF from the control was greater than the spray stake treatments on day 1, 2, and 16 (Figure 5.3). The load of acephate recovered from the OH treatment was equivalent to the control on days 1, 2, 4, and 8; however, on day 16 a greater load was recovered in the control. Only the OH treatment had a

significant model estimating surface IRF load (Table 5.5), exhibiting a linear decrease when both axes were transformed. The total load of acephate recovered per hectare across these 5 sample dates in surface IRF was 461 g, 134 g, and 26.0 g in the control, OH and spray stake treatment, respectively, corresponding to 83%, 24 %, and 5% of applied acephate (Table 5.6). There were no differences between the control and treatments in the concentration of acephate in surface IRF (Table 5.7); however, the load exported was often greater in the control when compared to the spray stake treatment, particularly soon after application, as a function of the greater volume of surface IRF generated via the control.

There were no differences between the control or treatments in the load of acephate recovered in subsurface IRF on any sample date (Figure 5.3). The control and both treatments exhibited a linear decrease in the load of acephate in subsurface IRF when log transforming both axes (Table 5.5). Total subsurface IRF acephate recovery over these 5 sample dates yielded 54.1 g, 125 g, and 60.8 g for the control, OH and spray stake treatment respectively, representing 10%, 23%, and 11% of applied acephate (Table 5.6). There were no differences between the control and treatments in the concentration of acephate in subsurface IRF (Table 5.7).

Total load recovered over these sample dates in combined surface and subsurface IRF yielded 515 g, 259 g, and 86.8 g in the control, OH and spray stake treatments, respectively corresponding to 93%, 47% and 16% of applied acephate (Table 5.6).

5.4.2.6 Triflumizole

A greater amount of triflumizole was recovered in surface IRF from the control than both treatments on day 1; however, there were no differences between the control and treatment on all subsequent sample dates (Figure 5.3). A linear relationship between the log transformed triflumizole load and log transformed days after application was identified in modeling the

surface IRF content of triflumizole exported from the control beds (Table 5.5). There was no significant relationship in surface IRF load over time for either treatment. The load of triflumizole recovered per hectare on these 5 sample dates in surface IRF was 5.99 g, 1.66 g, and 0.13 g in the control, OH and spray stake treatment, respectively, corresponding to 2%, 0.5 %, and less than 0.1% of applied triflumizole (Table 5.6). Surface concentrations for the control peaked at 38.3 µg L^{-1} on day 1, for OH at 15.86 µg L^{-1} on day 2, and SS at 4.07 µg L^{-1} on day 4 (Table 5.7).

The load of triflumizole recovered in subsurface IRF was equivalent between the control and both treatments on all sample dates, with the exception of day 16, where the OH treatment was greater than the spray stake treatment, but the control was equivalent to both treatments (Figure 5.3). Subsurface IRF triflumizole recovery over these sample dates yielded 0.1 g, 0.2 g, and 0.08 g for the control, OH and spray stake treatment respectively, representing less than 1% of applied triflumizole in all cases (Table 5.6). No relationships for subsurface IRF triflumizole load and days after application was significant for any control/irrigation treatment. Subsurface concentrations for the control peaked at 5.65 µg L^{-1} on day 4, for OH at 2.57 µg L^{-1} on day 8, and SS at 1.17 µg L^{-1} on day 1 (Table 5.7).

Total load recovered over these sample dates in combined surface and subsurface IRF yielded 6.09 g, 1.85 g, and 0.21 g in the control, OH and spray stake treatments, respectively corresponding to 2.1%, 1%, and less than 0.1% of applied triflumizole (Table 5.6).

5.4.2.7 Chlorpyrifos

A greater load of chlorpyrifos was recovered in surface IRF from the control than either treatment on day 1, 2, and 8, whereas on day 4 and 16 the control and both treatments were equivalent (Figure 5.3). The load of chlorpyrifos exported in surface IRF water from the controls

exhibited a linear decrease when both axes were log transformed; however, there was no relationship between surface IRF load of chlorpyrifos and days after application for either treatment (Table 5.5). A total of 4.54 g was recovered over the five sample dates in surface IRF from the control; whereas, 0.84 g and 0.04 g were recovered from the OH and spray stake treatment, respectively (Table 5.6). Chlorpyrifos concentrations in surface IRF peaked for the control and OH on day 1 at 33.89 µg L^{-1} and 15.65 µg L^{-1}. SS often eliminated surface IRF, and the peak concentration was 1.27 µg L^{-1} on day 4 (Table 5.7).

An equivalent load of chlorpyrifos was recovered in subsurface IRF from the control and both treatments on day 1, 2, 4, and 8; however, on day 16 a greater load of chlorpyrifos was exported from the OH treatment than the spray stake treatment, while the control was equivalent to both (Figure 5.3). A quadratic decrease between chlorpyrifos load recovered in subsurface IRF and days after application was identified in both the OH treatment and the spray stake treatment; whereas, no significant relationship was identified in the control (Table 5.5). The load of chlorpyrifos recovered in subsurface IRF from the spray stake treatments increased from day 2 to day 4, followed by decreasing from day 4 to day 8, suggesting a lag effect in the movement of chlorpyrifos occurred. The total load recovered over these 5 sample dates in subsurface IRF was 0.03 g, 0.06 g, and 0.04 g in the control, OH treatment, and spray stake treatment, respectively (Table 5.6). Concentrations of chlorpyrifos in subsurface IRF were universally equivalent, and never exceed 1 µg L^{-1} in the control or either treatment (Table 5.7).

The total combined IRF load of chlorpyrifos recovered across these 5 sample dates was 4.56 g, 0.89 g, and 0.08 g for the control, OH treatment, and spray stake treatment, respectively, accounting for less than 1% of the applied chlorpyrifos across the control and treatments (Table 5.6).

5.4.2.8 Oxyfluorfen

A greater load of oxyfluorfen was recovered in surface IRF samples from the control than either treatment following the post pesticide application watering-in event (Figure 5.3). On sample days 1 and 2, a greater load of oxyfluorfen was also recovered in the control versus the two treatments. While the load of oxyfluorfen recovered in surface IRF samples was equivalent between the control and both treatments on day 4 and 16, the control was greater than both the OH and SS treatments, and the OH treatment was also greater than the SS treatment on day 8. There was no relationship between days after sampling and the load of oxyfluorfen recovered in surface IRF across the control and all treatments. Total oxyfluorfen recovery over the 6 surface IRF samples yielding 0.22 g, 0.08 g, and 0.02 g per hectare for the control, OH treatment, and spray stake treatment, respectively, universally corresponding to less than 0.1% recovery of applied oxyfluorfen (Table 5.6). The concentration of oxyfluorfen in surface IRF universally averaged below 1 $\mu g\ L^{-1}$; however, in cases where surface IRF was eliminated via spray stake irrigation, the concentration was lower in the spray stake irrigated treatment than the control and/or OH treatment (Table 5.7).

The load of oxyfluorfen recovered in subsurface IRF was equivalent between the control and both treatments on day 1, 4, and 8 (Figure 5.3). On day 2 and 16, a greater load of oxyfluorfen was recovered from the OH treatment than the spray stake treatment, while the control was equivalent to both. A linear decrease in oxyfluorfen load was observed in the spray stake subsurface IRF when log transforming both axes (Table 5.5). In assessing changes within subsurface IRF over time in spray stake irrigated beds, an increase in load was observed from day 2 to day 4 after application, suggesting the potential for a lag effect to occur as oxyfluorfen subsurface IRF load decreased over time. Across the 5 subsurface IRF sample dates the control,

OH, and spray stake treatment recovered 0.02 g, 0.05 g, and 0.03 g, respectively, in all cases accounting for less than 0.01% of applied oxyfluorfen (Table 5.6). The concentration of oxyfluorfen present in subsurface IRF across the control and treatments also averaged below 1 μg L^{-1} across all sample dates (Table 5.7).

In total IRF samples collected over the 6 sample dates, 0.24 g, 0.13 g, and 0.05 g were recovered in the control, OH treatment, and spray stake treatment, respectively, universally corresponding to less than 1% total recovery of applied oxyfluorfen (Table 5.6).

5.4.2.9 Acephate Monitoring Period 3

During the third monitoring period, the load of acephate recovered in surface IRF from the control was greater than the SS treatment on day 2 and 16 (Figure 5.4). The load of acephate recovered in surface IRF from the OH treatment was equivalent to the control on all sample dates, while also greater than the spray stake treatment on day 2. The control and OH exhibited a linear decrease in surface IRF load of acephate when both axes were log transformed (Table 5.5). The load of acephate recovered per hectare on these 5 sample dates in surface IRF was 541 g, 297 g, and 124 g in the control, OH and spray stake treatment, respectively, corresponding to 98%, 54 %, and 22% of applied acephate (Table 5.6). The concentration of acephate in surface IRF was only different on day 2, with a higher concentration exported in the OH treatment than the spray stake treatment, with the control no different from either treatment (Table 5.7).

There were no differences in the load of acephate recovered in subsurface IRF between the control and treatments on any of the 4 sample dates (Figure 5.4). There was no significant model assessing subsurface IRF acephate load in the control. The OH treatment exhibited a quadratic relationship (increasing before decreasing) in subsurface IRF (Table 5.5) when both axes were log transformed. The spray stake treatment exhibited a linear decrease (Table 5.5) in subsurface

IRF acephate load. Subsurface IRF acephate recovery over the 4 sample dates yielded 157 g, 276 g, and 295 g for the control, OH and spray stake treatment respectively, representing 28%, 50%, and 53% of applied acephate (Table 5.6). The only differences identified in subsurface IRF concentration occurred on day 1, where the spray stake treatment was greater than the OH treatment, again with the control no different from either treatment (Table 5.7).

Total combined IRF load recovered over these sample dates yielded 697 g, 574 g, and 419 g in the control, OH and spray stake treatments, respectively corresponding to 126%, 104% and 76% of applied acephate (Table 5.6).

5.4.2.10 TPM

A greater load of TPM was recovered in surface IRF samples from the control than either treatment on day 2, 8, and 16 (Figure 5.4). The load of TPM recovered in surface IRF on day 1 and 4 was equivalent between the control and both treatments. A linear decrease was identified in the load of TPM versus the days after sampling in surface IRF of the control and OH (Table 5.5). Across these 5 sample dates, a total of 42.8 g, 10.8 g, and 7.36 g were recovered in surface IRF samples of the control, OH treatment, and spray stake treatment, respectively, corresponding to 8.9%, 2.2%, and 1.5% recovery of the applied TPM (Table 5.6). There were no differences between the control and treatments in the concentration of TPM in surface IRF, with peak concentrations occurring on day 1 (Table 5.7).

The load of TPM recovered in subsurface IRF was equivalent between the control and both treatments on all four sample dates throughout the monitoring period (Figure 5.4). No relationship was identified in subsurface IRF load in the control when log transforming both axes. A linear decrease in subsurface IRF load of TPM versus days after application was identified in the OH and SS treatments when both axes were log transformed (Table 5.5).

Subsurface loads recovered over these sample dates yielded 3.03 g, 1.99 g, and 2.77 g for the control, OH treatment, and spray stake treatment, respectively, in all cases less than 1% of applied TPM (Table 5.6). There were no differences between the control and treatments in the concentration of TPM in subsurface IRF (Table 5.7). In total IRF loads collected over the 5 sample dates, 45.8 g, 12.8 g, and 10.1 g were recovered in the control, OH treatment, and spray stake treatment, respectively, corresponding to 9.5%, 2.7%, and 2.1% of applied TPM (Table 5.6).

5.4.2.11 Prodiamine

On every sample date within the monitoring period, a greater load of Prodiamine was recovered in surface IRF from the control than either treatment, while both treatments were equivalent to each other (Figure 5.4). A decreasing linear equation modeling log transformed prodiamine load in surface IRF versus days after application was identified for the control (Table 5.5). A total of 21.1 g, 2.28 g, and 2.69 g were recovered in surface IRF over these 5 sample dates in the control, OH treatment, and spray stake treatment, respectively, corresponding to 1.2%, 0.1% and 0.2% of applied prodiamine (Table 5.6). In the control, the concentration of prodiamine in surface IRF also exhibited a linear decrease when both axes were log transformed (F value 34.03; R square: 0.79). The OH treatment exhibited a linear decrease in prodiamine concentration over time in surface IRF (F value 11.4; R squared: 0.37), when both axes were log transformed. Prodiamine concentrations were greatest over the day of application (post watering-in) and the day after application, peaking at 102.61 µg L^{-1}, 37.02 µg L^{-1}, and 40.81 µg L^{-1} in the control, OH, and SS, respectively (Table 5.7).

The load of prodiamine recovered in subsurface IRF was equivalent between the control and treatments on all 4 sample dates (Figure 5.4). Subsurface IRF load models over time were

insignificant for the control or OH treatment, while subsurface IRF load from spray stake treatments exhibited a quadratic increase (Table 5.5). The load recovered in subsurface IRF was 0.15 g, 0.1 g, and 0.14 g per hectare for the control, OH treatment, and spray stake treatment, respectively, in all cases below 0.1% of applied prodiamine (Table 5.6). Prodiamine concentrations were universally below 8 $\mu g\ L^{-1}$ (Table 5.7). There was no change in prodiamine concentration in subsurface IRF within the control. The OH treatment exhibited a linear increase in subsurface IRF prodiamine concentration (F value 22.82 ; R squared: 0.48), when both axes were log transformed. Prodiamine concentration in subsurface IRF of spray stake irrigated beds exhibited a quadratic decrease then increase (F value: 4.65 ; R squared 0.30) when both axes were log transformed, suggesting a potential lag effect occurred.

Total prodiamine load recovered in combined IRF over the 6 sample dates was 21.3 g, 2.37 g, and 2.82 g in the control, OH treatment, and spray stake treatment, respectively, corresponding to 1.3% recovery of applied prodiamine in the control and less than 1% in either treatment (Table 5.6).

