Reducing Water and Pesticide Movement in Nursery Production

Damon E. Abdi and R. Thomas Fernandez¹

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SUMMARY. 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.

Container nursery crop production is an input-intensive industry with respect to water and agrochemical use, and daily irrigation, high fertilizer rates, and multiple applications of pesticides throughout the season are common practices (Agro and Zheng, 2014; Briggs et al., 2003; Dennis et al., 2010; Mangiafico et al., 2008; Riley, 2003; Wilson et al., 1995). Runoff water generated from irrigation or precipitation events can move agrochemicals out of the production area, exporting deleterious quantities of nutrients and pesticides to surface waters or on-site retention ponds (Lu et al., 2006; Warsaw et al., 2009b, 2012). Efforts to reduce the movement of

pesticides can be realized through improved irrigation practices, nursery infrastructure designs, pesticide application methods, and pesticide selection based on chemical properties (Chappell et al., 2013; Mahnken et al., 1999; Majsztrik et al., 2017; Wilson et al., 1996).

Irrigation method and scheduling

Irrigation in the nursery is often applied daily using overhead impact sprinklers (Beeson and Knox, 1991; Fulcher and Fernandez, 2013a; Paudel et al., 2016). Overhead irrigation provides water to the entire nursery production surface—the containerized plants and the intercontainer spaces; however, the majority of water applied using overhead irrigation fails to reach the crop, with 74% to 87% landing in the intercontainer spaces, where it may contribute to surface runoff or infiltrate the production surface (Ross et al., 2001; Weatherspoon and Harrell, 1980). The canopy architecture of container-grown plants as well as the spacing between containers influences water movement, potentially capturing more water within the container or shedding it

outside (Davies et al., 2016; Million et al., 2005). Nurseries irrigating with overhead systems will typically apply between 0.3 and 1.3 inches of water each day, thus necessitating an ample supply of water being available throughout the season (Fulcher and Fernandez, 2013a). Alternatively, microirrigation can be used for nursery production to provide water directly to plants, thereby increasing the application efficiency (Mathers et al., 2005). Generally, investments in microirrigation are reserved for the production of crops grown in larger containers (19 L or larger), where the plant canopy may undesirably intercept and redistribute overhead irrigation (Beeson and Knox, 1991; Majsztrik et al., 2017). Microirrigation methods such as individual container spray stakes require less water than overhead irrigation; however, although more efficient at applying, microirrigation systems demand higher-quality water and routine monitoring to ensure that emitters are not clogging and that all plants are receiving water, which is a less intensive consideration when using overhead irrigation (Owen et al., 2016).

Irrigation is preferentially applied in the morning during periods of low winds, when evapotranspiration is lowest (Fulcher and Fernandez, 2013a, 2013b). The volume of irrigation water applied can be reduced through irrigating to replace the crop daily water use and/or the use of cyclic applications (Karam and Niemiera, 1994; Pershey et al., 2015; Warsaw et al., 2009a, 2009b). Splitting a single, continuous irrigation event into cyclic applications may allow substrates to hydrate more evenly and reduce preferential channeling through the container substrate, particularly in dry substrates (Hoskins et al., 2014; Taylor et al., 2013). Substrate moisture sensors quantify water content within containers and may be used to make more informed irrigation decisions when controlled manually or as part of an automated irrigation control system

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Department of Horticulture, 1066 Bogue Street, Room A216, Michigan State University, East Lansing, MI 48824-1325

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¹Corresponding author. E-mail: fernan15@msu.edu.

