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Multi-Tactic Ecological Weed Management in a Changing Climate

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MULTI-TACTIC ECOLOGICAL WEED MANAGEMENT IN A CHANGING CLIMATE

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A DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy
(in Ecology and Environmental Sciences)

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The University of Maine
December 2018

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MULTI-TACTIC ECOLOGICAL WEED MANAGEMENT IN A CHANGING CLIMATE

By Sonja K. Birthisel

Dissertation Advisor: Dr. Eric R. Gallandt

An Abstract of the Dissertation Presented
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Climate change is expected to impact weed communities in Maine, and the efficacy of tools and tactics farmers use to manage them. Through seedbank sampling and surveys of Maine organic farms, we identified currently rare weeds that are known to be especially abundant or problematic in warmer areas of the USA and might therefore represent an emerging agronomic risk. Many ecological weed management strategies that focus on depleting the weed seedbank are expected to remain effective in a changing climate, and become increasingly important as efficacy of cultivation and some herbicide applications diminish or become more variable. Through field experiments, we evaluated the efficacy of one seedbank management strategy, soil solarization (clear plastic) for stale seedbed creation. We found that two weeks of solarization followed by flaming created an effective stale seedbed, reducing subsequent weed density by 78% as compared to a control prepared with flaming only. In response to farmer questions, we measured solarization's impacts on soil microbiota, and compared its weed control efficacy to that of tarping (black plastic). Soil biological activity was somewhat reduced by solarization, though results are likely temporary. Solarization was more effective than tarping in one site-year, but tarping outperformed solarization in the other. Overall, solarization is a promising weed management strategy for high-value crops, and one that is likely to remain effective in Maine's changing climate. Maine is home to a growing population of beginning farmers, who face steep learning curves related to weed management. As a first step toward improving beginning farmer education, we constructed a digital tool called WEEDucator designed to engage users in interactive learning related to ecological weed management. Through a structured educational intervention we found that WEEDucator improved knowledge of weed ecology and management among agriculture students, and was ranked as a preferred learning method. Overall, the findings of this dissertation can aid in the development of outreach materials on climate-resilient ecological weed management practices suitable for farmers in Maine.

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CHAPTER 1

REVIEW: HOW WILL CLIMATE CHANGE IMPACT THE 'MANY LITTLE HAMMERS' OF ECOLOGICAL WEED MANAGEMENT?

1.1. Introduction

Ecological weed management (EWM) is the application of ecological principles to weed management decisions. The goal of EWM is to simultaneously manipulate the relationships between crops, weeds, and other agroecosystem components to advantage the growth of the crop and limit the growth of weeds, while minimizing negative environmental impacts. The multiple benefits of EWM can include reduced need for pesticide application (Westerman et al., 2005), improved soil quality (Gallandt et al., 1999), and preservation of biodiversity (Benton et al., 2003). Successful EWM typically employs the use of multiple management tactics incorporated into diverse farm rotations, or "many little hammers" (Liebman & Gallandt, 1997), to stress weeds at multiple sensitive points in their lifecycles. Unfortunately, adoption of EWM by farmers has lagged behind our understanding of its benefits, due at least in part to the barrier of increased systems complexity associated with EWM (Bastiaans et al., 2008; Liebman et al., 2016).

Our climate is rapidly changing in response to anthropogenic activities (IPCC, 2014), and we can no longer claim the 'bliss of ignorance' on this subject (Ziska & Dukes, 2011). Climate change will likely affect multiple interconnected aspects of farming systems (IPCC, 2014), with substantial implications for weed management (Figure 1.1). It is human nature to discount the risks of large scale problems like climate change that seem distant or abstract (Jones et al., 2017), but according to the best available science, we cannot rationally afford to delay action on this issue: farmers in hard-hit areas of the world are already adapting to climate change impacts. For example, in response to increasing drought, Bangladeshi farmers reported harvesting rainwater, managing weeds, and implementing new cropping strategies (Hossain et al., 2016). The most recent assessment report from the International Panel on Climate Change (2014) warns that mitigation is needed immediately, as "insufficient responses are already eroding the basis for sustainable development" in some areas of the world. Integration of on-farm adaptation and mitigation strategies (Sivakumar & Stefanski, 2006) into practical and locally applicable farming practice (Johansen, Haque, Bell, Thierfelder, & Esdaile, 2012) is a pressing need.

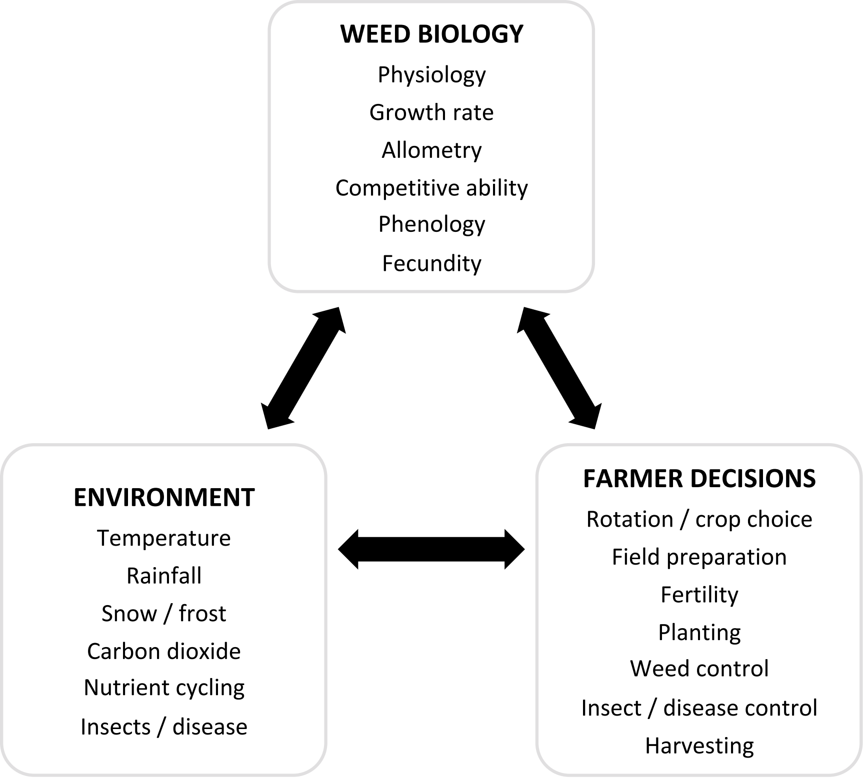


Figure 1.1. Factors Interacting with Weed Management in a Changing Climate. This conceptual diagram shows important factors that may interact to influence ecological weed management in a changing climate.

The principles of sustainable agriculture have been suggested by the IPCC (2014) and others (Ngouajio, 2005; Wall and Smit, 2005; Wolfe et al., 2018) as a helpful existing framework for climate change response. EWM fits within this framework (Liebman & Gallandt, 1997), and may be considered analogous to a pre-adaptation: practitioners of EWM already employ diverse rotations that may help spread risk, while minimizing greenhouse gas emissions and building soil quality by increasing soil organic matter, all of which are likely to aid in the adaptation to or mitigation of climate change (Lengnick, 2015). Recognizing that increased diversity of rotations and integration of non-chemical control tactics are already being advocated and adopted to combat herbicide-resistant weeds (Davis & Frisvold, 2017; Liebman et al., 2016) the barrier of increased management complexity that has heretofore hindered adoption of EWM (Bastiaans et al., 2008) may be less prohibitive than in the past.

1.1.1. Climate Change Effects on Weeds

The ramifications of climate change for weeds growth, phenology, and distribution were first considered by Patterson (1995) more than a decade before Al Gore's film An Inconvenient Truth was released. Recent reviews, and an excellent book (Ziska & Dukes, 2011), have summarized the literature on potential impacts of rising [CO_2] and climate change on weed biology (Kathiresan & Gualbert, 2016; Ramesh, Matloob, Aslam, Florentine, & Chauhan, 2017; Roger et al., 2015; Ziska & McConnell, 2016), demography (Bradley et al., 2010; Clements et al., 2014; Peters et al., 2014), and chemical control (Ziska, 2016).

In isolation from other changes, [CO_2] enrichment benefits both crops and weeds, favoring species with C3 photosynthetic pathways over C4 species (Ziska & Dukes, 2011). However, C4 plants are favored by increasing temperature and water stress, both likely climate change impacts in many regions (IPCC, 2014). From a physiological standpoint, increased [CO_2] typically results in increasing (i) weed biomass, (ii) C:N ratio of leaf tissue, and (iii) root:shoot ratio (Ziska & Dukes, 2011). Increased temperatures can facilitate the spread of invasive weeds (Clements et al., 2014), and high phenotypic plasticity likely pre-adapts many weed species to succeed under increasingly variable temperature and moisture conditions. Moreover, weeds evolve rapidly (Neve et al., 2009), which could contribute to greater range expansion under climate change than predicted with current models (Clements & Ditommaso, 2011).

How [CO_2] impacts combine with temperature, moisture, and other climatic factors to affect future competitive outcomes between crops and weeds existing in real-world communities remains largely an open question (Figure 1.1; Ziska & McConnell, 2016), though the impact of many factors have been examined individually. Competition studies on the impacts of [CO_2] on crops vs. weeds show mixed results, with weeds favored in 8 of 15 studies reviewed by Korres et al. (2016). Less research has been done on the effects of tropospheric ozone (O_3) on weeds, but this too can impact weed-crop competition (Li, Meng, Guo, & Jiang, 2015; Shrestha & Grantz, 2005). Some studies suggest that under drought conditions, weeds can gain a competitive advantage against crops (Finger, Gilgen, Prechsl, & Buchmann, 2013; Valerio, Lovelli, Perniola, Di Tommaso, & Ziska, 2013), while conversely, dry conditions benefitted soybean (*Glycine max* (L.) Merr.) in competition with *Ambrosia artemisiifolia* L. (common ragweed) (Coble et al., 1981).

1.1.2. Climate Change and Weed Management

Research and reviews of the practical ramifications of climate change for specific weed control practices has predominantly focused on herbicide application and efficacy. Overall, weeds are expected to become more difficult to reliably control with herbicides under increasing [CO_2] and climate change (reviewed in Ziska, 2016). For example, glyphosate tolerance can increase in response to [CO_2] (Manea et al., 2011), some grasses can survive pinoxaden under elevated temperatures (Matzrafi, Seiwert, Reemtsma, Rubin, & Peleg, 2016), and isoproturon persistence (effectiveness) can decrease due to soil warming (Bailey, 2004). EWM can include strategic herbicide use, but typically relies on a suite of tactics, or ‘many little hammers’ in addition to or in lieu of chemical control (Liebman & Gallandt, 1997). Practical implications of climate change for the many non-chemical tactics integral to EWM have received scant treatment in past reviews (Ziska & Dukes, 2011).

1.1.3. Purpose of Review and Methods

Ziska (2016) identified as a critical area for future research: “Identification or synthesis of non-chemical weed management strategies that could strengthen weed management with projected changes in climate and [CO_2].” In this chapter, we begin to address this knowledge gap via an applications-focused synthesis of the literature on EWM and climate change. In the sections below, we (i) summarize likely impacts of climate change to agriculture in the 21st century; (ii) consider the implications of these changes for commonly employed non-chemical EWM practices; (iii) identify opportunities for the use of EWM in climate change adaptation and mitigation; (iv) examine barriers to farmer adoption of climate change responses including EWM; and (v) suggest directions for future research.