5.5 Discussion

5.5.1 Water Applied and IRF

Irrigating using θ reduced water use across all three rounds. Compared to the control, OH reduced water applied by 42-63% over the three monitoring periods. SS reduced water applied compared to the control by 73-81% over the three monitoring periods. During the second and third monitoring periods, SS reduced water use compared to OH by 54-67%. The reduced volume of irrigation applied in the treatments often reduced the volume of surface IRF compared to the control, especially when irrigating using SS. Subsurface IRF volumes were almost always equivalent between the control and the treatments. Warsaw et al. (2009) investigated using θ

based irrigation practices in container nursery production and the effects it had on IRF volume. Our results were consistent with their findings, where irrigating based on θ reduced water use by up to 44% while also reducing IRF by between 66% and 79%. They posited that the reduction in IRF was twofold, resulting from both the reduced volume of irrigation applied as well as more substrate capacity to absorb water due to likely lower substrate θ pre-irrigation. Mathers et al. (2005), also suggested that the use of micro-irrigation and/or cyclic irrigation can reduce water use as well as runoff.

5.5.2 Highly Mobile Pesticides

All three pesticides exhibited a linear or quadratic decrease in surface IRF load from the control and the OH treatments; whereas, SS irrigation often times eliminated surface IRF generation, leading to less movement from SS. While the OH treatment reduced water applied, and at times the volume of surface IRF generated, an equivalent load of each pesticide was typically exported compared to the control via surface IRF on each sample date. In subsurface IRF, all three pesticides were exported in equivalent amounts between the control and OH and SS treatments for each sample day. However, the quadratic relationship exhibited by acephate and mefenoxam movement in OH and/or SS subsurface IRF highlights how reduced (and more precise) irrigation may modify infiltration and percolation of pesticides through subsurfaces.

5.5.2.1. Acephate

Acephate is an organophosphate insecticide which inhibits acetylcholinesterase within the nervous system (http://npic.orst.edu/factsheets/archive/acephatech.html). Acephate is unlikely to undergo photodegradation or volatilization; however, aerobic degradation is a prominent degradation mechanism, where Ramu et al. (2014) reported that the bacterial strain *Pseudomonas aeruginosa* strain Is-6 was capable of degrading acephate, as well as a number of

other organophosphorus pesticides, with efficacy maintained at concentrations as high as 1 gram / L (https://pubchem.ncbi.nlm.nih.gov/compound/Acephate). Acephate was hypothesized to exhibit a high degree of both surface and subsurface mobility based on both its high solubility and low Koc coefficient (Table 5.2).

Acephate solubility is over 31 times greater than the next most soluble pesticide (mefenoxam), and 818,000,000 times greater than the least soluble pesticide (bifenthrin); therefore, it was hypothesized that this compound would be the most mobile of all investigated pesticides. The mobility of acephate in water has been reported by Sun et al. (2018), where in assessing pesticide concentrations in the Yangtze River, acephate was present in higher concentrations than any other pesticide investigated. Over all three monitoring periods, acephate was recovered in both greatest quantity and greatest percentage of amount applied of all pesticides in both surface and subsurface IRF (Table 5.6). Similarly, acephate was the pesticide with the highest concentration in both surface and subsurface IRF.

Across the three monitoring periods, nearly 2-3 times more acephate was recovered in surface IRF from the control than the OH treatment. Spray stakes typically reduced or eliminated surface IRF generation, with total acephate recovered in surface IRF approximately 4 to 1,000 times lower than the control. The amount of acephate recovered in surface IRF represented a substantial portion of the amount applied; with 83-107% of the 553 g ha^{-1} recovered in the control, 24-54% in the OH, and <1%-22% in the SS, across all three rounds. Conversely to the total load recovered in surface IRF, the OH exported 2 to 3 times more acephate than the control in subsurface IRF over the three monitoring periods. Spray stakes exported a similar total load of acephate in subsurface IRF as the control during round 2, but nearly twice as much for round 1 and 3. Roughly 3-28% of applied acephate was recovered in subsurface IRF from the control,

14-50% for the OH, and 7-53% in SS; demonstrating how subsurface IRF is a critical vector in the movement of acephate regardless of irrigation practice.

For the control, total acephate recovery was 3.5 to 27 times greater in surface IRF than subsurface IRF; however, for the OH treatment the total acephate recovered in surface IRF was typically equivalent to the subsurface IRF load recovered during the second and third monitoring period, but approximately 3.2 times greater during the first monitoring period. Considering that SS reduced and often eliminated surface IRF, subsurface IRF was the predominant pathway of loss for acephate. Nearly 2.3 times as much acephate was recovered in subsurface IRF than surface IRF from the SS treatment during the second and third monitoring period, while in monitoring period one it was approximately 75 times greater.

5.5.2.2 Mefenoxam

Mefenoxam is a phenylamide fungicide which disrupts RNA polymerases thus inhibiting mycelium growth and sporulation (Hu et al., 2008). Mefenoxam solubility and Koc suggest it may be mobile in the environment (Table 5.2), and it is unlikely to volatilize based on a Henry's Law constant of $3.5x10^{-5}$ atm-cu m/mole or undergo photolysis or hydrolysis (Triantafyllidis et al., 2012). Microbial degradation has been considered the primary pathway of degradation for mefenoxam (Gardner and Branham, 2001; Monkiedje and Spiteller, 2005. Mefenoxam was hypothesized to be present in both surface and subsurface IRF based on its solubility and low Koc.

Nearly twice as much mefenoxam was recovered in surface IRF from the control than the OH treatment, while the total load of mefenoxam recovered from the SS was approximately 120 times lower than the control; however, considering the 18.2 g applied per hectare, this corresponded to nearly 2 g in the control and less than one gram per hectare in the OH and SS

treatments, or 9%, 5%, and less than 1% of applied mefenoxam. Mefenoxam total load recovered in subsurface IRF was 0.5 g ha^{-1} in the OH treatment, which was approximately 4-5 times greater than the control, and nearly 1.5 times greater than the SS. The amount of the applied 18.2 g recovered in subsurface IRF was less than 1% in the control, and roughly 3% and 2% for the OH and SS. The mobility of mefenoxam was investigated by Gardner and Branham (2001), where turf or barren soil plots received either static (10 mm, 5 times per week) or estimated evapotranspiration based irrigation. Regardless of the irrigation practice, mefenoxam rapidly infiltrated through soil profiles. The quadratic model for mefenoxam movement in subsurface IRF from the SS treatment suggested a lag effect occurred, where the reduced volume (and non-target application) of irrigation applied relative to the overhead applications delayed the movement of mefenoxam through subsurface profiles.

In assessing its mobility, the amount of applied mefenoxam recovered was second only to acephate in % of applied compound recovered for both surface and subsurface IRF, demonstrating its capacity to move through subsurface profiles. The total amount of mefenoxam recovered in surface IRF from the control was nearly 20 times greater than subsurface IRF, and for the OH treatment, nearly twice as much mefenoxam was recovered in surface versus subsurface IRF. Considering SS reduced or eliminated surface IRF, thus providing subsurface IRF as the prominent vector for movement, approximately 22 times more mefenoxam was recovered in subsurface IRF versus surface IRF.

5.5.2.3 TPM

Thiophanate-Methyl (TPM) is a benzimidazole fungicide which disrupts the mitotic process through inhibiting nuclear division in susceptible fungi (Cycon et al., 2011). Photolysis and volatilization are unlikely pathways of degradation for TPM; however, microbial

degradation is considered a likely pathway. (Briggs et al., 2002; Cycon et al., 2011). With a solubility of 26.6 mg/L, and a Koc of 330, TPM is classified as moderately mobile and readily soluble (Table 5.2), and may be readily mobile in IRF or precipitation events shortly after application (Briggs et al., 1998).

The total load of TPM recovered in surface IRF from the control was 4 times greater than the OH treatment and 6 times greater than the SS treatment. Of the 482 g of TPM applied per hectare, 42 g was recovered from the control, roughly 9% of the total amount applied, while the OH and SS treatments led to total recovery of 2.2 and 1.5% of total TPM applied. TPM total load recovered in subsurface IRF was approximately 3 g ha^{-1}in the control, 2 for the OH, and 2.75 for the SS; however, in all cases it accounted for less than 1% of the TPM applied per hectare. Comparing the amount of TPM recovered in surface IRF versus subsurface IRF, nearly 14, 5.5, and 2.7 times more TPM was recovered in the control, OH treatment, and SS treatment, respectively, demonstrating that surface IRF is a more likely vector in TPM movement than subsurface IRF.

TPM in movement in IRF from container nurseries has been reported to be greatest shortly following application, where Briggs et al. 2002 reported that between 3.5% and 7% of applied TPM was recovered in the first irrigation event post-application. In the third monitoring period of our study, no irrigation was applied the first day following application due to precipitation. However, the return surface return flow generated from that precipitation event transported a similar percentage of applied TPM (Control 7.2%; OH 1.8%; SS 1.5%) as Briggs et al. (2002) observed. Concentrations of TPM were greatest in both surface and subsurface IRF the first two days following application (Table 5.7), but by day 8 were universally below 1 µg L^{-1} in

both surface and subsurface IRF. The results demonstrate that TPM rapidly moves in both surface and subsurface vectors.

5.5.3 Moderately Mobile Pesticides

Similarly to the high mobility pesticides, all three of the moderately mobile pesticides exhibited a linear decrease in load over time in surface IRF generated from the control; however, the OH only exhibited a linear decrease in the movement of isoxaben. SS irrigation often times eliminated surface IRF generation, reducing or eliminating this vector for pesticide movement. Subsurface IRF loads for each pesticide were no different between the treatment and controls on any given sample date, with the exception of day 16 for chlorpyrifos and triflumizole, where OH was greater than SS, and control no different from either. The Koc values of each of these three pesticides suggest that sorption to organic matter or lipophilic sites may occur. In the case of this system, soilless media (comprised of purely organic materials), plastic containers, and plastic nursery surfaces were utilized, providing non-ionic sorption sites that could reduce infiltration through the subsurface.

5.5.3.1 Triflumizole

Triflumizole is a sterol-demethylation inhibiting (DMI) fungicide which acts through disrupting ergosterol biosynthesis within fungal cells (Hashimoto et al., 2003; Rosenberger et al., 2003). Triflumizole is widely used in numerous agricultural sectors; therefore, increasing the risk of surface water contamination where it has been reported to be detrimental towards freshwater algal species, such as *Chlorella vulgaris* (Xi et al., 2019). Volatilization is not considered a prominent pathway of degradation with a vapor pressure of 1.4×10^{-6} mm Hg and Henry Law constant of 6.2×10^{-8} atm-cu m/mole; however triflumizole may photodegrade. (https://pubchem.ncbi.nlm.nih.gov/compound/91699). Triflumizole is considered to be readily

soluble at 10 mg L^{-1}; however, it is considered to have low to slight mobility based on a Koc of 1,400 (Table 5.2).

Across the total 5 sample dates, 6 g of triflumizole was recovered in surface IRF from the control, nearly 4 times greater than the OH treatment and 45 times greater than the SS, considering SS typically reduced or eliminated surface IRF generation. This corresponded to recovering approximately 2% of the applied triflumizole per hectare from the control, less than 1% for OH, and less than 0.1% for SS. Approximately twice as much triflumizole was recovered in subsurface IRF from OH vs the control, and 3 times as much from OH vs the SS; however, this amounted to less than 0.2 g total recovery for the control and each treatment, or less than 0.1% of the triflumizole applied. In total, less than 2% of the total amount of triflumizole applied was recovered in combined IRF.

Comparing the amount of triflumizole recovered in surface IRF versus subsurface IRF, nearly 58, 8.4, and 1.7 times more triflumizole was recovered in the control, OH treatment, and SS treatment, respectively, demonstrating that surface IRF is a more likely vector in triflumizole movement than subsurface IRF.

5.5.3.2 Isoxaben

Isoxaben is a pre-emergent benzamide herbicide which inhibits cell wall biosynthesis in plants and prevents germination and/or growth (Dow Form No. 233-00845-MM-1111).

Isoxaben is considered moderately soluble based on a solubility of 1.42 mg L^{-1}, but is only slightly mobile based on its Koc, which suggests it is most likely to adsorb to sediments or other materials but may exhibit mobility in water (Table 5.2). Volatilization is not expected to be a major pathway of degradation from either dry or moist soils, nor is it considered likely to

hydrolyze based on the composition of its functional group; however, photodegradation may occur with Isoxaben (https://pubchem.ncbi.nlm.nih.gov/compound/Isoxaben). Bacterial degradation, particularly in aerobic and moist soils, has been reported to be a prominent pathway in the dissipation of isoxaben (Camper et al., 2001; Walker, 1987).

Across the 6 total sample dates where isoxaben loads were collected from surface IRF, 86 g were recovered from the control, which was nearly twice as much as the OH and 4 times greater than the SS. This corresponded to 10%, 5%, and 2% of applied isoxaben recovered via this vector for the control, OH and SS treatments, respectively. Total subsurface isoxaben recovered in OH was nearly 4 times greater than the control and nearly 3 times greater than the SS, in all cases representing less than 0.1% of applied isoxaben. Comparing the amount of isoxaben recovered in surface IRF versus subsurface IRF, nearly 61, 7.3, and 8.2 times more isoxaben was recovered in the control, OH treatment, and SS treatment, respectively, demonstrating that surface IRF is a more likely vector in isoxaben movement than subsurface IRF.

Isoxaben movement in nursery IRF was reported to be greatest on the days immediately following application (Briggs et al., 1998), but declined with each subsequent irrigation event following the day of application. In our study, the total amount of Isoxaben recovered in surface IRF, the majority was transported on the day of application and first two days following application, representing 96%, 97%, and 89% of the total amount recovered for the control, OH, and SS, respectively.

5.5.3.3 Chlorpyrifos

Chlorpyrifos is an organophosphate insecticide which inhibits acetylcholinesterase and is likely to degrade via volatilization, photolysis, and/or microbial degradation

(https://pubchem.ncbi.nlm.nih.gov/compound/2730). Chlorpyrifos is considered moderately soluble; however, based on a Koc range of 995-31,000 may be considered moderately mobile to immobile (Table 5.2).

Across the total 5 sample dates, 4.5 g of chlorpyrifos was recovered in surface IRF from the control, nearly 5.5 times greater than the OH treatment and over 100 times greater than the SS, considering SS typically reduced or eliminated surface IRF generation. In all cases, this amounted to less than 0.1% of the applied chlorpyrifos recovered in surface IRF. Less than 0.06 g of chlorpyrifos per hectare was recovered in subsurface IRF for the control and all treatments, representing less than 0.0001% of applied chlorpyrifos. The lack of subsurface movement exhibited by chlorpyrifos was consistent with Milhome et al (2015) report of chlorpyrifos below detection in groundwater samples, where in our study concentrations in subsurface IRF never exceed 1 µg L^{-1}.

