ABSTRACT

RAY, ALISHA OLIVER. Assessing the Presence and Management of Weed Seeds in Surface Irrigation Water of Container Production Nurseries. (Under the direction of Drs. Joseph C. Neal and Anthony V. LeBude)

Southeastern U.S. container nurseries frequently utilize unfiltered water from open ponds for irrigation. While many growers suspect irrigation water to be a source of weed seed dispersal, data on the presence of weed seeds within irrigation ponds are lacking. This study was designed to address knowledge gaps on the role of irrigation water as a source of weed seed dispersal. Studies included evaluations of weed seed buoyancy and weed seed survival in water, and a two-year field survey of weed seed presence in irrigation pond water. Seed buoyancy was assessed for thirteen weed species common to nurseries, including two species evaluated with and without attached pappus. Among the tested species, buoyancy ranged from 0% to 100%. *Eclipta prostrata* L. and *Rorippa palustris* (L.) Besser exhibited near-complete buoyancy (100% and 99%, respectively), while seeds of *Cardamine flexuosa* With. and *Oxalis stricta* L. were not buoyant (2% and 0%, respectively). The presence of an attached pappus significantly increased buoyancy for both *Senecio vulgaris* L. and *Eupatorium capillifolium* (Lam.) Small. To test survival in irrigation ponds, seeds of *Euphorbia maculata* L., *Eclipta prostrata*, *Cardamine flexuosa*, and *Oxalis stricta*. were submerged at a depth of 60 cm in mesh bags in irrigation ponds of four North Carolina commercial container nurseries. Seeds were collected at nine time intervals over 360 days and germinated. All weed species germinated following 240 days after submergence (DAS). However, the germination of *Oxalis stricta* seeds decreased over time with less than 15% germination after 240 days and less than 5% after 360 days in three of four locations. *Euphorbia maculata* seed germination declined over time but remained above 15% after 360 days. In contrast, *Cardamine flexuosa* and *Eclipta prostrata* seeds maintained over 80% germination following 360 DAS in three of four locations. These results indicate that seeds of several common nursery weeds are buoyant and can remain viable in irrigation ponds for extended periods. Seeds possessing both buoyancy and survivability in water may have greater potential for distribution by irrigation systems. To investigate the presence and diversity of viable weed seeds in irrigation pond water, authors conducted a two-year survey at six commercial container nurseries in central and eastern North Carolina. Irrigation filtration samples were collected during the spring, summer, and late-summer seasons. A total of 216 water samples were filtered using a custom pump and filter system (Gra-Mac Irrigation, Farmington, NC). The volume of water filtered for each sample was 20,000-gal (75,708 L), equivalent to 0.75 acre-inch (19 mm) of water used to irrigate one acre for container nursery crops in the Southeastern U.S. Filtrates were spread on potting mix and seedling emergence was documented weekly for 12 weeks. Viable seeds were detected in irrigation samples from all locations, seasons, and years, with the average number of seeds per sample ranging from 9 to 35. Seasonal averages across years and locations were 12.5, 24.8, and 18.2 germinable seeds in spring, summer, and late-summer, respectively. A total of 75 taxa were identified from the irrigation samples, including 28 weed species commonly found in container nurseries. Some prevalent weeds, such as *Eclipta prostrata*, *Rorippa palustris*, *Digitaria sanguinalis* (L.) Scop., *Cardamine flexuosa*, and *Euphorbia maculata*, were consistently present across all seasons while others exhibited seasonal specificity. These results indicate that irrigation water serves as a pathway for the introduction of weed seeds into nursery environments. However, the relatively low seed numbers observed suggest that other mechanisms of weed seed dispersal within the nursery contribute more to overall weed seed distribution.

Assessing the Presence and Management of Weed Seeds in Surface Irrigation Water of Container Production Nurseries.

by
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DEDICATION

To my devoted dog, Snow. My sassy companion of 17 years, by my side through every new adventure, including graduate school. She lay next to my desk and was always eager to give me an excuse for a much-needed walk and a break. Her sturdy ears and side eye have been the throughline for my continued effort to better both our lives, and thus the motivation I needed to keep going.

BIOGRAPHY

Alisha Oliver Ray was born in Fayetteville, North Carolina, and experienced a diverse upbringing, including time spent overseas. Ray pursued their undergraduate studies in horticulture at West Virginia University, where they earned a bachelor's degree. After graduation, they gained extensive industry experience, working as a container nursery grower, a greenhouse grower, and on the retail side of horticulture.

Feeling increasingly disconnected from the horticulture industry in retail roles, Ray pursued an opportunity to become a research associate at North Carolina State University, returning to a more direct engagement with horticulture. There, they developed a profound interest in the research process and in the resilient and opportunistic plants considered weeds. Ray seized the chance to pursue a Master of Science degree, completing their studies while serving as a Research Operations Manager at the university.

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Scope and Justification

Weeds pose a significant threat to container crop production, directly impacting crop quality and marketability. Weeds compete with desirable plants for essential resources like water, light, nutrients, and space, often leading to reduced growth, marketability, and increased cost-of-production (Case et al. 2005). Fretz (1972) reported that highly competitive weed species can significantly reduce crop growth even at low densities; one redroot pigweed (*Amaranthus retroflexus* L.) or large crabgrass (*Digitaria sanguinalis* L.) plant per container decreased Japanese holly (*Ilex crenata* Thunb.) growth by 47% and 60%, respectively. Similarly, the presence of eclipta (*Eclipta prostrata* L.) in container-grown azaleas reduced plant growth by up to 78% (Berchielli-Robertson et al. 1990). That study also found that even a single plant of eclipta or prostrate spurge (*Euphorbia prostrata* Ait.) was as competitive as a greater quantity of weeds. Given the aesthetic value of ornamental nursery crops, even minor weed infestations require management to maintain marketability (Simpson et al. 2004). The combined effects of competitive impacts and marketability standards establish a near zero-tolerance weed threshold in container nursery production.

To mitigate losses from weed competition, container nursery crop producers regularly apply preemergence herbicides every six to eight weeks (Gilliam et al. 1992; Neal et al. 2017). Typically, growers broadcast these herbicides over the top of stock with a cyclone spreader (Mathers 2003). This application method, however, results in substantial non-target herbicide loss, with up to 86% of the herbicide falling between pots, depending on plant growth habit and container spacing (Gilliam et al. 1992). Despite this economic inefficiency and environmental concerns regarding off-site herbicide movement (Pimentel 2009), preemergence herbicides remain the most effective option for weed control in container nurseries, yet weed emergence persists.

Postemergence chemical control options are limited. Only a small number of graminicides are available for postemergence control of weedy grasses in several dicotyledonous crops; however few, if any, selective postemergence herbicide options are available for broadleaf weed control in nursery crops (Alluri and Saha 2024). These postemergence chemical options are often most effective when weeds are small, which can be a brief timeframe for some weed species. For instance, spotted spurge (*Euphorbia maculata* L.) initiates flowering as few as 22 days after seeding (Neal et al. 2016). Considering the rapid growth rate of some weed species, growers have a narrow window of opportunity for effective postemergence chemical control. These factors lead to a heavy reliance on labor-intensive hand weeding as the primary means of postemergence weed control (Neal et al. 2017; Stewart et al. 2017). In 2003, annual hand weeding costs were estimated to reach as high as $9,800 (USD) per hectare (Mathers 2003). Today, growers face increasing costs and labor shortages. In a 2023 industry survey, labor costs and availability were the greatest business concern for 59% of growers (McClellan 2024). Therefore, identifying and understanding the sources of weed seed contamination and spread is crucial for developing effective prevention strategies and ultimately reducing weed management expenditures and reliance on manual weed removal in container nursery production.

Preventative management efforts target established pathways of weed seed contamination, including contaminated transplants, carryover from reused containers, dispersal from adjacent weeds (Neal 2016; Bachman and Whitwell 1995; Cross and Skroch 1994), and occasionally contaminated bark-based soilless substrates (Neal, personal observation; Cross and Skroch 1994). Although implementing preventative measures for known sources of weed seeds can decrease weed emergence, it does not eliminate emergence, suggesting other introductory sources of weed seeds. Many container nursery producers perceive irrigation water as a source of weed seed dispersal. However, with limited reports, the role of surface irrigation ponds as a weed seed source remains unclear.

Existing literature on weed seeds in container nursery irrigation is sparse. One study found only three weed seeds in approximately 5,000 gallons (18,900 L) of water sampled across five nurseries (Williams and Saunders 1984). Extrapolating this data suggests a distribution of about 12 weed seeds per acre per irrigation event. However, the sampled volume in that study accounts for only 25% of the daily irrigation need for one production acre and those seeds were not tested for viability. In contrast, other agricultural systems have documented water as a significant vector for weed seed dissemination. Kelley and Bruns (1975) investigated two farmland irrigation sources in Washington state for weed seeds: irrigation canals fed by the Yakima River and the Columbia River, which served as a direct source of irrigation water. The study concluded that, on average, 233,500 and 34,800 seeds per acre respectively, would be disseminated during the growing season by irrigation water from the irrigation canals and the Columbia River. Additionally, germination tests of the collected seeds indicated that nearly half of all seeds were viable, demonstrating that irrigation water represented a potential source for plant establishment when deposited onto agricultural land. The results of a 1980 study on weed presence in irrigation water from irrigation canals in Nebraska support Kelley and Bruns's findings, concluding that approximately 30,800 viable weed seeds per hectare were disseminated via irrigation (Wilson

1980). Rice-wheat cropping systems have extensively documented water as a significant vector for weed seed dissemination (Zhang et al. 2019), particularly for weed species with highly buoyant seeds readily transported in runoff and deposited into source water (Li and Quang 2009; Merrit et al. 2006; Shi et al. 2020).

Hydrochory, the passive dissemination of seeds or plants by water, is an important mode of seed dispersal for riparian species in natural environments (Nilsson et al. 2010; Rasran et al. 2023). Hydrochorous transport can significantly extend seed distribution ranges, even for some species without specific adaptations for this vector (Nilsson et al. 2010; Rasran et al. 2023). However, seeds with high buoyancy achieve much greater dispersal distances from parent plants compared to those with low buoyancy (Nilsson et al. 2002; Fryirs et al. 2022). For example, de Rouw et al. (2028) found that heavy rainfall increased weed seed deposits in runoff water, and floating weed seeds were transported greater distances in runoff than nonbuoyant seeds. Moreover, buoyancy also plays an important role in slow-flowing systems where seeds with lower buoyancy are more likely to sink before deposition in habitats suitable for germination (Nilsson et al. 2002). In the Southeastern U.S., many container nurseries re-capture excess irrigation water and rainfall, returning this water to the irrigation ponds via drainage ditches and culverts. Growers then reuse this for irrigation, often without filtration. Mature weeds present in containers, nursery roadways, and pond edges shed seeds in areas where captured runoff water flows. These seeds may be transported in runoff and deposited into irrigation ponds, where they can potentially enter irrigation intakes. Weed seeds with high buoyancy may have a greater potential of flowing to irrigation intakes than non-buoyant seeds. While the seed buoyancy of most common nursery weed species is unknown, Shi et al. (2020) reported that eclipta has highly buoyant seeds, suggesting that its seeds may be deposited in surface irrigation ponds via captured tail water. Determining the buoyancy of other common nursery weed species is necessary for understanding their potential for hydrochorous transport and availability in irrigation ponds.

Nursery irrigation ponds typically have large surface areas, suggesting that weed seeds could take a considerable amount of time to travel from their entry points to irrigation pump intakes. This implies that the longevity of seed survival after submergence in water may be an important factor in determining the potential for surface irrigation ponds to serve as a source of weed seed dissemination. Comes (1978) tested seed germination for 82 weed species following twelve months of submergence in water and reported that seeds of 58 species maintained up to 78% germination. Seeds of 27 species, including black henbane (*Hyoscyamus niger* L.), pale smartweed (*Persicaria lapathifolia* (L.) Delarbre), and hairy nightshade (*Solanum physalifolium* Rusby), germinated after 60 months of submersion. In that same study, seeds of 13 species, including smooth crabgrass (*Digitaria ischaemum Schreb.* ex Muhl.), spotted knapweed (*Centaurea stoebe* L.), and blue mustard (*Chorispora tenella* (Pall.) DC.), showed little to no germination after three months of submersion in water. A separate study on spotted spurge, a common weed in container nursery crops, reported greater than 60% seed germination after three weeks of submergence but no germination after nine weeks (Asgarpour et al. 2015). The authors concluded that spotted spurge seed longevity in water is relatively low but remains viable long enough to be transported via irrigation canals and infest farmland. Little information is available on the effects of submersion on seed viability for other weeds common to container nursery crop production. Whether those seeds remain viable in water and suspended long enough to reach irrigation intakes has not been studied.

Understanding the traits of common nursery weed seeds, such as buoyancy and longevity in water, and their effects on hydrochorous transport, along with examining the presence of weed seeds in irrigation water, is crucial for determining the potential and importance of nursery irrigation ponds as a source of weed seed dissemination across production areas. This series of experiments were designed to determine the potential for weed seed dissemination in container nursery production systems via overhead irrigation and its significance as a source of weed seed contamination by:

- Documenting the buoyancy of common nursery weed seeds
- Examining common weed seed survival, *in situ*, by submergence in source water used for irrigation in nurseries
- Determining the number of germinable weed seeds and the diversity of species present, including seasonal and site variations, in source water used for irrigation in container nurseries.

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Chapter 1
Buoyancy and Survival of Weed Seeds in Container Nursery Irrigation Ponds

(In the format appropriate for submission to Weed Technology

Abstract

As part of a larger study evaluating irrigation ponds as a reservoir for weed seed dispersal in container nurseries, weed seed buoyancy and survival in irrigation ponds were investigated. Seed buoyancy was assessed for thirteen weed species (two with and without attached pappus) common to nurseries. Seeds were placed in water and observed for settling over 7 days. Among the species tested, seed buoyancy ranged from 0% to 100%. Eclipta and marsh yellowcress maintained 100% and 99% buoyancy. In contrast, flexuous bittercress and yellow woodsorrel had 2% and 0% buoyancy. The presence of an attached pappus significantly increased buoyancy for both common groundsel and dogfennel. To test seed survival in irrigation ponds, seeds of spotted spurge, eclipta, flexuous bittercress, and yellow woodsorrel were placed in mesh bags and submerged at a depth of 60 cm in irrigation ponds at four nurseries. Seeds were collected from each location at 7, 15, 21, 30, 60, 90, 120, 240, and 360 days after submergence then germinated. All weed species germinated following 240 days of submergence. Germination of yellow woodsorrel seeds decreased to less than 15% following 240 days of submergence, and less than 5% after 360 days in three of four locations. Spotted spurge seed germination declined over time but maintained over 15% germination following 360 days of submergence. In contrast, flexuous bittercress and eclipta maintained over 80% germination following 360 days of submergence in three of four locations. Results of these experiments show that seeds of several common nursery weeds are buoyant and remain viable in irrigation ponds for extended periods of time. Seeds possessing both buoyancy and survivability in water may have greater potential for distribution by irrigation systems.

Nomenclature:

common groundsel, *Senecio vulgaris* L.; dogfennel, *Eupatorium capillifolium* (Lam.) Small; eclipta, *Eclipta prostrata* L.; flexuous bittercress, *Cardamine flexuosa* With.; marsh yellowcress, *Rorippa palustris* (L.) Besser; spotted spurge, *Euphorbia maculata* L.; yellow woodsorrel, *Oxalis stricta* L.

Keywords dispersal; hydrochory; persistence; seed germination; seed viability

Introduction

Hydrochory, the passive dissemination of seeds or plants by water, is an important mode of seed dispersal for riparian species in natural environments (Nilsson et al. 2010, Rasran et al. 2023). In those habitats, seed buoyancy is considered an essential trait for hydrochorous transport (Vogt et al. 2006). Seeds with high buoyancy were dispersed greater distances than seeds that floated less than one day (Fryirs et al. 2022, Nilsson et al. 2002). High seed buoyancy is particularly important in slow-flowing systems where seeds with lower buoyancy are more likely to sink and not be deposited in habitats suitable for germination (Nilsson et al. 2002).

Movement in water has also been reported as an important means of seed dispersal for some weed species in agroecosystems (Benvenuti 2007). Shi et al. (2020) reported that 95% of weed species common to rice-wheat cropping systems produced seeds with some ability to float and could be spread through flood-irrigation. Surface irrigation water has also been shown to be an important vector for weed seed dispersal in non-flooded agronomic cropping systems. Irrigation water samples from irrigation canals in Nebraska revealed the presence of seeds of the ten most detrimental weed species in farm fields (Wilson 1980). Additionally, that study calculated that 12,500 viable seeds/ha were disseminated via irrigation. From those data we can conclude that irrigation from surface water may be an important source of weed seed contamination for certain agronomic cropping systems, but no information is available on its importance for container nursery crops where irrigation events are more frequent.

In the Southeastern U.S., container nursery crop producers typically irrigate daily during the growing seasons. There are an average of 168 irrigation days per year where 1.9 cm of water are delivered per acre, approximately 75,700 L (20,000 gallons) per acre per day (Fare et al. 1992). Most nurseries use open ponds as source water for nursery irrigation. Rain and water from irrigation events are captured and deposited into surface ponds via drainage ditches and culverts and often reused for irrigation without filtration. Through this practice, seeds produced from mature weeds in containers, nursery roadways and pond edges may be deposited into irrigation water and potentially enter irrigation intakes. de Rouw et al. (2018) reported that heavy rainfall increased weed seeds captured in runoff water of drainage channels of mountainous farmland, and floating weed seeds were transported in runoff greater distances than nonbuoyant seeds. From this evidence it is reasonable to conclude that in container nurseries, where water is captured and recycled to irrigation ponds, weed seeds with high buoyancy will have greater potential of flowing to the irrigation intakes than non-buoyant seeds. While eclipta, a common weed in container nurseries of the Southeastern U.S., is reported to have highly buoyant seeds (Shi et al. 2020), seed buoyancy of other common container nursery weed species is unknown.