We began this review by systematically querying the databases Web of Science and Agricola with targeted combinations of search terms (Table 1.1). Two searches were conducted on 3 Aug 2017, the second of which utilized a broader set of terms than the first. Combined, these searches yielded 41 unique abstracts. Considering this insufficient coverage, a third search using a yet broader set of terms was conducted on 16 Aug 2017 (Table 1.1), through which an additional 137 abstracts were identified. Many identified papers are cited herein, though some were omitted due to lack of direct relevance or redundancy with other papers. We have also consulted and cited several additional sources. Although we have attempted a comprehensive review, it is almost certain that, given the interdisciplinary nature of the topic, we have missed relevant studies.

Table 1.1. Summary of Systematic Literature Review. This review was conducted using the databases Web of Science and Agricola.

Date	Abstracts (No.)	Search terms (Boolean phrase)
3 Aug 2017	41	"ecological weed management" AND "climate change"
		"ecological weed management" AND "global warming"
		"ecological weed control" AND "climate change"
		"ecological weed control" AND "global warming"
		"cultural weed management" AND "climate change"
		"cultural weed management" AND "global warming"
		"cultural weed control" AND "climate change"
		"cultural weed control" AND "global warming"
		"integrated weed management" AND "climate change"
		"integrated weed management" AND "global warming"
		"organic weed management" AND "climate change"
		"organic weed management" AND "global warming"
		"organic weed control" AND "climate change"
		"organic weed control" AND "global warming"
		"ecological weed management" AND climate
		"ecological weed management" AND weather
		ecology AND "weed management" AND climate
		ecology AND "weed management" AND weather
16 Aug 2017	137	"weed management" AND "climate change"
		"weed management" AND "global warming"
		"weed control" AND "climate change"
		"weed control" AND "global warming"
TOTAL	178	

1.2. Climate Change Impacts to Agricultural Systems

Climate change is already impacting agriculture, and according to the most recent Intergovernmental Panel on Climate Change assessment report, negative impacts of climate change on crop yields have been more common than positive impacts (IPCC, 2014). This coming century, along with further increases in [CO_2] and mean global temperature, weather patterns are expected to become more variable overall, with likely increased incidence of extreme high temperatures and heat waves across most regions, and increased incidence of heavy precipitation in many parts of the world (Figure 1.2).

Changes in temperature and atmospheric conditions, and their ramifications for plant growth, may be more nuanced than is widely appreciated. Minimum winter temperatures, which often limit plant species ranges and form the basis for hardiness zone designations, are expected to increase in the USA at a faster rate than mean winter temperatures this century (Parker & Abatzoglou, 2016). This has obvious implications for poleward expansion of cold-limited species like *Pueraria montana* (Lour.) Merr. var. lobata (Willd.) Maesen & S.M. Almeida ex Sanjappa & Predeep (kudzu) (Ziska & Dukes, 2011). Similarly, night time temperatures in the Northeast USA have increased at a faster rate than daytime temperatures in recent years, a trend which is expected to continue and may increase night respiration, reducing carbohydrate accumulation and crop yields (Wolfe et al., 2018). The greenhouse gas tropospheric ozone (O_3) is likely to increase in parts of Asia throughout this century, with negative effects on plant growth varying by species and cultivar (Singh et al., 2010).

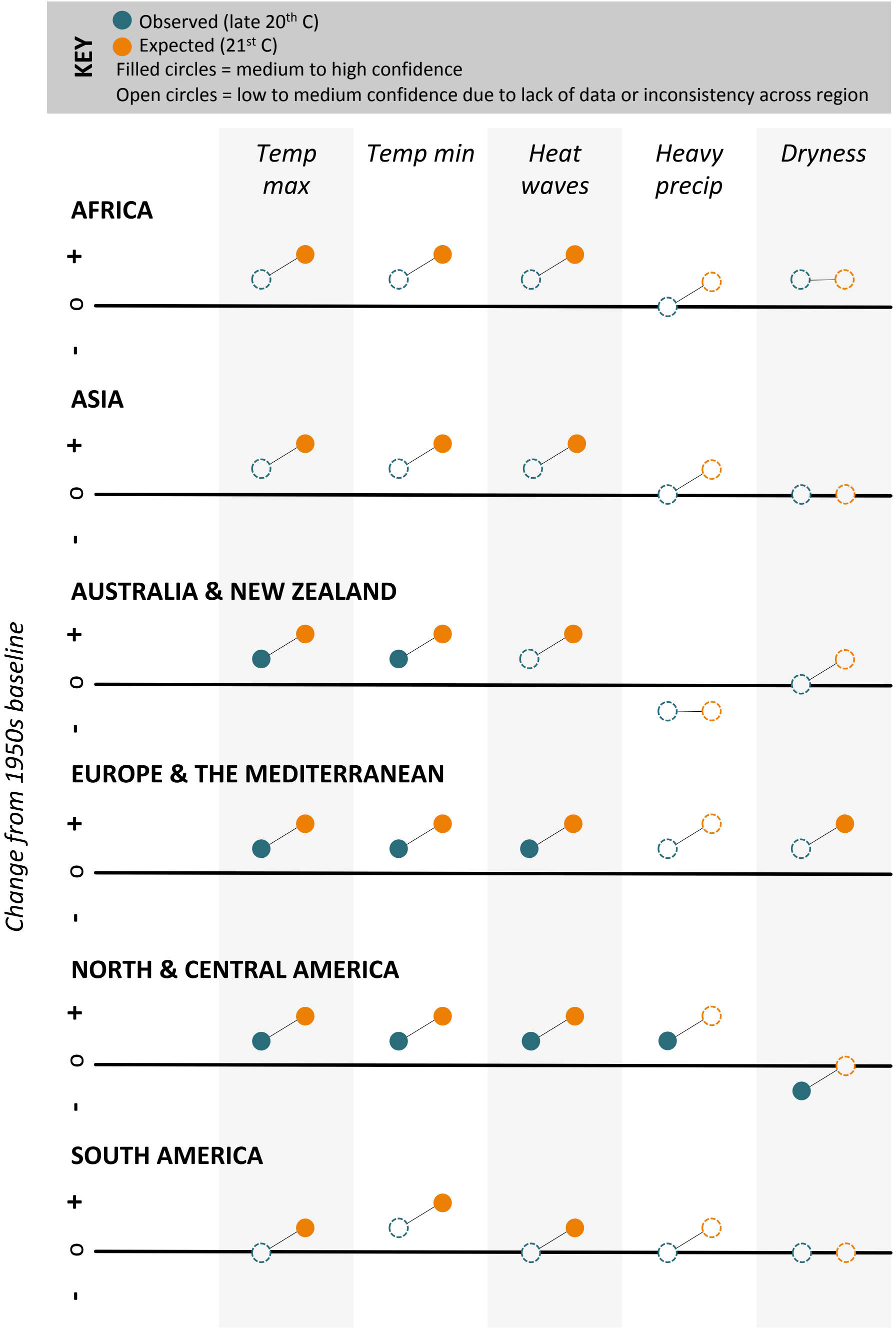


Figure 1.2. Observed and Expected Changes in Climate Extremes. Location of points above or below 1950s baseline indicates trends toward higher (+) or lower (-) incidence of periods with high maximum temperatures, high (less cold) minimum temperatures, heat waves, heavy precipitation events, and unusual dryness. Trends are summarized for six major world regions based on IPCC SREX (Handmer et al., 2012).

An assessment of recent drought risk found overall risk to be most severe in parts of Africa, Europe, and Asia (Carrão et al., 2016), and noted that most areas of the globe currently lack sufficient infrastructure (e.g., irrigation) to cope with drought. Li et al. (2009) used historical data to project future drought risk and potential impacts on yields. They anticipate that drought-affected area and drought severity will increase this century, with resulting significant yield losses to major food crops. Flood risk is likely to increase in some regions of the world while decreasing in others (Kundzewicz et al., 2014). Hirabayashi et al. (2013) projected potential increased flood risk from rivers in much of Central and South America, Africa, and Asia, and decreased risk in the Middle East, much of Europe, and portions of North America.

Future climate change impacts to agriculture are likely to include location-specific changes in the number and timing of 'field working days,' or days when soils are warm and dry enough to conduct field operations. Increased precipitation can decrease field working days by leaving soils too waterlogged to conduct field operations. Few models have been constructed to predict changes in field working days under climate change, and all on fairly limited spatial scales (e.g., Harris and Hossell, 2001). Tomasek et al. (2015, 2017) proposed methods to optimize such models, and projected that for Illinois, USA growing season length by end of century could increase by several weeks, but with potential decreases in field working days during spring planting times.

1.3. Implications for Ecological Weed Management

Fundamental principles of EWM include reducing seedling recruitment, improving crop competitiveness, and reducing seedbank size (Bastiaans et al., 2008). Diversifying in-season management to include physical weed control – either in addition to or in lieu of herbicide use – is also a typical component of EWM schemes (Liebman et al., 2016). In a changing climate, the "many little hammers" (Liebman & Gallandt, 1997) used by growers in implementing EWM will very likely be subject to changes in efficacy. Potential implications of rising [CO_2] and climate change for the utility of important EWM practices, encompassing both efficacy and likely co-benefits provided by practices, are discussed below and summarized in Table 1.2.

1.3.1. Reducing Seedling Recruitment

Practices that limit weed emergence may become increasingly useful, especially mulching strategies, which in addition to smothering weeds can contribute multiple benefits likely to increase on-farm climate change resilience (Lengnick, 2015).

In many vegetable and fruit crops, use of natural and plastic mulches are expected to remain effective methods of weed suppression, while further allowing conservation of soil moisture in dry conditions, and reducing erosion and damage to soil structure from heavy rain (Kader, Senge, Mojid, & Ito, 2017). Mulches are therefore considered likely to become increasingly beneficial under either increasingly wet or dry conditions (Table 1.2). Mulches may change the seasonal distribution of a farmer's workload, as they require labor input at application, but can thereafter diminish hand weeding labor (Brown and Gallandt, 2018A). Mulching is therefore a promising strategy for reducing risk of worker heat stress, which is expected to increase with climate change (IPCC, 2014), though the warming effect of black plastic could lead some crops to overheat with rising temperatures, a factor which could be overcome by switching to white plastic. Both plastic and natural mulches may improve yields, but in developing nations plastic may be less available and more expensive than natural materials (Kader et al., 2017). By contributing to increased soil organic matter, natural mulches could result in less nutrient leaching over time (Connor et al., 2011), mitigating an additional challenge posed by increased rainfall.

Table 1.2. Expected Climate Change Effects on EWM Efficacy. Summary of expected changes in utility of ecological weed management practices under climate change conditions: + indicates positive change, - indicates negative change, ± indicates mixed positive and negative change, and blank space indicates insufficient data.