Comparing the amount of chlorpyrifos recovered in surface IRF versus subsurface IRF, nearly 179, 14.2, and 1.2 times more chlorpyrifos was recovered in the control, OH treatment, and SS treatment, respectively, demonstrating that surface IRF is a more likely vector in chlorpyrifos movement than subsurface IRF.

5.5.4 Low Mobile Pesticides

The Surface IRF load of Prodiamine and Bifenthrin both exhibited a linear decrease over time in the control, similar to all previously described pesticides; however, oxyfluorfen did not. Subsurface IRF samples were typically below the limit of detection for bifenthrin for both the control and treatments. Oxyfluorfen was similarly detected at low concentrations in subsurface IRF, where it never exceeded 0.5 µg L^{-1}. Prodiamine subsurface concentration peaked on day 8 from the control at nearly 8 µg L^{-1}. Bifenthrin was typically below the limit of detection in

subsurface IRF samples. In the case of all pesticides within the low mobility group, subsurface IRF movement of pesticides was minimal.

5.5.4.1 Oxyfluorfen

Oxyfluorfen is a diphenyl-ether pre-emergent herbicide that inhibits the protoporphyrinogen oxidase enzyme within the chlorophyll biosynthesis pathway in plants (Stagg et al., 2012). Oxyfluorfen is not expected to volatilize based on Henry's Law constant (8.2×10^{-7} atm-cu m/mole); however, microbial degradation is considered a prominent degradation mechanism (https://pubchem.ncbi.nlm.nih.gov/compound/Oxyfluorfen). Oxyfluorfen is considered slightly soluble (0.12 mg L^{-1}), and based on a Koc of 8,900 is considered slightly mobile to immobile (Table 5.2).

0.2 g of oxyfluorfen was recovered in surface IRF from the control, nearly 3 times greater than the OH treatment and 11 times greater than the SS, considering SS typically reduced or eliminated surface IRF generation. This corresponded to recovering approximately 0.0001% of the applied oxyfluorfen per hectare from the control, and far less for either treatment. Approximately 3 times as much oxyfluorfen was recovered in subsurface IRF from OH vs the control, and 2 times as much from OH vs the SS; however, this amounted to less than 0.05 g total recovery for the control and each treatment, or less than 0.0001% of the oxyfluorfen applied.

Comparing the amount of oxyfluorfen recovered in surface IRF versus subsurface IRF, nearly 15 and 1.5 times more oxyfluorfen was recovered in the control and OH treatment; however, the SS treatment had nearly 1.6 times more oxyfluorfen recovered in subsurface IRF than surface IRF. The results demonstrate that surface IRF is a more likely vector in oxyfluorfen movement than subsurface IRF.

The low concentrations of oxyfluorfen detected in surface and subsurface IRF (universally below 1 µg L^{-1}), as well as the lack of mobility in subsurface profiles, are consistent with Riley et al.'s (1994) report of oxyfluorfen samples being below the level of solubility, and Alister et al.'s (2009) report that over 74% of oxyfluorfen was found in the top 2.5 cm of soil after 90 and 340 days following application in a vineyard system. Oxyfluorfen dissipation in soils was investigated by Wu et al (2019), where they found that higher pH and organic matter content could increase the degradation rate, while soils with a larger clay fraction reduced the degradation rate in response to less pore space for oxyfluorfen to spread. Considering that this study used sand for its soil profile, this may have enhanced degradation.

5.5.4.2 Prodiamine

Prodiamine is a dinitroaniline herbicide which inhibits polymerization of cell microtubules (Breeden et al., 2017; Briggs et al., 2003). Prodiamine is considered insoluble (0.13 mg L^{-1}) and relatively immobile based on a Koc range of 5,440-16,200 (Table 5.2). Photolysis and microbial degradation are considered to be the primary routes of dissipation (Stearman et al., 2012). Herbicides within the dinitroaniline class typically are characterized by their high molecular weight, predilection for hydrophobic sorption, and lower mobility compared with other pesticide classes; however, volatilization can occur, particularly in moist soils given their low solubility (Weber, 1990).

21 g of prodiamine was recovered in surface IRF from the control, nearly 10 times greater than the OH treatment and the SS. This corresponded to recovering approximately 1% of the applied prodiamine per hectare from the control, and less than 0.1% either treatment. In subsurface IRF, less than 0.15 g was recovered for the control and all treatments, or less than 0.0001% of all applied Prodiamine. Comparing the amount of prodiamine recovered in surface

IRF versus subsurface IRF, nearly 141, 23.2, and 19.6 times more prodiamine was recovered in the control, OH, and SS, respectively. The results demonstrate that surface IRF is a more likely vector in prodiamine movement than subsurface IRF.

Stearman et al. (2012) investigated prodiamine removal from nursery IRF using subsurface constructed wetlands, where prodiamine concentrations from nursery IRF of 500-3,200 µg L^{-1} were reduced by 48-65%, with biodegradation and sorptive processes reducing movement. The concentrations in our study peaked on the watering-in event following application for the control (102.6 µg L^{-1}), OH (37 µg L^{-1}), and SS (40.8 µg L^{-1}); however, this was still substantially lower than Stearman et al.'s (2012) reported concentrations.

5.5.4.3 Bifenthrin

Bifenthrin is a pyrethroid insecticide which delays closure of the axon sodium channel gates within nervous systems (http://npic.orst.edu/factsheets/archive/biftech.html). Bifenthrin is considered insoluble and relatively immobile (Table 5.2), suggesting that soil infiltration is unlikely. While the low solubility of bifenthrin suggests volatilization from moist soils or surface water may occur, the strong sorptive tendencies of this compound may limit this pathway of degradation (https://pubchem.ncbi.nlm.nih.gov/compound/5281872).

Despite bifenthrin being considered a fairly immobile compound, potential risk to water bodies may occur based on its persistence in the environment and wide use (Sardiña et al., 2019), and bioactivity at low concentrations for aquatic life (Bertotto et al., 2019; Brander et al., 2016).

Bifenthrin is considered unlikely to photodegrade (Jin et al., 2009); however, microbial degradation by species such as *Pseudomonas* sp. CB2 and *Stenotrophomonas acidaminiphila* have been reported (Lee et al., 2004; Zhang et al., 2018). Bifenthrin was hypothesized to move

predominantly in surface return flow via erosive detachment of sediments/particles. Bifenthrin was hypothesized to exhibit minimal movement in subsurface return flow considering its low solubility.

The control exported 0.32 g of bifenthrin in surface IRF, roughly 2.5 times more than the OH and 110 times more than SS; however, this amount represented less than 0.1% of applied bifenthrin in all cases. Bifenthrin was almost always below the limit of detection (0.125 µg L^{-1}) in subsurface IRF samples, yielding total amounts recovered of less than 0.02 g across the control and both treatments. This corresponded to less than 0.01% of applied bifenthrin.

Comparing the amount of bifenthrin recovered in surface IRF versus subsurface IRF, nearly 19.1 and 9.9 times more bifenthrin was recovered in the control and OH, while subsurface IRF bifenthrin content was nearly 3 times greater than surface IRF for SS. The results demonstrate that surface IRF is a more likely vector in bifenthrin movement than subsurface IRF.

Weston et al. (2009) reported concentrations of 0.073 µg L^{-1} and 1.2 µg/g of bifenthrin in water and suspended sediments collected from an urban creek in California. The peak concentration of bifenthrin in surface IRF was 1.9 µg L^{-1} from the control surface IRF, and 1.41 µg L^{-1} from the OH treatment, both measured on the day following application; however, all subsequent sample dates were below 1 µg L^{-1} subsurface IRF concentrations. Concentrations of bifenthrin in subsurface IRF were nearly universally below the limit of detection and never exceeded 0.25 µg L^{-1}. The results demonstrate that subsurface movement is unlikely to occur with bifenthrin; however, the potential for sorbed bifenthrin to be erosively detached and transported in surface IRF represents the primary vector of movement.

5.5.5 Ecological Toxicity

Pesticides, and degradation products of pesticides such as methadimophos from acephate, a potent acetylcholinesterase inhibitor in its own right, may be ecologically deleterious if present in bioactive levels in water (Yen at al., 2000). *Daphnia magna* (water flea) and *Oncorhynchus mykiss* (rainbow trout) are used as indicator species to evaluate the negative impacts that pesticide residues may have on aquatic ecosystems in relation to the lethal concentration that kills 50% of a test population (LC50). In assessing both of these indicator species, the only pesticides found exceeding typical LC 50 measurements were bifenthrin (*Daphnia magna* 1.6 µg L^{-1} *; Oncorhynchus mykiss* 0.15 µg L^{-1}*)* and chlorpyrifos (*Daphnia magna* 3.7 µg L^{-1}*; Oncorhynchus mykiss* 15 µg L^{-1}*)*, where the average concentrations occurring in surface IRF in the days shortly following application were 1.9 and 33.9 µg L^{-1}. However, it should be noted that this study represents a worst case scenario in pesticide movement, considering that samples were collected immediately after leaving each replicate bed. In practice, IRF would likely be directed through several IRF channels (ditches) prior to either on-site collection or off-site release. As pesticide residues move in IRF through such channels, the potential for other degradative processes may further reduce concentration of these compounds, while sedimentation of suspended solids bearing sorbed pesticides may limit movement (Majsztrik et al., 2017).

5.6 Conclusions

Irrigating based on θ reduced the volume of water applied, as well as the volume of IRF. For the OH, reductions in the volume of water applied reduced the amount of irrigation to non-target areas, contributing to less IRF. The direct application of water to containers via SS allowed more precise irrigation applications, eliminating non-target access and oftentimes resulting in complete elimination of surface IRF. No differences were identified in subsurface

IRF volumes between the treatments and the control; however, the consistently greater volumes of surface IRF from the control indicates that more efficient irrigation practices have a greater impact on surface return volume than subsurface IRF volume. Pesticide mobility in surface and subsurface IRF was reflective of each compounds physiochemical properties, with more soluble pesticides capable of moving in both surface and subsurface IRF, while less soluble pesticides were typically only mobile in surface IRF. For all pesticides studied, surface IRF typically exported a greater amount of each pesticide. A linear decrease in surface IRF loads exported from the control was identified for all pesticides except oxyfluorfen, thus indicating that reductions in surface IRF volumes generated in the days immediately following pesticide applications reduce overall movement of pesticides.

Through reducing pesticide movement, compounds may degrade in-situ. Irrigating via overhead using θ reduces water use and IRF when compared to a standard overhead irrigation practice; whereas, spray stake irrigation applies water directly to containers, and often eliminates surface IRF in general. Furthermore, the avoidance of applying irrigation to inter-container spaces may maintain pesticides on the production surface, where photolysis and volatilization rates may increase. A practical strategy in minimizing pesticide movement is to select pesticides possessing low solubilities and high adsorption coefficients, when possible. It was observed that a greater amount of applied pesticides were lost to IRF from the high mobility group than the moderately and low mobility groups (Table 5.6). Regardless of a compounds physiochemical properties, implementing irrigation practices that delay irrigation applications, reduce the volume of irrigation applied, and/or provide water directly to crops/containers are management practices that can effectively limit pesticide movement, particularly with highly mobile compounds.

APPENDIX

Table 5.1: Pesticide Applications at MSU Research Nursery 2018: Pesticides were applied in three rounds at the MSU research nursery during the 2018 season using label recommendations for ornamental crops. Following application of pre-emergent herbicides Isoxaben, the control and treatments all received 190 kl ha^{-1} of irrigation for the post-application watering-in. Following oxyfluorfen application the control received 190 kl ha^{-1}, but the treatments received the minimum recommended 63.3 kl ha^{-1}. Following prodiamine application, the control received 190 kl ha^{-1}, but the treatments received the minimum recommended 126.6 kl ha^{-1}.

Round 1 (Applied 11 June 2018)	***Active Ingredient***	***Trade Name***	***Grams A.I. Applied per Hectare***
Herbicide	Isoxaben	Gallery 75DF	866.5
Insecticide	Acephate	Acephate 97UP	553
Insecticide	Bifenthrin	Talstar P	130
Fungicide	Mefenoxam	Mefenoxam 2AQ	18.2
Round 2 (Applied 9 July 2018)	***Active Ingredient***	***Trade Name***	***Grams A.I. Applied per Hectare***
Herbicide	Oxyfluorfen	Goaltender	1142.2
Insecticide	Acephate	Acephate 97UP	553
Insecticide	Chlorpyrifos	Lorsban 4E	1145.8
Fungicide	Triflumizole	Terraguard SC	288.5
Round 3 (Applied 20 August, 2018)	***Active Ingredient***	***Trade Name***	***Grams A.I. Applied per Hectare***
Herbicide	Prodiamine	Barricade 65WG	1697.9
Insecticide	Acephate	Acephate 97UP	553
Fungicide	Thiophanate-Methyl	Thiophanate-Methyl 85WDG	482.5

Table 5.2: Pesticide mobility groups, chemical class, solubility, and Koc for each active ingredient. Pesticides were categorized based on solubility and Koc Mccalls and FAO classifications. [1]https://www.chemsafetypro.com/Topics/CRA/Mobility_

Group	*Active Ingredient:*	*Pesticide Class:*	*Solubility in mg/L*	*Koc*	*Mccalls (Koc Class)[1]*	*FAO Classification of mobility (Koc)[1]*	*FAO Classification of mobility (solubility)[2]*
High Solubility / Low Koc	**Acephate**	Insecticide	818,000 mg L^{-1}	4.7	Very High	Highly Mobile	Highly Soluble
	Mefenoxam	Fungicide	26,000 mg L^{-1}	660	Low	Moderately Mobile	Highly Soluble
	Thiophanate-Methyl	Fungicide	26.6 mg L^{-1}	330	Medium	Moderately Mobile	Readily Soluble
Moderate Solubility / Moderate Koc	**Triflumizole**	Fungicide	10.2 mg L^{-1}	1400	Low	Slightly Mobile	Readily Soluble
	Isoxaben	Herbicide	1.42 mg L^{-1}	3,300	Slightly	Slightly Mobile	Moderately Soluble
	Chlorpyrifos	Insecticide	1.4 mg L^{-1}	995 - 31,000	Low to Immobile	Moderately to Hardly Mobile	Moderately Soluble

Table 5.2 (cont'd)

Low Solubility / High Koc	**Oxyfluorfen**	Herbicide	0.116 mg L^{-1}	8900	Immobile	Slightly Mobile	Slightly Soluble
	Prodiamine	Herbicide	.013 mg L^{-1}	5,440 - 16,200	Immobile	Slightly to Hardly Mobile	Not Soluble
	Bifenthrin	Insecticide	<0.001 mg L^{-1}	8,387 - 14,332	Immobile	Slightly to Hardly Mobile	Not Soluble

Table 5.3: Retention times, precursor and product ions, and MS parameters used for identification and quantification of target pesticides by LCMS.