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
3.7854	gal	L	0.2642
25.4	inch(es)	mm	0.0394

(Lea-Cox et al., 2013; Pershey et al., 2015). Crop quality may be improved through irrigating to meet substrate moisture thresholds, and it can be used to influence root/shoot growth, plant size, and flowering (Bayer et al., 2015; Pershey et al., 2015; Warsaw et al., 2009a, 2009b). Irrigating using sensor-controlled irrigation systems reduced the instances of water-borne pathogen mortality in gardenia [*Gardenia augusta* 'MADGA 1' (Heaven ScentTM)] production, and it decreased the time necessary to produce a salable crop, thereby increasing operation profitability by reducing input expenses and increasing crop production and leading to a 116% increase in annual profit relative to previous practices (Lichtenberg et al., 2013). Reducing water use provides economic benefits; however, modifying irrigation practices may not be fiscally motivating because increasing regulatory pressure may also guide decision-making (Bolques et al., 2011; Fulcher et al., 2016; Lea-Cox and Ross, 2001).

Runoff generation

The amount of water applied in nurseries contributes to nursery runoff, with increasing application rates resulting in greater volumes of runoff water (Fulcher and Fernandez, 2013b; Pershey et al., 2015; Warsaw et al., 2009a, 2009b). Reducing the volume of runoff generated can be accomplished through irrigating based on plant water use (Bayer et al., 2015; Pershey et al., 2015; Warsaw et al., 2009b). Surface runoff can facilitate the movement of agrochemicals, either in the dissolved phase or in a bound particulate phase; however, water infiltrating through the soil has the potential to transport dissolved compounds through soils. Substantial volumes of runoff are generated from irrigation falling between containers, precipitation, and container leachate, thus contributing to the removal of nutrients and pesticides from production areas. Agrochemical loss from container nursery production poses an environmental threat because recycled irrigation water at phytotoxic concentrations may be deleterious to crops (Mahnken et al., 1999). Concerns regarding the level of contamination present in runoff water can be mitigated through using best management

practices (BMPs), such as installing buffer zones and improving water/chemical application practices; however, additional treatments to remove pesticide residues may be necessary before environmental discharge or use as recycled irrigation water (Grant et al., 2019; Lu et al., 2006). The implementation of treatment systems to address agrochemical content in runoff water requires a financial investment in an associated infrastructure, encouraging the use of these systems for recycling irrigation water to capitalize on the investment (Pitton et al., 2018).

Nursery production surface and infrastructure

Nursery production sites should be constructed to facilitate the movement of runoff water to desired locations as part of a larger water infrastructure system (Majsztrik et al., 2011). The slope and material used for constructing the production surface impact the movement of water and associated agrochemicals, erosion of soil/organic matter and adsorbed compounds, as well as weed presence (Million et al., 2005; Wilson et al., 1995). Groundcover surfaces common in nursery production include plastics, landscape fabric, and uncovered porous aggregate, each of which are capable of generating substantial amounts of runoff water and of influencing agrochemical export (Briggs et al., 2002). Although the authors did not compare water runoff or infiltration due to groundcover, it is likely that different groundcovers will result in different partitioning of water effluent to runoff or infiltration. Contaminant and sediment contents in runoff or infiltration water can be addressed through the implementation of BMPs, such as installing sedimentation basins, phytoremediation areas, filter socks, and vegetated filter strips, for the interception of contaminated water as it exits production areas and before discharge to the environmental or on-site retention (Briggs et al., 1998; Fulcher and Fernandez, 2013b; Majsztrik and Lea-Cox, 2013; Majsztrik et al., 2017; Shipitalo et al., 2010; Spangler et al., 2019; Warsaw et al., 2012). Because many pesticides exhibit a tendency to adsorb to soils and other suspended particles in runoff water, facilitating the

settling of sediments can reduce the movement of certain compounds. The design of sediment-reducing treatments should consider the maintenance and management of these systems, particularly regarding periodic removal of sequestered sediments.