Principles & practices	↑[CO_2]	↑Temp	↑H_2O	↓H_2O
Reducing seedling recruitment				
Plastic mulch		±	+	+
Natural mulch		+	+	+
Cover crop mulch		+	+	+
Tarping		+		
Manipulating competition				
Competitive crops & cultivars				±
Increase plant density				±
Alter spatial arrangement				±
Intercropping & living mulch			+	±
Cover crops			+	-
Irrigation placement			-	+
Fertility placement			-	+
Transplant	+	±	+	+
Seedbank reduction				
Stale seedbed		+	±	+
Soil solarization		+	±	±
Harvest weed seed control	±		-	+
Short duration cover crops	±		+	
Summer fallow				+
Seed predation				
Diverse physical weed control				
Tillage	-		-	
Cultivation	-	-	-	+
Flaming	-		±	-
Flooding				
Mowing	-		-	
Grazing & herbivory	-	±		
Biocontrol				
Hand weeding		-		

Advances in planter technology are allowing some crops, including wheat, to be sown into heavy residue (Kumar et al., 2013) following cover crop termination, while roller-crimping has emerged as a cover crop termination method that allows for creation of a weed suppressive cover crop mulch without the use of herbicides (as reviewed in Diacono et al., 2016). Combined with high-residue cultivators, these practices can facilitate no-till or conservation agriculture (CA), which can result in high water infiltration rates and increased conservation of soil moisture (Syswerda and Robertson, 2014; Thierfelder et al., 2017), making this a potentially useful adaptation to drier climate conditions (Feiza, Feiziene, Auskalnis, & Kadziene, 2010). CA can also reduce erosion (Mafongoya et al., 2016), and may therefore be adaptive in areas that experience increased incidence of heavy precipitation (Figure 1.2). Indeed, fields in which pumpkins were being grown under CA lost nine times less soil than conventional plots during a simulated storm event, without sacrificing yields (O'Rourke & Petersen, 2016). However, most CA is still heavily dependent on herbicides, and weed management can be a challenge for farmers who either choose to farm organically or lack access to chemical control options. Mafongoya et al. (2016) found in a review and meta-analysis of CA in Africa that adoption led to more hand-hoeing labor. For smallholder farmers, improved tools for two-wheel tractors or animal-drawn rippers and seeders may facilitate adoption of CA (Johansen et al., 2012).

Because light cues are needed to break dormancy in many species (Baskin & Baskin, 1998), practices that limit the exposure of weed seeds to light can reduce seedling recruitment (Riemens, Van Der Weide, Bleeker, & Lotz, 2007). Tarping, the practice of covering soil with black plastic tarps for several weeks prior to planting, has become popular among growers of high-value crops in the Northeast USA and Canada (Fortier, 2014) and can result in creation of an effective stale seedbed (see Chapter 3). Though the mechanisms through which tarping reduces seedling recruitment have yet to be fully elucidated, elevated soil temperatures can contribute to weed seed mortality under black plastic (Standifer et al., 1984); thus, we expect the practice could become more effective in a warming world (Table 1.2).

1.3.2. Manipulating Competition

Choosing fast-growing species and cultivars, manipulating plant spatial arrangement, and increasing plant density are all strategies that have long been used to benefit crops at the expense of weeds (Kumar et al., 2013; Liebman & Gallandt, 1997). By allowing more rapid canopy closure, these strategies could potentially reduce evapotranspiration (Connor et al., 2011) and therefore be helpful under conditions in which moisture is limiting. However, at increased plant densities, intra-specific competition for limited water resources could negatively impact crop yields; results will likely be context-specific (Table 1.2).

Cover-crops provide multiple agronomic benefits (Brennan, 2017; Syswerda & Robertson, 2014), and can contribute to weed control, particularly when termination is timed to pre-empt seed rain (Mirsky, Gallandt, Mortensen, Curran, & Shumway, 2010). In the future, cover crops may become less desirable in increasingly dry areas in which crops rely on stored soil moisture as depletion of water resources may limit growth of subsequent crops (Hunt et al., 2011). In areas where increased heavy precipitation is expected, however, cover crops may reduce erosion risk.

We would intuitively expect intercropping and use of living mulch to become less desirable under reduced moisture conditions, due to competition for water resources. There are, however, success stories: drought-tolerant living mulches decreased weeds without impacting yields in a Japanese asparagus (*Asparagus officinalis* L.) crop (Araki et al., 2012), and some Bangladeshi farmers have responded to recent droughts by intercropping mango (*Mangifera indica* L.) and Indian jujube (*Zizyphus mauritiana* Lamarck) with rice (*Oryza* spp.) (Hossain et al., 2016), diversifying their farm income by incorporating drought-tolerant trees into their rice cropping system. As with mulching and cover crops, intercropping may help protect against erosion in heavy rains.

Where decreased precipitation and soil moisture levels are expected, strategies like drip irrigation and banded fertilizer application may be increasingly effective at providing crops with a competitive advantage against weeds. Conversely, competition for water resources may decrease, and fertility may be more likely lost due to leaching, in areas that experience increased precipitation and soil moisture levels (Table 1.2). More efficient use of water resources is likely to benefit farmers in many regions of the world under climate change (Figure 1.2), and innovations in irrigation technology may therefore be of great use. Gerçek et al. (2017) describe a novel 'water pillow' irrigation system in which long water-filled black plastic tubes with 1mm drip holes are placed alongside crop rows, providing both mulch and gravity-driven drop irrigation. In comparison to a drip irrigated control, their water pillow treatment showed higher water use efficiency and less weed pressure, while maintaining tomato (Solanum lycopersicum L.) yield (Gerçek et al., 2017).

In applicable crops, transplanting may become increasingly beneficial under a range of future conditions (Table 1.2). Transplanting provides crops with a 'head start' against weeds, which may be increasingly important if weed seedling growth rates increase in response to temperature and rising [CO_2] (Peters & Gerowitt, 2014; Ziska & Dukes, 2011). By providing a controlled environment for root system development, transplanting may also reduce mortality at early growth stages that could occur due to moisture extremes in a field setting (Table 1.2). Use of larger containers for starting seedlings could be a simple adaptation to increasing weather variability, providing farmers with greater flexibility in transplant dates.

Many authors have suggested that breeding programs aimed at developing climate change-adapted varieties should select for cultivars that exhibit rapid growth rates or enhanced weed supressiveness (Ngouajio, 2005; Kumar et al., 2013; Korres et al., 2016; Liebman et al., 2016; Robertson et al., 2016). Specific climate-adaptive traits to prioritize in new cultivar development may include greater root:shoot ratio, changes in leaf area and arrangement, and allelopathic attributes (Korres et al., 2016), as well as growth response to [CO_2]. Ziska and Blumenthal (2007) found that older (1920s) varieties of oat (*Avena sativa* L.) had a stronger response to [CO_2] than varieties from the 1990s, suggesting that, unfortunately, past breeding efforts have not necessarily selected plants that are well adapted to rising [CO_2]. Crop varieties with a higher degree of plasticity than has been favored in the past, including landraces or heritage varieties, may be worth re-considering; though maximum yields in a good year may be reduced, choosing varieties with a moderate likelihood of success under a wide variety of conditions could be increasingly sensible in a more variable climate (IPCC, 2014).

1.3.3. Seedbank Reduction

Seedbank depletion can lead to a sustained reduction in weed pressure (Gallandt, 2006), which is expected to be increasingly desired as herbicides (Ziska, 2016) and physical weed control measures (Table 1.2) exhibit lower or more variable efficacy with climate change. Successful seedbank management requires strategies that both maximize seedbank 'debits' and minimize 'credits' (Forcella, Eradat-Oskoui, & Wagner, 1993), effectively targeting weed germination and seed rain. Methods of weed seedbank management include stale seedbed preparation, soil solarization, harvest weed seed control, strategic use of fallow and cover crops, and seed predation.

Encouraging germination is the most effective way to debit the weed seedbank (Gallandt, 2006). This is the principle behind creating a stale seedbed: encouraging weed seeds to germination, then subsequently killing seedlings prior to crop planting or emergence, often with shallow cultivation (Johnson & Mullinix, 2000) or flaming (Rasmussen, 2003). A major trade-off to stale seedbed creation is that it takes time for weeds to germinate, and farmers in regions with short growing seasons may be unwilling to 'waste' growing degree days on this practice. The longer growing seasons expected with continued global temperature rise could therefore lead to wider applicability of this practice (Table 1.2). Efficacy may be increased by irrigating after tillage to encourage a larger 'flush' of weeds (Benvenuti & Macchia, 2006; Kumar et al., 2013). This suggests that stale seedbeds could become increasingly effective under a climate future with increasing moisture, provided wet soils do not limit field access. Though it seems paradoxical, efficacy could also increase with aridity in some circumstances: greenhouse experiments designed to measure the effect of variable precipitation on emergence of *Chenopodium album* L. (common lambsquarters) and *Setaria faberi* Herrm. (giant foxtail) found that emergence of both species increased with longer intervals between precipitation events at low precipitation, but responses varied under typical precipitation amounts (Robinson & Gross, 2010).

Solarization is an intensive form of stale seedbed preparation that utilizes clear plastic to trap solar energy, heating soils to temperatures hot enough to kill weed seeds or seedlings (Horowitz et al., 1983; Standifer et al., 1984). We recently demonstrated that solarization can result in reduced weed density and mortality of weed seeds in the Northeast USA (Chapters 3-4), suggesting that its applicability in temperate regions may be greater than previously assumed (Walters & Pinkerton, 2012). Efficacy of this practice generally increases with both ambient air temperature and soil moisture (Yitzhak Mahrer & Shilo, 2012), though it is also strongly affected by light intensity, which is impacted by cloudiness.

Harvest weed seed control (HWSC) uses specialized machinery pulled behind a combine to pulverize harvested weed seeds before releasing the debris back into the field (Walsh et al., 2013). Weed seed retention at harvest is essential for success of HWSC. Rising [CO_2] is expected to alter flowering dates of many crop and weed species, which may impact future efficacy of HWSC depending on weed-crop combination (Table 1.2). For example, elevated [CO_2] delayed flowering of *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot (Italian ryegrass) (Cleland, Chiariello, Loarie, Mooney, & Field, 2006) but did not alter flowering of wheat (*Triticum aestivum* L.) (Sæbø & Mortensen, 1996), suggesting that HWSC could become more effective for this weed-crop combination due to increased seed retention at harvest. In contrast, elevated [CO_2] accelerated flowering of *Amaranthus retroflexus* L. (redroot pigweed) (Garbutt, Williams, & Bazzaz, 1990) and did not alter flowering in maize (*Zea mays* L.) (Leakey, 2006), suggesting a potential for reduced HWSC efficacy in this weed-crop combination. For a thorough review of [CO_2] effects on flowering time, see Springer and Ward (2007). Of course, [CO_2] does not act in isolation; temperature also affects crop and weed phenology (Ziska & Dukes, 2011), while the impacts of altered precipitation regimes (Figure 1.2) on field working days during the harvest period may increase or restrict the timely use of HWSC (Table 1.2).