Nursery irrigation ponds have large surface areas and thus it could take a considerable amount of time for weed seeds to move from the entry points to irrigation pump intakes. This suggests that the longevity of seed survival after submergence in water may also be an important factor in the potential for surface irrigation ponds to be a source of weed seed dissemination. Numerous weed species have been shown to maintain viability after submergence in water. Comes (1978) tested seed germination for 82 weed species following twelve months of submergence in water and reported that seeds of 58 species maintained up to 78% germination. Seeds of 27 species, including black henbane (*Hyoscyamus niger* L.), pale smartweed (*Persicaria lapathifolia* (L.) Delarbre), and hairy nightshade (*Solanum physalifolium* Rusby), germinated following 60 months of submergence. The study author noted that annual monocot seeds had lower germination rates after water submergence compared to the dicot species tested. In that same study seeds of 13 species including smooth crabgrass (*Digitaria ischaemum* Schreb. ex Muhl), spotted knapweed (*Centaurea stoebe* L.), and blue mustard (*Chorispora tenella* (Pall.) DC.) had little to no germination after 3 months of submergence in water. A separate study with spotted spurge, a common weed of container nursery crops, reported greater than 60% seed germination following 3 weeks of submergence, but no germination after 9 weeks (Asgarpour et al. 2015). The authors of that experiment concluded that spotted spurge seeds remained viable long enough to be transported via irrigation canals.

Little information is available on the effects of submergence on seed viability for other weeds common to container nursery crop production. Whether those seeds remain viable in water and suspended long enough to reach irrigation intakes has not been studied. Therefore, the objectives of this research were to evaluate the buoyancy and survival after submergence of common container nursery weed seeds, seeking to determine the potential for uptake and dispersal via overhead irrigation systems.

Materials and Methods

Seeds of common container nursery weeds used in these experiments were field-collected from 2019 to 2021 at the Horticulture Field Laboratory, Raleigh, North Carolina (35.79161° N, 78.69783° W), and a local container nursery in Johnson County, North Carolina (35.59353° N, 78.39443° W). Species used in the study included eclipta, spotted spurge, rice flatsedge (*Cyperus iria* L.), redroot pigweed, fringed willowherb (*Epilobium ciliatum* Raf.), dogfennel, marsh yellowcress, large crabgrass (*Digitaria sanguinalis* (L.) Scop.), American burnweed (*Erechtites hieraciifolius* (L.) Raf. Ex DC.), livid amaranth (*Amaranthus blitum* L.), and common groundsel. Seeds of yellow woodsorrel and flexuous bittercress were originally sourced from local nurseries and seed numbers were increased by growing plants to maturity in greenhouses at North Carolina State University (35.78742° N, 78.67314° W). All collected seeds were air-dried in paper bags at room temperature, then screened and stored at 3°C.

Weed seed buoyancy

Seed buoyancy experiments utilized the basic methodology of Shi et al. (2020). Tests were performed in the Weed Science Laboratory at North Carolina State University, Raleigh, North Carolina (35.78839° N, 78.67286° W) maintained at approximately 23°C. In July 2021, buoyancy was tested on the seeds of eclipta, spotted spurge, rice flatsedge, redroot pigweed, fringed willowherb, dogfennel, marsh yellowcress, large crabgrass, American burnweed, livid amaranth, and common groundsel. To measure the effect an attached pappus may have on seed settling, dogfennel and common groundsel seeds were included with the pappus intact or with the pappus removed. Ten seeds of a species were placed in a 180 mL cylindrical glass jar (Danyang EnCheng Glass Co., LTD) filled with 120 mL of tap water. The jar was sealed with a lid and agitated for 30 seconds to break surface tension then placed on a level laboratory bench. Seeds were allowed to settle for 1 hour then the number of seeds that settled to the bottom was recorded. Thereafter, the number of settled seeds was recorded at 24-h intervals for 7 days. There were five replicate jars for each species and the test was repeated in November 2021. Buoyancy was calculated as percent (%) of unsettled seeds after 7 days. Differences in percent buoyancy among the species were tested using a general linear models procedure (PROC GLM) in SAS 9.4

(SAS Institute, Cary NC) and means separated using a Tukey's HSD test at $\alpha=0.05$. The effect of pappus on seed buoyancy was tested using single-degree-of-freedom comparisons.

Seed submergence and viability

This experiment was conducted at four container nurseries in eastern North Carolina over two consecutive years. The study locations were near Raleigh (35.79161° N, 78.69783° W), Holly Springs (35.61105° N, 78.85265° W), Garner (35.70547° N, 78.55251° W), and Willow Springs, NC (35.60629° N, 78.68402° W). Seeds of spotted spurge, eclipta, flexuous bittercress and yellow woodsorrel were submerged in irrigation ponds in November 2019 and July 2020, then repeated in November 2020 and July 2021. Henceforth, seeds submerged in November 2019 and 2020 will be referred to as winter one and winter two, and seeds submerged in July 2020 and 2021 will be referred to as summer one and summer two. Two hundred seeds of one species were placed in a 150-µm mesh nylon bag, this process was repeated for each species. One bag of each species was then tied together to create a seed bundle. Nine seed bundles were placed inside a perforated polyvinyl chloride (PVC) cylinder with a capped bottom and a threaded PVC lid. The cylinder was large enough to allow water movement through the perforations while protecting seeds from predation. At each location, a PVC cylinder was deployed and maintained at a submergence depth of 60 cm. This depth, approximately that of irrigation intakes, was achieved using a buoy attached to the lid. A weighted anchor was attached to the bottom of the PVC cylinder by nautical rope to keep it in the desired location.

One seed bundle, containing 200 seeds of each species, was collected from each location 7, 15, 21, 30, 60, 90, 120, 240, and 360 days after submergence (DAS). Note: for the 120 DAS winter one collection, seeds were collected 135 DAS due to COVID-19 restrictions that did not allow in-person site visitation at 120 DAS. The authors believe the 15-day difference in collection dates was inconsequential, thus all data were analyzed and presented assuming a 120-day submergence. Seed bags were separated from the bundles, rinsed for 60 seconds in tap water, surface-sterilized with 0.6% NaOCl + 1 drop of dishwashing liquid (Dawn Original, The Procter & Gamble Company, 1 P&G Plaza Cincinnati, OH) for 30 seconds, then rinsed for 30 seconds with tap water to remove NaOCl. Four sub-samples of 50 seeds each were placed in Petri dishes double lined with filter paper saturated with distilled water. Additional distilled water was added as needed to keep the filter paper moist for the duration of the germination period. The seeded Petri dishes were placed in one of two germination chamber environments: 35/25 °C day/night temperatures for spotted spurge and eclipta, or 23/13 °C day/night temperatures for flexuous bittercress and yellow woodsorrel. Higher temperatures in the chambers were synchronous with a 14-hour photoperiod. The different temperature regimens were selected to optimize germination based upon prior studies with these and related species (Altom et al.1996, Andersen 1968, Asgarpour et al. 2015, Kimata 1983). Seeds from the lots used for seed bundles were held in cold storage at 3 °C and were added to each germination test to serve as a control to test for natural changes in seed germination independent of submergence and to confirm germination conditions. Germination was recorded every 5 days for 30 days after placement in germination chambers. Seeds were recorded as germinated when the radical, hypocotyl, and cotyledons reached 1 mm in length, and were removed after counting. Percent germination was calculated for each Petri dish.

To isolate the effects of submergence on seed germination from natural declines in viability over time, control seed germination rates were used as a covariate in the analysis of submerged seed germination. The resulting adjusted LSMEANS for percent germination of submerged seeds were utilized for all subsequent analyses and are referred to as percent germination hereafter. Seed germination data were subjected to analysis of variance using a mixed model (Proc GLMMIX) and linear regression models (REML – TYPE 3) in SAS 9.4 (SAS Institute Inc., Cary NC). Year, season, species, and days after submersion (DAS) were treated as fixed effects. Replication of ponds within each location was not possible. Therefore, when testing for differences among locations the four 50-seed petri dish sub-samples of each seed germination test were treated as replicates. The resulting error term used to test location effects was 'year*season*DAS*replicate'. Due to the high number of parameters within the error term, a p-value of < 0.01 was used to indicate significance for all main effects and interactions.
For regression analyses examining the effect of DAS on germination, data were transformed to percent germination relative to the control seed germination for each species using Equation 1.

Equation 1. $$\% \, germination = 100 * \frac{\text{observed germination}}{\text{control seed germination}}$$

This conversion allows the isolation of submergence effects on seed germination from natural declines in germination over time. Graphs of percent germination over time were generated using Microsoft Excel (Microsoft Corporation 2021).

Results and Discussion

Weed seed buoyancy

Species were categorized as non-buoyant, semi-buoyant, buoyant, and super-buoyant based on the Tukey means separations of buoyancy at 7 days and categories in Shi et al. (2020). Nine weed species had less than 10% seeds floating after 7 days and were classified as non-buoyant (Table 1). These were: redroot pigweed, spotted spurge, common groundsel, large crabgrass, fringed willowherb, American burnweed, flexuous bittercress, livid amaranth, and yellow woodsorrel. Of those nine species, redroot pigweed, fringed willowherb, flexuous bittercress, livid amaranth and yellow woodsorrel had less than 16% of seed floating after one day. Yellow woodsorrel was the only species to have 100% of the seed settled at 7 days, and only 1% buoyancy at one day (Table 1).

Dogfennel and rice flatsedge were classified as semi-buoyant with 47% and 54% buoyancy, respectively. Dogfennel and common groundsel seeds with attached pappus were 72% and 82% buoyant, respectively, and categorized as buoyant. Eclipta and marsh yellowcress seeds were 100% and 99% buoyant, respectively, and were categorized as super-buoyant (Table 1). Our results are consistent with those of Shi et al. (2020) who reported eclipta seeds floated and redroot pigweed seeds sank when the water surface was disturbed.

The presence of a pappus increased seed buoyance for dogfennel and common groundsel (Table 2). There was an interaction between experimental repetitions and pappus presence for dogfennel, but not for common groundsel. Therefore, data for the two repetitions with dogfennel are presented separately, but for groundsel the data are combined (Table 2). The buoyance of common groundsel seeds with pappus attached was 89% after one day in water and 82% at seven days. In contrast, buoyancy of seeds without a pappus was 36 % and 8% after one and seven days, respectively. The presence of pappus also increased dogfennel seed buoyancy at seven days by 20% to 30% compared to seeds without the pappus. The difference in buoyance for common groundsel seeds was great enough to categorize the species as non-buoyant without pappus but buoyant with pappus (Table 1). Dogfennel was categorized as semi-buoyant without pappus and buoyant with pappus. These data are consistent with prior reports of higher seed buoyancy attributed to the presence of specialized appendages such as a pappus (Fryirs et al. 2022).

Seed submergence and viability

The germination of control (refrigerated) seed lots decreased over time. Control seed lots of flexuous bittercress and spotted spurge displayed a slight, linear loss of germination over time Figure 1A). The rate of decline in seed germination for yellow woodsorrel best fit a log function, with a more rapid decline up to about 90 days and a more gradual rate of decline thereafter (Figure 1A). The eclipta seed lot one used for the winter one repetition had overall low germination rates. For this seed lot germination declined rapidly up to about 90 days with a slight linear decline thereafter (Figure 1B). Eclipta seed lot two, used for all other deployments, germinated at over 90% throughout the study with very little decline in germination over time (Figure 1B).

The main effect of species and interactions between species and all other variables were significant ($p<0.001$); therefore, data were analyzed and are presented by species. Although differences among locations were statistically significant, the trends in the data were consistent and the differences were inconsequential in relation to the overall objective of determining whether seeds persist long enough in water to be of concern to nurseries. Therefore, to test for differences between seasons, years, and days after submergence (DAS), the error terms for locations were pooled for hypothesis testing.

Significant differences were observed for days after submergence for each species (Table 3). Germination for all species declined over time but the rate of decline differed. Seeds of all tested species germinated for at least 240 days after submergence in both years, seasons and all locations (Figures 2A-D). Eclipta, flexuous bittercress, and spotted spurge maintained some germination for 360 days, supporting Wilson's (1978) research concluding seeds of annual dicot weed species germinated after long periods of submergence in water.

Flexuous bittercress

Flexuous bittercress maintained greater than 80% germination following 360 days of submergence in three of four locations for both seasons and years. Decline in germination was gradual and linear for both years and seasons (Figure 2A). There was no significant seasonal effect, $p = 0.3178$ (Table 3), suggesting the survival of bittercress seed in irrigation ponds is not affected by the time of year the seed enters the pond.

Yellow woodsorrel

Germination of yellow woodsorrel declined rapidly from the first collection at 7 DAS until 120 DAS, after which the rate of decline in germination was more gradual (Figure 2B). There was a significant seasonal effect, $p = 0.0017$, where seeds submerged in the winter maintained greater than 50% germination up to 90 DAS compared to less than 20% for summer deployed seeds. This suggests that yellow woodsorrel seeds may have greater survival in water during cool seasons. Seed germination declined to less than 15% following 240 days of submergence in both seasons, and less than 5% after 360 days of submergence in 3 out of 4 locations.

Eclipta

Seeds submerged in winter one had lower than expected germination in both the submerged seeds and control seeds. Previous eclipta seed collections by the authors had achieved nearly 100% germination. Therefore, for remaining deployments we selected a different seed lot with higher germination rates. Despite differences in initial germination rates, the decline in germination of seeds submerged in winter one follows the same trend as those deployed in other seasons and years using the second seed lot (Figure 2C). Eclipta seeds maintained high percentages of germination after 360 days of submergence in water. Decline in germination over time was gradual and linear for seed lot 2. For seed lot one, the decline in germination over time was best described by a log function but a low R2 indicated a poor fit for the regression equation.

Spotted spurge

Spotted spurge germination declined over time following a log-function (Figure 2D). A sharp decline in germination occurred between 7 DAS and 90 DAS. At 90 DAS spotted spurge seed germination was greater than 50% in 3 out of 4 deployments. There was a significant year by season interaction (Table 3) reflecting that the rate of decline in seed germination appears to have been greater for summer one, compared to the three other seed deployments. However, after 360 days submerged in ponds, seed germination was greater than 15%. In contrast, Asgarpour et al. (2015) reported that spotted spurge germination declined rapidly after submergence in water with no germination recorded after 63 days. Reasons for differences between their results and our present study are unknown. There was no significant seasonal effect (Table 3) suggesting the survivability is not affected by the time of year the seed enters the pond.

Individually, seed buoyancy and seed survival in water could increase the probability that weed seeds may be present in irrigation water. However, species with a combination of buoyancy and persistence in water should have much greater potential for spread in irrigation water. The current study demonstrates that seeds of several common nursery weeds, including eclipta, common groundsel, dogfennel and rice flatsedge are buoyant and thus have the potential to enter and remain suspended in irrigation ponds. Furthermore, seeds of eclipta, flexuous bittercress, yellow woodsorrel, and spotted spurge maintained some germination after 270 or more days of submergence in water. Eclipta seeds were buoyant and maintained high levels of germination for 360 days. In contrast, flexuous bittercress maintained high levels of germination for 360 DAS but were non-buoyant suggesting seeds of that species would have a lower probability of remaining in the irrigation water column long enough to be dispersed. Yellow woodsorrel seeds were non-buoyant and germination declined significantly after submergence in water suggesting that this species would have low potential for spread in irrigation water. Although non-buoyant seeds are ineffectively dispersed by flowing water (Andersson et al. 2000), there is increased potential for non-buoyant seeds to be transported via water during heavy rain events when caught in debris being transported (Xiong and Nilsson 1997). During such an event, it may be possible for seeds with lower buoyance, such as yellow woodsorrel and spotted spurge, to be transported and deposited into an irrigation pond. Due to yellow woodsorrel's rapid sinking, it is highly unlikely that seed would be available for dispersal via irrigation water as it would sink upon being deposited into the irrigation pond. In contrast, there may be a short window of time where viable spotted spurge seed is deposited into an irrigation pond, suspended in the water column, and has some potential to be taken up with irrigation water and disseminated across production areas.

Practical implications

Weed seed survivability in irrigation water alone doesn't indicate potential for that seed to be disseminated via irrigation. Seeds of some important nursery weed species, like spotted spurge, remained viable after 360 DAS, but have low buoyancy. Due to this seed trait, the risk of spotted spurge seed being both viable and suspended in the water column for irrigation uptake is lower than eclipta which displays high seed buoyancy and long persistence in water.

Adopting weed management practices that control weeds along irrigation pond edges and run-off pathways, especially those species with high buoyancy and survivability in water, would reduce the number of seeds transported and deposited into surface irrigation ponds. Preventing the transport of weed seeds into irrigation ponds would decrease the concentration of weed seeds suspended in the water and thereby reduce the potential for weed seed spread via irrigation. Additionally, ponds designed with long flow paths between runoff deposits and irrigation inlet pipes increase the opportunity for suspended solids, which may include weed seeds, to settle out before being drawn into the irrigation system (Yazdi et al 2021). Nursery producers including elements such as long flow paths in their irrigation pond designs may reduce weed seed uptake into the irrigation. However, further research is needed to determine if these assumptions about the relationship between buoyancy and survival while submerged and distribution via irrigation systems are valid. And, if so, are the numbers of seeds dispersed via irrigation significant compared to other potential sources of weed seed spread.