Compound	Retention time (min)	Precursor ion	Product ions	Dwell (ms)	Cone (V)	CE (V)
Acephate	1.27	184	125, 143	0.5	25	17
Isoxaben	8.86	333	165	0.5	22	17
Metalaxyl-m	8.44	280	192, 220	0.5	17	17
Thiophanate-methyl	0.85	343	151, 226	0.5	20	17
Triflumizole	9.8	346	73, 278	0.5	22	17
AMPA	6.59	110	63, 79	0.5	20	21
^{13}C-AMPA	6.59	114	63.2, 79	0.5	23	19
Glyphosate	4.35	168	63, 79	0.5	20	20
^{13}C-Glyphosate	4.35	169.7	63.2, 79.1	0.5	23	17

Table 5.4: Retention times used for identification and quantification of target pesticides by dual column GCECD.

Compound	Column retention time (min)	
	DB-5MS + DG	DB-35MS
Bifenthrin	30.37	31.49
Chlorpyrifos	22.65	25.73
Oxyfluorofen	25.79	28.28
Prodiamine	21.96	24.30

Table 5.5: Regression equations modeling pesticide load (g per ha-1) in surface and subsurface irrigation return flow across the 16 day monitoring period.

Pesticide	Irrigation	Surface / Subsurface	Equation	F Value	R^2
Acephate Round 1	Control	Surface	LogY= (-1.87 (LogDOS)) + 5.98	228	0.97
Acephate Round 1	OH	Surface	LogY= (-1.58 (LogDOS)) + 4.45	15.2	0.54
Acephate Round 1	SS	Subsurface	LogY= (5.28 (LogDOS)) + (- 1.34 (LogDOS*LogDOS)) + -2.96	9.81	0.51
Bifenthrin	Control	Surface	LogY= (-1.00 (LogDOS)) + -1.93	70	0.90
Bifenthrin	OH	Surface	LogY= (-1.31 (LogDOS)) + -2.62	47.2	0.77
Mefenoxam	Control	Surface	LogY= (-1.19 (LogDOS)) + -0.10	193	0.96
Mefenoxam	OH	Surface	LogY= (-1.07 (LogDOS)) + -0.87	14.7	0.5
Mefenoxam	SS	Subsurface	LogY= (5.21 (LogDOS)) + (- 1.45 (LogDOS*LogDOS)) + -7.55	9.69	0.45

Table 5.5 (cont'd)

Isoxaben	Control	Surface	LogY= (-0.66 (LogDOS)) + (- 0.68 (LogDOS*LogDOS)) + 3.63	93	0.96
Isoxaben	OH	Surface	LogY= (-2.43 (LogDOS)) + 3.39	116	0.89
Isoxaben	Control	Subsurface	LogY= (-1.74 (LogDOS)) + -0.52	9.11	0.53
Isoxaben	SS	Subsurface	LogY= (2.33 (LogDOS)) + (- 1.11 (LogDOS*LogDOS)) + -2.03	7.21	0.38
Acephate Round 2	OH	Surface	LogY= (0.78 (LogDOS)) + (- 0.85 (LogDOS*LogDOS)) + 3.64	10.9	0.58
Acephate Round 2	Control	Subsurface	LogY= (-1.66 (LogDOS)) + 2.96	8.94	0.53
Acephate Round 2	OH	Subsurface	LogY= (-1.11 (LogDOS)) + 3.31	13.59	0.34
Acephate Round 2	SS	Subsurface	LogY= (-0.95 (LogDOS)) + 2.43	5.76	0.20
Triflumizole	Control	Surface	LogY= (-1.03 (LogDOS)) + 0.64	7.26	0.55
Chlorpyrifos	Control	Surface	LogY= (-1.57 (LogDOS)) + 0.88	32.32	0.84
Chlorpyrifos	OH	Subsurface	LogY= (-0.03 (LogDOS)) + (- 0.18 (LogDOS*LogDOS)) + - 4.49	3.74	0.23
Chlorpyrifos	SS	Subsurface	LogY= (0.17 (LogDOS)) + (- 0.31 (LogDOS*LogDOS)) + - 5.04	4.63	0.30

Table 5.5 (cont'd)

Oxyfluorfen	SS	Subsurface	LogY= (-0.52 (LogDOS)) + -4.83	6.23	0.21
Acephate Round 3	Control	Surface	LogY= (-1.59 (LogDOS)) + 5.55	19.1	0.73
Acephate Round 3	OH	Surface	LogY= (-1.63 (LogDOS)) + 4.83	22.11	0.54
Acephate Round 3	OH	Subsurface	LogY= (2.07 (LogDOS)) + (- 1.11 (LogDOS*LogDOS)) + 2.78	4.82	0.34
Acephate Round 3	SS	Subsurface	LogY= (-2.47 (LogDOS)) + 5.49	65.47	0.78
TPM	Control	Surface	LogY= (-3.29 (LogDOS)) + 2.92	24.86	0.78
TPM	OH	Surface	LogY= (-2.48 (LogDOS)) + 0.88	20.26	0.52
TPM	OH	Subsurface	LogY= (-1.31 (LogDOS)) + -2.92	4.79	0.19
TPM	SS	Subsurface	LogY= (-2.44 (LogDOS)) + -1.10	18.82	0.51
Prodiamine	Control	Surface	LogY= (-1.34 (LogDOS)) + 1.98	31.29	0.78
Prodiamine	OH	Surface	LogY= (-0.61 (LogDOS)) + -0.53	7.29	0.23
Prodiamine	SS	Subsurface	LogY= (-2.66 (LogDOS)) + (0.87 (LogDOS*LogDOS)) + 2.98	5.62	0.398167

Table 5.6: The amount of active ingredient for each pesticide applied, and the total grams recovered over the sample period in surface IRF, subsurface IRF, and combined IRF, respectively, followed by the percentage of applied pesticide that corresponds to.

Pesticide	Amount applied g ha^{-1}	Treatment	Total Grams Recovered in Surface RF ha^{-1}	% of applied Pesticide	Total Grams Recovered in Subsurface RF ha^{-1}	% of applied Pesticide	Total Grams in Combined IRF	% of applied Pesticide
Acephate	553	Control	590.98	107%	21.92	4%	612.90	111%
Period 1		OH	255.62	46%	79.43	14%	335.06	61%
		SS	0.51	<1%	38.67	7%	39.18	7%
Acephate	553	Control	461.16	83%	54.14	10%	515.30	93%
Period 2		OH	133.92	24%	124.62	23%	258.54	47%
		SS	25.99	5%	60.84	11%	86.83	16%
Acephate	553	Control	540.67	98%	156.74	28%	697.41	126%
Period 3		OH	297.42	54%	276.42	50%	573.84	104%
		SS	124.05	22%	294.54	53%	418.59	76%
Mefenoxam	18.2	Control	1.68	9%	0.09	<1%	1.77	10%
		OH	0.95	5%	0.49	3%	1.45	8%
		SS	0.01	<1%	0.31	2%	0.33	2%

Table 5.6 (cont'd)

TPM	482	Control	42.81	9%	3.03	1%	45.84	10%
		OH	10.83	2%	1.99	<1%	12.81	3%
		SS	7.36	2%	2.77	1%	10.13	2%
Triflumizole	288	Control	5.99	2%	0.10	<1%	6.09	2%
		OH	1.66	1%	0.20	<1%	1.85	1%
		SS	0.13	<1%	0.08	<1%	0.21	<1%
Isoxaben	867	Control	86.36	10%	1.41	<1%	87.78	10%
		OH	44.31	5%	6.07	1%	50.39	6%
		SS	19.15	2%	2.34	<1%	21.49	2%
Chlorpyrifos	1,146	Control	4.54	<1%	0.03	<1%	4.56	<1%
		OH	0.84	<1%	0.06	<1%	0.90	<1%
		SS	0.04	<1%	0.04	<1%	0.08	<1%

Table 5.6 (cont'd)

Oxyfluorfen	1,142	Control	0.22	<1%	0.01	<1%	0.24	<1%
		OH	0.08	<1%	0.05	<1%	0.13	<1%
		SS	0.02	<1%	0.03	<1%	0.05	<1%
Prodiamine	1,698	Control	21.10	1%	0.15	<1%	21.25	1%
		OH	2.27	<1%	0.10	<1%	2.37	<1%
		SS	2.69	<1%	0.14	<1%	2.82	<1%
Bifenthrin	130	Control	0.32	<1%	0.02	<1%	0.34	<1%
		OH	0.13	<1%	0.01	<1%	0.14	<1%
		SS	0.002	<1%	0.01	<1%	0.01	<1%

Table 5.7: Pesticide concentrations in surface and subsurface IRF over respective monitoring periods.

Monitoring Period 1 Acephate Concentration (µg L^{-1})					
	Surface Return Flow				
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	4,418.90 a	1,012.45 a	247.85 a	118.82 a	20.65 a
OH	2,589.18 ab	629.45 a	306.73 a	0.00 b	53.24 a
SS	6.04 b	1.67 a	0.00 a	0.00 b	22.43 a
	Subsurface Return Flow				
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	518.82 a	466.11 a	356.88 a	76.17 a	74.33 a
OH	653.41 a	1,477.31 a	572.20 a	213.48 a	27.81 a
SS	234.61 a	107.23 a	1,327.27 a	328.96 a	217.49 a

Table 5.7 (cont'd)

Monitoring Period 2 Acephate Concentration (µg L^{-1})					
Surface Return Flow					
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	2,899.23 a	954.85 a	541.00 a	61.47 a	180.93 a
OH	1,419.55 a	1,167.93 a	1,070.54 a	65.44 a	16.48 a
SS	219.68 a	0.00 a	719.91 a	0.00 a	302.53 a
Subsurface Return Flow					
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	1,541.30 a	3,823.40 a	195.00 a	163.45 a	22.10 a
OH	1,332.13 a	1,067.65 ab	788.46 a	136.60 a	110.30 a
SS	1,002.76 a	160.77 b	888.90 a	292.03 a	80.42 a

Table 5.7 (cont'd)

Monitoring Period 3 Acephate Concentration (µg L^{-1})					
Surface Return Flow					
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	3,122.43 a	1,864.99 ab	508.76 a	84.38 a	38.52 a
OH	2,709.58 a	3,134.85 a	544.58 a	57.54 a	17.48 a
SS	1,979.44 a	0.00 b	161.69 a	64.95 a	2.82 a
Subsurface Return Flow					
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	3,741.01 ab	1,757.78 a	1,675.76 a	133.15 a	12.34 a
OH	1,963.27 b	8,248.60 a	1,732.57 a	250.19 a	1,032.32 a
SS	6,121.31 a	4,571.21 a	2,761.61 a	118.49 a	26.04 a

Table 5.7 (cont'd)

Mefenoxam Concentration (µg L^{-1})					
Surface Return Flow					
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	9.98 a	3.97 a	1.53 a	0.75 a	0.39 a
OH	8.22 a	4.58 a	1.20 a	0.00 b	0.85 a
SS	0.09 b	0.04 a	0.00 a	0.00 b	0.83 a
Subsurface Return Flow					
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	1.79 a	2.73 a	1.19 a	0.60 a	0.37 a
OH	1.80 a	8.32 a	4.82 a	1.68 a	0.65 a
SS	2.33 a	3.53 a	11.39 a	3.16 a	1.00 a

Table 5.7 (cont'd)

Thiophanate-Methyl Concentration (µg L^{-1})					
	Surface Return Flow				
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	341.71 a	88.81 a	0.28 a	0.13 a	0.13 a
OH	130.81 a	64.16 a	3.62 a	0.06 a	0.06 a
SS	134.05 a	0.00 a	0.05 a	0.14 a	0.02 a
	Subsurface Return Flow				
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	71.16 a	4.99 a	8.63 a	0.31 a	0.06 a
OH	9.89 a	66.12 a	2.94 a	0.13 a	0.10 a
SS	70.71 a	38.71 a	2.17 a	0.14 a	0.10 a

Table 5.7 (cont'd)

Triflumizole Concentration (µg L^{-1})					
Surface Return Flow					
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	38.30 a	10.60 a	11.15 a	2.73 ab	0.80 a
OH	6.92 ab	15.86 a	8.63 a	5.20 a	1.36 a
SS	2.44 b	0.00 a	4.07 a	0.00 b	0.39 a
Subsurface Return Flow					
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	0.53 a	1.27 a	5.65 a	2.25 a	0.69 a
OH	0.43 a	2.27 a	2.13 a	2.57 a	1.33 a
SS	1.17 a	0.20 a	0.79 a	0.81 a	0.45 a

Table 5.7 (cont'd)

Chlorpyrifos Concentration (µg L^{-1})					
Surface Return Flow					
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	33.89 a	14.12 a	1.89 a	1.20 a	0.26 a
OH	15.65 a	4.79 ab	3.34 a	0.78 a	0.49 a
SS	0.24 a	0.00 b	1.27 a	0.00 b	0.31 a
Subsurface Return Flow					
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	0.48 a	0.20 a	0.63 a	0.48 a	0.17 a
OH	0.52 a	0.70 a	0.42 a	0.33 a	0.15 a
SS	0.41 a	0.17 a	0.93 a	0.16 a	0.11 a

Table 5.7 (cont'd)

Bifenthrin Concentration (µg L^{-1})					
	Surface Return Flow				
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	1.90 a	0.64 ab	0.37 a	0.13	0.13 a
OH	1.41 a	0.57 a	0.12 b	0.00	0.10 a
SS	0.09 b	0.04 b	0.00 b	0.00	0.07 a
	Subsurface Return Flow				
Days After Application	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean
Control	0.13 a	0.13 a	0.13 a	0.23 a	0.21 a
OH	0.13 a	0.13 a	0.11 a	0.09 b	0.10 a
SS	0.13 a	0.13 a	0.13 a	0.13 ab	0.11 a

Table 5.7 (cont'd)