Pesticide properties

The fate of a pesticide is influenced by its inherent chemical properties, with the mobility of a compound dependent on how it is partitioned within the nursery and the environment at large. Pesticides exhibit a range of chemical properties between and within chemical classes, with solubility in water, adsorption coefficients, and vapor pressure of a particular compound suggesting the likely fate (Langeron et al., 2014). Pesticide movement in runoff water can occur with the pesticide either dissolved in water or transported and adsorbed on soil particles/organic matter (Boithias et al., 2014; Lao et al., 2008). Soils, particularly clay and organic matter fractions, serve as adsorption sites for pesticides, with the clay fraction critical to the adsorption of polar pesticides and organic matter (particularly organic carbon) providing the non-ionic sorption sites for lipophilic pesticides (Dion et al., 2001; Mantzos et al., 2014). Partition coefficients indicate the likelihood of a compound to bind or adsorb to soils [K_d (concentration of the chemical in soil/concentration of the chemical in water)], the organic material portion within soils [K_{om} (concentration of the chemical in organic matter/concentration of the chemical in water)], and, specifically, the organic carbon fraction of soils [K_{oc} ($K_d \times 100/\%$ of organic carbon)] (Bedos et al., 2002). Plastics are capable of adsorbing certain pesticides, particularly nonionic compounds, and the partition coefficient K_{pw} (concentration of chemical in a plastic polymer/concentration of chemical in water) may be used to measure the sorption of a pesticide with various plastic polymer chemistries (Lee et al., 2014; O'Connor et al., 2016). Unfortunately, K_{pw} is not available for most pesticides, and sorption may vary with different polymer compositions. Adsorption and desorption are constantly occurring. The adsorption coefficients provide an indication of the strength with

which compounds are bound to various substrates individually at equilibrium. In a natural setting where equilibrium is unlikely and many compounds are present, a particular pesticide may be adsorbed in one area of an operation, such as the production surface, and transported to another area, such as a reservoir, where it is desorbed and replaced on the binding site by a different compound.

Pesticides will also partition between phases, with Henry's Law constant indicating the likelihood of a pesticide volatilizing into the air or remaining within water. This coefficient, calculated as a particular compound vapor pressure divided by solubility, provides an indication of the likely partitioning between water or the atmosphere, with a greater value indicating that volatilization is more likely to occur (Suntio et al., 1988). The length of time for which a particular contaminant may be present in a given environment can be estimated through half-life (the amount of time required for half of a given compound to degrade) measurements (Hanson et al., 2015).

Application method and formulation

The formulation and method by which a pesticide is applied influences treatment efficacy, as well as movement after application (Briggs et al., 2002; Derr, 1994). The active ingredient of a pesticide may be incorporated in different forms, such as granules, liquids, or emulsifiable concentrates, where components found within different formulations, including activators, solvents, and adjuvants, impart characteristics to the pesticide, thus influencing mobility in the environment (Włodarczyk, 2014; Włodarczyk and Siwek, 2016). Pesticides applied in solid forms will move as solids in water until dissolved, suspensions will move more freely but are typically insoluble, and dissolved pesticides will move freely in water unless adsorbed to soils or organic matter. However, soluble pesticides may not move as expected due to the properties of the pesticide. Isoxaben was present in runoff water at higher concentrations in the granular formulation compared to the sprayable formulation, most likely due to adsorption of the sprayable

isoxaben following application, whereas the granules were dissolved with each irrigation application and with runoff before adsorption could occur (Briggs et al., 2002). Pesticides can be broadcast over the entirety of the production surface area, covering plants, containers, and interspace areas; applied to target locations, for example, postemergence herbicide applications; or incorporated as part of a container substrate mix (Graves et al., 2014). Agrochemicals applied as broadcast applications are more likely to be exported because they have fewer areas and opportunities for adsorption, whereas those applied to plants or in container substrates typically move through the substrate, where adsorption can occur, before being exposed to leaching events (Mahnken et al., 1999).