Acknowledgments

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Tables

Table 1.1. Percent (%) buoyancy of common weed seeds following seven days in water, and buoyancy categorical ranking.

Species	Seed appendage	% Buoyant[a] 1 day		% Buoyant[a] 7 days		Buoyancy category[b]
eclipta	none	100	a	100	a	super-buoyant
marsh yellowcress	none	100	a	99	a	super-buoyant
common groundsel	pappus	89	abc	82	b	buoyant
dogfennel	pappus	96	ab	72	b	buoyant
rice flatsedge	none	64	d	54	c	semi-buoyant
dogfennel	none	78	bcd	47	c	semi-buoyant
redroot pigweed	none	15	f	9	d	non-buoyant
spotted spurge	none	41	e	9	d	non-buoyant
common groundsel	none	36	e	8	d	non-buoyant
large crabgrass	none	36	e	7	d	non-buoyant
fringed willowherb	none	16	f	7	d	non-buoyant
American burnweed	none	74	cd	3	d	non-buoyant
flexuous bittercress	none	9	f	2	d	non-buoyant
livid amaranth	none	11	f	1	d	non-buoyant
yellow woodsorrel	none	1	f	0	d	non-buoyant

[a]Analysis of variance indicated no difference between repetitions of the experiment; data presented are averages of the two repetitions. Means within a column followed by the same letter were not significantly different based upon Tukey means separation procedures with $\alpha=0.05$.

[b]Buoyancy categories based upon Tukey means separations of % buoyancy at 7 days and modeled after defined categories in Shi et al (2020).

Table 1.2. Effects of pappus on seed buoyancy of dogfennel and common groundsel.

Pappus +/-	Dogfennel		Common groundsel
	Repetition 1	Repetition 2	Average[a]
	------------------------------%--------------------------------		
With pappus	60	84	82
Pappus removed	42	52	8
	---------------------*P*-values for F-tests----------------------		
ANOVA			
Pappus	<0.0001		<0.0001
Repetition	0.0003		0.6482
Pappus x repetition	0.0748		0.6482

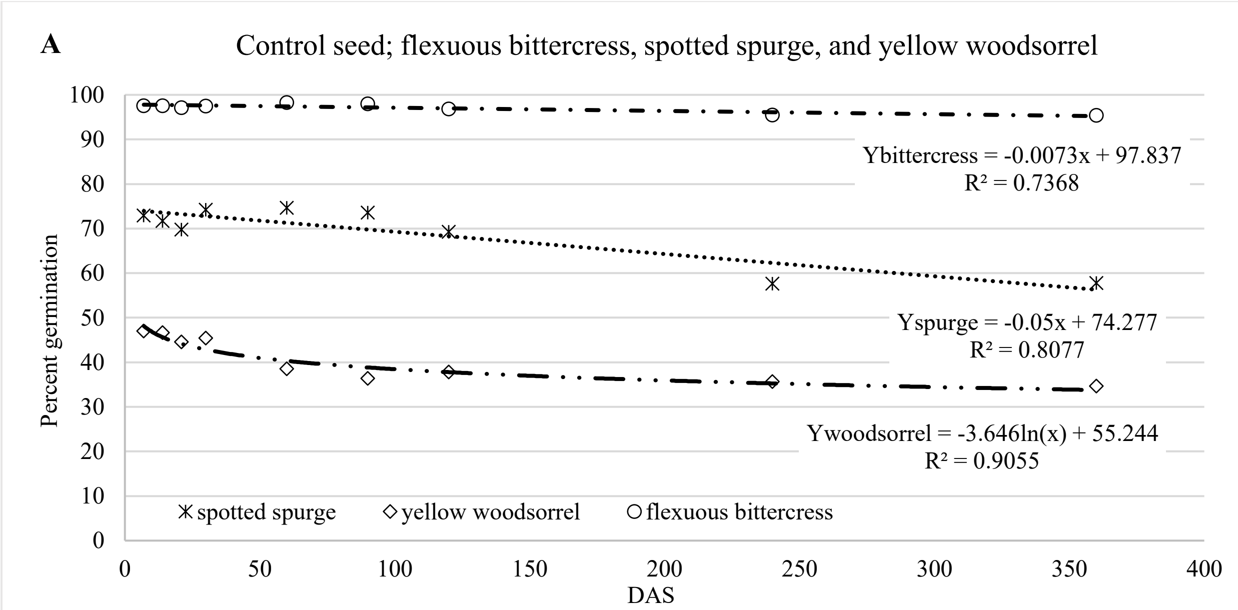
[a]For common groundsel there were no significant differences between repetitions of the experiment, therefore the average of the two repetitions is presented.

Table 1.3. Analysis of variance for main effects and interactions for percent germination of weeds submerged in irrigation ponds. Seeds were deployed in winter and summer, in two years, at each of four locations in North Carolina. Seeds were extracted and germination tested 7, 15, 21, 30, 60, 90, 120, 240, and 360 days after submergence (DAS).

Effects	spotted spurge	eclipta	yellow woodsorrel	flexuous bittercress
season (winter vs. summer)	NS[a]	<0.0001	0.0017	NS
year	<0.0001	<0.0001	<0.0001	NS
location	<0.0001	<0.0001	0.0002	<0.0001
DAS	<0.0001	<0.0001	<0.0001	<0.0001
year*location	NS	0.005	<0.0001	<0.0001
season*year	0.0017	<0.0001	NS	<0.0001
season*location	<0.0001	0.0003	0.0013	0.0004
DAS*year	<0.0001	0.0003	<0.0001	<0.0001
DAS*season	<0.0001	<0.0001	<0.0001	<0.0001
DAS*location	<0.0001	<0.0001	<0.0001	<0.0001

[a]NS, not significant. On the advice of a consulting statistician, comparisons with p-values greater than 0.01 were deemed not significant because the number of variables in the model contributed to very high degrees of freedom for tests.

Figures



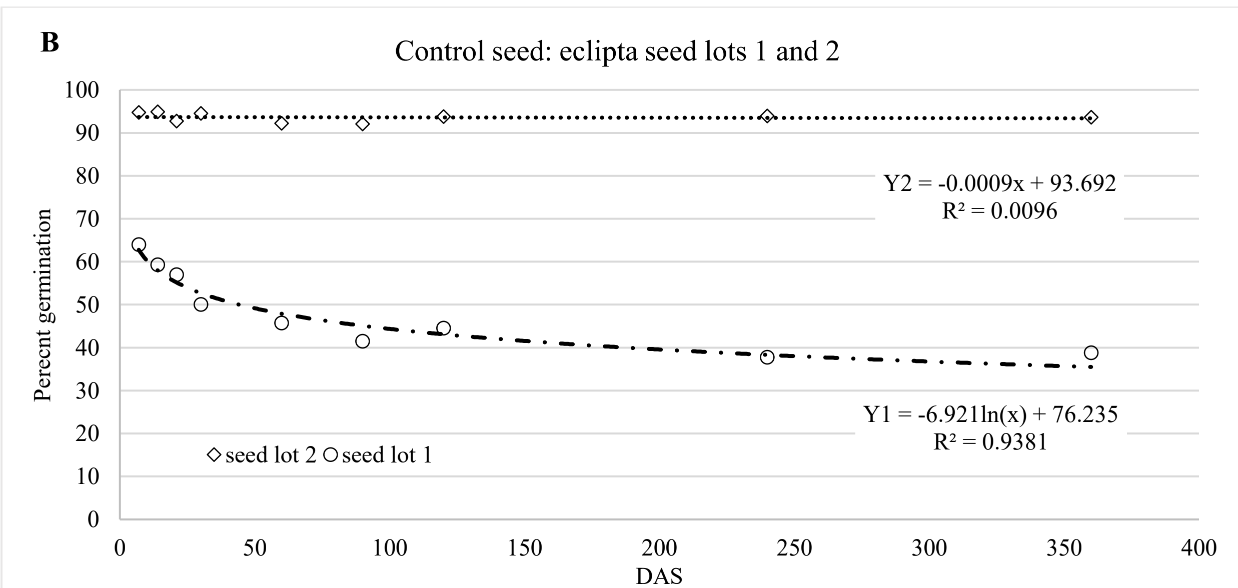
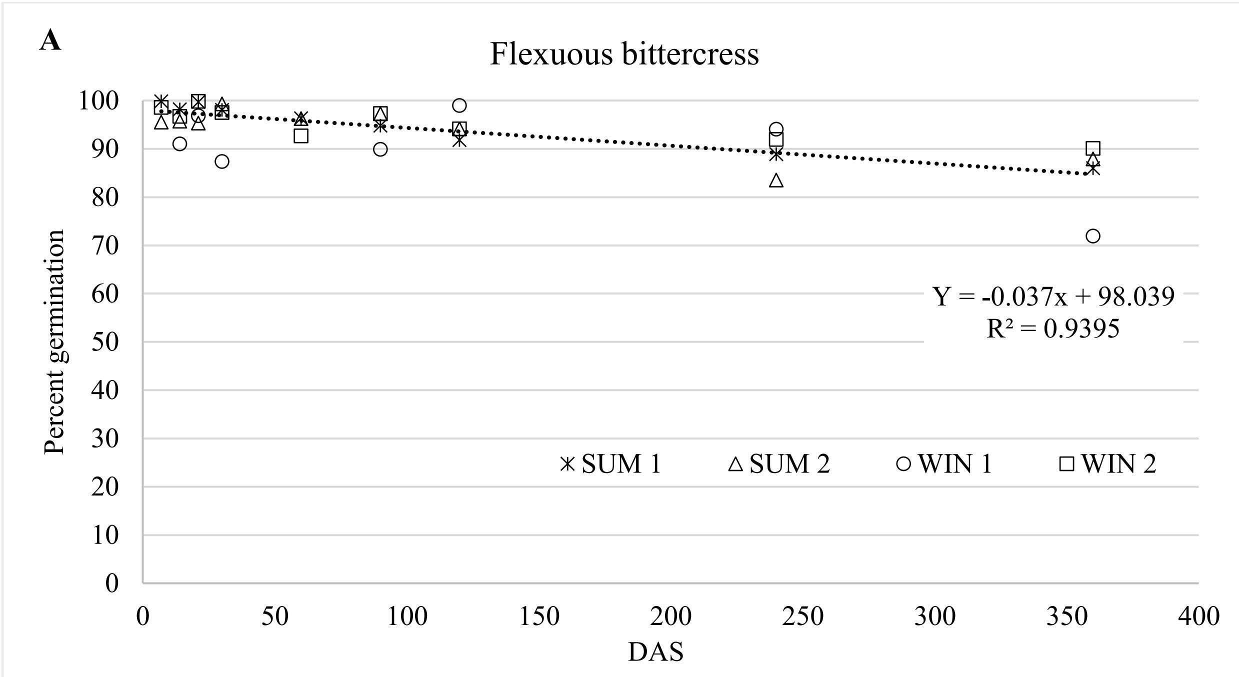
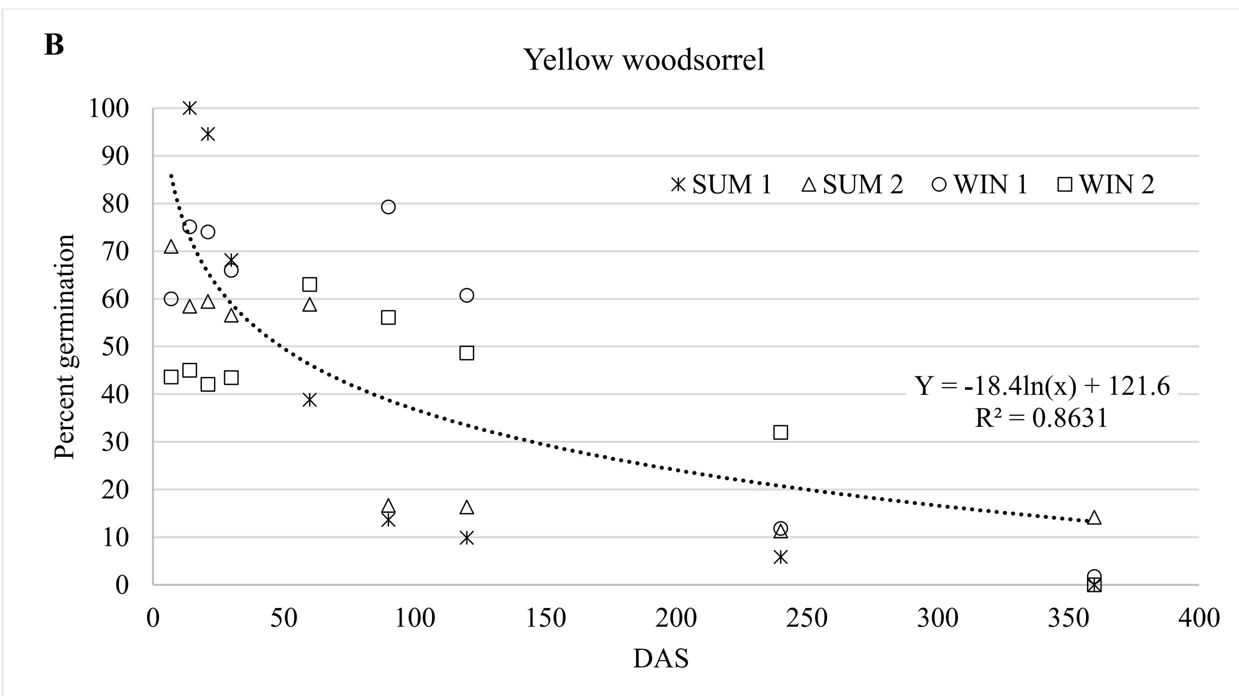
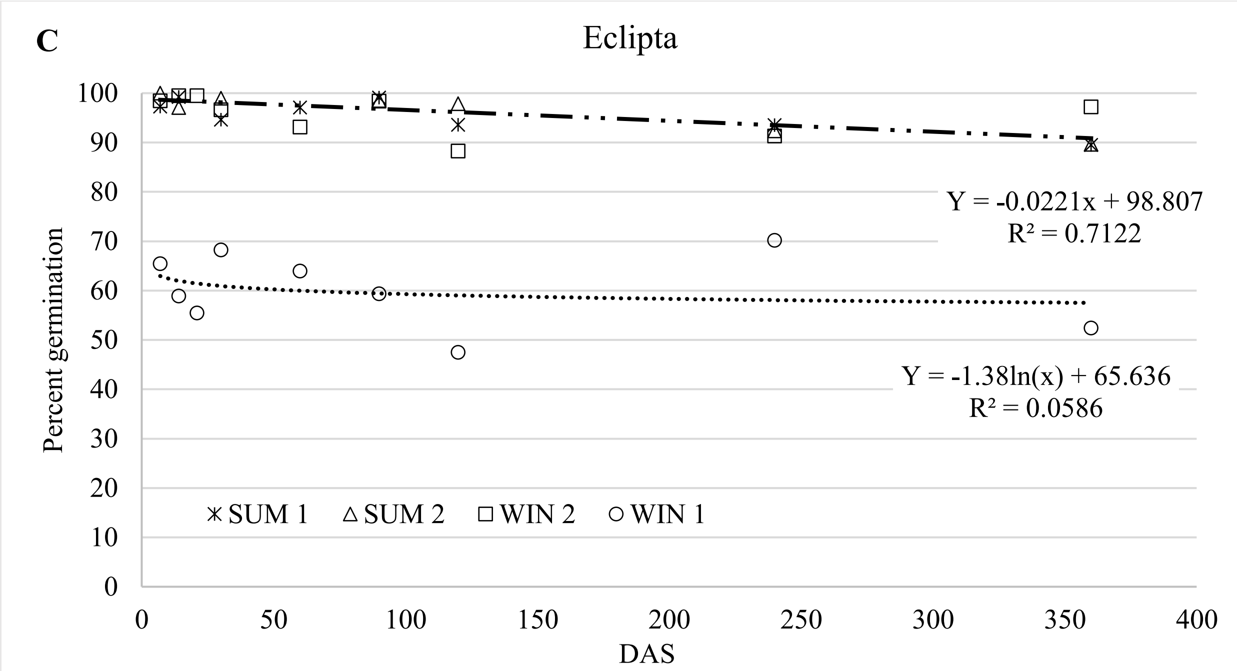


Figure 1.1. Percent germination of control seeds for each species following 7, 15, 21, 30, 60, 90, 120, 240 and 360 days in cold storage. A) flexuous bittercress, spotted spurge, and yellow woodsorrel, and B) eclipta, seed lots 1 and 2. The regression lines are for the averages of all tested control seed except for eclipta where the first seed lot had overall low germination and was replaced by seed lot 2, with higher germination, for all subsequent tests. Therefore, separate regression lines are presented for eclipta seed lots 1 and 2.