Fallow periods (Gallandt, 2014; Rodenburg, 2011) and short duration cover crops (Mirsky et al., 2010) both rely upon timely disturbance, usually by shallow tillage to encourage seedbank depletion through germination and subsequent pre-emption of seed rain. As with HWSC, effects of rising [CO_2] (Springer & Ward, 2007) and temperature (Ziska & Dukes, 2011) on flowering time in some weed species may impact the necessary timing or frequency of disturbance. Summer fallow periods also have utility for conserving soil moisture in water-limited areas (Hunt & Kirkegaard, 2011; Manalil & Flower, 2014), suggesting an important co-benefit of this practice for water-limited systems. Short duration cover crops, however, may become increasingly advantageous in areas with more frequent or heavier precipitation events, as they offer the co-benefits of soil protection and erosion control (Table 1.2).

Seed predation by invertebrates including carabid beetles could increase locally in a warming climate, since invertebrate activity-density and seed consumption rates often increase with rising temperature (Saska et al., 2010; Noroozi et al., 2016). However, these relationships will be impacted by changing demography of seed predators and the flora and fauna with which they interact, including changing migration patterns of birds (Charmantier & Gienapp, 2014) which can be important seed predators in some systems (Birthisel, Gallandt, Jabbour, & Drummond, 2015). Mohles and Westoby (2003) undertook a literature review to test the hypothesis that seed predation is greater in the tropics than in cooler regions. Contrary to expectations, they found no relationship between seed predation and latitude, suggesting that large-scale trends in seed predation might be relatively unaffected by climate change, and more information is needed before making strong predictions on this topic (Table 1.2).

Climate change likely has further implication for the longevity and dynamics of not only weed seeds (Long et al., 2015), but other propagules including perennial roots and rhizomes. As one example, declining winter snowpack may allow soils to freeze to greater depths (Tatariw et al., 2017; Patel et al., 2018), potentially increasing propagule mortality. Farmers in Japan have employed this mechanism to kill overwintering *Solanum tuberosum* L. (potato) weeds, mechanically removing snow from their fields to increase frost depth (Yanai et al., 2014). Strategic fallowing to bring perennating organs closer to the soil surface, thereby increasing mortality through freezing in winter (Schimming and Messersmith, 1988) or desiccation in summer (Foster, 1989; Liebman et al., 2001) may become increasingly effective with, respectively, decreasing snowpack and increasing aridity.

1.3.4. Diverse Physical Weed Control

Physical weed control practices, especially tillage and cultivation, are integral to many EWM systems. Climate change has substantial implications for efficacy of physical weed control since as these practices are generally more sensitive to environmental conditions than are herbicide-based controls (Liebman et al., 2001).

Changes in precipitation frequency and amount will likely alter the number and seasonal distribution of field working days, affecting a farmer's ability to implement timely physical weed control. Whether field working days will increase or decrease at key times of year is expected to vary by locale (Tomasek et.al., 2017). Attempts to predict field working day probabilities under simulated climate change conditions are surprisingly few (Cooper et al., 1997; Harris and Hossell, 2001; Trnka et al., 2011; Tomasek et al., 2017), but may offer a window into future risk that could help farmers prioritize strategic equipment and infrastructure investments.

Tillage efficacy for control of perennial weeds may decrease in future as rising [CO_2] is known to increase root:shoot ratio of several perennial species (Ziska & Dukes, 2011), which could facilitate regrowth from root fragments. Though tillage will likely continue to be an effective means of killing annual weeds, changes in phenology may alter the times of year at which tillage is most helpful. For example, Zahra et al. (2009) reported that all the significant winter annual weeds in Canada are facultative; movement away from fall weed management might therefore encourage current summer annuals to become winter annuals with climate change. Conversely, Tozzi et al. (2014) found that winter warming periods limited the success of *Erigeron canadensis* L. (Canada fleabane) as a winter annual by reducing the survival of rosettes and seedlings, but also promoted earlier flowering, implying that earlier spring tillage or other suitable control measures might be needed in future to pre-empt seed rain for this species.

Efficacy of shallow soil disturbance (cultivation) often improves with dry soil conditions (Cirujeda and Taberner, 2004; Evans et al., 2012), implying that cultivation may be increasingly useful in areas of the world expected to experience increased dryness, but less reliable in areas experiencing increasing soil moisture (Figure 1.2). Duration of the 'critical weed free' period during which weeds must be controlled to avoid reductions in crop yield is also moisture sensitive. For example, Coble et al. (1981) reported that the critical weed free period for *A. artemisiifolia* was two weeks in dry years compared to four weeks in wet years. Peters and Gerowitt (2014) measured increased height in three annual weed species grown under increased temperature and low humidity, suggesting that, given cultivation is most effective on small seedlings (Cirujeda & Taberner, 2004), rising temperatures could contribute to declining efficacy in some circumstances. The utility of cultivation for control of perennial weeds is already low, and may decline with the positive effects of rising [CO_2] on root:shoot allocation (Ziska & Dukes, 2011). We are aware of no studies comparing impacts of rising [CO_2] to growth allocation in annual weeds compared to crops, though studies on this topic would be useful in predicting ramifications of [CO_2] increase for selectivity, a crucial consideration for in-row cultivation (Kurstjens & Perdok, 2000).

In regions where field working days may become fewer or less predictable, strategies that increase cultivation efficacy and reduce variability may help farmers make best use of ‘breaks in the weather’ when conditions are suitable for cultivation. Brown and Gallandt (2018) found that strategically “stacking” multiple cultivation tools for a single pass resulted in relatively high cultivation efficacy (75%), with evidence of synergistic effects based on the combined modes of action between implements. For some tool combinations, this synergy was maintained across a range of weed sizes and soil moisture conditions (Brown & Gallandt, 2018), making this a promising practice for a climate future characterized by increased seedling growth rates and precipitation variability. Use of wider cultivation machinery could allow more ground to be covered per cultivation pass, representing another strategy for optimizing use of potentially limited field working days. Similarly, camera guidance systems that use hydraulic side-shifting to maintain precise distance between cultivation implements and crop rows

(Melander, Lattanzi, & Pannacci, 2015) may improve working rates, and are being adopted for use in vegetable, row, and cereal crops. Finally, progress in robotic technology is paving the way for further mechanization of cultivation operations (Fennimore et al., 2016; Merfield, 2016; Bawden et al., 2017); lightweight autonomous robotic weeders could access fields too muddy for tractor operations, expanding the conditions suitable for cultivation and other physical weed control techniques.

Flaming can be conducted with tractor-drawn equipment, or at small scales with a hand-held torch and backpack-mounted propane cylinder. It remains effective when soils are moist (Ascard, Hatcher, Melander, & Upadhyaya, 2007), but tractor accessibility could become limited under wet conditions. In increasingly arid regions, applicability of flaming could be limited due to danger of wildfires (Ziska and Dukes, 2011; Table 1.2).

Flooding is an effective and commonly used weed control strategy for transplanted rice (Kumar et al., 2013), and was listed by Rodenburg (2011) as a practice that may contribute to climate change adaptation in African rice systems. However, its continued applicability and potential for expansion in a changing climate will be contingent upon future water availability. Irrigation and water-holding infrastructure may be forward-looking investments for some farmers (Kumar et al., 2013), but will only be beneficial if sufficient irrigation water is locally available, and given that projections of future precipitation and water availability are characterized by uncertainty (Kundzewicz et al., 2014; Li et al., 2009), we defer to Rodenburg's (2011) view that there is no "one-size fits all" solutions for rice growers in a changing climate.

Where water is not limiting, increasing [CO_2] could increase plant growth, thereby necessitating more frequent mowing or grazing to control grassland weeds (Ziska and Dukes, 2011). Rotational grazing can be beneficial for weed control (Tozer et al., 2008), and has been cited as a climate change best management practice in Vermont, USA (Helling, Conner, Heiss, &

Berlin, 2015), but it may not be ideally suited to all regions: grazing with sheep in a Montana dryland cropping system did not reduce global warming potential in comparison to herbicide application (Barsotti, Sainju, Lenssen, Montagne, & Hatfield, 2013). Rising temperatures and changes to the C:N content of weed biomass (e.g., Blumenthal et al., 2016) could impact grazing, herbivory by insects, and biological control of weeds. Some biological control agents may be capable of increasing efficacy (Kriticos, Watt, Withers, Leriche, & Watson, 2009) by increasing feeding rates or number of generations possible per year (Seastedt, 2014). However, different responses to warming between agent and host may alter phenological synchrony, potentially decreasing efficacy (Seastedt, 2014). Overall, it seems premature to set general expectations for how this might impact EWM.

Hand weeding remains common practice in organic (Baker and Mohler, 2015) and specialty crop systems (Fennimore & Doohan, 2008), as well as among many smallholder farmers worldwide (Gianessi, 2013; Johansen et al., 2012). The IPCC (2014) indicates increased risk of mortality and morbidity for those working outdoors during periods of extreme heat. Since incidence of extremely warm days and heat waves are expected to increase globally (Figure 1.2), it follows that this may reduce working rates for hand weeding (Table 1.2) and other manual tasks, making timely and effective implementation of more mechanized control tactics, as well as cultural practices and a focus on reducing seedbanks and seedling recruitment, increasingly important. Difficulties with weed control were reported among several forms of climate-related occupational stress in Southwest Nigeria (Oyekale, 2015), where increased heat waves due to climate change may already be impacting farming (Figure 1.2). Farmers in Bangladesh, however, reported strategic hand hoeing as a climate change adaptation they used to minimize drought impacts (Hossain et al., 2016); farmers simultaneously hoed and closed surface cracks in their soil to minimize water loss. Innovation in and adoption of hand tools that increase working rates with little cost to efficacy (E. Gallandt, unpublished data) could benefit small-scale growers under diverse climatic conditions.

1.4. Adoption of Value-Added EWM Practices

"If you are doing something for just one reason… Stop."

The successful vegetable farmer quoted above expressed the view that every farm management decision should result in multiple benefits (T. Roberts, personal communication). IPCC guidance is in concordance, recommending climate adaptation strategies that have co-benefits, including adoption of more environmentally sustainable agricultural practices (IPCC, 2014). Many EWM tactics including mulching, transplanting, and situationally appropriate practices to target the weed seedbank could gain greater utility with climate change (Table 1.2), either by increasing efficacy of weed management or conferring co-benefits likely to enhance system resilience.

Given that farmers may underestimate the challenge of climate change (Jones et al., 2017), outreach outcomes (i.e., adoption of climate resilient EWM practices) might be improved by focusing on co-benefits. Highlighting this point, Li et al. (2017) found that the climate change adaptation behavior of Hungarian farmers was largely driven by financial and managerial considerations, though experience with extreme weather and social factors were also important. In developed nations, the need for increased systems complexity has been a barrier to farmer adoption of EWM (Bastiaans et al., 2008). However, complexity of conventionally managed systems is expected to increase regardless: the proliferation of herbicide-resistant weeds and paucity of new herbicide modes of action (Davis and Frisvold, 2017; but see Yan et al., 2018) will likely necessitate application of more diverse tactics (Ziska & McConnell, 2016). Identification of diversified management strategies that allow farmers to simultaneously address the co-occurring challenges of herbicide resistance and climate change, coupled with tailored outreach that considers farmer decision making contexts (Chatrchyan et al., 2017; Liebman et al., 2016), could be of great benefit in our present climate.