Isoxaben Concentration (µg L^{-1})						
Surface Return Flow						
Days After Application	0	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean	Mean
Control	389.30 a	373.64 a	214.15 a	28.85 a	7.85 a	0.38 a
OH	342.26 a	336.72 a	195.96 a	16.00 a	0.00 b	1.33 a
SS	389.60 a	385.16 a	125.39 a	0.00 a	0.00 b	104.82 a
Subsurface Return Flow						
Days After Application		1	2	4	8	16
		Mean	Mean	Mean	Mean	Mean
Control		111.06 a	44.88 a	4.72 a	0.62 a	0.36 a
OH		60.00 a	99.42 a	42.86 a	5.03 a	1.02 a
SS		116.99 a	78.25 a	68.96 a	7.50 a	1.78 a

Table 5.7 (cont'd)

Oxyfluorfen Concentration (µg L^{-1})						
Surface Return Flow						
Days After Application	0	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean	Mean
Control	0.68 a	0.71 a	0.49 a	0.19 a	0.33 ab	0.13 a
OH	0.68 a	0.31 a	0.26 a	0.40 a	0.36 a	0.21 a
SS	0.31 a	0.08 a	0.00 b	0.30 a	0.00 b	0.12 a
Subsurface Return Flow						
Days After Application		1	2	4	8	16
		Mean	Mean	Mean	Mean	Mean
Control		0.43 a	0.33 a	0.19 a	0.26 a	0.18 a
OH		0.42 a	0.50 a	0.29 a	0.42 a	0.19 a
SS		0.47 a	0.17 a	0.40 a	0.34 a	0.16 a

Table 5.7 (cont'd)

Prodiamine Concentration (µg L^{-1})						
Surface Return Flow						
Days After Application	0	1	2	4	8	16
	Mean	Mean	Mean	Mean	Mean	Mean
Control	102.61 a	85.22 a	10.70 a	7.34 ab	5.66 a	3.59 a
OH	37.02 a	11.36 a	8.06 a	6.38 a	2.68 a	1.62 a
SS	40.81 a	29.25 a	0.00 b	0.87 b	2.79 a	0.54 a
Subsurface Return Flow						
Days After Application		1	2	4	8	16
		Mean	Mean	Mean	Mean	Mean
Control		3.75 a	1.49 a	2.95 a	7.90 a	1.13 a
OH		0.70 a	0.62 a	0.99 b	2.40 b	1.96 a
SS		2.53 a	1.57 a	0.76 b	1.80 b	3.28 a

Figure 5.1: MSU Experimental Nursery.

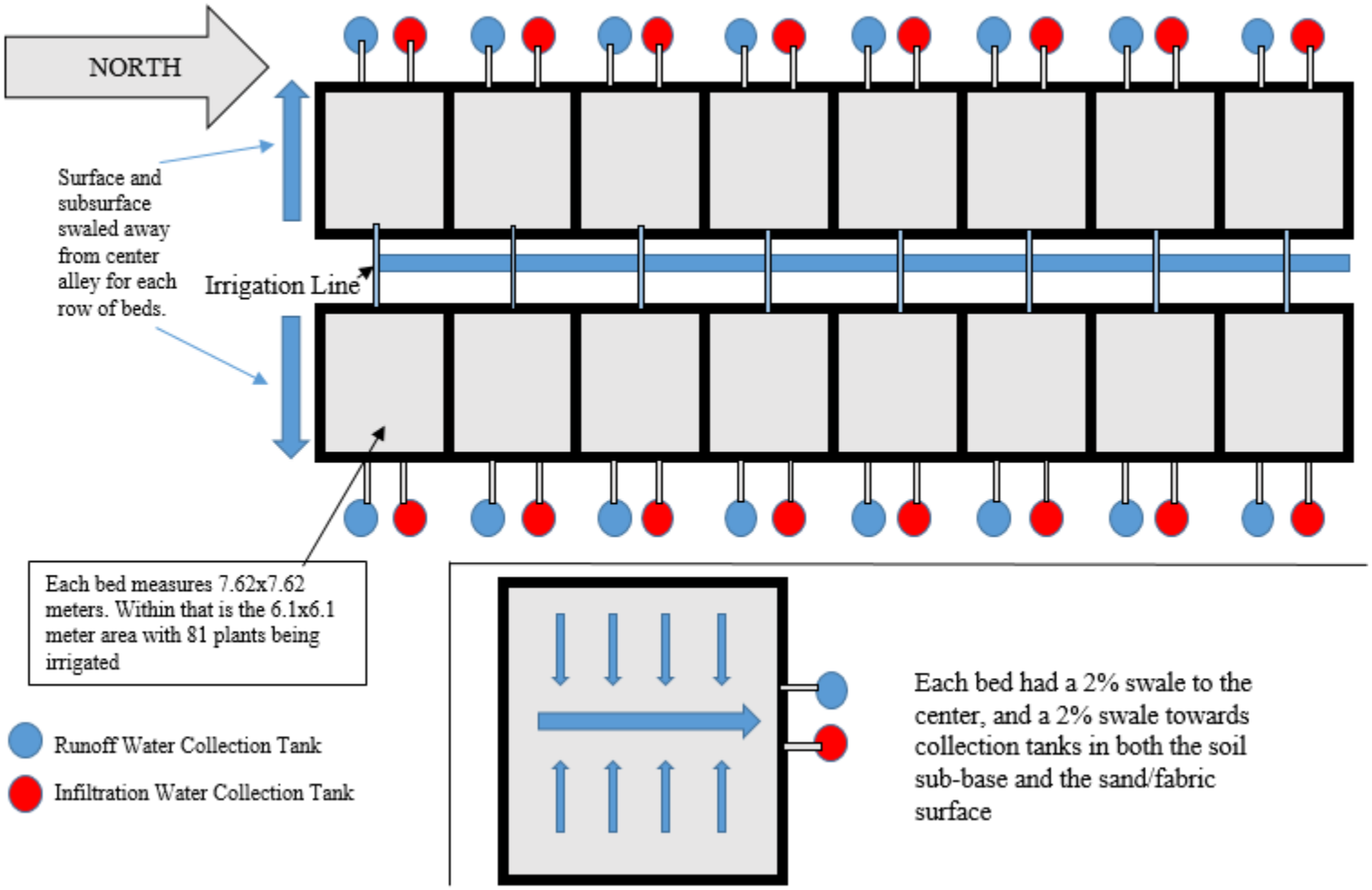


Figure 5.2: Pesticides were applied on 11 June 2018, with Isoxaben applied on Day 0, followed by 190 kl ha^{-1} of irrigation via overhead for the control and treatments. The volume of irrigation applied was recorded over the ensuing 16 days at the MSU Research Nursery, in addition to measuring the volume of surface and subsurface return flow and associated load of pesticide content exported 1, 2, 4, 8, and 16 days after application. Irrigation Applied: A; Surface IRF: B; Subsurface IRF: C; Acephate Surface: D; Acephate Subsurface: E; Mefenoxam Surface: F; Mefenoxam Subsurface: G; Bifenthrin Surface: H; Bifenthrin Subsurface: I; Isoxaben Surface: J; Isoxaben Subsurface: K.

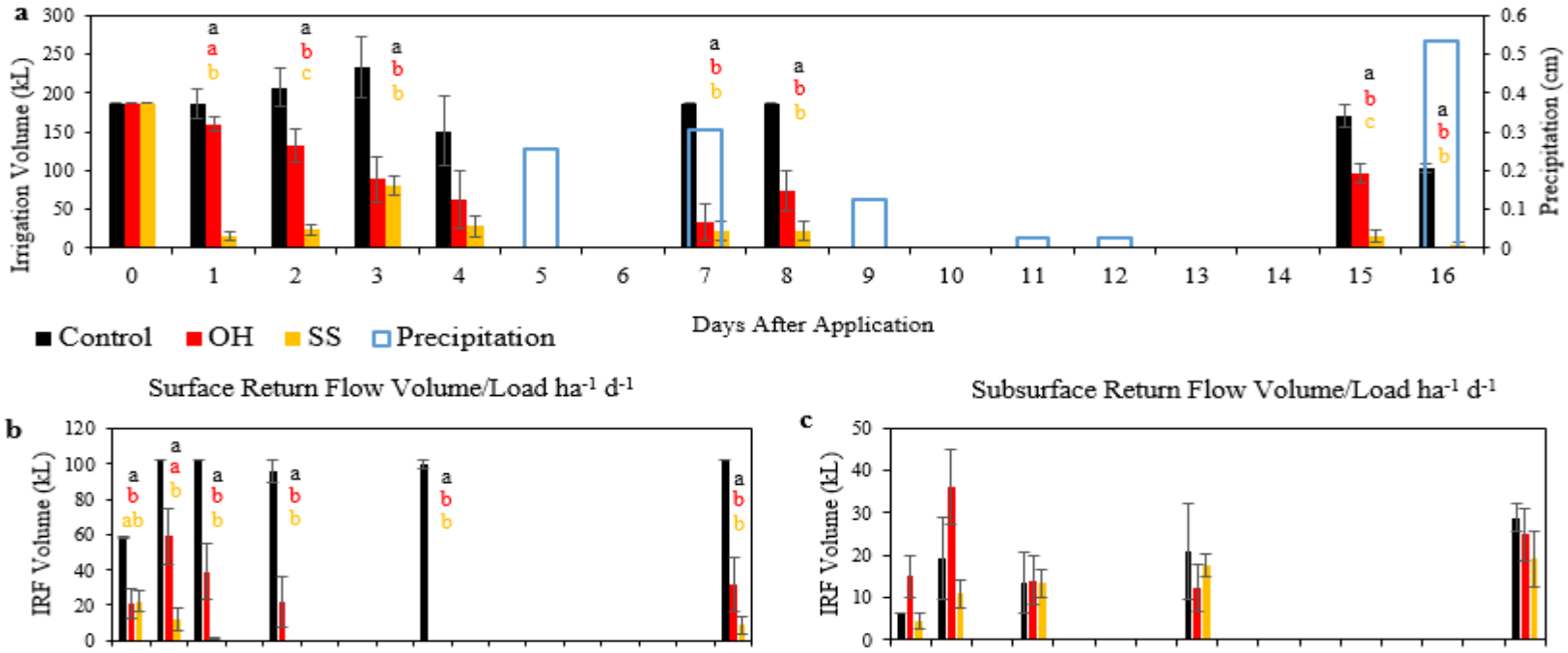


Figure 5.2 (cont'd)

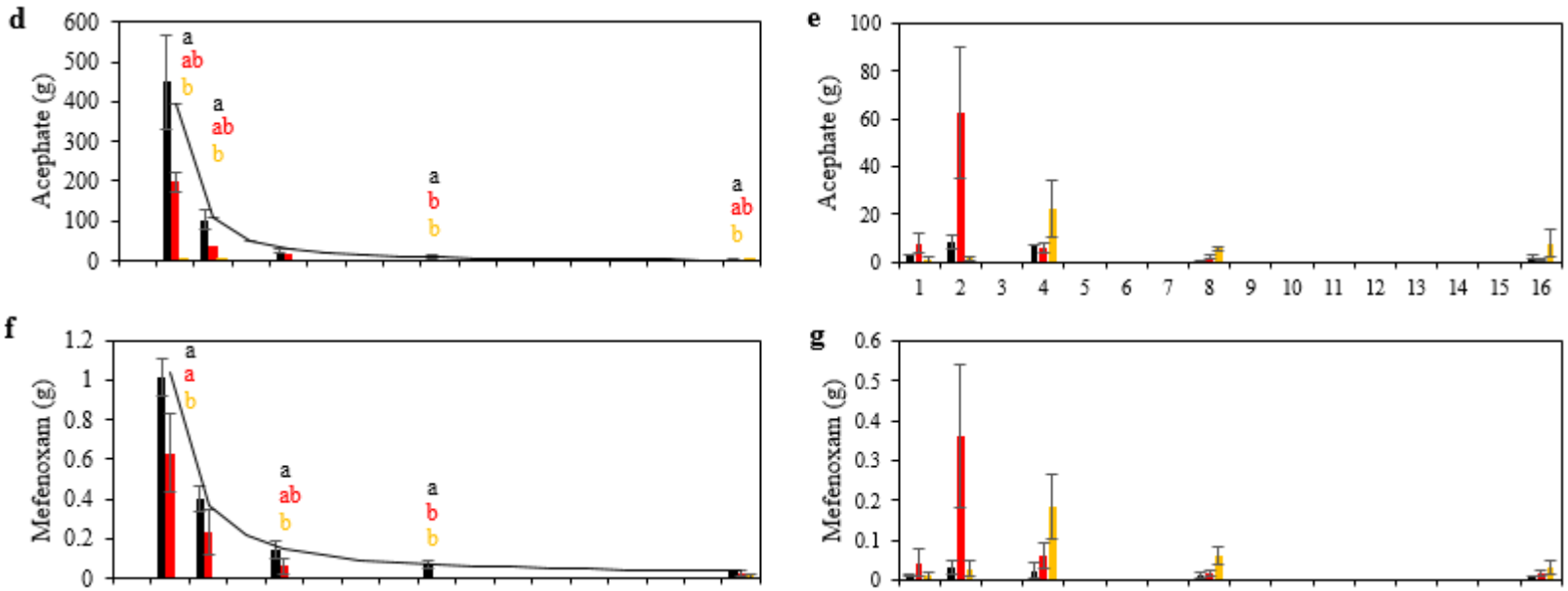


Figure 5.2 (cont'd)