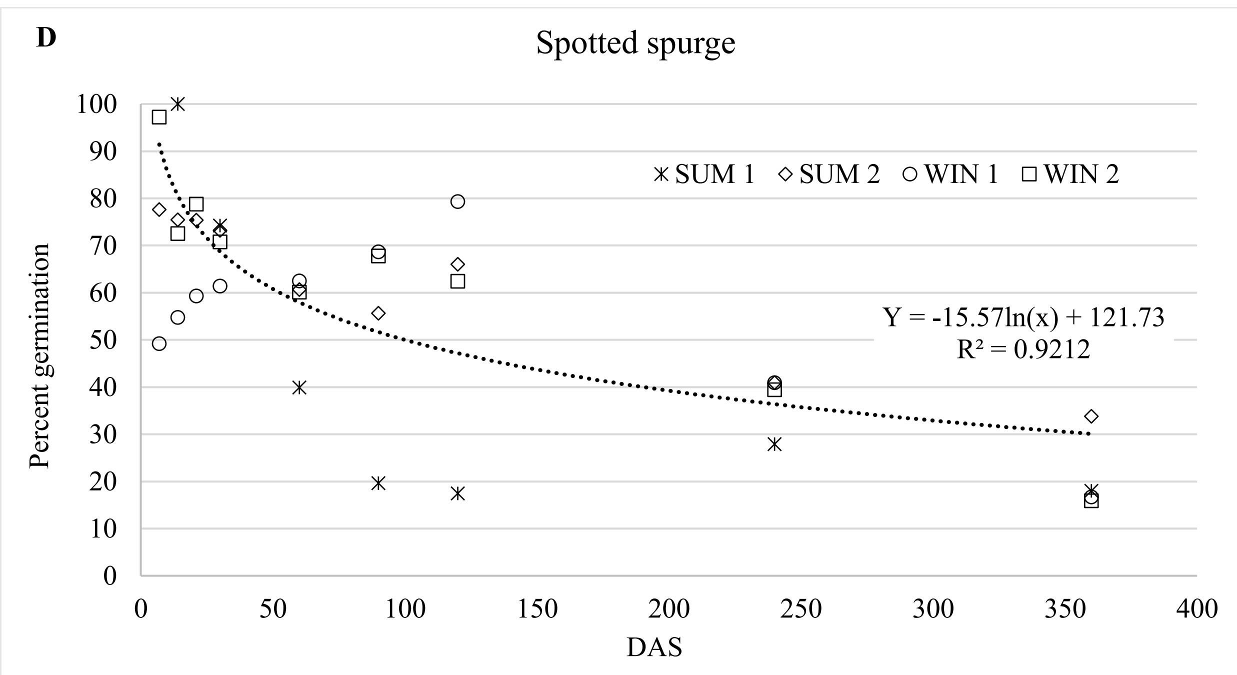
Figure 1.2. Percent germination for each species following 7, 15, 21, 30, 60, 90, 120, 240, and 360 days after submergence (DAS). A) flexuous bittercress, B) yellow woodsorrel, C) eclipta, and D) spotted spurge. SUM 1, SUM 2, WIN 1, and WIN 2 are abbreviations for the four seed deployments in summer year one, summer year two, winter year one, and winter year two, respectively. The regression lines are for the averages of all deployments except for eclipta where the first seed lot used had overall low germination and was replaced by another seed lot with higher germination for all subsequent tests. The regression lines for each seed lot are presented.


A
Flexuous bittercress
Percent germination
DAS
Y = -0.037x + 98.039
R² = 0.9395
SUM 1
SUM 2
WIN 1
WIN 2
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400


B
Yellow woodsorrel
Percent germination
DAS
Y = -18.4ln(x) + 121.6
R² = 0.8631
SUM 1
SUM 2
WIN 1
WIN 2
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400



C
Eclipta
Percent germination
DAS
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
Y = -0.0221x + 98.807
R² = 0.7122
Y = -1.38ln(x) + 65.636
R² = 0.0586
SUM 1
SUM 2
WIN 2
WIN 1



D
Spotted spurge
Percent germination
DAS
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
SUM 1
SUM 2
WIN 1
WIN 2
Y = -15.57ln(x) + 121.73
R² = 0.9212

Chapter 2
Assessing the Presence of Weed Seeds in Surface Irrigation Water in Container Nurseries

(In the format appropriate for submission to Weed Technology)

Abstract

Nursery crop producers in the Southeastern U.S. use open ponds of captured source water for irrigating container-grown plants, often without filtration. Many growers perceive irrigation water as a source of weed seed dispersal, but data on the presence of weed seeds in nursery irrigation ponds are lacking. The presence and diversity of viable weed seeds in irrigation pond water samples from six commercial container nurseries in central and eastern North Carolina, U.S. were documented in the spring, summer, and late-summer for two consecutive years. Irrigation pond water was filtered, in 75,708-L (20,000-gal) increments, using a custom-fabricated filtration system. The sample volume was chosen to approximate 0.75 acre-in (19 mm) of daily irrigation for one acre of nursery production. A total of 216 filtrate samples were collected, six for each location, season and year. Filtrates were spread on soilless substrate in plastic trays and seedling emergence was recorded every 7 days for 12 weeks. Irrigation samples from all locations, seasons, and years contained viable seeds. The average number of seeds collected at each location ranged from 9 to 35 per sample. Averaged across years and locations, there were 12.5, 24.8, and 18.2 germinable seeds in spring, summer, and late-summer samples, respectively. A total of 75 different taxa were present in the irrigation filtrates including 28 weed species common to container nurseries. Some common weed species, such as eclipta, marsh yellowcress, large crabgrass, flexuous bittercress and spotted spurge, were present in samples from each season's collections, while other species were unique to a single season. Although irrigation water introduced weed seeds, the number of weed seeds was small compared to other potential sources of weed seed dispersal within the nursery environment.

Nomenclature:

eclipta, *Eclipta prostrata* L.; flexuous bittercress, *Cardamine flexuosa* With.; large crabgrass, *Digitaria sanguinalis* (L.) Scop.; marsh yellowcress, *Rorippa palustris* (L.) Besser; spotted spurge, *Euphorbia maculata* L.

Keywords hydrochory; nursery crops; seed dispersal; weed seeds

Introduction

Weeds are prevalent pests in container nursery crop production resulting in high management costs and reduced marketability (Case et al. 2005). To prevent losses from weed competition, growers routinely apply preemergence herbicides every six to eight weeks, but weeds continue to emerge (Gilliam et al. 1992, Neal et al. 2017). In these crops postemergence control options are limited necessitating substantial reliance on hand weeding (Neal et al. 2017, Stewart et al. 2017). Annual costs for hand weeding were estimated in 2003 to be as much as $9,800 per ha (Mathers 2003). According to a 2023 industry survey, 59% of growers reported that labor costs and availability are their greatest business concern (McClellan 2024). Identifying and understanding the sources of weed seed contamination and spread could allow growers to implement effective prevention strategies and lessen weed management costs.

Limited research has been conducted to identify weed seed sources in container nurseries. The most recognized weed seed sources include contaminated transplants, weed seeds carried over to new crops in unwashed and reused containers, and dispersal from nearby plants (Neal 2016, Bachman and Whitwell 1995, Cross and Skroch 1994). Occasionally bark-based potting substrates have been contaminated with weed seeds (Neal, personal observation), they are generally weed free (Cross and Skroch 1994). Each of the other seed sources listed above can be managed with available management strategies and tools; however, weeds continue to emerge in containers. While nursery crop producers perceive overhead irrigation systems as a potential vector for weed seed dispersal (authors' personal communications), little is known of the importance of surface irrigation ponds as a weed seed source within container nurseries. Reports on the presence of weed seeds in nursery irrigation are limited to a single study in which researchers sampled a total of about 18,900 L (5,000-gal) of irrigation water from ponds and natural streams at five nurseries, and found only 3 weed seeds, which were not tested for germinability (Williams and Saunders 1984). Container nursery crop producers in the Southeastern U.S. apply about 0.75 acre-in (19 mm) of irrigation water per acre daily to container grown nursery crops, equivalent to about 187,000 L ha-1 (20,000-gal A-1) per day (Fare et al. 1992). Using these values, we can extrapolate that about 12 weed seeds would be distributed per acre per day. These data have not been independently confirmed. Furthermore, the sample size at each location was about 25% of daily irrigation for one acre, likely too small to draw strong conclusions about irrigation water as a source of weed seeds in container nurseries.

In other agricultural systems, such as rice-wheat cropping fields, water has been reported to be an important vector of weed seed dissemination (Zhang et al. 2019). The most prevalent weeds in these systems have highly buoyant seeds that are more effectively transported via hydrochory and deposited into source water through runoff (Li and Quang 2009, Merrit et al. 2006, Shi et al. 2020). Like those weed species in rice-wheat cropping systems, seeds of several container nursery weeds, including eclipta, common groundsel (*Senecio vulgaris* L.), marsh yellowcress (*Rorippa palustris* (L.) Bess), and rice flatsedge (*Cyperus iria* L.), are buoyant (Ray et al. 2025). Additionally, seeds of several common nursery weeds, including eclipta, flexuous bittercress, and spotted spurge, germinated after being submerged for up to one year in source water contained in ponds that was used for irrigation (Ray et al. 2025). Considering that seeds of several common container nursery weed species share traits of buoyancy and year-long viability in water with species disseminated via irrigation water in agricultural systems, it is plausible that viable seeds in source water could reach intake pipes and be disseminated across container production areas via overhead impact sprinkler systems used for irrigation. Therefore, this experiment was conducted to document the number of germinable weed seeds and the diversity of species in irrigation source water drawn from surface ponds, and to evaluate the significance of irrigation water as a source of weed seed contamination in container nurseries.

Materials and Methods

The presence and diversity of viable weed seeds in irrigation water was determined by conducting experiments over two consecutive years, at six commercial container nurseries located in central and southeastern North Carolina. Nurseries were selected to represent a range of historical weed population densities, based on the principal investigator's personal observations, and accessibility to the irrigation ponds (Table 1). Additionally, source water contained in ponds for reuse, remediation, or storage is common among nurseries in North Carolina to increase water quality and prevent water shortage during drought. At all locations, production runoff as well as ambient rainfall was returned to the irrigation pond via a series of culverts or drainage ditches. Pond edge characteristics varied, encompassing riprap, managed vegetation, and unmanaged natural vegetation. Vegetation, including common nursery weeds, was observed at the pond edges of all nurseries, although the frequency of common nursery weeds was reduced at one site that routinely mowed the pond edges. Detailed descriptions of pond surroundings, drainage ditches, and maintenance practices for each location are provided in Table 1.

Source water used for irrigation contained in ponds at each location was filtered through three LP Disc-Kleen filters (Netafim USA, Fresno, CA). The filtration system components were mounted to a single-axle (3500 lb. capacity) pull behind trailer for transportation to locations (Gra-Mac Irrigation, Farmington, NC). A gas powered water pump (Honda GX240 American Honda Motor Company, Inc. Torrance, CA) drew water through a 4.6 m long, 7.6 cm diameter spiral wire hydraulic hose with a cylindrical strainer basket that excluded anything greater than 1.3 cm diameter. The intake strainer was positioned near the nursery irrigation intakes at a depth of 60 cm and held in place with an attached anchor and buoy. Filtered water was discharged via a 7.6 m long, 7.6 cm diameter lay-flat PVC hose placed as far from the intake hose as possible to minimize water disturbance near the intake. The system was equipped with a back-flow flush that was manually engaged at 75,708-L (20,000-gal) intervals, approximating the daily irrigation amount for one acre of container nursery crops (Fare et al. 1992). Back-flow water from the filters was then screened through a series of sieves and weed seeds were collected in 355 µm-mesh sieves (Avantech Manufacturing, Mentor, OH), a mesh opening smaller than the diameter of most common nursery weed seeds of ~1000 µm (Neal et al. 2023). Six 75,708-L (0.75 ac-in) samples were filtered at each location in spring, summer, and late-summer for two years. In total, over 15 million L (4 million gal) of water was filtered and 216 filtrate samples were collected. The filtration system was back-flow flushed between each sample collection to ensure no seed contamination carried from previous samples. Each 0.75 ac-in sample required over two hours to filter, necessitating two days to collect six samples. Samples collected on the first day were designated A, B, and C; the second day samples were D, E, and F. The exact volume of water filtered with each sample was recorded using an in-line flow meter (Gra-Mac Irrigation). Each filtrate sample was placed in 150-µm mesh nylon bag, labeled and transported to the NC State University Horticultural Field Lab in Raleigh, NC (35.79159°N, -78.69389°W). Filtrate samples were spread onto the surfaces of 28 x 53 cm plastic trays (T.O. Plastics, Clearwater, MN) filled with a commercial bagged potting mix (Jolly Gardener Pro-Line C/P growing mix, Oldcastle Lawn & Garden, Atlanta, GA) amended with 3.6 kg/m^3 of 18N-1.75P-6.6K controlled release fertilizer (CRF) (Harrell's 18N-4P_2O_5-8K_2O, Harrell's LLC, Sylacauga, AL) then hand watered with municipal tap water. Trays were placed onto benches in a weed-free, polyethylene covered hoop house, and irrigated daily with municipal tap water via an overhead irrigation system. To confirm weed-free conditions, control trays of potting mix were included with no irrigation filtrates yet irrigated similarly with each germination test. No seedlings were observed in the control trays, thus no data for these trays are presented. Bottom heat was provided as needed to maintain soil temperatures above 15 C, adequate for germination of common nursery weed species (Asgarpour et al. 2015, Holt 1987, Andersen 1968). Trays were treated with an azoxystrobin drench (Heritage, 2.83 g ai / 378 L^{-1}, Syngenta, Greensboro, NC) to minimize seedling losses due to disease. Emerged seedlings were counted weekly for 12 weeks, identified to species, and removed after each count. Unidentified seedlings were transplanted into containers and grown to maturity for identification.

Actual source water sample volumes ranged from 75,708 L to 77,601 L. Seedling counts were adjusted to reflect the number of germinable seeds per 75,708 L using equation 1. These adjusted values were used in all statistical analyses.

Equation 1. $$\frac{\text{observed germination}}{\text{actual volume}} = \frac{\text{germinable seeds}}{\text{75,708 L}}$$

Example: $$\frac{\text{10.0 seeds}}{\text{77,250 L}} = \frac{\text{9.8 seeds}}{\text{75,708 L}}$$

We acknowledge that there could be a small number of dormant weed seeds within the samples that could not be counted using the methods employed. However, the authors submit that seeds that did not germinate within 12 weeks of placement in conditions suitable for germination would have a minimal effect on overall weed populations in the nursery.

The standard units of measure for irrigation in container nurseries in the Southeastern U.S. are inches per acre or gallons per acre, the experiments were conducted and are reported herein using these standard units. From this point forward we will refer to the number of seedlings counted in germination tests as the number of germinable seeds per 0.75 ac-in (4.6 cm ha^{-1}) (19 mm ac^{-1}) of irrigation. To convert from seeds per acre to seeds per hectare, multiply by 2.47.

Data were analyzed using a full factorial ANOVA in SAS 9.4 (PROC GLIMX, SAS Institute, Cary, NC) with year, season, and location as fixed effects and germinable seed count as a random effect. The number of germinable seeds is presented as predicted means (LSMEANS) and mean comparisons for main effects were performed using a Tukey HSD test at α=0.05. Due to insufficient numbers of individual species across all years and locations seedling counts for all species were combined for analysis.

Weed population scouting

Crops were scouted for weed populations at each filtration collection. A newly potted crop was selected within a production block irrigated by the collection pond. Due to labor constraints, individual weed counts were impractical. Instead, the number of containers infested with individual weed species were counted and converted to percent frequency. Despite the researchers' efforts to coordinate these weed frequency counts with growers, labor crews often removed weeds before our arrival. Furthermore, three locations changed their weed management practices midway through this study, increasing hand weeding frequency. Data from the three impacted locations were omitted from this analysis. Weed scouting at three locations were considered by the authors to be sufficiently complete for presentation and analysis. Pearson correlation coefficients were calculated (JMP 18, SAS Institute, Cary, NC) to assess the relationship between weed species frequencies in containers versus the number of seeds present in irrigation samples. Bivariate linear regression plots with 95% confidence intervals were generated using the 'Fit y by X' function in JMP 18. Falsely high correlations occurred when many species with rare occurrences in frequencies and irrigation filtrates were included in the analysis. To reduce the likelihood of false correlation only the top 10 weed species present in each dataset were used in correlation analyses.

Results and Discussion

Species diversity

Germinable seeds were found in irrigation water samples from all locations, seasons, and years. A total of 75 taxa were present in the irrigation filtrates (Table 3), including 28 species that are known to be common weeds in container nurseries (Neal and Derr 2005, Neal et al. 2023) and were present in crop scouting reports (Figure 2). Among the ten most abundant species, six are common weeds in container nurseries: eclipta, anglestem primrose-willow (*Ludwigia leptocarpa* (Nutt.) H. Hara), common chickweed (*Stellaria media* (L.) Vill.), marsh yellowcress, spotted spurge, and large crabgrass (*Digitaria sanguinalis* (L.) Scop.). Four of the ten most abundant species, forked rush (*Juncus dichotomus* Elliot), vaseygrass (*Paspalum urillei* Steud.), Japanese stiltgrass (*Microstegium vimineum* (Trin.) A. Camus), and smallspike false nettle (*Boehmeria cylindrica* (L.) Sw.), have not been reported as weeds of container nurseries and were absent in surveys of the crops at these study locations. Forked rush was present at the irrigation pond edge at one location; vaseygrass was observed on the banks of the ponds at three locations; Japanese stiltgrass was observed on the pond edge at one location and in high populations at the nursery border at one location; and smallspike false nettle was present at two locations (Table 1). The presence of Japanese stiltgrass in irrigation water supports previous reports of dispersal of this species by hydrochory (Tekiela and Barney 2013, Eschtruth and Battles 2011). The absence of these four species in container crops suggests that nursery conditions or management practices may limit their establishment and survival within the crops.

Location and seasonal effects on seed numbers

The species present was highly variable among locations and seasons; thus, it was not possible to statistically compare seasonal or location differences at the species level, instead the total number of germinable seeds were compared. Germinable seeds were present in all filtrate samples, but all main effects of location, season, and years, as well as all two-way interactions were significant (Table 2).