1.4.1. Directions for Future Research

The best available science suggests that climate change is already impacting agriculture and will do so increasingly throughout this century (Figure 1.2; IPCC, 2014). Many questions remain regarding the impacts of climate change and rising [CO_2] on weeds and the control strategies employed in EWM. Below, we briefly outline three directions for future research that we consider to be of high priority, on topics that have been little addressed in weed science research to date.

1. Understanding farmer decision-making. Few studies have examined farmer perceptions and decision-making around EWM (Jabbour, Gallandt, Zwickle, Wilson, & Doohan, 2014; Jabbour, Zwickle, et al., 2014; Zwickle, Wilson, Bessette, Herms, & Doohan, 2016; Zwickle, Wilson, & Doohan, 2014), and though there is a growing literature on farmers perceptions of climate change (e.g., Roco et al., 2015; Arshad et al., 2016; Niles and Mueller, 2016; Chatrchyan et al., 2017; Li et al., 2017), substantial knowledge gaps remain. We are aware of only one study in which weed management and climate change perceptions have been jointly considered (Hossain et al., 2016). More collaboration with social scientists in bridging this gap could provided guidance for designing targeted outreach approaches (Jones et al., 2017) that can help overcome barriers to adoption of climate resilient EWM practices (Liebman et al., 2016).
2. Creating engaging decision-aid tools. The interface of EWM and climate change is a complex, dynamic system (Figure 1.1). Simulation models have been extensively used to predict weed demographic shifts under climate change (e.g., Kriticos et al., 2009), and can facilitate the design of cost-effective invasive species management plans (Richter,

Dullinger, Essl, Leitner, & Vogl, 2013), but we have seen few examples of success in translating such models into user-friendly tools accessible to stakeholders. Summers et al., (2015) developed a decision-aid called the Landscape Futures Analysis Tool that includes a weed management model and an ability to project climate changes, and the Climate Smart Farming project has developed several excellent tools, though none as yet related to weed management (CSF Extension Team, 2018). Tools that engage users in learning through virtual trial and error may be useful for outreach on topics like EWM that at the outset can appear complex or abstract (Chapter 5).

3. Practical research. Expert opinion holds that, given the magnitude of the challenge, humanity's collective response to climate change has thus far been too slow (IPCC, 2014). Given this, there seems pressing need to pursue applied solutions that offer both mitigation and adaptation benefits (IPCC, 2014). Research to reduce variability in efficacy and improve the fossil fuel efficiency of physical weed control, including through innovative tool design (Brown and Gallandt, 2018) and robotic weeders (Bawden et al., 2017), is a promising area of inquiry. Given that 72% of the world's farms are less than 1 ha in size (Lowder et al., 2016) we also think it important to consider what innovations in small-scale tools (Johansen et al., 2012) could enhance the basis for EWM among smallholder farmers. Finally, we believe there is a pressing need for cropping systems research aimed at developing 'value-added' approaches that (i) are profitable and help diversify farm income, (ii) consider local farmer opinions and constraints, and 3) utilize ecological pest management and minimize external inputs (Khan et al., 2016; Khan et al., 2014). Interdisciplinary teams (Jordan et al., 2016; Liebman et al., 2016) may facilitate the development of EWM approaches that can be fully integrated into profitable and climate-resilient cropping systems .

CHAPTER 2

SCOUTING FOR 'RARE' WEEDS ON MAINE ORGANIC FARMS

2.1. Introduction

Agricultural weeds are a significant production challenge on organic farms in the Northeast USA (Walz, 2004). To better understand how climatic and edaphic factors impact weed communities in our region, we previously undertook a study of weed seedbanks across Maine, New Hampshire, and Vermont. We found that temperature-related variables including latitude, longitude, and mean maximum and minimum temperatures were generally stronger and more consistent correlates with weed seedbank composition than were edaphic factors (Smith et al., 2018). Further, an indicator species analysis suggested that particular plant hardiness zones were associated with a number of regionally problematic weed species (Smith et al., 2018), suggesting that climate may be an important factor impacting species abundances in our region.

Maine's climate is already changing, and recent trends are expected to continue in coming decades. Average annual temperatures and total precipitation increased by 1.7 °C and 15 cm, respectively, between 1895 and 2015 (Fernandez et al., 2015). The average length of the warm season in Maine increased from 32 to 34 weeks over this time frame, and another two weeks are expected by mid-century (Fernandez et al., 2015). Throughout this coming century, plant hardiness zones are expected to move northward (Parker & Abatzoglou, 2016), average snow pack depths to decrease substantially (Fernandez et al., 2015), and despite continued precipitation increases, drought risk may intensify due to greater evapo-transpiration (Wolfe et al., 2018).

Climate change is generally expected to increase the spread of invasive weeds (Clements et al., 2014; Hatfield et al., 2014), but increasing [CO_2] and climate change will likely also alter competitive relationships between currently endemic species (Ziska & Dukes, 2011). Most studies in the weed science literature, including those related to effects of climate change on weeds, tend to focus on abundant species that pose the greatest present threat to farm management. Few studies have focused specifically on rare weeds, and these have typically emphasized species of conservation concern in Europe (e.g., Albrecht & Mattheis, 1998; Epperlein, Prestele, Albrecht, & Kollmann, 2014; Kleijn & Voort, 1997; Pinke & Gunton, 2014; Rotchés-Ribalta, Blanco-Moreno, Armengot, José-María, & Sans, 2015). We considered that some weed species currently rare in Maine might be at the northern end of their range, and thus potentially pre-adapted to future climatic conditions. We hypothesized that these species could pose an emerging risk to farm management. To identify species of likely future agronomic risk, we undertook a study of relatively uncommon weedy flora in Maine (referred to hereafter as 'rare') through further analysis of our prior seedbank work (Smith et al., 2018) and new surveys conducted at 32 farms across Maine.

2.2. Materials and Methods

2.2.1. Seedbank Analysis

Rare weeds present in our prior seedbank sampling work were identified using the methods detailed in Smith et al. (2018) and summarized here. Weed seedbank samples were collected during the spring of 2013 from 30 Maine organic farms. Farm locations were chosen to provide a broad geographic coverage of the state, representing six USDA plant hardiness zones (6a to 3b; Figure 2.1). Most farms grew primarily vegetables, though some also kept livestock and several in Aroostook County grew primarily potatoes or small grains. Two replicate samples for seedbank analysis, each consisting of five bulked soil cores, were collected from a single field at each farm. To measure the weed community, germinable seedbank assays were conducted in a greenhouse (Jabbour, Gallandt, et al., 2014). Samples were spread evenly atop medium grade vermiculite in greenhouse flats and kept moistened to promote germination. Flats were monitored, and emerged seedlings identified and removed regularly until emergence slowed, at which point samples were dried, mixed, and re-watered to promote another 'flush' of emergence. This process was repeated over the course of 6 months to thoroughly exhaust the germinable seedbank. Replicate samples from each farm were averaged.

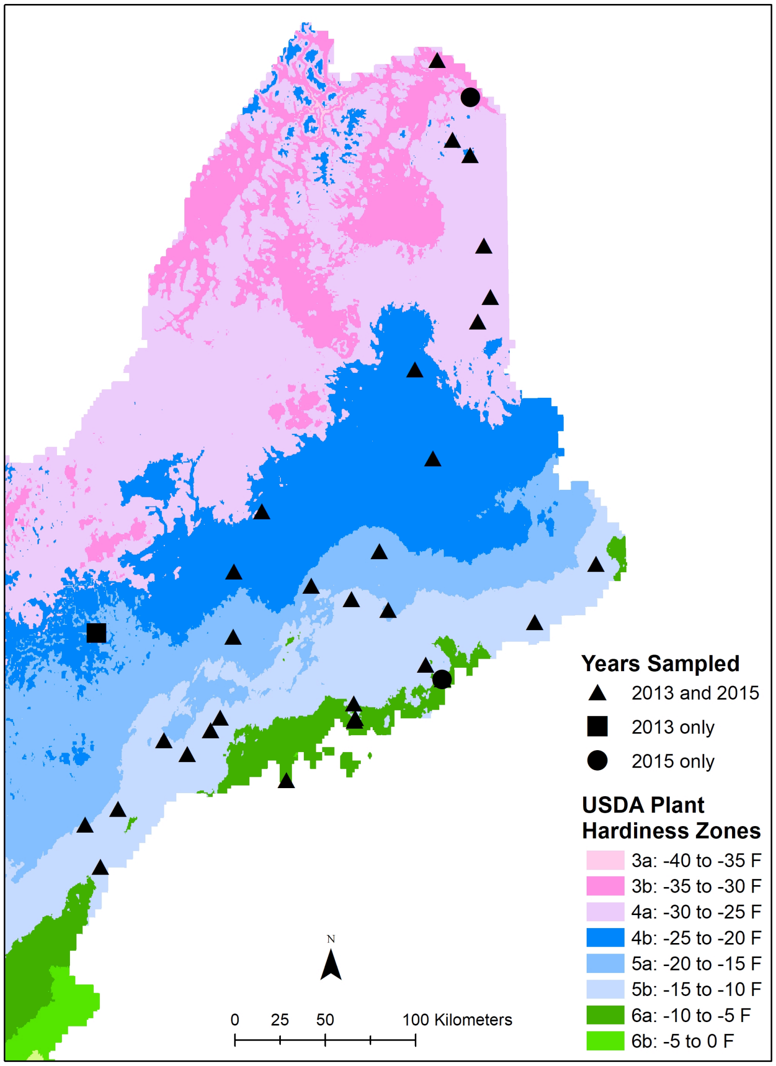


Figure 2.1. Map of Sample and Survey Site Locations. Locations of farms in Maine participating in 2013 weed seedbank and 2015 surveys, overlaid on a map showing plant hardiness zones (ARS, 2017).

Two criteria were used to identify rare weed species in these data. First, species were categorized as rare if they were found in the seedbank of only one farm. Second, they were considered rare if present at low densities relative to other species. We compared the sum of seeds m^{-2} across the 30 farms to an arbitrary threshold of 100 seeds (per 30 m^2) and categorized species present below this density as rare. A limitation to this method was that some perennials, especially those that reproduce through vegetative propagules, were likely underrepresented in the seedbank relative to their on-farm density and might therefore have been erroneously categorized as rare.

2.2.2. Field Surveys

Field surveys were conducted on Maine organic farms during the period 9 July 2015 through 29 August 2015. Farms were prioritized for inclusion based on geographic coverage of the state and participation in our prior study of weed seedbank communities (Smith et al., 2018). We sampled 32 total farms, 29 of which had previously participated in our seedbank sampling work and six of which were located on islands off the Maine coast that could be reached only by ferry (Figure 2.1).