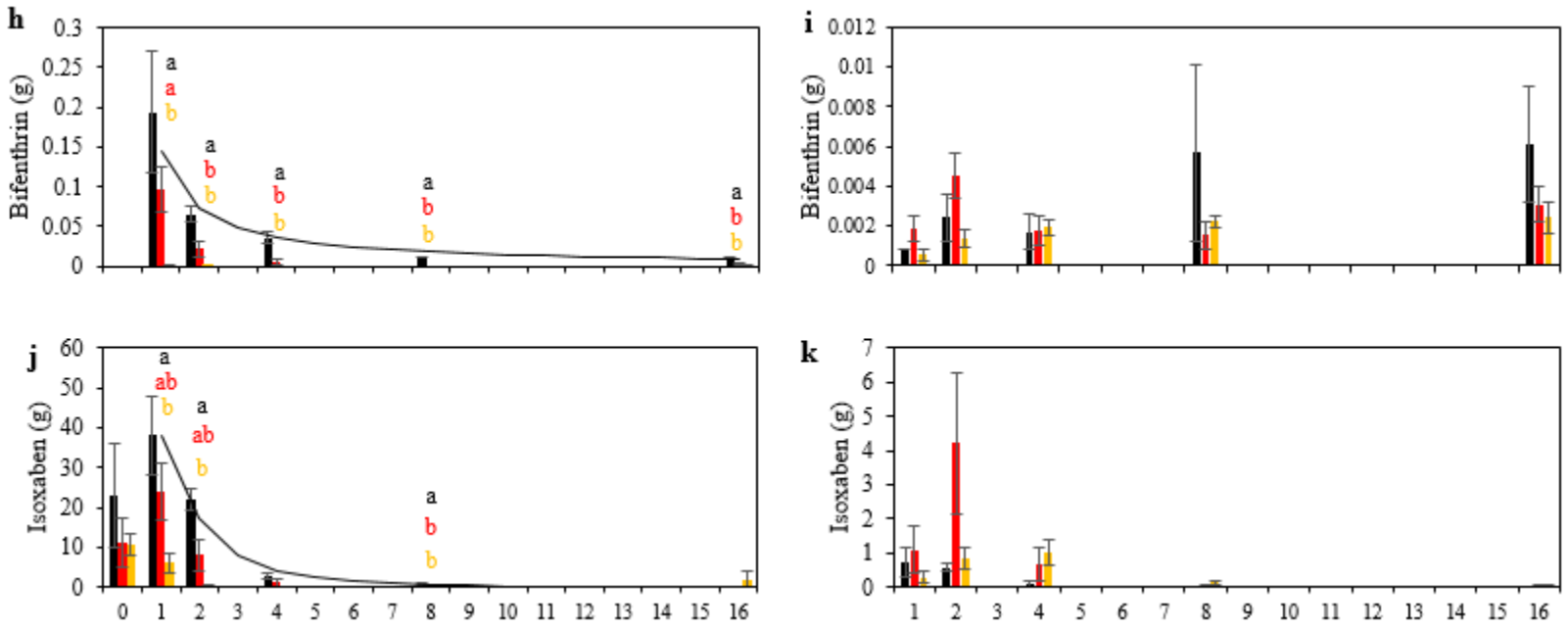


Figure 5.3: Pesticides were applied on 9 July, 2018, with Oxyfluorfen applied on Day 0, followed by the requisite watering in (63.3 kl ha^{-1} via overhead for treatments, 190 kl ha^{-1} via overhead for control), followed by triflumizole, chlorpyrifos, and acephate application as a tank mix. The volume of irrigation applied was recorded over the ensuing 16 days at the MSU Research Nursery, in addition to measuring the volume of surface and subsurface return flow and associated load of pesticide content exported 1, 2, 4, 8, and 16 days after application. Irrigation Applied: A; Surface IRF: B; Subsurface IRF: C; Acephate Surface: D; Acephate Subsurface: E; Triflumizole Surface: F; Triflumizole Subsurface: G; Chlorpyrifos Surface: H; Chlorpyrifos Subsurface: I; Oxyfluorfen Surface: J; Oxyfluorfen Subsurface: K.

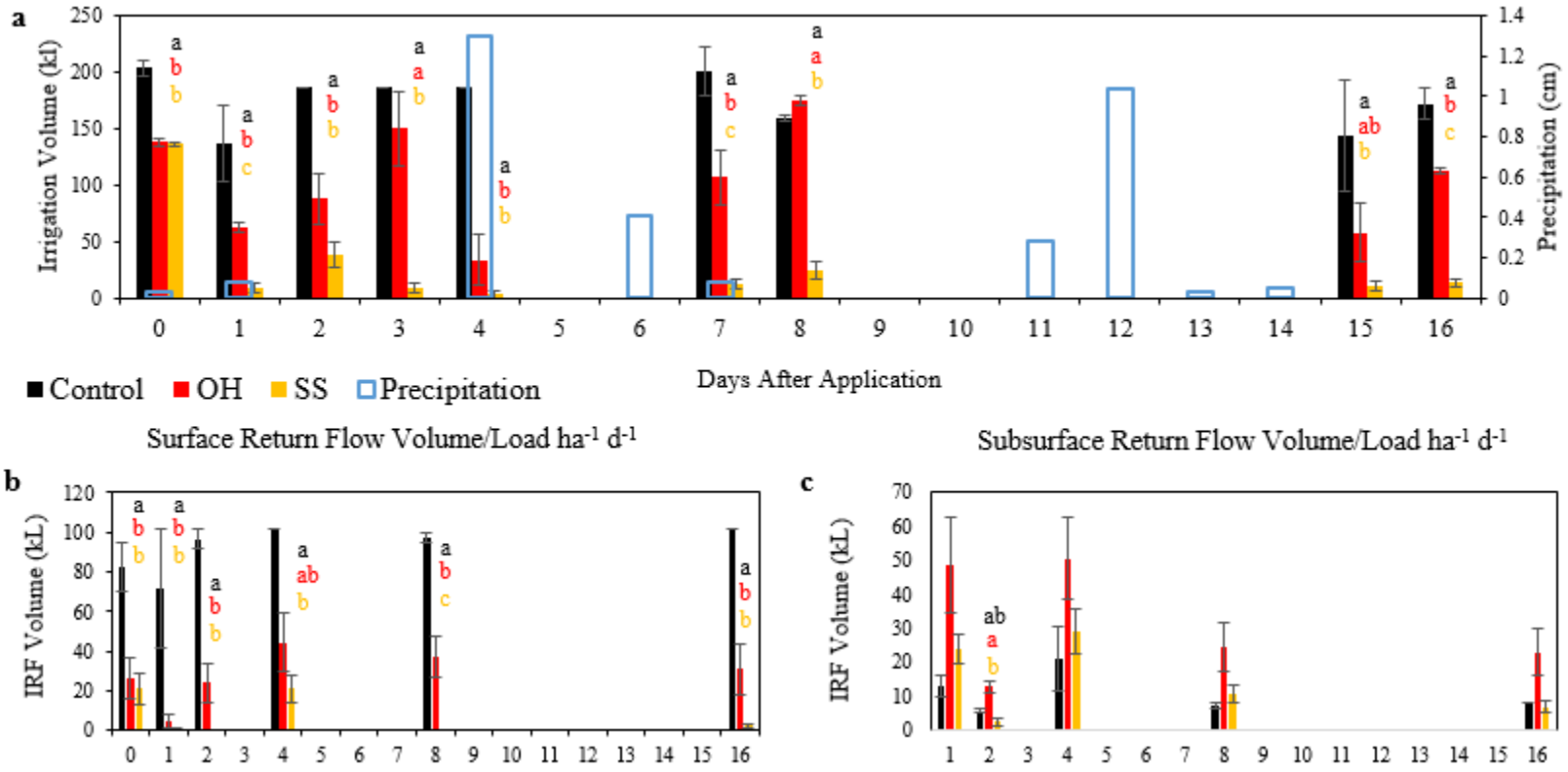


Figure 5.3 (cont'd)

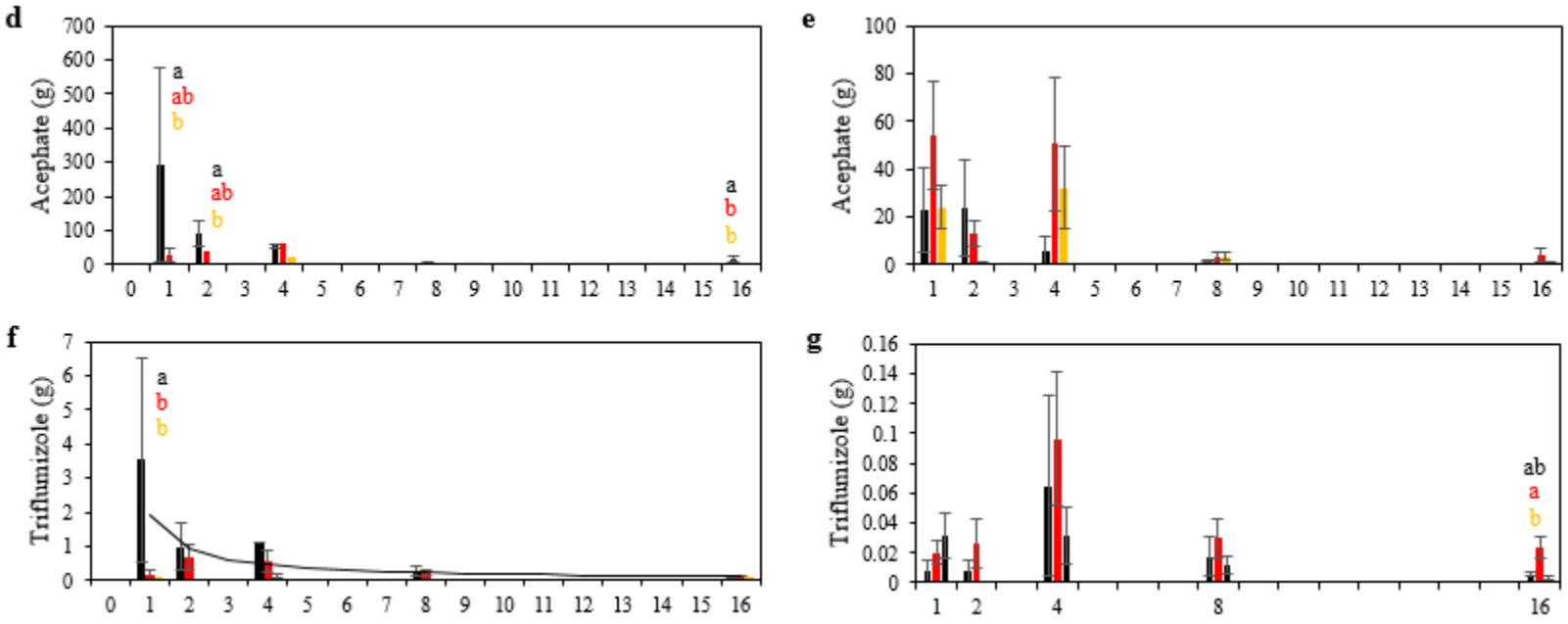


Figure 5.3 (cont'd)

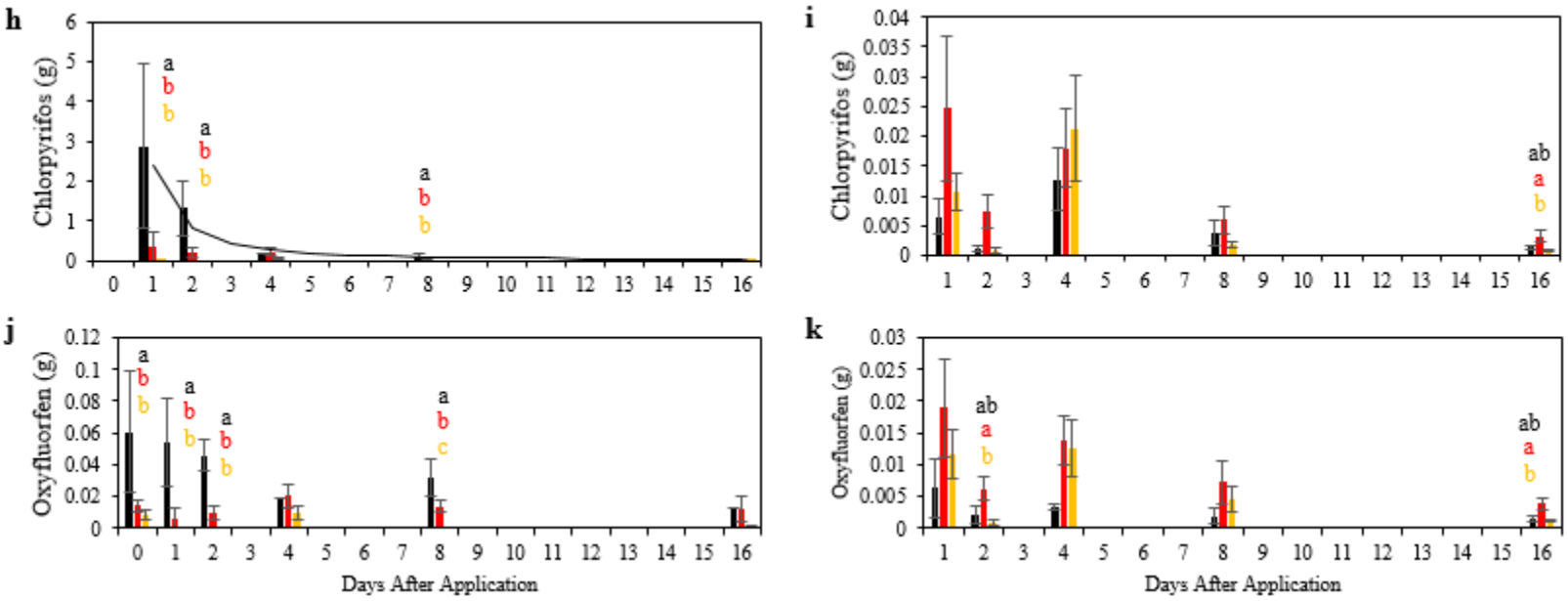


Figure 5.4: Pesticides were applied on 20 August 2018, with prodiamine applied on Day 0, followed by the requisite watering in (126.6 kl ha^{-1} via overhead for treatments, 190 kl ha^{-1} via overhead for control) before thiophanate-methyl and acephate were applied. The volume of irrigation applied was recorded over the ensuing 16 days at the MSU Research Nursery, in addition to measuring the volume of surface return flow and associated load of pesticide content exported 1, 2, 4, 8, and 16 days after application, and subsurface return flow 1, 2, 4, and 16 days after application. Irrigation Applied: A; Surface IRF: B; Subsurface IRF: C Acephate Surface: D; Acephate Subsurface: E; TPM surface: F; TPM Subsurface: G; Prodiamine surface: H; Prodiamine subsurface: I.