Summer collections had the highest number of taxa, 52, while spring and fall collections had 40 and 43 taxa, respectively (Table 3). Seasonal seed shedding patterns were reflected in some species; for example, black willow (*Salix nigra* Marshall) seeds are shed in the spring (Neal et al. 2023) and was only present in irrigation filtrates collected in the spring season (Table 3). Other species were present in irrigation filtrates even when mature plants were not present in the nursery. Marsh yellowcress and low cudweed (*Gnaphalium uliginosum* L.) which shed seeds from spring to late summer, were present in irrigation samples from all seasons. Similarly, eclipta, horseweed, and spotted spurge seeds were present in irrigation samples from all seasons despite shedding seeds summer through autumn (Neal et al. 2023). These data support previous findings by Kelley and Bruns (1975) where certain seeds present in irrigation water of canal fed farmlands peaked when mature plants of that species were present in the environment, but for many species these peaks were not prevalent or well defined. This suggests that seeds of some species can persist in irrigation water and remain available for intake into the irrigation system. In prior studies, eclipta seeds maintained high germination after being submerged in irrigation ponds for 360 days and are highly buoyant (Ray et al. 2025), traits that are reported to increase hydrochory (Shi et al. 2020).

Rain events impact on seed presence in irrigation samples

Heavy rain occurred during two sub-sample collections, each dramatically increasing weed seed collections (Figure 1A and 1B). At location 4, in the first year spring collection, approximately 0.57 cm of rain fell in two hours during the collection of sub-sample E. The number of seeds collected in filtrate samples increased from 4 seeds in subsample D immediately before the rain to 49 seeds during sub-sample E (Figure 1A). In the second year summer collection at location 3, 0.41 cm of rainfall occurred in 1.5 hours during sub-sample E. There were 83 germinable seeds collected before the rain, 1415 during the rain, and 106 in the sub-sample immediately after the rain (Figure 1B). In each case a single species accounted for over 90% of the increase seed presence; marsh yellowcress at location 4 and eclipta at location 3. Both weed species have highly buoyant seeds (Ray et al. 2025) and were present in water drainage areas near the ponds. Seeds with high levels of buoyancy are known to be more efficiently transported via hydrochory (Shi et al. 2020, Merrit et al. 2006). It is highly likely that heavy rain events transport buoyant seeds into irrigation ponds where they can be distributed via irrigation. The effect of rain events was short-lived, with seed counts returning to lower levels after rain ceased.

Weed population scouting results

The three locations exhibited varying weed populations, with the highest populations observed at location 3 and the lowest at location 2. This observation was consistent with the initial location selections to include locations with low, moderate, and high weed populations. For five of the six assessments included in this comparison, there was no significant correlation between weed species in irrigation water and those within crop containers (Figure 2). Pearson correlation coefficients ranged from -0.197 to -0.361 for Locations 1 and 2 and had insignificant p-values, indicating a weak negative correlation. These results suggest that seeds in irrigation water did not contribute substantially to weed populations in containers. However, at Location 3 in year 2, a strong positive correlation ($r = 0.91$) ($p<0.0001$) between weeds in irrigation filtrates and frequency of weeds in containers was observed. Removing eclipta from the dataset reduced the correlation coefficient to -0.026 ($p=0.90$), demonstrating the disproportionate influence of this species on the correlation. This finding indicates that irrigation water may serve as a significant vector for certain weed species, like eclipta. Weed management strategies should focus on controlling species with buoyant and persistent seeds, such as eclipta, near pond edges and drainage ditches where runoff can transport seeds into the water source.

Practical Implications

Assuming 20 irrigation days per month (Fare et al. 1992) and observed average germinable seed counts of 12.5, 24.8, and 18.2 seeds per 0.75 acre-inch of irrigation, it was estimated that within one month 252, 498, and 360 viable seeds could be distributed per acre via irrigation during spring, summer, and late-summer, respectively (Table 4). These results corroborate previous findings by Williams and Saunders (1984), who reported 16 to 17 seeds per acre-inch of irrigation water. While that previous study sampled a much smaller volume of irrigation water, it yielded comparable results. The number of seeds dispersed by irrigation appears to be small in comparison to other potential sources. The few existing reports on weed seed spread in container nurseries suggest that secondary seed spread from existing weed populations is a more significant source of weed seeds (Cross and Skroch 1992, Williams and Sanders 1984). For example: a single flexuous bittercress plant can produce up to 4,980 seeds per plant in a five week period and disperse seeds up to 106 cm from the parent plant, resulting in an average seedling density of 1860 seeds m^{-2} (Bachman and Whitwell 1995). This potential for secondary seed dispersal far exceeds the potential number of seeds spread via irrigation. From this we conclude that hydrochory of weed seeds via irrigation is not likely to be a significant contributor to overall weed populations in container nursery crops.

Nevertheless, irrigation may facilitate persistent low-level introductions of weed seeds throughout the growing season. For instance, spring irrigation samples contained an average of 1.1 flexuous bittercress seed per 0.75 ac-in. The initial seven day irrigation period for newly potted and weed free crops could introduce approximately 8 flexuous bittercress seeds evenly distributed over the production acre. Uncontrolled, these 8 flexuous bittercress plants could produce up to 39,840 seeds within 5 weeks through secondary dispersal and dehiscent seed pods contributing to a wider dispersal than the initial irrigation (Table 4). In contrast, continuous irrigation over the same 5 week period would only disseminate 40 flexuous bittercress seeds.

Similarly, eclipta, horseweed, and spotted spurge were detected in spring irrigation samples despite the absence of mature plants at that time of year in the nursery. Early introductions of these species could lead to establishment and spread of weeds if not managed before secondary spread occurs. Early detection and control of these initial introductions are crucial to minimize subsequent weed proliferation driven by secondary dispersal.

Irrigation could contribute to the spread of invasive weed species. For example, a nursery recent visit (a location not included in this study) by the principal investigator revealed a small infestation of sessile joyweed (*Alternanthera sessilis* (L.) R. Br. ex DC.), a federally regulated species (USDA Plants Database, https://plants.usda.gov/plant-profile/ALSE4/noxious-invasive). A subsequent survey revealed that the species was absent from the nursery's irrigation water source and drainage areas, indicating that irrigation was unlikely to be the source of the infestation. While irrigation was not the seed source in this instance, its potential for dispersing such species is a concern.

Weed species with highly buoyant seeds that persist in water, such as eclipta, as well as wind dispersed species, like black willow, common groundsel, or horseweed, pose a high risk of dissemination via irrigation systems. These species should be removed from drainage pathways, pond edges, and vegetation surrounding ponds to reduce direct deposition of seeds into source water and potential introduction via irrigation systems. Heavy rain events while filtering source water significantly increased eclipta and marsh yellowcress seed counts, highlighting the risk of seed spread during heavy rain. During spring, however, many tasks make irrigation management difficult, especially when thunderstorms occur unexpectedly. Use of coarse substrates in containers reduces water holding capacity, thus allowing common microburst thunderstorms to pass right through plants and not cause flooding stress. Short-lived thunderstorms do not usually provide the daily volume of irrigation necessary for container plants, thus growers may let irrigation cycles continue to run to maintain both irrigation schedules and water pressure in the system. Unfortunately, the entire production area captures the rain event channeling that large effluent volume into one drainage location in a pond. Even though outbursts were short-lived or of low volume, weed seed carried in production runoff and surrounding pond rims can concentrate near intake pipes while irrigation systems continue to operate during the storm. Thus more dissemination of weed seed to production areas could occur normally than what is estimated based on data collected herein. However, the effect of rain events on increasing seed presence in source water were short-lived. In all cases, deactivating irrigation during heavy rain events can substantially reduce the potential for weed seed spread in irrigation, particularly for buoyant species like eclipta.

Preventing capture and concentration of weed seed species in source water used for irrigation is a primary management concern for growers. Growers should implement and maintain consistent weed management practices including pre- and postemergence herbicide applications, mechanical control, hand weeding, and mowing in production areas. Additionally, management practices should concentrate on removing major weed pests from drainage ditches, pond edges and aprons, then couple these management tasks with water-saving cultural practices to minimize the possibility of production runoff transporting weed seed species back to source water used for irrigation. The goal is to reduce weed seed presence in and around irrigation systems. These findings have implications for any cropping system that draws irrigation water from surface ponds.

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Tables

Table 2.1. Locations (Loc.) of the six nurseries in North Carolina where research was conducted and location descriptions including historic weed population densities and descriptions and maintenance practices for pond edges and drainage pathways.

Loc.	City and GPS	Weed Density[a]	Location descriptions and general maintenance	
			Pond Edges	Drainage pathways
1	Goldsboro 35.434°N, 78.029°W	Medium	Vegetative border of over 30 native and weedy species including; annual bluegrass, crabgrass, vaseygrass rice flatsedge, dogfennel, horseweed, sowthistle, and American burnweed. Infrequently mowed.	Unlined drainage ditches with some vegetation, including grasses, sedges, and broadleaf weeds Infrequently sprayed with POST herbicides.
2	Willow Spring 35.606°N, 78.684°W	Low	Vegetative border, Mowed infrequently. Predominately grasses and rushes, with some horseweed, Eastern baccharis, angelstem primrose, and cudweed. 25% covered with landscape fabric	Ditches lined with landscape fabric, very little vegetation Hand weeded as needed.
3	Clayton 35.650°N, 78.454°W	High	60% rip rap border, 40% tree line/vegetation; some established vegetation in rip rap. Species included eclipta, common and mouseear chickweed, marsh parsley, Eastern Baccharis, rice flatsedge and black willow. Infrequently spayed with herbicides	60% ditches lined with landscape fabric. 40% unlined sand and gravel paths with sedges, grasses, and broadleaf weeds observed. Infrequently sprayed with POST herbicides.

Table 2.1 (continued).

4	Willard 34.681°N, 77.961°W	Medium	80% border of unmanaged tree line/vegetation. Other 20% vegetated with mixture of native and weedy species including; horseweed, spurge, eclipta, dogfennel, sedge, goosegrass, yellowcress, and crabgrass. Mowed occasionally	Series of culverts and ditches lined with landscape fabric, few species observed. Infrequently spayed with POST herbicides.
5	Garner 35.705°N, 78.552°W	Medium	Vegetative border of over 45 native and weedy species, including; spotted spurge, hyssop spurge, eclipta, dogfennel, Japanese stiltgrass, large crabgrass, vaseygrass, rice flatsedge, compressed sedge, and black willow. Mowed occasionally.	Ditches lined with rip rap and/or sand, with grasses and broadleaf weeds observed. Infrequently spayed with POST herbicides.
6	Holly Springs 35.611°N, 78.852°W	Medium	Vegetative border with 25% tree line. Native and weedy vegetation infrequently mowed and included goldenrod, spurge, eastern baccharis, beggarsticks, horseweed, cudweed and vaseygrass.	Ditches lined with landscape fabric, few species observed. Infrequently treated with POST herbicides.

[a]Ranking of historical weed population densities. Weed population rankings were entirely subjective and based on the principal investigator's 20+ years of observing these locations. The low population nursery had very few weeds in crops or noncrop areas due to intensive management. The high population nursery only removed weeds prior to herbicide reapplication or shipment, allowing many weeds to mature. Medium density nurseries maintained weed management practices that reduced weed populations in crops and non-crop areas, but weeds were not uniformly controlled before reproductive maturity, ensuring some secondary spread.

Table 2.2. Number of germinated seeds per 0.75 acre-inch of irrigation, by season and location, and results from analysis of variance for main effects and interactions.

Locations (by avg. # seeds collected)	Number of emerged seedlings per 0.75 acre-inch of irrigation, overall average and by season[a]			
	Average	Spring	Summer	Late-summer
3	37.1 a	25.8 a	61.0 a	24.5 ab
6	23.7 b	8.3 a	25.5 b	38.7 a
1	16.4 bc	14.0 a	17.7 b	17.5 ab
4	11.9 bc	9.5 a	21.1 b	5.2 b
2	11.5 bc	8.7 a	16.7 b	8.9 b
5	10.1 c	8.5 a	7.1 b	14.5 b
Average[b]	18.5 --	12.5 --	24.8 --	18.2 --
ANOVA	P-values for main effects and interactions			
season	0.0002	--	--	--
year	<.0001	--	--	--
location	<.0001	--	--	--
location*year	<.0001	--	--	--
season*year	<.0001	0.2071	<0.0001	0.3767
season*location	0.0001	0.1055	<0.0001	0.0001
season*location*year	<.0001	0.086	<0.0001	<0.001

[a]LSmeans within columns followed by the same letter are not significantly different based upon a Tukey-Kramer means comparison with α=0.05.

[b]Averages of all data, not means of the averages from each location.

Table 2.3. Species in irrigation filtrate samples, and the number of seeds per 20,000-gal (one acre's daily irrigation requirement) present in each sampling season. Species are ranked by abundance across seasons from greatest to least.

Weed Species	Spring	Summer	Late-Summer	Common Weed[a]
Eclipta prostrata L.	3.1	19.8	4.4	x
Ludwigia leptocarpa (Nutt.) H. Hara	1.3	11.2	2.9	x
Stellaria media (L.) Vill.		10.3		x
Juncus dichotomus Elliot	1.8	2.4	1.8	
Rorippa palustris (L.) Besser	2.7	1.5	1.5	x
Paspalum urvillei Steud.	1.3	1.3	2.0	
Euphorbia maculata L.	1.0	1.6	1.6	x
Microstegium vimineum (Trin.) A. Camus	4.0			
Digitaria sanguinalis (L.) Scop.	1.2	1.2	1.5	x
Boehmeria cylindrica (L.) Sw.	1.4	1.1	1.4	
Cardamine flexuousa With.	1.1	1.5	1.1	x
Hydrocotyle ranunculoides L. f.		2.2	1.5	
Polypremum procumbens L.	1.1	1.5	1.0	
Erechtites hieraciifolius (L.) Raf. ex DC.	1.0	1.3	1.3	x
Eupatorium capillifolium (Lam.) Small	1.2	1.2	1.2	x
Hydrolea quadrivalvis Walter	1.1	1.0	1.5	
Callitriche stagnalis Scop.	1.1	1.1	1.4	
Cyperus iria L.	1.1	1.2	1.2	x
Erigeron canadensis L.	1.0	1.4	1.0	x
Euphorbia hyssopifolia L.	1.2	1.0	1.1	x

Table 2.3 (continued).

Amaranthus blitum L.	1.0	1.3	1.0	x
Ranunculus sceleratus L.		1.3	1.9	
Gnaphalium uliginosum L.	1.2	1.0	1.0	x
Sonchus asper (L.) Hill	1.0	1.2	1.0	x
Veronica peregrina L.		3.1		
Lepidium didymum L.		3.0		
Solidago canadensis L.	2.0	1.0		
Euphorbia serpens Kunth	1.0	1.0	1.0	x
Eryngium prostratum Nutt. ex DC.	1.0	1.0	1.0	
Cyperus polystachyos Rottb. var. texensis (Torr.) Fernald	1.4		1.3	
Andropogon virginicus L.		1.2	1.4	
Ludwigia palustris (L.) Elliot	1.7		1.0	x
Cyclospermum leptophyllum (Pers.) Sprague ex Britt.		1.2	1.3	x
Poa annua L.	1.3	1.1		x
Echinochloa crus-galli (L.) P. Beauv.	1.5	1.0		
Baccharis halimifolia L.	1.0		1.2	x
Cyperus compressus L.	1.0		1.2	x
Cyperus odoratus L.		1.1	1.0	x
Carex longii Mack.	1.1		1.0	
Kyllinga pumila Michx.		2.0		
Galium palustre L.		1.0	1.0	
Persicaria lapathifolia (L.) Delarbre	1.0		1.0	

Table 2.3 (continued).

Oxalis stricta L.	1.0		1.0	x
Salix nigra Marshall	1.8			
Cerastium vulgatum L.		1.7		x
Puccinellia distans (Jacq.) Parl.	1.7			
Dichanthelium clandestinum (L.) Gould			1.6	
Limosella australis R. Br.		1.6		
Carex alata Torr.		1.5		
Mazus pumilus (Burm. f.) Steenis		1.3		
Hypericum perforatum L.		1.2		
Portulaca oleracea L.		1.2		
Geranium carolinianum L.			1.2	
Dysphania pumilio (R. Br.) Mosyakin & Clemants		1.0		
Capsella bursa-pastori (L.) Medik.		1.0		
Plantago major L.		1.0		
Setaria pumila (Poir.) Roem. & Schult.		1.0		
Eleusine indica (L.) Gaertn.	1.0			x
Persicaria hydropiperoides (Michx.) Small	1.0			
Typha latifolia L.	1.0			
Sonchus oleraceus L.		1.0		x
Houttuynia cordata Thunb.		1.0		
Digitaria ciliaris (Retz.) Koeler			1.0	
Sacciolepis striata (L.) Nash		1.0		
Youngia japonica (L.) DC.		1.0		x
Eragrostis sp.	1.0			

Table 2.3 (continued).

Mollugo verticillata L.		1.0		
Fimbristylis autumnalis (L.) Roem. & Schult.		1.0		
Ranunculus sardous Crantz			1.0	
Bidens aristosa (Michx.) Britton		1.0		
Erianthus giganteus (Walter) P. Beauv.	1.0			
Scutellaria incana Biehler			1.0	
Trifolium repens L.			1.0	
Digitaria ischaemum (Schreb.)			1.0	
Euphorbia prostrata Ait.			1.0	x
Number of germinable seeds, all species	54.4	105.8	57.5	
Total number of taxa present	40	52	43	
Number of germinable seeds of common nursery weed species only	28.2	64.8	31.5	
Total number of taxa present that are considered common to nursery crops	21	22	21	
Percent of the total germinable seeds that are common nursery weeds	51.8%	61.2%	54.8%	

[a]Species with an ‘x’ have been reported to be common in container nurseries in the U.S. (Neal and Derr 2005). Based on the authors’ experiences, *Amaranthus blitum* is also marked as ‘common’ but is not present in the cited reference because it was relatively unknown in nurseries in 2005.