Reducing pesticide movement

Pesticides are subject to a range of degradation mechanisms based on the formulation, method of application, environmental conditions, and the site to which they are applied (Lu et al., 2006). The breakdown of pesticides is critical to the prevention of excessive accumulation of persistent compounds in the environment (Arbeli and Fuentes, 2007). Degradation of pesticides occurs through chemical and biological processes and is influenced by site-specific conditions and environmental factors. Pesticides applied to nursery production sites are expected to adsorb to surfaces/soils or dissolve in water based on measured partition coefficients and solubility. Pesticides at the ground surface and in ponds are subject to photolysis (the breakdown of pesticides in response to sunlight), which is the primary degradation pathway for certain pesticides, such as the insecticide pirimicarb and the herbicide oxyfluorfen (Mantzos et al., 2014; Pirisi et al., 1996). The photodecomposition of pesticides occurs in either a direct or an indirect manner, with the former resulting from the compound reaching a photo-excited state, and the latter in response to reactions driven by light-induced reactive oxygen species present in water (Katagi, 2018). Pesticides may degrade in water via hydrolysis (Linde, 1994) or, based on the Henry's Law constant of a given compound, may volatilize, which is a physico-chemical process that

results when a compound enters a gaseous state through either evaporation from water or sublimation from a solid form (Bedos et al., 2002).

Biological degradation

Microbially mediated degradation is a major pathway in the breakdown of certain pesticides, and it is considered a cost-effective, environmentally friendly treatment method for removing contaminants (Camper et al., 2001; Cycoń et al., 2011; Zhang et al., 2018). The degradation of pesticides by microbial communities may yield small organic molecules, such as carbon dioxide and water, or metabolites with properties that may differ from the parent compound (Huang et al., 2018; Ricking and Schwarzbauer, 2012). Pesticide breakdown occurs through a range of enzymatic reactions, such as oxidoreductases, monooxygenases, dioxygenases, P450 oxidoreductases, hydrolases, lyases, and dehalogenases (Coats, 1991; Sharma et al., 2016). Site-specific conditions modify the degradation process, with temperature, soil texture, soil moisture, and access to carbon and nutrient sources influencing microbial degradation (Javaid et al., 2016; Kumar et al., 2018; Ortiz-Hernandez et al., 2013). The amount of a particular pesticide available to surrounding microbial communities also influences the rate at which degradation occurs, with lower quantities potentially limiting the breakdown processes (Cederlund et al., 2016). Metabolites generated with the degradation of pesticides may be deleterious to water resources (Reemtsma et al., 2013) and may modify surrounding microbial communities (Mauffret et al., 2017). The organophosphate insecticide chlorpyrifos degrades via microbially mediated processes as well as hydrolysis; however, accumulation of the intermediate product trichloropyridinol occurs (Racke et al., 1990); upon breakdown, this releases free chlorine, which acts as a sanitizer inhibiting further degradation (Singh and Walker, 2006). The herbicide glyphosate has the tendency to bind to soils, which when detached via erosive water movement may be transported downstream and/or dissolve, allowing accumulation in stream sediments and receiving water bodies (Spengler et al., 2018). Microbial species are capable of using glyphosate as a phosphorus source (Hove-Jensen et al.,

2014), and converting it to metabolites such as aminomethylphosphonic acid (Yael et al., 2014), which is a compound that is more recalcitrant to degradation and more toxic than glyphosate itself (Ndjeri et al., 2013). The capacity for microbial communities to degrade pesticides is critical to their survival when facing contaminant pressure; ideally, the targeted biological processes convert a pesticide into a less toxic form, and that ideal end product is carbon dioxide and water (Mohan and Naveena, 2015; Parte et al., 2017).

Conclusions

Frequent irrigation and pesticide use are typical components in the production of container nursery crops. Water is the main mechanism of pesticide movement after application. Time is a critical factor in reducing pesticide movement that allows adsorption and degradative processes to occur. Practices that reduce the amount of water applied and delay irrigation after pesticide application can reduce pesticide movement. Irrigation practices that generate substantial volumes of runoff may export deleterious amounts of pesticides from production areas. Management practices that irrigate based on crop water use can reduce the volume of irrigation water applied, as well as the amount of runoff water generated. Pesticide movement varies between (and within) chemical classes, with environmental conditions, nursery infrastructure/layout, and other factors further influencing pesticide mobility. When possible, the selection of compounds or formulations with characteristics that limit mobility, such as low solubility and high-adsorption coefficients, may be an effective operational tool that can be used to limit pesticide movement in the nursery.

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