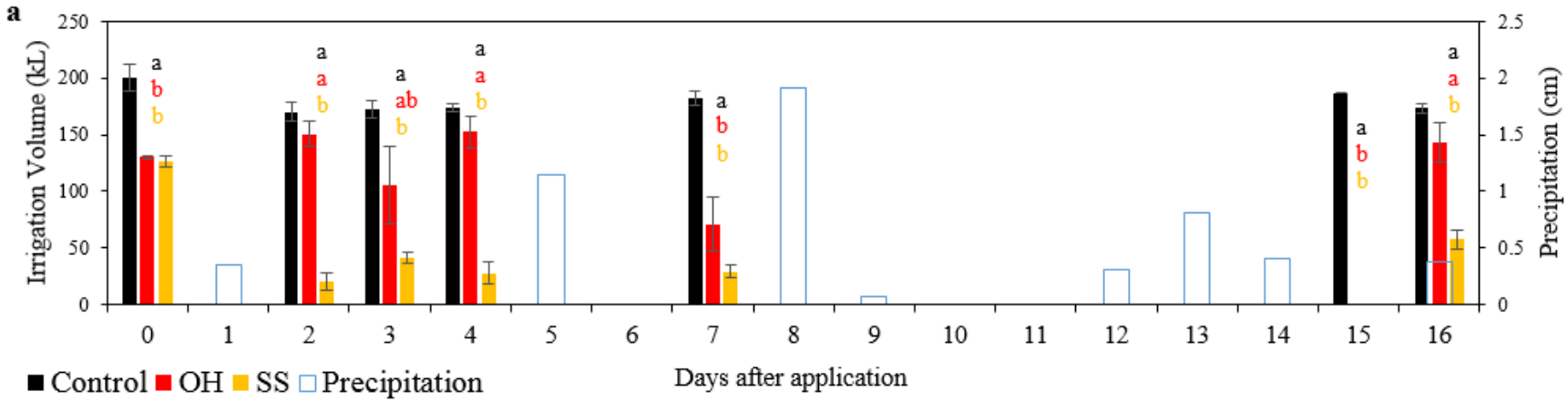


Figure 5.4 (cont'd)

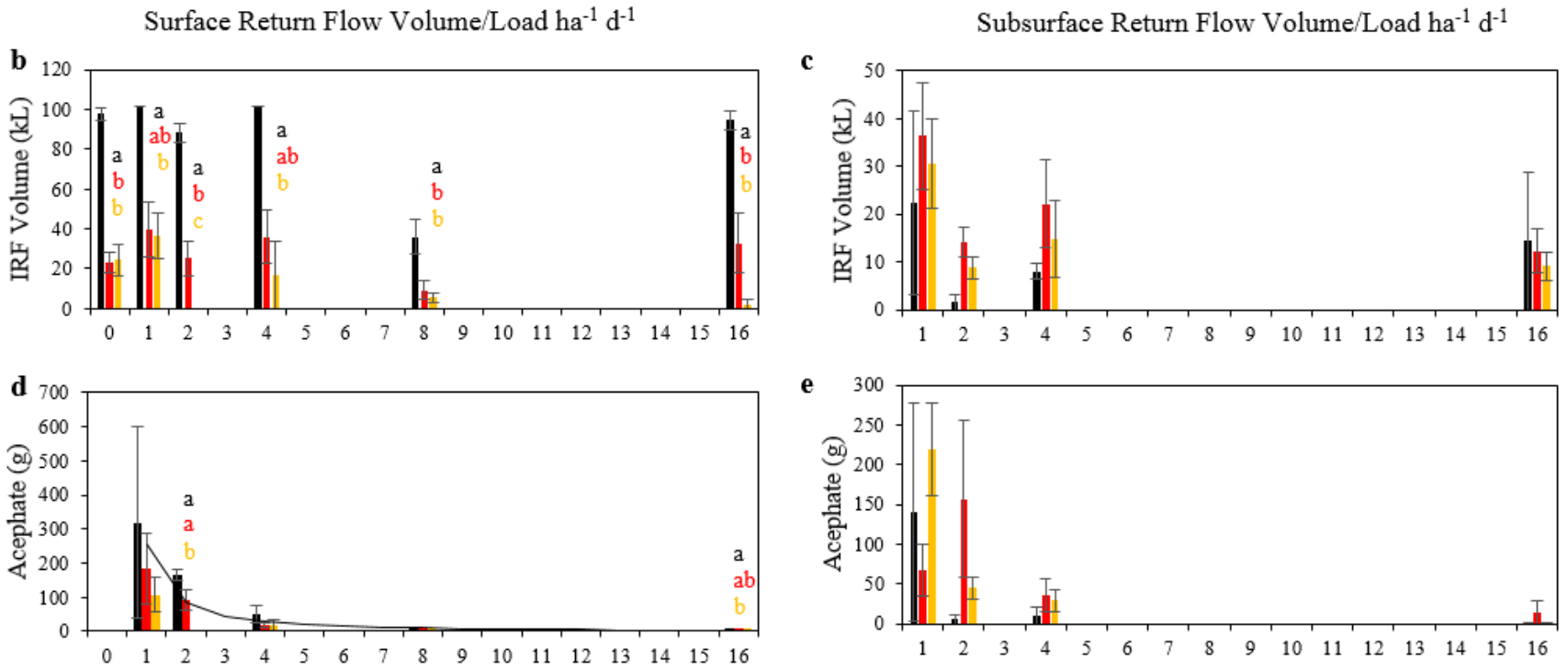
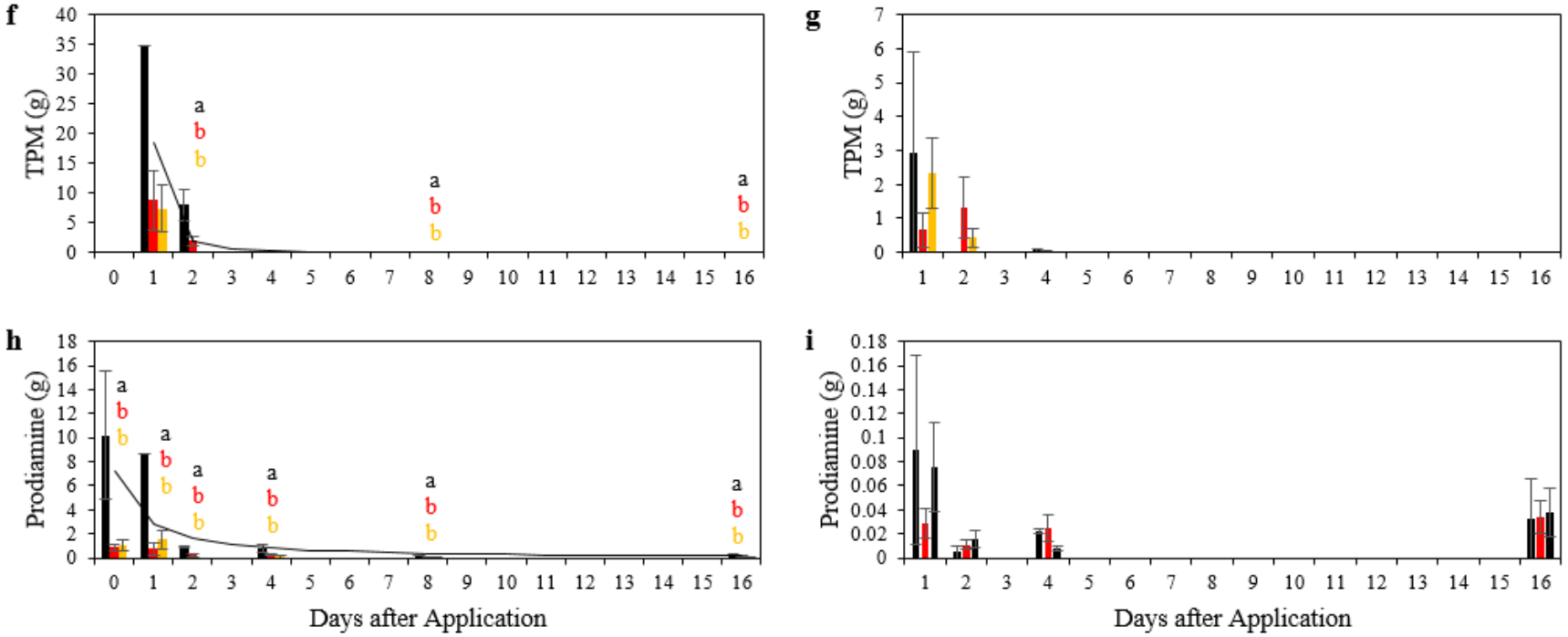


Figure 5.4 (cont'd)



LITERATURE CITED

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Abdi, D.E., Fernandez, R.T., 2019. Reducing water and pesticide movement in nursery production. HortTechnology. 04298, 1-6.

Agro, E., Zheng, Y., 2014. Controlled-release fertilizer application rates for container nursery crop production in southwestern Ontario, Canada. HortScience. 49, 1414-1423.

Alister, C.A., Gomez, P.A., Rojas, S., Kogan, M., 2009. Pendimethalin and oxyfluorfen degradation under two irrigation conditions over four years application. J. of Environ. Sci. and Health part B. 44, 337-343.

Beeson, R.C. Jr., Knox, G.W., 1991. Analysis of efficiency of overhead irrigation in container production. HortScience. 26, 848-850.

Beggel, S., Connon, R., Werner, I., Geist, J., 2011. Changes in gene transcription and whole organism responses in larval fathead minnow (Pimephales promelas) following short-term exposure to the synthetic pyrethroid bifenthrin. Aquat. Toxicol. 105, 180-188.

Bertotto, L.B., Dasgupta, S., Vliet, S., Dudley, S., Gan, J., Volz, D.C., Schlenk, D., 2019. Evaluation of the estrogen receptor alpha as a possible target of bifenthrin effects in the estrogenic and dopaminergic signaling pathways in zebrafish embryos. Sci. of the Total Environ. 651, 2424-2431.

Brander, S.M., Gabler, M.K., Fowler, N.L., Connon, R.E., Schlenk, D., 2016. Pyrethroid pesticides as endocrine disruptors: molecular mechanisms in vertebrates with a focus on fishes. Environ. Sci. and Technol. 50, 8977-8992.

Breeden, S.M., Brosnan, J.T., Breeden, G.K., Vargas, J.J., Eichberger, G., Tresch, S., Laforest, M., 2017. Controlling dinitroaniline-resistant goosegrass (Eleusine indica) in turfgrass. Weed Technol. 31, 883-889.

Briggs, J.A., Riley, M.B., Whitwell, T., 1998. Quantification and remediation of pesticides in runoff water from containerized plant production. J. of Environ. Qual. 27, 814-820.

Briggs, J., Whitwell, T., Fernandez, R.T., Riley, M.B., 2002. Effect of integrated pest management strategies on chlorothalonil, metalaxyl, and thiophanate-methyl runoff at a container nursery. J. of Am. Hortic. Sci. 127, 1018-1024.

Briggs, J.A., Whitwell, T., Riley, M.B., 2003. Effect of delayed irrigation on isoxaben and oryzalin runoff from a container nursery. Weed Sci. 51, 463-470.

Camper, N.D., Kim, J.H., Riley, M.B., 2001. Degradation of isoxaben in soils and an aqueous system. J. of Environ. Sci. and Health part B. 36, 729-739.

Cycon, M., M. Wojcik, and Z. Piotrowska-Seget., 2011. Biodegradation kinetics of the benzimidazole fungicide thiophanate-methyl by bacteria isolated from loamy sand soil. Biodegradation. 22, 573-583.

Davies, M.J., R. Harrison-Murray, C.J. Atkinson, O.M. Grant., 2016. Application of deficit irrigation to container-grown hardy ornamental nursery stock via overhead irrigation, compared to drip irrigation. Agr. Water Manage. 163, 244-254.

Dow Form No. 233-00845-MM-1111

Garber, M.P., Ruter, J.M., Midcap, J.T., Bondari, K., 2002. Survey of container nursery irrigation practices in Georgia. HortTechnology. 12, 727-731.

Gardner, D.S., Branham, B.E., 2001. Effect of turfgrass cover and irrigation on soil mobility and dissipation of mefenoxam and propiconazole. J. of Environ. Qual. 30, 1612-1618.

Giroux, M., Gan, J., Schlenk, D., 2019. The effects of bifenthrin and temperature on the endocrinology of juvenile chinook salmon. Environ. Toxicol. and Chem. 38, 852-861.

Graves, G.M., Vogel, J.R., Belden, J.B., Rebek, E.J., Simpson, A.M., 2014. Investigation of insecticide leaching from potted nursery stock and aquatic health benefits of bioretention cells receiving nursery runoff. Environ. Sci. Pollut. Res. 21, 8801-8811.

Hashimoto, Y., Sugimoto, S., Soeda, Y., Sano, S., Nakata, A., Hashimoto, S., 1990. Absorption, translocation, and metabolism of the fungicide triflumizole in cucumber plants. J. of Pestic. Sci. 15, 375-383.

Hinz, F.O., Fisher, P.R., and Wilson, P.C., 2019. Losses of Selected Pesticides in Drainage Water from Containerized Ornamental Plants. J. Environ. Qual. In Review.

Hu, J.H., Hong, C.X., Stromberg, E.L., Moorman, G.W., 2008. Mefenoxam sensitivity and fitness analysis of Phytophtora nicotianae isolates from nurseries in Virginia, USA. Plant Pathol. 57, 728-736.

Ilhan, Z., Ong, S.K., Moorman, T.B., 2012. Herbicide and antibiotic removal by woodchip denitrification filters: sorption processes. Water Air Soil Pollut. 223, 2651-2662.

Incrocci, L., Marzialetti, P., Incrocci, G., Di Vita, A., Balendonck, J., Bibbiani, C., Spagnol, S., Pardossi, A., 2019. Sensor-based management of container nursery crops irrigated with fresh or saline water. Agr. Water Manage. 213, 49-61.

Jin, M., Zhang, X., Wang, L., Huang, C., Zhang, Y., Zhao, M., 2009. Developmental toxicity of bifenthrin in embryo-larval stages of zebrafish. Aquat. Toxicol. 95, 347-354.

Lea-Cox, J.D., Bauerle, W.L., van Iersel, M.W., Kantor, G.F., Bauerle, T.L., Lichtenberg, E., King, D.M., Crawford, L., 2013. Advancing Wireless Sensor Networks for Irrigation Management of Ornamental Crops: an Overview. HortTechnology. 23, 717-724.

Lee, S., Gan, J., Kim, JS, Kabashima, J.N., Crowley, D.E., 2004. Microbial transformation of pyrethroid insecticides in aqueous and sediment phases. Environ. Toxicol. and Chem. 23, 1-6.