Table 2.4. Estimates of the number of germinable seeds per acre distributed via irrigation each month, averaged across six nursery locations in North Carolina and two years: assuming 0.75 acre-inch of irrigation per day and 20 irrigation days per month. Estimates are presented for total seed dispersal, as well as the potential seed deposition into individual containers at two crop plant spacing configurations, accounting for irrigation loss to gaps between containers. Additionally, theoretical estimates of flexuous bittercress seed distribution resulting from secondary dispersal are provided.

	Number of viable seeds in one month's irrigation		
	One production acre	Within 11-L containers on 1 acre, at two plant spacings[a]	
Season of collection		no spacing	5 cm spacing
Spring	252	198	142
Summer	498	391	280
Autumn	360	283	203
Average	370	291	208
Theoretical secondary seed production of flexuous bittercress resulting from 1 week of irrigation within 1 production acre [b]	39,840	31,075	22,310

[a]Based upon average numbers of containers per acre from Yeary et. al. (2016) Nursery irrigation: a guide to irrigation. Univ. Tenn. Extension PB1836

[b]Assumptions: eight flexuous bittercress seeds introduced in production acre in 7 days of irrigation; estimated flexuous bittercress seed production of up to 4,980 seeds per plant within 5 weeks (Bauchman and Whitwell, 1995).

Figures

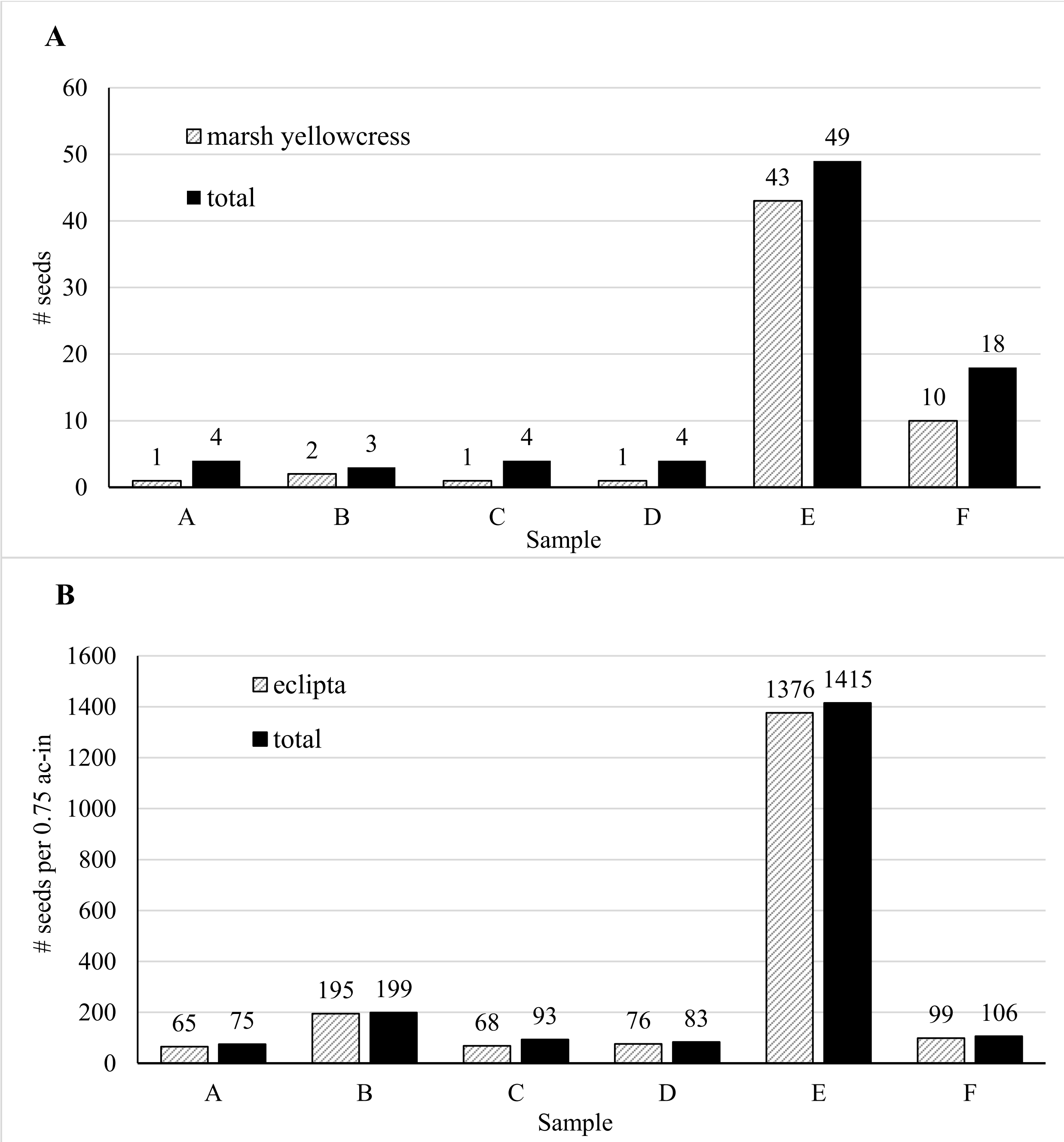
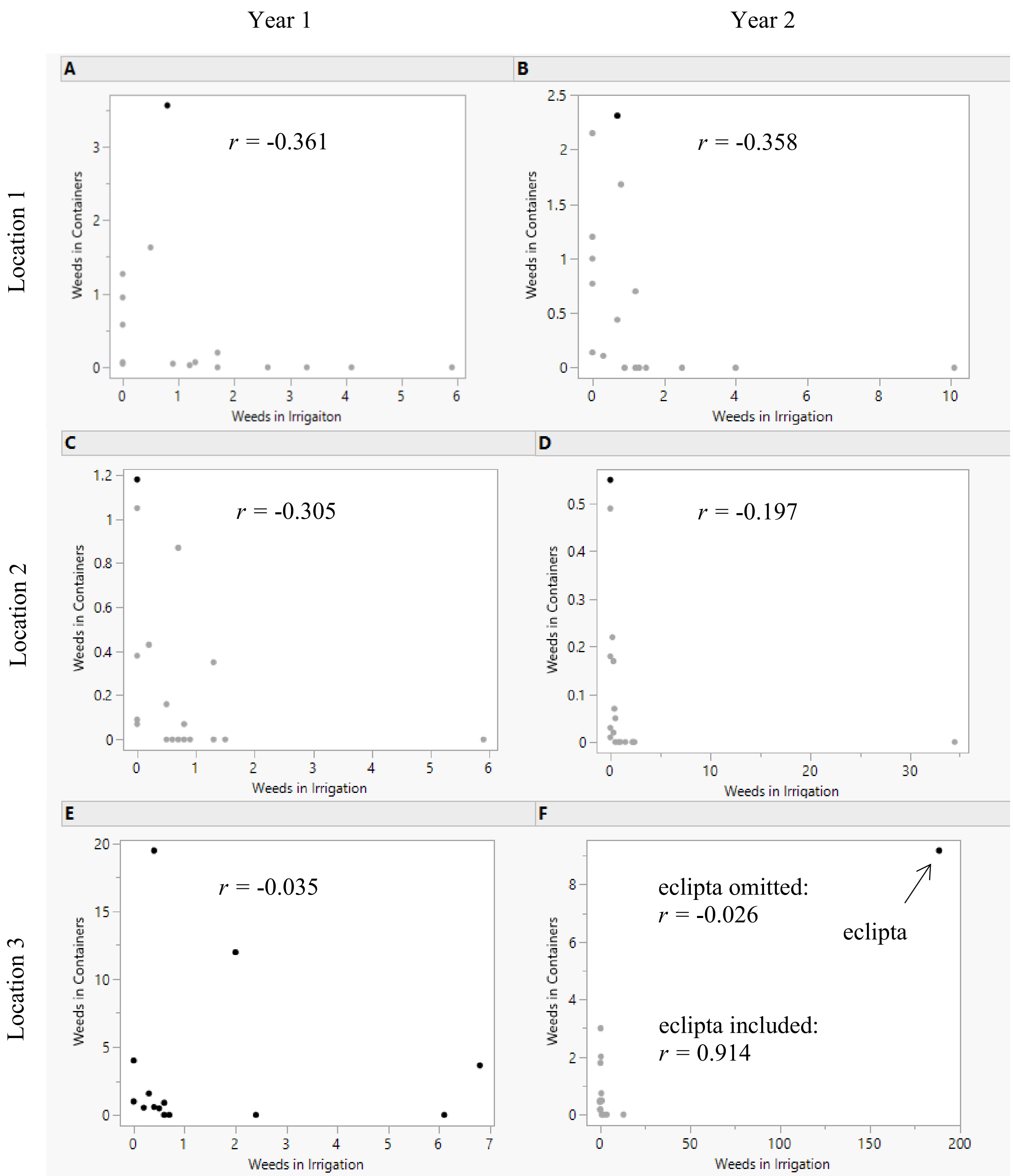


Figure 2.1. The number of germinable seeds per 0.75 acre-in of irrigation in six subsamples, at two location-years when heavy rainfall occurred during the collection of sub-sample E. Plot A = year 1, spring at location 4. Plots B = year 2, summer at location 3. Each sub-sample represents about 75708 L of irrigation filtration. Heavy rain events increased seed collections, and in both cases a single species accounted for 90% of the increase.

Figure 2.2. Pearson correlations between the ten most abundant weed species identified in container scouting (% frequency) and those found in irrigation samples (number of seeds per 0.75 ac in-1 irrigation) at: (A) Location 2, Year 1; (B) Location 2, Year 2; (C) Location 1, Year 1; (D) Location 1, Year 2; (E) Location 3, Year 1; and (F) Location 3, Year 2 . The number of species shown varies across panels due to overlaps in species between containers and irrigation. For most locations and years, low r-values and species clustering along the axes indicate little or no relationship between dominant species in containers versus irrigation. However, due to high abundance of eclipta in both container and irrigation for Location 3, Year 2 (Fig. 2,F), the two variables were highly correlated (r = 0.914). Excluding eclipta from the analysis reduced the correlation coefficient to -0.026, similar to r-values for the other locations and years.


Year 1
Year 2
Location 1
Location 2
Location 3
A
r = -0.361
Weeds in Containers
Weeds in Irrigaiton
B
r = -0.358
Weeds in Containers
Weeds in Irrigation
C
r = -0.305
Weeds in Containers
Weeds in Irrigation
D
r = -0.197
Weeds in Containers
Weeds in Irrigation
E
r = -0.035
Weeds in Containers
Weeds in Irrigation
F
eclipta omitted:
r = -0.026
eclipta
eclipta included:
r = 0.914
Weeds in Containers
Weeds in Irrigation

Discussion and Conclusions

In the Southeastern U.S., container nursery crop producers commonly use surface ponds for irrigation, and many suspect this water serves as a vector for weed seeds. However, limited information exists regarding the actual contribution of irrigation ponds to weed contamination in container nurseries. To address this knowledge gap, we evaluated weed seed buoyancy, seed survival in irrigation ponds, and viable weed seed presence within nursery irrigation ponds. Additionally, we surveyed weed population in crops during filtration collections. The resulting data allow us to help us understand the role of nursery irrigation ponds as a weed seed source and to speculate on effective prevention strategies for growers

Nursery irrigation ponds typically have large surface areas and slow flow, suggesting that it could take a considerable amount of time for weed seeds deposited into irrigation ponds to reach the intake. Seed buoyancy and survivability experiments were conducted to determine potential weed seed availability in irrigation ponds. We found that seeds of several common nursery weeds, including eclipta (*Eclipta prostrata* L.), marsh yellowcress (*Rorippa palustris* (L.) Besser), common groundsel (*Senecio vulgaris* L.) with attached papus, dogfennel (*Eupatorium capillifolium* (Lam.)) with and without attached papus, and rice flatsedge (*Cyperus iria* L.) are buoyant and thus could remain suspended in irrigation ponds. Whereas other common weeds such as yellow woodsorrel (*Oxalis stricta* L.), spotted spurge (*Euphorbia maculata* L.), and flexuous bittercress (*Cardamine flexuosa* With) were non-buoyant. Furthermore, seeds of eclipta, flexuous bittercress, yellow woodsorrel, and spotted spurge seeds maintained some germination after ≥270 days of submergence. Notably, eclipta seeds were buoyant and highly viable for 360 days, indicating a high potential for dispersal through irrigation water. Conversely, while flexuous bittercress seeds remained viable for 360 days, their non-buoyancy suggests a lower probability of reaching irrigation ponds through runoff and dispersal via irrigation water. Spotted spurge's declining seed viability over time, and temporary buoyancy offers a limited opportunity for irrigation-mediated dissemination. Yellow woodsorrel seeds were non-buoyant and showed significantly reduced germination after submergence, indicating low potential for dispersal through irrigation. These findings highlight that seed buoyancy and prolonged survival in water may contribute to the presence and dispersal of several common nursery weeds. And, seeds that lack those traits are less likely to be present in irrigation water.

To assess the actual presence of weed seeds in irrigation water, we collected irrigation filtrates from six commercial container nurseries across three seasons and over two years. In total, we filtered over 4 million gallons (15 million L) of water and collected 216 filtrate samples, which were tested for viable seeds. All irrigation water samples contained germinable weed seeds across every season, year, and location. The average number of germinable seeds collected in one 0.75 acre-inch of irrigation across years and locations was 12.5 in spring, 24.8 in summer, and 18.2 in late-summer, with an overall average of 18.5 across years, locations, and seasons. These results corroborate previous findings by Williams and Saunders (1984), who reported 16 to 17 seeds per acre-inch of irrigation water. Although that previous study sampled a much smaller volume of irrigation water, it yielded comparable results.

We observed two instances where heavy rainfall significantly increased germinable seed counts In one spring sample, total seeds in 0.75 acre-inch of irrigation rose from 4 seeds before a rain event to 49 seeds during a rainstorm, with marsh yellowcress accounting for 88% of the seeds collected. Similarly, a summer collection during a heavy rainstorm saw total germinable seeds increase from 83 before the rain to 1415 after the rain, with eclipta accounting for 97% of the seeds collected. In both cases, seed counts returned to lower, pre-rainfall levels once the rain ceased, suggesting a short-lived effect of rainfall disturbance on seed populations in the water. These observations align with results from our buoyancy and survival experiments, confirming that species with both buoyancy and persistence in water, like eclipta, have a greater potential for distribution via irrigation, especially during heavy rain events. These findings also align with research demonstrating that heavy rain events increase weed seed deposits in runoff water, particularly for buoyant seeds (Rouw et al. 2018; Xiong and Nilsson 1997). While reports indicate that flowing water generally poorly disperses non-buoyant seeds (Andersson et al. 2000), heavy rain can facilitate their transport along with debris (Rouw et al. 2018; Xiong and Nilsson 1997). During such events, low buoyancy seeds, such as yellow woodsorrel, might enter irrigation ponds but seeds would rapidly sink reducing the likelihood of seeds being present in irrigation water. It is highly probable that heavy rain events transport buoyant seeds into irrigation ponds, from where they can be distributed via irrigation. Nevertheless, the effect of rain events was short-lived, with seed counts returning to lower levels once the rain ceased.

Of the 75 taxa identified in the irrigation filtrates, 28 were common container nursery weeds. Several species present in irrigation samples have not been reported as container nursery weeds and were absent from crop surveys at the study sites. This suggests that nursery environments may not be suitable for the establishment of all weed seeds present in irrigation water. Conversely, we observed some species in irrigation samples and on nursery sites but not within containers. Japanese stiltgrass (*Microstegium vimineum* (Trin.) A. Camus), for example, was observed on the pond edge at one location and in high populations at the nursery border at another. The presence of Japanese stiltgrass in irrigation water supports previous reports of dispersal of this species by hydrochory (Tekiela and Barney 2013; Eschtruth and Battles 2011). Its absence in containers suggests that management practices may limit its establishment and survival within crops. This highlights the potential for irrigation to contribute to the broader dissemination of invasive species, even if they don't establish within containers. For instance, a recent nursery visit (a location not included in this study) by the principal investigator revealed a small infestation of sessile joyweed (*Alternanthera sessilis* (L.) R. Br. ex DC.), a federally regulated species (USDA Plants Database, https://plants.usda.gov/plant-profile/ALSE4/noxious-invasive). A subsequent survey revealed that the species was absent from the nursery's irrigation water source and drainage areas, indicating that irrigation was unlikely to be the source of the infestation. While irrigation was not the seed source in this instance, its potential for dispersing such species remains a concern.

Seasonal seed shedding patterns were evident for some species. Black willow (*Salix nigra* Marshall) seeds shed in the spring (Neal et al. 2023) and were only present in irrigation filtrates collected during the spring season. However, we detected other species in irrigation filtrates even when mature plants were absent from the nursery. Eclipta, horseweed (*Erigeron canadensis* L.), and spotted spurge seeds were present in irrigation samples from all seasons, despite typically shedding seeds from summer through autumn (Neal et al. 2023). Kelley and Bruns (1975) observed similar findings in irrigation water of canal-fed farmlands, noting that while seeds of certain species peaked when mature plants were present in the environment, for many species these peaks were not prevalent or well-defined. This suggests that seeds of some species can persist in irrigation water and remain available for uptake into irrigation systems, supporting persistence in water as a critical factor in a seed's probability of dissemination via irrigation.