Upon arrival at each farm, we asked the farmer or a field crew leader (a) whether they had noticed any new weeds on the farm, and (b) to direct us to three fields with the most growth of mature weeds. Multiple 1 m by 10 m transects were surveyed in each of the fields: one transect across the center of the field perpendicular to the direction of tillage, and one or more additional transects running parallel to field edges such that there was a 1 m buffer between the field edge and the transect, and 50 m distance left between the end of each transect and the beginning of the next. In the event that a farm had fewer than three fields in production (five farms), one or two fields were sampled. Transect size and distances between transects were measured by visual estimation. Number of edge transects per field varied based on field size, and was capped at a maximum of ten per field in most cases. In total, 512 transects were sampled. This sample design was adapted from Rotchés-Ribalta et al. (2015); inclusion of edge transects was considered important because these areas can be refugia for rare species.

Presence of rare plant species in a transect was determined by expert opinion of the surveyors; two surveyors participated in this project, both of whom were graduate students with research foci in weed science. If the identity of a plant was unknown, the surveyor either collected a specimen or, if only one plant of that type was present, took a picture for later identification. Visual estimates of percent ground cover (ranked: 1 = 0-19%; 2 = 20-39%; 3 = 40-59%; 4 = 60-79%; 5 = 80-100%) and vegetation height (ranked: 1 = < 5 cm; 2 = 5-9 cm; 3 = 10-19 cm; 4 = 20-49 cm; 5 = > 50 cm) were also recorded in each transect. A separate record of rare species noticed outside the transect sampling scheme or pointed out by the farmer was kept for each farm.

2.2.3. Identifying Unknown Specimens

Unknown plant specimens were identified to the highest taxonomic level possible using dichotomous keys (Gleason & Cronquist, 1991; Haines, 2011) cross-referenced with other identification resources (GoBotany, 2018; Hitchcock, 1971; Knobel, 1977; Uva, Neal, & DiTomaso, 1997) and the University of Maine Herbarium collection and staff expertise. Specimens were identified in their fresh condition whenever possible, but because a large number of unknowns were collected, a plant press was used to dry some specimens for later identification. We were unable to identify some specimens that were in poor condition or at an immature life stage when sampled. Immature stages prevented us from identifying many members of the Asteraceae, likely including those in the *Erigeron, Solidago,* and *Symphyotrichum* genera, which can be difficult to distinguish in immature forms.

2.2.4. Identifying Species of Concern

We categorized rare species found via seedbank sampling and surveys as weedy if they were listed in the Weed Science Society of America's Composite List of Weeds database (WSSA, 2018); other species were categorized as non-weedy. The USDA PLANTS database was used to determine if species were native or non-native to Maine, and endangered or of conservation concern (NRCS, 2018b).

We identified species of likely agronomic risk by cross-referencing our species lists with data from a recent survey of weed scientists (Van Wychen, 2016) that asked respondents to list the five most abundant and five most troublesome weeds for major crops in their state. To determine whether any of our presently rare weed species are especially abundant or problematic in areas with warmer climate, we compared our species lists to a subset of these survey results ($N_{subset} = 121$) corresponding to annual crops grown in states with median plant hardiness zones warmer than that of Maine (ARS, 2017).

2.2.5. Statistical Analysis and Data Visualization

To assess whether richness of rare weed species in our 2015 transect sampling might be related to environmental variables, we constructed a hurdle model using the {pscl} package (Jackman, 2017) in R (R Core Team, 2016). Species richness per transect was the dependent variable. Latitude and longitude were fit as explanatory variables; in Maine, these gradients represent proxies for northerly and coastal climate effects, respectively, and were important predictors of weed community composition in our past work (Smith et al. 2018). Average vegetation height, percent ground cover, and surveyor were included as additional explanatory variables to account for variability in farm management and sampling. A hurdle model with a Poisson distribution was selected based on a relatively low AIC value in comparison to other candidate models (Crawley, 2013). Hurdle models handle count data with many zeros and overdispersion by simultaneously fitting separate models to zero and non-zero counts (Zeileis, Kleiber, & Jackman, 2008), and are recommended for data with many ‘true zero’ values (Martin et al., 2005).

We used principle coordinates analysis (PCoA) to visualize the relationships between communities of rare weeds and environmental variables. These analyses utilized presence/absence of weeds found in our transect sampling (81 species). We excluded transects in which no rare weeds were reported ($N_{included}$ = 273). PCoA was chosen and Jaccard selected as the distance measure because Gotelli and Ellison (2004) suggest these methods as well suited to analysis of presence/absence data. The ordination was performed in R (R Core Team, 2016) using the {vegan} package (Oksanen et al., 2016). Environmental data was overlaid on the first two PCoA axes using the surf() function in package {labdsv} (Roberts, 2016), which fits a generalized additive model to a surface and calculates D^2, a goodness of fit metric based on deviance explained by the model.

To determine how environmental variables might be related to the distribution of individual species of likely agronomic risk, we constructed logistic regression models in R (R Core Team, 2016). Analyses were restricted to species of likely risk (identified in section 2.2.4) for which more than twenty presence values were recorded across at least five different farms. For each species, presence/absence was fit as the response, and latitude, longitude, vegetation height, ground cover, and surveyor were explanatory variables. Presumably due to many zero values in these data, assumptions of low leverage were generally not met. Maps showing transect occupancy were created using ArcMap (ESRI, 2011).

2.3. Results

2.3.1. Species Diversity

A total of 87 plant species were identified from our 2013 seedbank samples collected at 30 farms across Maine. Of these, 26 were categorized as rare weeds according to one or both of our metrics (see Table A.1 in Appendix A for species list). Through subsequent surveys conducted in 2015 to scout for rare weeds on 32 farms, we found 11 of these species previously identified as rare, and an additional 84 plant species unique to our surveys. Of these unique species, 81 were within the transect sampling scheme, and three were noted outside of transects only; 73 species were weedy (see Appendix A Table A.2 for species list).

Richness of rare species identified via transect surveys varied by farm, ranging from one to 16 species per farm with a mean and standard deviation of 7.0 ± 4.6. In the count portion of our hurdle model, there were significant relationships between richness of rare species and longitude, vegetation height, and surveyor (Table 2.1). Specifically, species richness was positively associated with both longitude and vegetation height (Figure 2.2), and one surveyor reported significantly more rare species than did the other.

Table 2.1. Hurdle Model Analysis of Deviance Table. Analysis of deviance for count model portion of species richness hurdle model. Asterisks (*) denote significance at $\alpha = 0.05$.

	DF	Chi-squared	*P*
Latitude	1	2.97	0.08
Longitude	1	6.86	<0.01*
Vegetation height	1	7.90	<0.01*
Ground cover	1	2.24	0.13
Surveyor	1	48.39	<0.01*

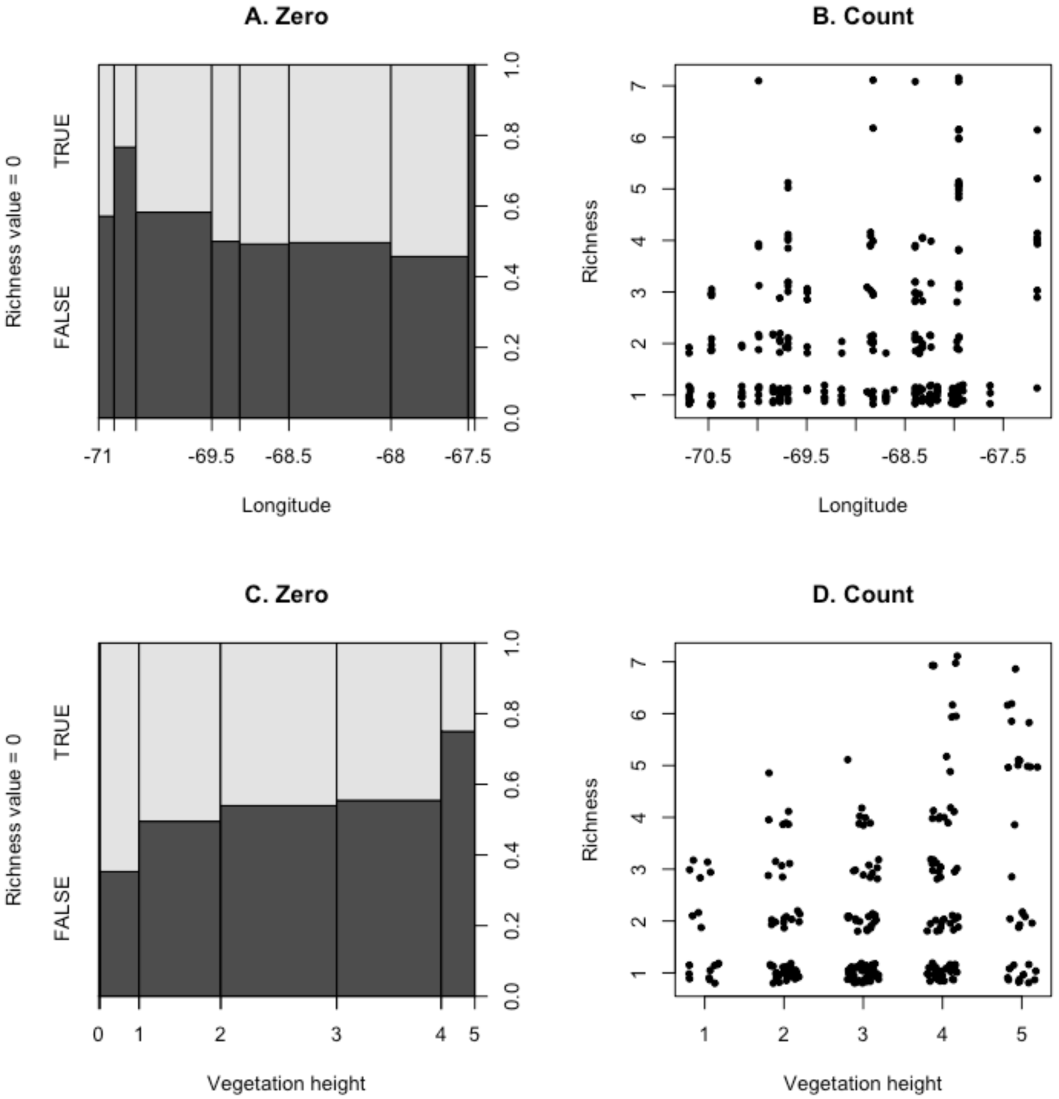


Figure 2.2. Effects of Longitude and Vegetation Height on Species Richness. Relationships between richness of rare weed species and longitude in zero (A) and count (B) components of hurdle model, and between richness and vegetation height for zero (C) and count (D) components. A ‘jitter’ graphical setting was used to diffuse points in (B) and (D) for ease of viewing.

2.3.2. Community-Level Analyses

Principle coordinates analysis was used to visualize community-level patterns of the transect survey data and overlay these with environmental variables (Figure 2.3). The first principle coordinate (PCO 1) explained 10% of variance, and the second (PCO 2) explained 7%. Of the four environmental variables examined, latitude was the most strongly related to the ordination (D^2 = 0.30; Figure 2.3A), followed by average vegetation height (D^2 = 0.25; Figure 2.3C), ground cover (D^2 = 0.17; Figure 2.3D), and longitude (D^2 = 0.16; Figure 2.3B).