Leiva, J.A., Wilson, P.C., Albano, J.P, Nkedi-Kizza, P., and O'Conner, G.A., 2019. Pesticide Sorption to Soilless Media Components Used for Ornamental Plant Production and Aluminum Water Treatment Residuals. ACS Omega. https://doi.org/10.1021/acsomega.9b02296

Majsztrik, J.C., Fernandez, R.T., Fisher, P.R., Hitchcock, D.R., Lea-Cox, J., Owen Jr., J.S., Oki, L.R., White, S.A., 2017. Water Use and Treatment in Container-grown specialty crop production: a review. Water Air Soil Pollut. 228, 1-27.

Martins, V.L., Ogden, M.D., Jones, M.R., Trowsdale, S.A., Hall, P.J., 2020. Opportunities for coupled electrochemical and ion-exchange technologies to remove recalcitrant micropollutants in water. Sep. and Purif. Technol. 239, 1-12.

Mathers, H.M., Yeager, T.H., Case, L.T., 2005. Improving irrigation water use in container nurseries. HortTechnology. 15, 8-12

Milhome, M.A.L., Sousa, P.L.R., Lima, F.A.F., Nascimento, R.F., 2015. Influence the use of pesticides in the quality of surface and groundwater located in irrigated areas of Jaguaribe, Ceara, Brazil. Int. J. of Environ. Res. 9, 255-262

Million, J.B. and T.H. Yeager., 2015. Capture of Sprinkler Irrigation Water by Container-grown Ornamental Plants. HortScience. 50, 442-446.

Monkiedje, A., Spiteller, M., 2005. Degradation of metalaxyl and mefenoxam and effects on the microbiological properties of tropical and temperate soils. Int. J. of Environ. Res. and Public Health. 2, 272-285.

NCBI https://pubchem.ncbi.nlm.nih.gov/ (18 September 2020).

Nie, J., Sun, Y., Zhou, Y., Kumar, M., Usman, M., Li, J., Shao, J., Wang, L., Tsang, D.C.W., 2020. Bioremediation of water containing pesticides by microalgae: mechanisms, methods, and prospects for future research. Sci. of the Total Environ. 707, 1-13.

http://npic.orst.edu/factsheets.html (18 September 2020).

Pershey, N.A., Cregg, B.M., Andresen, J.A., Fernandez, R.T., 2015. Irrigating based on daily water use reduces nursery runoff volume and nutrient load without reducing growth of four conifers. HortScience. 50, 1553-1561.

Poudyal, S. Cregg, B., 2019. Dose dependent phytotoxicity of pesticides in simulated nursery runoff on landscape nursery plants. Water. 11, 1-18.

Ramu, S., Seetharaman, B., 2014. Biodegradation of acephate and methadimophos by a soil bacterium Pseudomonas aeruginosa strain Is-6. J. of Environ. Sci. and Health part B. 49, 23-34.

Riley, M.B., Keese, R.J., Camper, N.D., Whitwell, T., Wilson, P.C., 1994. Pendimethalin and oxyfluorfen residues in pond water and sediment from container plant nurseries Weed Technol. 8, 299-303.

Rosenberger, D.A., Robinson, T.L., Schupp, J.R., Engle-Ahlers, C.A., F.W. Meyer., 2003. Effect of sterol-demethylation inhibiting fungicides on apple fruit set, fruit size, total yield, and gross returns. HortScience. 38, 601-604.

Sardiña, P., Leahy, P., Metzeling, L., Stevenson, G., Hinwood, A., 2019. Emerging and legacy contaminants across land-use gradients and the risk to aquatic ecosystems. Sci. of the Total Environ. 695, 1-13.

Singh, B.K. and A. Walker., 2006. Microbial degradation of organophosphorus compounds. FEMS Microbiol. Review. 30, 428-471.

Stagg, N.J., LeBaron, M.J., Eisenbrandt, D.L., Gollapudi, B.B., Klaunig, J.E., 2012. Assessment of possible carcinogenicity of oxyfluorfen to humans using mode of action analysis of rodent liver effects. Toxicol. Sci. 128, 334-345.

Stearman, G.K., George, D.B. Hutchings, L.D., 2012. Removal of nitrogen, phosphorus, and Prodiamine from a container nursery by a subsurface flow constructed wetland. J. of Bioremediation and Biodegrad. S7, 1-5.

Sun, S., Chen, Y., Lin, Y., An, D., 2018. Occurrence, spatial distribution, and seasonal variation of emerging trace organic pollutants in source water for Shanghai, C. Sci. of the Total Environ. 639, 1-7.

Triantafyllidis, V., Hela, D., Papadaki, M., Bilalis, D., Konstantinou, I., 2012. Evaluation of mobility and dissipation of mefenoxam and pendimethalin by application of CSTR model and field experiments using bare and tobacco tilled soil columns. Water Air Soil Pollut. 223, 1625-1637.

United States Department of Agriculture., 2011. Agricultural chemical use nursery and floriculture crops 2009. U.S. Department ofAgriculture, Washington, DC. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/NurseryFloricultureChemicalUseFactSheet.pdf. (Accessed 15 March 2019)

US Environmental Protection Agency., 1996. Test Methods. EPA Methods 3510C. Revision 3. [CD-ROM].

Von Merey, G., Manson, P.S., Mehrsheikh, A., Sutton, P., Levine, S.L., 2016. Glyphosate and Aminomethylphosphonic acid chronic risk assessment for soil biota. Environ. Toxicol. and Chem. 35, 2742-2752.

Vryzas, Z., 2018. Pesticide fate in soil-sediment-water environment in relation to contamination preventing actions. Curr. Opin. Environ. Sci. Health. 4, 5e9.

Walker, A., 1987. Evaluation of a simulation model for prediction of herbicide movement and persistence in soil. Weed Res. 27, 143-152.

Warsaw, A.L, Fernandez, R.T., Cregg, B.M., Andresen, J.A., 2009. Container-grown ornamental plant growth and water runoff nutrient content and volume under four irrigation treatments. HortScience. 44, 1573-1580.

Weber, J.B., 1990. Behavior of dinitroaniline herbicides in soils. Weed Technol. 4, 394-406.

Weston, D.P., Holmes, R.W., You, J., Lydy, M.J., 2005. Aquatic toxicity due to residential use of pyrethroid insecticides. Environ. Sci. and Technol. 39, 9778-9784.

Weston, D.P., Holmes, R.W., Lydy, M.J., 2009. Residential runoff as a source of pyrethroid pesticides to urban creeks. Environ. Pollut. 157, 287-294.

Wu, C., Liu, X., Wu, X., Dong, F., Xu, J., Zheng, Y., 2019. Sorption, degradation and bioavailability of oxyfluorfen in bio-char amended soils. Sci. of the Total Environ. 658, 87-94.

Xi, J., Shao, J., Wang, Y., Wang, X., Yang, H., Zhang, X., Xiong, D., 2019. Acute toxicity of triflumizole to freshwater green algae Chlorella vulgaris. Pestic. Biochem. and Physiol. 158, 135-142.

Yen, J.H., Lin, K.H., Wang, Y.S., 2000. Potential of the insecticides acephate and methadimophos to contaminate groundwater. Ecotoxicol. and Environ. Saf. 45, 79-86.

Zhang, Q., Li, S., Ma, C., Wu, N., Li, C., Yang, X., 2018. Simultaneous degradation of bifenthrin and chlorpyrifos by Pseudomonas sp. CB2. J. of Environ. Sci. and Health part B. 53, 304-312.

CHAPTER SIX

Nutrient and pesticide remediation using a two-stage bioreactor-adsorptive system under two hydraulic retention times

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6.1 Abstract

Nutrients and pesticides in agricultural runoff contribute to the degradation of water resources. Nitrates and phosphates can be remediated through the use of treatment systems such as woodchip bioreactors and adsorbent aggregate filters; however, concerns remain over potential effects of pesticides on nutrient removal efficiency in these systems. To test this, we designed laboratory-scale woodchip bioreactors equipped with secondary adsorbent aggregate filters and investigated the capacity of these systems to remediate nutrients when operated under two hydraulic retention times (HRT) and in the presence of commonly used pesticides. The woodchip bioreactors effectively removed over 99% of nitrate per day when operated under a 72 h hydraulic retention time, with the secondary expanded shale aggregate filters consistently reducing phosphate concentrations by 80-87%. Treatment efficacy of both systems was maintained in the presence of the insecticide chlorpyrifos. Reducing HRT in the bioreactors to 21 min decreased nitrate removal efficiency; however, the insecticides bifenthrin, chlorpyrifos, and the herbicide oxyfluorfen were reduced by 76%, 63%, and 31%, respectively. Cultivation approaches led to the isolation of 45 different species from the woodchip bioreactors operated under a 21 min HRT, with *Bacillus* species being the most prevalent throughout the treatment. By contrast, pesticide application decreased the number and diversity of Bacillus isolates and enriched for *Pseudomonas* and *Exiguobacterium* species. Woodchip bioreactors and adsorbent aggregate filters provide effective treatment platforms to remediate agrochemicals, where they maintain treatment efficacy in the presence of pesticides and can be modulated through HRT management to achieve environmental and operational water quality goals.

CONCLUSION

As global water security concerns mount, water resource management in agricultural production will demand the implementation of innovative solutions and technologies in order to remain sustainable, especially in input intensive sectors such as nursery crop production. Water availability is anticipated to be subject to increasing regulation; therefore, opportunities to produce a quality crop using less water is critical. Additionally, the management of irrigation return flow (IRF) and associated contaminants may also face increased legislation, and may necessitate remediation of agrochemical contaminants. Improving water management in nursery crop production encompasses both economic and ecological considerations, where the implementation of more efficient irrigation practices and installation of treatment systems such as woodchip bioreactors and expanded aggregate filters provide the opportunity to reduce, remediate, and potentially even recycle operational water use and irrigation return flow.

Nursery producers will be tasked with maintaining crop quality while reducing water use. Considering that standard irrigation practices involve daily overhead irrigation applied in a static volume, the opportunity to reduce water use can be accomplished through the use of alternative irrigation delivery methods in which water is applied with more precision and/or the use of θ sensors to apply only the amount of irrigation required. The use of in-container spray stakes are effective in reducing the volume of irrigation applied compared to standard grower practices in the region by nearly 75%, regardless of whether sensors were used. Implementation of θ sensors in overhead systems was similarly effective in reducing water use compared to a static overhead regiment, nearly halving the volume of irrigation applied. In this sense, nurseries with existing overhead infrastructure can phase in the implementation of irrigation technologies to reduce water use (sensors), without incurring the up-front financial and labor costs necessary in a complete retrofitting for micro-irrigation.

Balancing crop quality with operational expenses is of primary concern to nursery growers. Irrigating using micro-irrigation delivery systems and sensor based application methods produced all 7 of the studied taxa to an equivalent size (growth index) and visual quality; however, shoot dry biomass was often greatest in plants grown under higher application volumes. Despite the increase in shoot biomass when irrigating at higher volumes, it was observed that for certain taxa there was less shoot structural strength, producing leggy, brittle crops, compared to crops grown under more efficient irrigation practices,. The implementation of water reducing irrigation measures may be more appropriate for certain taxa, such as *Hydrangea*, where equivalent GI, shoot dry mass, and root dry mass was achievable; however, for taxa such as *Spiraea,* these measures may reduce crop quality. A recommended practice in nursery production is to group crops by water requirements; therefore, phasing in of irrigation technologies to groups of taxa capable of being produced to equivalent (or greater) quality first may offer the potential for nurseries to implement these technologies without incurring substantial financial/labor expenses rather than a universal overhaul.

Aside from reducing the volume of irrigation applied, sensor and micro-irrigation technologies also reduce irrigation return flow. While the method of delivery in overhead irrigation still produces surface IRF, it is typically generated in lower volumes when using θ sensors rather than a static overhead regiment. Micro-irrigation systems are oftentimes effective in complete elimination of surface IRF, effectively removing this vector of water and agrochemical movement. Regardless of irrigation application method, subsurface return flow volumes is similar between irrigation practices. Nurseries may elect, or be required, to recapture IRF leaving operational sites. Allocating the most efficient irrigation technologies in terms of reducing surface IRF (micro-irrigation), and by extension the taxa produced under them, to areas

within a nursery that contribute most to IRF may further provide benefits towards implementation of these systems.

Reducing IRF, particularly surface IRF, leads to substantial reductions in agrochemical movement. Nitrate exhibits mobility in both surface and subsurface IRF given its solubility; however, phosphate moves predominantly in surface IRF given its relative insolubility and potential to sorb to soils. Similarly, pesticide mobility is dependent on solubility, sorption coefficients, and other physiochemical properties. More soluble pesticides are capable of moving in both surface and subsurface IRF. Pesticides with a low solubility, and oftentimes inversely high sorption coefficient are unlikely to infiltrate and percolate through the production surface and subsurface profile. The generation of surface IRF is the most critical vector in the movement of agrochemicals, regardless of the physiochemical properties of a compound.

Pesticides which exhibit less mobility are likely to remain in place, allowing their respective degradation mechanisms to occur prior to transport off site from production areas. Pesticides are most likely to be transported shortly after application; therefore, reducing irrigation applied and IRF in the days immediately following application may facilitate degradation in-situ. Provided the opportunity to select between pesticide active ingredients or formulations, choosing compounds which possess physiochemical properties that limit mobility can be an effective method in limiting movement off-site.

Regardless of irrigation practice, the potential for IRF and concomitant contaminant movement may still be present. Treatment systems such as woodchip bioreactors and adsorbent aggregate filters are capable of remediating agrochemicals. The use of these systems under extended HRTs can allow near complete nutrient remediation; however, more rapid HRTs can capably remove pesticides without affecting nutrient content. In this sense, HRT can be

modulated to achieve different treatment goals, with the former best suited for IRF that will not be retained/recycled on site, while the latter may be ideal for producing recycled water without phytotoxic quantities of pesticides. The microbial community within woodchip bioreactors is capable of selecting for more tolerant species when exposed to pesticides, demonstrating the capacity for these treatment systems to adapt to various contaminant pressures.

Improving water management, both in terms of improving water usage as well as remediating contaminated IRF, is essential to maintaining the sustainability of nursery crop production. Nurseries may elect to phase in irrigation technologies that reduce water use and subsequent IRF generation for certain taxa without sacrificing crop quality, while woodchip bioreactors and expanded aggregates can be used to remediate IRF to regulatory standards and/or provide recycled irrigation water on-site. Implementing these technologies, as well as modifying best management practices to select less mobile pesticides, can capably reduce water use and minimize the environmental impact of nursery crop production.