The number of seeds dispersed by irrigation appears small in comparison to other potential sources. Assuming 20 irrigation days per month (Fare et al. 1992) and observed average germinable seed counts of 12.5, 24.8, and 18.2 seeds per 0.75 acre-inch of irrigation, within one month we estimated that 252, 498, and 360 viable seeds could be distributed per acre via irrigation during spring, summer, and late-summer, respectively. The few existing reports on weed seed spread in container nurseries suggest that secondary seed dispersal from existing weed populations is a significant source of weed seeds (Cross and Skroch 1992; Williams and Sanders 1984). For example, a single flexuous bittercress plant can produce up to 4,980 seeds in a five-week period and disperse seeds up to 106 cm from the parent plant, resulting in an average seedling density of 1860 seeds m^{-2} (Bachman and Whitwell 1995). This potential for secondary seed dispersal far exceeds the potential number of seeds spread via irrigation. From these findings, we conclude that hydrochory of weed seeds via irrigation is unlikely to be a significant contributor to overall weed populations in container nursery crops.

Despite its relatively low contribution to overall weed populations, irrigation may facilitate persistent, low-level introductions of weed seeds throughout the growing season. For instance, spring irrigation samples contained an average of 1.1 flexuous bittercress seeds per 0.75 ac-in, or about 8 flexuous bittercress seeds distributed in the first week. If not controlled, these eight flexuous bittercress plants could produce up to 39,840 seeds and spread those seeds to pots within a two meter radius via forcefully dehiscent seed pods. In contrast, continuous irrigation over the same five-week period would disseminate only 40 flexuous bittercress seeds. Similarly, eclipta, horseweed, and spotted spurge were detected in spring irrigation samples despite the absence of mature plants at that time of year in the nursery. Early introductions of these species could lead to establishment and spread of weeds if not managed before secondary dispersal occurs. Therefore, early detection and control of these initial introductions are crucial to minimize subsequent weed proliferation driven by secondary dispersal.

These findings indicate that irrigation water may serve as a vector for some weed species, and those possessing both buoyancy and persistence in water are more likely to be disseminated via irrigation water. Current automatic backwash disc filtration systems that can filter particles as small as weed seeds and are suitable for installation in container nursery pumphouses greatly vary in cost. The size and quantity of the filtration units needed depends on nursery size, flow rate and other factors including unique customizations. Small base models are estimated to cost between $3,000 and $5,000 USD, while larger, higher-capacity models range from approximately $12,000 to $31,000 USD. These figures were derived from current market prices provided by supplier data (Baldr, Fujian, China and Netafim USA, Fresno, CA) and exclude associated installation expenses such as parts and labor. Installation of such systems solely for weed seed filtration is likely not justified given the relatively low significance of irrigation water as a source of weed contamination. Lower-cost in-line rapid sand or mesh screen filters are often ineffective for container nurseries due to frequent clogging from suspended solids, algae, and organic matter from irrigation water. Chemical clogging can also occur from mineral precipitation, especially in systems that recycle irrigation water, such as container nurseries. Based on personal communication with container nursery growers, they report finding these types of filtration options to require too much repair and maintenance. My personal experience as a container nursery grower aligns with this opinion. I installed mesh screen filters to prevent clogging in one of my sections due to the specialized emitter type being prone to clogging. The mesh pore size was not small enough to filter weed seeds, and the filters required daily cleaning to prevent clogging. The filter would likely need to be cleaned multiple times a day if the pore size was small enough to capture weed seeds. Due to the maintenance commitment, it might be impractical to install these filters in nursery irrigation systems.

Therefore, we recommend that growers focus on implementing consistent standard weed management practices (e.g., herbicide applications, hand weeding, mowing) in production areas. Additionally, growers should expand weed management efforts to include irrigation pond edges and runoff pathways to minimize weed seed deposits into irrigation water. Prioritizing control of species with buoyant and persistent seeds, like eclipta, in these areas is particularly important. Removing wind-dispersed species like black willow, common groundsel, or horseweed from pond surroundings will also reduce direct seed deposition into the water. Furthermore, growers should consider forgoing automatic irrigation during heavy rain events. Our data showed significant increases in weed seeds, particularly buoyant species, during rainstorms, although this effect was short-lived. Deactivating irrigation during these periods can substantially reduce the potential for weed seed spread.

In a 2023 industry survey, 59% of growers reported labor costs and availability as their greatest business concern (McClellan 2024), indicating labor availability may represent a practical barrier to extending weed management practices to previously unmaintained areas such as runoff pathways and pond surroundings. Considering this, irrigation pond and runoff path design options to reduce the potential for weed seed deposit into irrigation ponds may be desirable. New ponds could be designed with long flow paths between runoff deposits and irrigation inlet pipes, which increases the opportunity for suspended solids, potentially including weed seeds, to settle out before being drawn into the irrigation system (Yazdi et al. 2021). Alternatively, newly constructed nurseries or sections could direct all recaptured water to settling ponds (also known as retention ponds) before it reaches the irrigation source pond, reducing direct runoff deposits in source irrigation ponds. This design facilitates the sedimentation of weed seeds that are either non-buoyant or exhibit buoyancy for only a short duration, thereby preventing their transport to the irrigation source. Furthermore, buoyant weed seeds may become trapped at pond edges or within debris, potentially reducing their availability for transfer to the source pond. Implementing this design necessitates higher upfront costs due to the requirement for a dedicated settling pond for each irrigation source pond. Additional energy input may also be required if passive gravitational transfer is not feasible and a pump is necessary to move the water.

In conclusion, while irrigation water may not be the primary source of weed contamination, its potential for persistent, low-level introductions of weed seeds across production areas highlights the need to manage this source as an important component of comprehensive weed management programs. Expanding weed management to include water flow paths and pond surroundings, with a focus on species whose seeds are buoyant and persistent in water, could reduce weed seed introduction via irrigation. This, in turn, should reduce postemergence weed management expenditures and reliance on hand weeding.

Further research to identify more weed species with traits of seed buoyancy and persistence in water would be beneficial for targeted control of weed species with a high risk for dissemination via irrigation. Nursery producers can also include elements such as long flow paths or settling ponds in their irrigation pond designs. Additionally, research is needed on the use of pond or drainage design elements that can trap weed seeds before they reach irrigation ponds.

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APPENDICES

Appendix A. Scouting Reports: Categorical Rankings

Categorical weed assessments for plant blocks in container nurseries where irrigation water was tested for weed seed presence (locations 1 – 6). Rankings averaged across plant blocks for spring, summer, and late-summer assessments. Weed populations were ranked by prevalence using a 1 to 6 scale where 1 = high populations throughout, 2 = common, 3 = present but patchy distribution, 4 = a few plants, 5 = rare (one or two individuals), 6 = not present.

A.1. Location 1 categorical weed assessments for spring, summer, and late-summer.

Species	Spring	Summer	Late-Summer
Eupatorium capillifolium (Lam.) Small	3.2	3.4	4.4
Erigeron canadensis L.	4.0	3.8	3.8
Cyperus iria L.	6.0	4.0	4.0
Cardamine flexuousa With.	4.6	4.0	4.0
Euphorbia maculata L.	5.6	3.6	3.6
Eclipta prostrata L.	5.8	4.0	3.8
Cyperus sp.	5.4	4.6	4.6
Poa annua L.	4.2	5.4	5.6
Sonchus asper (L.) Hill	6.0	5.2	5.2
Digitaria sanguinalis (L.) Scop.	5.6	5.0	5.4
Cyclospermum leptophyllum (Pers.) Sprague ex Britt.	5.4	5.4	6.0
Phyllanthus urinaria L.	5.8	5.2	5.4
Baccharis halimifolia L.	5.4	5.6	6.0
Ludwigia leptocarpa (Nutt.) H. Hara	5.8	5.4	5.4
Oxalis stricta L.	5.6	5.4	5.6
Youngia japonica (L.) DC.	5.8	5.4	5.4
Euphorbia serpens Kunth	5.8	5.4	5.4
Gnaphalium uliginosum L.	5.8	5.6	5.4
Andropogon virginicus L.	6.0	5.6	6.0
Amaranthus retroflexus L.	6.0	5.6	6.0
Hypericum perforatum L.	6.0	5.8	5.4
Epilobium ciliatum Raf.	6.0	5.6	6.0
Cyperus esculentus L.	6.0	6.0	5.6

A.1 (continued).

Stellaria media (L.) Vill.	6.0	6.0	5.6
Setaria pumila (Poir.) Roem. & Schult.	5.8	6.0	6.0
Senecio vulgaris L.	5.8	6.0	6.0
Taraxacum officinale F. H. Wigg.	5.8	6.0	6.0
Rorippa palustris (L.) Besser	5.8	6.0	6.0
Senna obtusifolia (L.) H.S. Irwin & Barneby	5.8	5.8	5.8
Hypochaeris radicata L.	5.8	6.0	6.0
Euphorbia hirta L.	5.8	6.0	6.0
Lactuca serriola L.	6.0	6.0	5.8

A.2. Location 2 categorical weed assessments for spring, summer, and late-summer.

Species	Spring	Summer	Late-Summer
Eupatorium capillifolium (Lam.) Small	4.4	4.4	5.2
Cardamine flexuousa With.	5.0	4.8	4.8
Oxalis stricta L.	5.4	4.8	5.2
Poa annua L.	5.0	5.0	5.8
Euphorbia maculata L.	6.0	5.2	4.6
Erigeron canadensis L.	5.0	5.2	5.8
Gnaphalium uliginosum L.	5.4	5.2	5.4
Sagina procumbens L.	5.2	5.6	5.6
Erechtites hieraciifolius (L.) Raf. ex DC.	5.8	5.4	5.6
Salix nigra Marshall	5.6	5.2	6.0
Pinus sp.	5.8	5.6	5.6
Ambrosia artemisiifolia L.	6.0	5.8	6.0
Cytisus scoparius (L.) Link	5.6	5.6	6.0
Persicaria sp.	5.6	5.6	6.0
Cyperus sp.	6.0	6.0	5.2
Erigeron bonariensis L.	5.6	5.8	6.0
Amaranthus blitum L.	5.8	5.6	6.0
Amaranthus retroflexus L.	5.8	5.8	5.8
Setaria pumila (Poir.) Roem. & Schult.	6.0	5.6	5.8
Hydrolea quadrivalvis Walter	6.0	5.8	5.6
Cynodon dactylon (L.) Pers.	6.0	6.0	5.4
Digitaria sanguinalis (L.) Scop.	6.0	6.0	5.4
Cyperus iria L.	6.0	6.0	5.4

A.2 (continued).

Geranium carolinianum L.	5.8	5.8	6.0
Cerastium vulgatum L.	5.8	5.8	6.0
Gamochaeta purpurea (L.) Cabrera	5.8	5.8	6.0
Lepidium virginicum L.	5.8	5.8	6.0
Solidago canadensis L.	5.8	5.8	6.0
Chenopodium album L.	5.8	5.8	6.0
Youngia japonica (L.) DC.	5.8	5.8	6.0
Erogrostis sp.	6.0	6.0	5.6
Euphorbia prostrata Ait.	6.0	5.8	6.0
Mollugo verticillata L.	6.0	6.0	5.8
Digitaria ischaemum (Schreb.)	6.0	6.0	5.8
Epilobium ciliatum Raf.	6.0	6.0	5.8
Mentha sp.	6.0	6.0	5.8
Lespedeza cuneata (Dum. Cours.) G. Don	6.0	6.0	5.8

A.3. Location 3 categorical weed assessments for spring, summer, and late-summer.

Species	Spring	Summer	Late-Summer
Cardamine flexuousa With.	3.8	3.7	3.9
Eclipta prostrata L.	5.6	3.2	3.1
Euphorbia maculata L.	5.7	3.6	3.3
Eupatorium capillifolium (Lam.) Small	5.3	4.2	4.4
Cyperus sp.	6.0	4.1	4.0
Cyclospermum leptophyllum (Pers.) Sprague ex Britt.	4.8	4.6	4.8
Erigeron canadensis L.	5.0	4.8	5.1
Erechtites hieraciifolius (L.) Raf. ex DC.	6.0	4.8	4.7
Digitaria sanguinalis (L.) Scop.	5.9	4.9	5.0
Oxalis stricta L.	6.0	5.1	5.0
Stellaria media (L.) Vill.	5.8	5.1	5.4
Senecio vulgaris L.	5.2	5.4	5.7
Geranium carolinianum L.	5.5	5.4	5.5
Poa annua L.	5.2	5.6	5.7
Dysphania pumilio (R. Br.) Mosyakin & Clemants	6.0	5.2	5.3
Vicia sativa L.	4.9	5.8	5.9
Euphorbia hyssopifolia L.	6.0	5.4	5.2
Erogrostis sp.	6.0	5.4	5.3
Eleusine indica (L.) Gaertn.	6.0	5.3	5.5
Sagina procumbens L.	5.3	5.7	5.9
Cerastium vulgatum L.	5.3	5.8	5.8
Amaranthus blitum L.	6.0	5.4	5.5
Portulaca oleracea L.	5.9	5.4	5.7

A.3 (continued).

Gnaphalium uliginosum L.	5.9	5.6	5.5
Cyperus iria L.	6.0	5.7	5.7
Pinus sp.	6.0	5.6	5.8
Baccharis halimifolia L.	6.0	5.7	5.7
Veronica peregrina L.	6.0	5.6	5.9
Solidago canadensis L.	6.0	5.8	5.8
Salix nigra Marshall	5.7	6.0	6.0
Cyperus esculentus L.	6.0	5.7	6.0
Acer sp.	6.0	5.8	5.9
Nuttallanthus canadensis (L.) D. A. Sutton	6.0	5.8	5.9
Triodanis perfoliate (L.)	6.0	5.8	5.9
Amsonia tabernaemontana	6.0	5.8	5.9
Hypericum perforatum L.	6.0	5.8	5.9
Erigeron bonariensis L.	5.8	6.0	6.0
Paspalum urvillei Steud.	6.0	6.0	5.8
Cirsium vulgare (Savi) Ten.	6.0	5.9	6.0
Dichanthelium clandestinum (L.) Gould	5.8	6.0	6.0
Sonchus asper (L.) Hill	5.9	6.0	6.0
Lactuca serriola L.	5.9	6.0	6.0
Juncus dichotomus Elliot	5.9	6.0	6.0
Mikania scandens	6.0	5.9	6.0
Ludwigia decurrens Walter	6.0	5.9	6.0
Solanum carolinense L.	6.0	5.9	6.0
Taraxacum officinale F. H. Wigg.	6.0	6.0	5.9

A.4. Location 4 categorical weed assessments for spring, summer, and late-summer.

Species	Spring	Summer	Late-Summer
Eupatorium capillifolium (Lam.) Small	3.7	3.7	4.6
Cardamine flexuousa With.	4.1	4.0	4.6
Euphorbia maculata L.	5.7	4.8	3.7
Eclipta prostrata L.	5.5	4.8	4.1
Baccharis halimifolia L.	4.7	4.8	6.0
Eleusine indica (L.) Gaertn.	5.2	5.0	4.6
Digitaria sanguinalis (L.) Scop.	5.3	5.2	5.3
Erogrostis sp.	5.6	5.6	4.8
Poa annua L.	5.2	5.3	6.0
Erigeron canadensis L.	5.5	5.3	5.8
Cyperus sp.	5.9	5.5	5.4
Erechtites hieraciifolius (L.) Raf. ex DC.	5.8	5.4	5.8
Cyperus iria L.	6.0	5.8	5.2
Oxalis stricta L.	5.7	5.8	5.7
Euphorbia serpens Kunth	5.9	5.7	5.7
Rorippa palustris (L.) Besser	6.0	5.8	5.4
Amaranthus blitum L.	5.8	5.7	5.9
Sagina procumbens L.	5.8	5.8	6.0
Gnaphalium uliginosum L.	5.8	5.7	6.0
Portulaca oleracea L.	5.9	5.8	5.8
Sonchus oleraceus L.	6.0	5.8	5.8
Epilobium ciliatum Raf.	6.0	5.5	5.7
Youngia japonica (L.) DC.	5.8	5.8	6.0

A.4 (continued).

Erigeron bonariensis L.	5.8	5.8	6.0
Mollugo verticillata L.	5.9	5.8	5.8
Senecio vulgaris L.	5.8	5.8	6.0
Phyllanthus tenellus Roxb.	6.0	5.8	5.8
Murdannia nudiflora (L.) Brenan	6.0	6.0	5.7
Geranium carolinianum L.	5.9	5.8	6.0
Vicia villosa Roth.	5.9	5.8	6.0
Cyclospermum leptophyllum (Pers.) Sprague ex Britt.	5.9	5.8	6.0
Juncus dichotomus Elliot	5.9	5.8	6.0
Artemisia vulgaris L.	6.0	5.8	6.0
Setaria pumila (Poir.) Roem. & Schult.	6.0	6.0	5.8
Malva neglecta Wallr.	6.0	6.0	5.8
Andropogon virginicus L.	6.0	6.0	5.8
Fatoua villosa (Thunb.) Nakai	6.0	6.0	5.8
Phyllanthus urinaria L.	6.0	6.0	5.8
Cerastium vulgatum L.	5.9	5.9	6.0
Ranunculus bulbosus L.	5.9	6.0	6.0
Solidago canadensis L.	5.9	6.0	6.0
Rumex crispus L.	5.9	6.0	6.0
Capsella bursa-pastoris (L.) Medicus	6.0	5.9	6.0
Amaranthus retroflexus L.	6.0	5.9	6.0
Cyperus rotundus L.	6.0	6.0	5.9
Acer sp.	6.0	6.0	5.9
Taraxacum officinale F. H. Wigg.	6.0	6.0	5.9

A.5. Location 5 categorical weed assessments for spring, summer, and late-summer.