2.3.3. Species of Concern

2.3.3.1. Species of Likely Agronomic Risk

Among the rare species identified using our seedbank methods and surveys, 20 were identified by our analysis of Van Wychen's (2016) data as either very abundant or particularly troublesome in warmer regions of the USA (Table 2.2). Four of these species were considered abundant enough to fit with logistic regression models. Presence/absence of *Elymus repens* and *Persicaria pensylvanica* were not significantly related to latitude or longitude (Figure 2.4A,D; Table 2.3), but *Panicum capillare* and *Persicaria maculosa* were both positively associated with more southerly latitudes (Figure 2.4B,C; Table 2.3). There was a significant effect of surveyor in three out of four models (Table 2.3).

One species of likely agronomic risk, *Erigeron canadensis*, was reported in our seedbank samples but not our transect surveys. Maps showing site occupancy of the other 19 species of likely agronomic risk can be found in Appendix A (Figure A.1). Seven of these were each reported on one farm only: *Avena fatua, Cerastium glomeratum, Lactuca serriola, Panicum dichotomiflorum, Senecio vulgaris, Setaria viridis,* and *Solanum physalifolium*; others were reported present at multiple farms.

One species found outside the transect sampling scheme, *Pastinaca sativa* L. (wild parsnip), was pointed out by two different farmers as a new weed of concern on their farms.

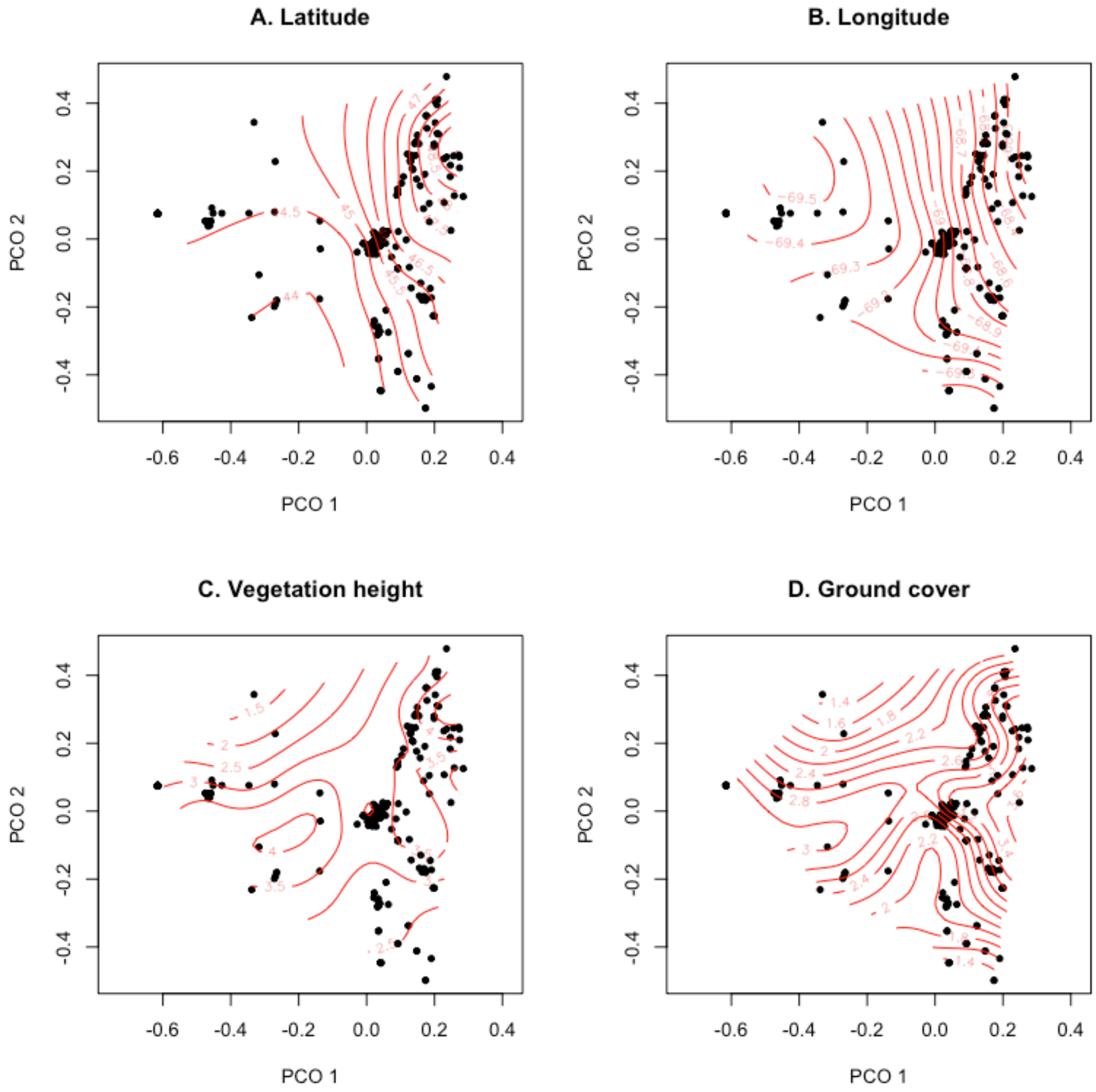
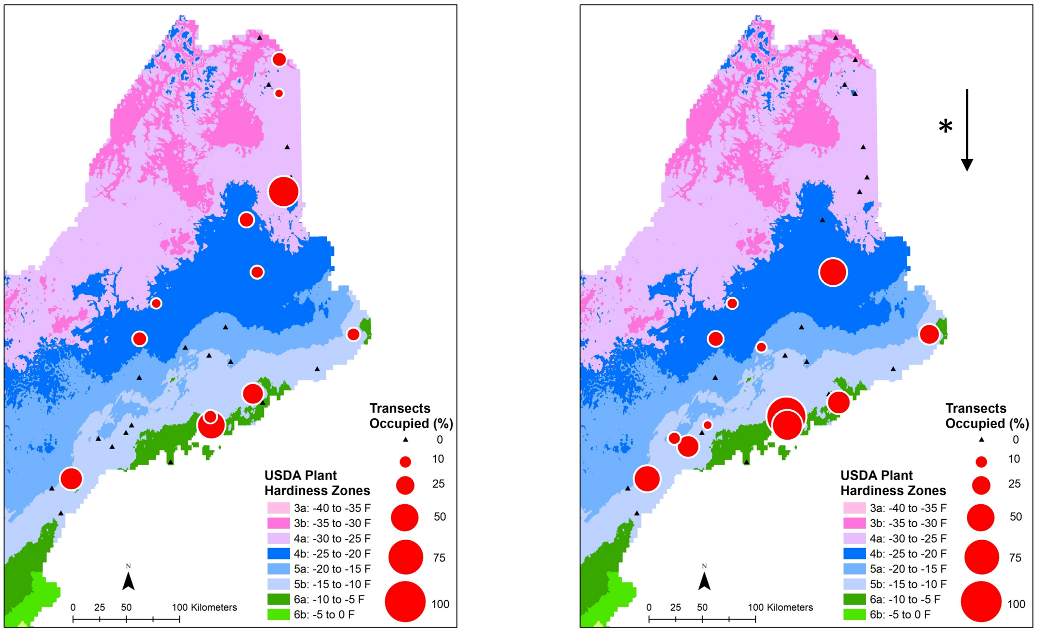


Figure 2.3. PCoA Ordination of Rare Weed Communities. Principle coordinates analysis (PCoA) overlaid with environmental gradients: latitude (A), longitude (B), vegetation height (ranked: 1 = < 5 cm; 2 = 5-9 cm; 3 = 10-19 cm; 4 = 20-49 cm; 5 = > 50 cm) (C), and ground cover (ranked: 1 = 0-19%; 2 = 20-39%; 3 = 40-59%; 4 = 60-79%; 5 = 80-100%) (D).

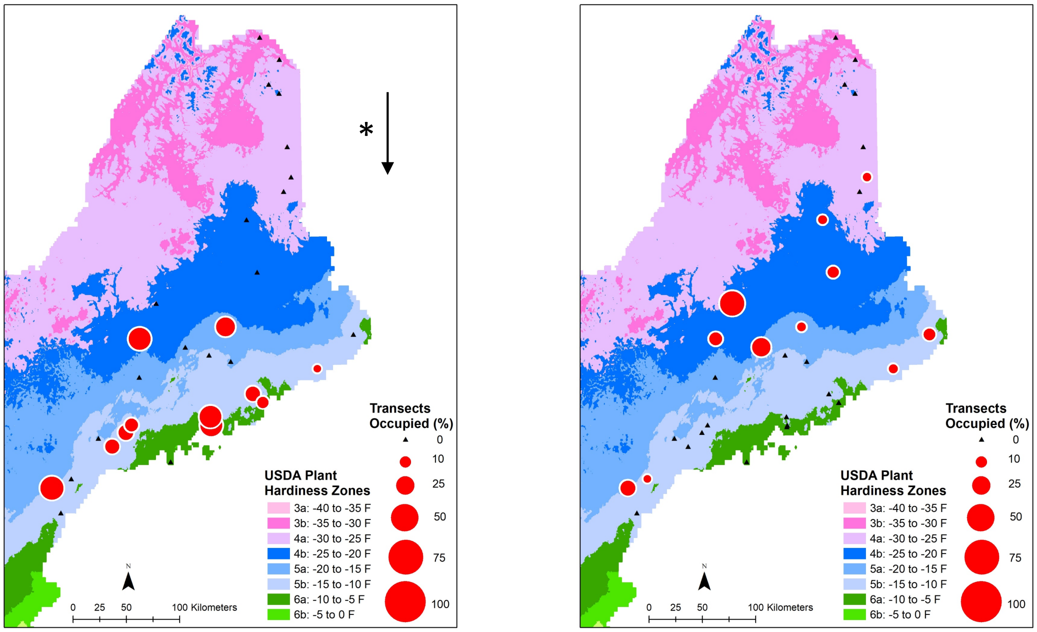
Table 2.2. Rare Weed Species of Likely Agronomic Risk. Species currently rare in Maine that are of likely agronomic risk since they are among the most common (†) or troublesome (‡) weeds in annual crop production in warmer regions of the USA.

Species of potential agronomic risk
Anthemis cotula L. (mayweed chamomile) †‡
Avena fatua L. (wild oat) †‡
Cerastium glomeratum Thuill. (sticky chickweed) †
Cirsium arvense (L.) Scop. (Canada thistle) †‡
Convolvulus arvensis L. (field bindweed) †‡
Cyperus esculentus L. (yellow nutsedge) †‡
Elymus repens (L.) Gould (quackgrass) †‡
Erigeron canadensis L. (horseweed) †‡
Galium aparine L. (catchweed bedstraw) †‡
Lactuca serriola L. (prickly lettuce) †‡
Lolium perenne L. ssp. multiflorum (Lam.) Husnot (Italian ryegrass) †‡
Panicum capillare L. (witchgrass) †
Panicum dichotomiflorum Michx. (fall panicum) †‡
Persicaria maculosa Gray (ladysthumb) ‡
Persicaria pensylvanica (L.) M. Gomez (Pennsylvania smartweed) †‡
Rumex crispus L. (curly dock) ‡
Senecio vulgaris L. (common groundsel) ‡
Setaria viridis (L.) P. Beauv. (green foxtail) †‡
Solanum physalifolium Rusby (hairy nightshade)
Solanum ptychanthum Dunal (eastern black nightshade) †‡



A. *Elymus repens*

B. *Panicum capillare*



C. *Persicaria maculosa*

D. *Persicaria pensylvanica*

Figure 2.4. Site Occupancy Maps for Four Species of Concern. Percentage of transects on 32 farms in Maine occupied by four relatively abundant rare weed species (A-D). Significant latitudinal effects based on logistic regression models are indicated with asterisks (*) and arrows indicating direction of effect.