Species	Spring	Summer	Late-Summer
Cardamine flexuousa With.	4.5	4.3	5.0
Euphorbia maculata L.	6.0	4.7	3.6
Poa annua L.	4.6	3.8	6.0
Eclipta prostrata L.	6.0	4.5	4.0
Erigeron canadensis L.	4.5	4.5	5.6
Eupatorium capillifolium (Lam.) Small	5.4	4.3	5.4
Cyperus sp.	6.0	5.0	4.1
Oxalis stricta L.	5.3	4.9	5.1
Cyclospermum leptophyllum (Pers.) Sprague ex Britt.	5.1	5.4	5.9
Gamochaeta purpurea (L.) Cabrera	5.5	5.3	5.9
Baccharis halimifolia L.	5.9	5.1	5.9
Senecio vulgaris L.	5.5	5.5	6.0
Cyperus compressus L.	6.0	6.0	5.0
Vicia villosa Roth.	5.6	5.6	5.9
Cyperus iria L.	6.0	6.0	5.1
Geranium carolinianum L.	5.6	5.8	5.9
Sonchus oleraceus L.	5.9	5.8	5.6
Digitaria sanguinalis (L.) Scop.	6.0	5.8	5.5
Cynodon dactylon (L.) Pers.	6.0	5.8	5.5
Euphorbia hyssopifolia L.	6.0	5.8	5.6
Acer sp.	6.0	5.8	5.6
Erechtites hieraciifolius (L.) Raf. ex DC.	6.0	5.6	5.8
Lepidium virginicum L.	5.8	5.8	6.0

A.5 (continued).

Salix nigra Marshall	5.8	5.8	6.0
Cerastium vulgatum L.	5.8	6.0	6.0
Bowlesia incana Ruiz & Pav.	5.9	5.9	6.0
Setaria pumila (Poir.) Roem. & Schult.	6.0	5.9	5.9
Oenothera laciniata Hill	6.0	5.8	6.0
Euphorbia prostrata Ait.	6.0	6.0	5.8
Sagina procumbens L.	6.0	5.9	6.0
Youngia japonica (L.) DC.	6.0	5.9	6.0
Bidens frondosa L.	6.0	5.9	6.0
Rumex acetosella L.	6.0	5.9	6.0
Solidago canadensis L.	6.0	5.9	6.0
Euphorbia hirta L.	6.0	5.9	6.0
Fatoua villosa (Thunb.) Nakai	6.0	5.9	6.0
Andropogon virginicus L.	6.0	5.9	6.0

A.6. Location 6 categorical weed assessments for spring, summer, and late-summer.

Species	Spring	Summer	Late-Summer
Cardamine flexuousa With.	4.6	4.8	4.6
Eupatorium capillifolium (Lam.) Small	4.4	4.9	5.1
Erigeron canadensis L.	4.4	4.9	5.2
Eclipta prostrata L.	5.4	5.1	4.6
Poa annua L.	4.9	5.2	6.0
Cynodon dactylon (L.) Pers.	5.6	5.6	5.1
Oxalis stricta L.	5.1	5.6	5.6
Euphorbia maculata L.	5.9	5.7	4.9
Gnaphalium uliginosum L.	5.6	5.4	5.6
Lepidium virginicum L.	5.6	5.4	5.7
Cyperus esculentus L.	5.7	5.7	5.6
Plantago lanceolata L.	5.7	5.7	5.7
Cyperus iria L.	6.0	6.0	5.0
Oenothera laciniata Hill	5.7	5.7	5.8
Cyperus compressus L.	6.0	5.9	5.2
Eryngium prostratum	5.8	5.6	5.9
Eleusine indica (L.) Gaertn.	5.9	5.7	5.7
Cyperus sp.	6.0	6.0	5.3
Solidago canadensis L.	5.6	5.9	5.9
Digitaria sanguinalis (L.) Scop.	5.9	5.9	5.6
Cyclospermum leptophyllum (Pers.) Sprague ex Britt.	5.6	5.9	6.0
Senecio vulgaris L.	5.7	5.9	5.9
Phyllanthus urinaria L.	5.9	5.8	5.8

A.6 (continued).

Sonchus asper (L.) Hill	5.9	5.8	5.9
Geranium carolinianum L.	5.8	5.9	5.9
Solanum carolinense L.	5.8	5.9	5.9
Paspalum notatum Flueggé	6.0	5.8	5.8
Salix nigra Marshall	6.0	5.6	6.0
Parthenocissus quinquefolia (L.) Planch.	5.9	5.9	5.9
Paspalum urvillei Steud.	6.0	6.0	5.7
Setaria pumila (Poir.) Roem. & Schult.	6.0	5.8	6.0
Bidens frondosa L.	5.9	5.9	6.0
Hypochaeris radicata L.	5.9	5.9	6.0
Diodia virginiana L.	6.0	5.9	5.9
Phyllanthus tenellus Roxb.	6.0	6.0	5.8
Andropogon virginicus L.	6.0	6.0	5.8
Erechtites hieraciifolius (L.) Raf. ex DC.	6.0	6.0	5.8
Leontodon nudicaulis (L.) Banks ex Schinz & R. Keller	5.9	5.9	6.0
Populus deltoides W. Bartram ex Marshall	6.0	5.9	5.9
Mollugo verticillata L.	6.0	6.0	5.9
Baccharis halimifolia L.	6.0	6.0	5.9
Kyllinga brevifolia Rottb.	6.0	6.0	5.9
Hypericum perforatum L.	6.0	6.0	5.9
Portulaca oleracea L.	6.0	6.0	5.9
Cyperus odoratus L.	6.0	6.0	5.9

Appendix B. Scouting Reports: Weed Frequency Assessments

Frequency assessment (% of pots infested with a weed species) were recorded within a newly potted crop species that was irrigated by water from the sampled pond. Weed frequency was assessed at approximately 6-week intervals. Average and maximum frequency of all crops tested are presented for locations 1 – 3 for each sample season and year.

B.1. Average and maximum frequency assessment for location 1, year 1 in spring, summer, and late-summer.

	Average Frequency			Maximum Frequency		
Weed Species	Spring	Summer	Late-Summer	Spring	Summer	Late-Summer
Cardamine flexuousa With.	0.57	1.98	8.13	2.28	6.42	30.38
Euphorbia maculata L.	0.01	1.16	3.73	0.03	1.57	6.82
Oxalis stricta L.	0.11	0.20	3.48	0.25	0.75	13.77
Eupatorium capillifolium (Lam.) Small	2.59	0.06	0.20	7.58	0.22	0.40
Erigeron canadensis L.	0.63	0.36	0.75	2.28	1.13	2.45
Eclipta prostrata L.	0.06	0.02	0.52	0.25	0.06	1.51
Euphorbia serpens Kunth	0.04	0.03	0.15	0.16	0.13	0.59
Poa annua L.	0.01	0.02	0.17	0.03	0.06	0.38
Cyperus sp.	0.01	0.14	0.01	0.03	0.51	0.04
Sonchus asper (L.) Hill	0.02	0.12	-	0.06	0.25	-
Baccharis halimifolia L.	0.12	-	-	0.25	-	-
Erechtites hieraciifolius (L.) Raf. ex DC.	-	-	0.10	-	-	0.29
Gnaphalium uliginosum L.	-	0.06	0.03	-	0.19	0.11
Youngia japonica (L.) DC.	-	0.07	-	-	0.29	-
Euphorbia hirta L.	-	-	0.07	-	-	0.29
Lactuca serriola L.	-	-	0.05	-	-	0.13
Euphorbia hyssopifolia L.	-	0.04	-	-	0.16	-
Mollugo verticillata L.	-	-	0.01	-	-	0.04

B.1 (continued)**.**

Fatoua villosa (Thunb.) Nakai	0.01	-	-	0.03	-	-
Digitaria sanguinalis (L.) Scop.	0.01	-	-	0.03	-	-

B.2. Average and maximum frequency assessment for location 1, year 2 in spring, summer, and late-summer.

	Average Frequency			Maximum Frequency		
Weed Species	Spring	Summer	Late-Summer	Spring	Summer	Late-Summer
Cardamine flexuousa With.	3.04	1.80	2.08	8.33	9.17	11.67
Eupatorium capillifolium (Lam.) Small	5.53	0.85	0.07	18.33	4.17	0.44
Poa annua L.	0.52	3.59	0.93	2.22	17.78	3.11
Oxalis stricta L.	1.39	0.97	1.25	8.33	5.83	7.50
Erigeron canadensis L.	2.63	0.36	-	1.40	1.78	-
Baccharis halimifolia L.	1.80	0.52	-	7.50	2.50	-
Euphorbia maculata L.	-	1.17	0.93	-	3.19	3.00
Eclipta prostrata L.	0.52	0.42	0.39	1.33	2.50	1.33
Youngia japonica (L.) DC.	0.43	-	-	1.60	-	-
Sonchus asper (L.) Hill	0.33	-	-	2.00	-	-
Gnaphalium uliginosum L.	0.16	-	-	0.83	-	-
Thlaspi arvense L.	0.14	-	-	0.83	-	-
Solanum carolinense L.	0.14	-	-	0.83	-	-
Digitaria sanguinalis (L.) Scop.	-	0.14	-	-	0.83	-
Euphorbia serpens Kunth	0.13	-	-	0.80	-	-
Geranium carolinianum L.	-	0.07	-	-	0.44	-
Cyperus sp.	-	0.04	-	-	0.25	-
Euphorbia hirta L.	-	0.04	-	-	0.25	-

B.3. Average and maximum frequency assessment for location 2, year 1 in spring, summer, and late-summer.

	Average Frequency			Maximum Frequency		
Weed Species	Spring	Summer	Late-Summer	Spring	Summer	Late-Summer
Oxalis stricta L.	2.45	0.78	0.32	8.65	3.37	0.96
Eupatorium capillifolium (Lam.)	2.99	0.10	0.07	10.58	0.48	0.24
Erigeron canadensis L.	2.58	-	0.04	8.17	-	0.10
Baccharis halimifolia L.	1.29	-	-	3.85	-	-
Euphorbia maculata L.	-	0.02	1.12	-	0.10	2.96
Cardamine flexuousa With.	0.85	-	0.19	2.88	-	0.77
Gamochaeta purpurea (L.) Cabrera	0.40	0.01	0.05	1.44	0.05	0.19
Sagina procumbens L.	0.26	0.02	-	0.83	0.10	-
Hydrolea quadrivalvis Walter	0.01	0.01	0.18	0.05	0.05	0.81
Amaranthus blitum L.	0.20	-	-	0.42	-	-
Lepidium virginicum L.	0.11	-	-	0.48	-	-

B.4. Average and maximum frequency assessment for location 2, year 2 in spring, summer, and late-summer.

	Average Frequency			Maximum Frequency		
Weed Species	Spring	Summer	Late-Summer	Spring	Summer	Late-Summer
Eupatorium capillifolium (Lam.)	1.32	0.14	0.20	5.29	0.29	0.50
Oxalis stricta L.	0.17	0.58	0.73	0.38	1.47	2.65
Baccharis halimifolia L.	0.51	-	-	2.06	-	-
Euphorbia maculata L.	-	0.30	0.35	-	0.59	0.64
Erigeron canadensis L.	0.31	-	0.24	0.64	-	0.48
Cardamine flexuousa With.	0.21	-	-	0.75	-	-
Hydrolea quadrivalvis Walter	-	-	0.15	-	-	0.59
Sonchus oleraceus L.	-	0.07	-	-	0.29	-
Sagina procumbens L.	0.09	-	-	0.25	-	-
Gamochaeta purpurea (L.) Cabrera	0.02	-	-	0.08	-	-

B.5. Average and maximum frequency assessment for location 3, year 1 in spring, summer, and late-summer.

	Average Frequency			Maximum Frequency		
Weed Species	Spring	Summer	Late-Summer	Spring	Summer	Late-Summer
Cardamine flexuousa With.	25.43	26.29	6.63	63.58	80.69	20.55
Euphorbia maculata L.	0.61	19.45	15.84	1.75	49.83	39.22
Eupatorium capillifolium (Lam.)	2.40	9.60	-	10.63	41.67	-
Eclipta prostrata L.	0.24	5.56	5.13	0.60	9.67	9.85
Digitaria sanguinalis (L.) Scop.	0.04	2.20	2.48	0.20	10.78	12.16
Oxalis stricta L.	-	0.70	2.27	-	2.62	11.11
Erigeron canadensis L.	1.84	0.84	-	6.50	3.60	-
Euphorbia hyssopifolia L.	-	1.60	0.13	-	7.08	0.42
Erogrostis sp.	-	1.58	-	-	7.65	-
Erechtites hieraciifolius (L.) Raf. ex DC.	-	1.43	-	-	6.96	-
Cyperus iria L.	-	1.09	0.16	-	4.51	0.78
Stellaria media (L.) Vill.	0.35	0.81	-	1.76	3.73	-
Cyperus sp.	0.20	0.86	-	0.98	2.16	-
Baccharis halimifolia L.	0.33	0.45	-	0.94	2.03	-
Geranium carolinianum L.	0.12	0.46	-	0.48	1.90	-
Senecio vulgaris L.	-	0.31	-	-	0.95	-
Amaranthus blitum L.	-	0.27	-	-	1.37	-
Poa annua L.	0.03	0.24	-	0.17	1.18	-
Amaranthus palmeri S. Watson	-	0.26	-	-	0.71	-

B.5 (continued)**.**

Amsonia tabernaemontana	-	0.24	-	-	0.98	-
Digitaria ischaemum (Schreb.)	-	0.20	-	-	0.98	-
Solidago canadensis L.	-	0.19	-	-	0.94	-
Erigeron annuus (L.) Pers.	-	0.05	0.13	-	0.24	0.63
Cyclospermum leptophyllum (Pers.) Sprague ex Britt.	0.15	0.03	-	0.42	0.16	-
Amaranthus retroflexus L.	-	0.13	-	-	0.39	-
Gnaphalium uliginosum L	-	0.13	-	-	0.39	-
Eleusine indica (L.) Gaertn.	-	0.12	-	-	0.59	-
Portulaca oleracea L.	-	0.12	-	-	0.59	-
Andropogon virginicus L.	-	0.09	-	-	0.24	
Vicia sativa L.	-	0.05	-	-	0.24	-
Emilia sonchifolia (L.) DC.	-	-	0.04	-	-	0.21
Sagina procumbens L.	-	0.04	-	-	0.20	-
Lolium multiflorum Lam.	-	0.04	-	-	0.20	-
Nuttallanthus canadensis (L.) D. A. Sutton	-	0.04	-	-	0.20	-
Kyllinga brevifolia Rottb.	-	0.04	-	-	0.20	-
Veronica peregrina L.	-	0.04	-	-	0.20	-
Ludwigia leptocarpa (Nutt.) H. Hara	-	0.04	-	-	0.20	-
Sonchus asper (L.) Hill	0.02	-	-	0.10	-	-
Mentha sp.	-	0.02	-	-	0.08	-
Parthenocissus quinquefolia (L.) Planch.	-	0.02	-	-	0.08	-

B.6. Average and maximum frequency assessment for location 3, year 2 in spring, summer, and late-summer.

	Average Frequency			Maximum Frequency		
Weed Species	Spring	Summer	Late-Summer	Spring	Summer	Late-Summer
Eclipta prostrata L.	-	15.65	11.90	-	41.00	25.46
Euphorbia maculata L.	-	4.35	4.66	-	14.33	1.75
Euphorbia hyssopifolia L.	-	5.53	0.53	-	27.33	2.67
Cardamine flexuousa With.	1.31	2.50	1.58	3.41	5.25	6.00
Cyclospermum leptophyllum (Pers.) Sprague ex Britt.	1.90	0.22	0.09	8.00	0.58	0.44
Geranium carolinianum L.	0.89	0.55	-	4.09	2.67	-
Cyperus sp.	-	1.44	-	-	7.00	-
Senecio vulgaris L.	-	1.33	0.08	-	6.67	0.22
Erigeron canadensis L.	0.49	0.09	-	1.59	0.33	-
Eupatorium capillifolium (Lam.)	0.15	0.32	-	0.37	1.33	-
Eleusine indica (L.) Gaertn.	-	0.33	-	-	1.67	-
Oxalis stricta L.	-	-	0.22	-	-	1.11
Digitaria sanguinalis (L.) Scop.	-	0.22	-	-	1.00	-
Poa annua L.	-	0.22	-	-	1.00	-
Amaranthus blitum L.	-	0.20	-	-	1.00	-
Vicia sativa L.	0.18	-	-	0.91	-	-
Callitriche stagnalis Scop.	-	-	0.15	-	-	0.67
Sonchus asper (L.) Hill	-	-	0.17	-	-	0.33
Stellaria media (L.) Vill.	-	0.08	-	-	0.33	-

B.6 (continued).

Nuttallanthus canadensis (L.) D. A. Sutton	-	0.07	-	-	0.33	-
Salix nigra Marshall	0.06	-	-	0.23	-	-
Epilobium ciliatum Raf.	-	0.05	-	-	0.25	-
Senecio jacobaea L.	0.08	-	-	0.23	-	-
Erechtites hieraciifolius (L.) Raf. ex DC.	-	-	0.01	-	-	0.08

Appendix C. Photographs.

Figure C.1. Experimental setup at a container nursery of the pumping system used for irrigation filtration experiments. The backflow discharged from a PVC pipe is directed through a series of three sieves to capture filtrate samples. These sieves captured filtrate samples, while a 5-gallon bucket, with holes drilled to allow water passage, kept the screens off the ground.

Figure C.2. Filtrate samples germinating in substrate filled flats with overhead irrigation (left) and seedling emergence from a sample (right).

Figure C.3. Unidentifiable seedlings grown to maturity after transplanting for identification.

Figure C.4. Components for constructing PVC cylinders for seed submergence tests (left) and an assembled cylinder (right).

Figure C.5. Germination of eclipta (left) and flexuous bittercress (right) following 360 days of submergence in irrigation pond water.