Table 2.3. Rare Weed Logistic Regression Model Results. Results of four logistic regression models fit with weed species presence/absence as response variables. P-values significant at α = 0.05 are denoted with asterisks (*).

Model	Factor	Estimate	SE	Z	*P*
Elymus repens	Intercept	10.46	17.30	0.61	0.55
	Latitude	0.07	0.07	1.00	0.31
	Longitude	0.27	0.23	1.18	0.23
	Vegetation height	-0.04	0.17	-0.23	0.82
	Ground cover	0.27	0.13	2.10	0.04*
	Surveyor	2.60	0.51	5.05	<0.01*
Panicum capillare	Intercept	22.33	22.74	0.98	0.33
	Latitude	-0.38	0.18	-2.13	0.03*
	Longitude	0.14	0.25	0.56	0.57
	Vegetation height	<0.01	0.18	0.01	0.99
	Ground cover	-0.22	0.16	-1.33	0.18
	Surveyor	3.35	1.03	3.26	<0.01*
Persicaria maculosa	Intercept	17.13	23.77	0.72	0.47
	Latitude	-0.63	0.22	-2.86	<0.01*
	Longitude	-0.11	0.24	-0.47	0.64
	Vegetation height	0.15	0.18	0.86	0.39
	Ground cover	0.17	0.14	1.23	0.22
	Surveyor	0.55	0.38	1.44	0.15
Persicaria pensylvanica	Intercept	-21.61	22.23	-0.97	0.33
	Latitude	0.02	0.10	0.19	0.82
	Longitude	-0.25	0.28	-0.89	0.38
	Vegetation height	-0.08	0.21	-0.38	0.71
	Ground cover	0.07	0.18	0.43	0.67
	Surveyor	1.08	0.52	2.08	0.04*

2.3.3.2. Species of Potential Conservation Concern

One native species found in our seedbank samples was listed in the USDA PLANTS database as possibly extirpated in Maine: *Lobelia siphilitica* L. (blue cardinal flower) (NRCS, 2018b). Two species found in our survey sampling were of potential conservation concern according to the USDA (NRCS, 2018b): *Gamochaeta purpurea* (L.) Cabrera (purple cudweed), which was listed as possibly extirpated, and *Calamagrostis coarctata* Eaton (Nuttall's reed grass), which was listed as a species of special concern in Maine.

2.4. Discussion

In our 2015 surveys, we found that richness of rare weed species was significantly associated with longitude, being higher in more coastal regions of Maine than inland (Figure 2.2B). Longitude was also a significant factor predicting species richness and total weed density in our prior study of weed seedbanks (Smith et al., 2018). We found that species richness was also positively related to vegetation height (Figure 2.2D). A likely explanation for this latter finding is that both high richness and relatively tall vegetation may be found at weedier sites. Supporting this idea, Kolářová et al. (2013) found that richness of rare and endangered weeds increased with weed cover across 290 sites in the Czech Republic.

Of the four environmental variables assessed for their relationship to weed community composition, latitude was the most strongly related (Figure 2.3A). This is congruent with Smith et al.'s (2018) finding that, among a wide array of correlates they evaluated, latitude was the most strongly related to seedbank communities in Maine. Given the climatic heterogeneity present along the latitudinal gradient in Maine (Figure 2.1), it is possible that climate is a factor driving patterns in community composition. However, other factors may also have impacted results, including geographic isolation of island farms in the south and differences in farm management across the latitudinal gradient.

Our study did not account directly for farm management, which is known to be an important factor shaping community composition (Ryan, Smith, Mirsky, Mortensen, & Seidel, 2010) and indeed was found by Fried et al. (2008) to be more important than climate and geography in predicting weed communities in France. Our study sought to minimize the effects of farm management variability on our results by limiting our study to organic farms, and by utilizing the covariates vegetation height and ground cover in our analyses as proxies for some aspects of farm management. However, differences in farm management may nonetheless have been a factor, particularly as several of our more northern sites (located in Aroostook county) grew primarily grains, whereas most surveyed farms grew primarily mixed vegetables.

Another source of variability in these data is the effect of human surveyor, which was a significant factor in several analyses (Table 2.1; Table 2.3). The two surveyors participating in this project trained together and communicated frequently throughout data collection, but given the inherently subjective nature of determining what constitutes a 'rare' plant it is perhaps unsurprising that differences in surveyor judgment are reflected in the data. Most farms were sampled by a single surveyor; however, each surveyor was responsible for farms distributed across Maine's latitudinal and longitudinal gradients, so we do not expect that surveyor effects strongly biased our results with regards to latitude and longitude.

2.4.1. Species of Likely Agronomic Risk

As expected, several species currently present but categorized as relatively rare in Maine are among the most abundant and troublesome weeds in warmer regions of the USA (Table 2.2). Two of these, *Panicum capillare* and *Persicaria maculosa,* were found to be abundant at more southerly sites but lacking at sites in northern Maine (Figure 2.4B,C; Table 2.3).

P. capillare is a C4 annual grass that commonly infests field crops. It is part of a complex of five closely related species native to North America, and has been reported in Eastern Canada since the 1870s (Clements, DiTommaso, Darbyshire, Cavers, & Sartonov, 2004). *P. capillare* is considered a poor competitor relative to many weeds, but it is tolerant to high temperatures, drought, and salt, and does best in more southerly parts of its range (Clements et al., 2004). Given that summer drought risk is likely to increase in our region with climate change (Wolfe et al., 2018), these trails could allow *P. capillare* to become more successful in future. Its ability to tolerate salt could also have contributed to its prevalence on some coastal and island farms in this study (Figure 2.4B).

Persicaria maculosa (Figure 2.4C) is an introduced species, present throughout much of the US and Canada. The morphologically similar species *Persicaria pensylvanica* (Figure 2.4D) and *Persicaria lapathifolia* are native to North America. Our finding that *P. maculosa* was associated with more southerly latitudes does not match Smith et al.'s (2018) finding that this species was most associated with plant hardiness zone 4. *P. maculosa* (Vleeshouwers, 1998), and other members of the *Persicaria* genus (Araki & Washitani, 2000) are known to exhibit multi-level dormancy and form persistent seedbanks, from which 'quasi-simultaneous' field germination has been reported under suitable conditions (Staniforth & Cavers, 1979). It is possible that our detection of *P. maculosa* in more southerly sites was a year effect; conditions may have been especially suitable for germination of this species in coastal regions in 2015, despite larger persistent seedbanks in mid-Maine (Smith et al., 2018).

Some perennial species producing relatively few seeds were likely under-represented in seedbank samples and therefore characterized here as 'rare' (Table 2.2) despite being in fact quite common in Maine. *Elymus repens* (Figure 2.4A) is a clear example; this species has been present in New England since the 1600s (Werner & Rioux, 1977), and was recently cited by

Maine farmers as one of the five most problematic weeds on their farms (Jabbour, Zwickle, et al., 2014). *E. repens* reproduces primarily vegetatively, producing as many as 150 rhizomes or rhizome branches per plant, whereas it does not flower every year, and typically produces only 25 to 40 seeds per flowering stem (Werner & Rioux, 1977). We made the decision to include *E. repens* and similar perennials in the present study to make up for the likelihood that they were underreported in past studies in Maine relying on weed seedbank data (Jabbour, Gallandt, et al., 2014; Smith et al., 2018).

The monocarpic biennial weed *Pastinaca sativa* L. (wild parsnip) was pointed out by farmers at two of the 32 farms we surveyed as a new weed about which they were concerned. This introduced species escaped cultivation and was reported growing wild by 1900 in Canada (Cain, Darbyshire, Francis, Nurse, & Simard, 2010). It is now present in most US states and Canadian provinces, with a northern limit of 49° latitude (Cain et al., 2010). *P. sativa* is phytotoxic to humans and livestock, and increasingly so in the presence of its coevolved herbivore the parsnip webworm *Depressaria pastinacella* (Zangerl & Berenbaum, 2005). While no broader trends can be inferred from the observations of two farmers, this species may warrant consideration based on its phytotoxic properties (Cain et al., 2010).

2.5. Conclusions

Through analysis of seedbank data and transect surveys, we identified weeds that are currently rare in Maine or have been under-represented in some prior studies. We determined that several of these species are very abundant or troublesome in warmer regions of the USA, and might therefore become increasingly problematic as Maine's environment continues to warm with climate change.

CHAPTER 3

SOLARIZATION AND TARPING FOR IMPROVED STALE SEEDBED PREPARATION ON MAINE ORGANIC VEGETABLE FARMS

3.1. Introduction

Vegetable growers commonly use stale seedbed periods prior to sowing high-value crops. Creating a false or stale seedbed, i.e., allowing weeds to emerge and then killing them, often with flaming (Rasmussen, 2003) or shallow cultivation (Johnson & Mullinix, 2000), can decrease subsequent weed pressure by depleting the germinable weed seedbank (Gallandt, 2006). The use of clear (Bond & Grundy, 2001) and black plastic mulches (Fortier, 2014) to enhance stale seedbed establishment is of interest to organic vegetable farmers in our region, the Northeast USA, many of whom are small to mid-sized growers with abundant weed seedbanks (Jabbour, Gallandt, et al., 2014), who rely extensively on hand weeding (Baker & Mohler, 2015).

Soil solarization using clear plastic mulch was developed in the 1970s as a method to control soil borne pathogens (Katan, Greenberger, Alon, & Grinstein, 1976). Solarization traps solar radiation, which under suitable conditions elevates soil temperatures enough to cause pest mortality. Its utility as a weed control technique in arid and some Mediterranean regions is well documented (Bajwa, Mahajan, & Chauhan, 2015; Cohen & Rubin, 2007; Rubin, 2012); however, solarization has received less research attention in cooler regions. Solarization reduced *Poa annua* L. seed viability in Oregon, USA (Peachey, Pinkerton, Ivors, Miller, & Moore, 2001), and reduced weed density but did not improve strawberry yield in Virginia, USA (Samtani, Derr, Conway, & Flanagan, 2017). Covering soil with perforated polyethylene tarps in England, UK increased weed emergence (Bond & Bursch, 1989). Studies testing solarization for control of fungal pathogens in the Northwest USA and Canada have shown mixed results (Berlanger, 1999; Lazarovits, Hawke, Tomlin, Olthof, & Squre, 1991), leading to the conclusion in a review by

Walters and Pinkerton (Walters & Pinkerton, 2012) that solarization is not consistently effective in cool northern regions. Therefore, we expected that solarization alone during the springtime in Maine would not cause weed mortality, but would instead deplete the weed seedbank by increasing weed emergence, allowing weeds to be killed with subsequent flaming.

Tarping, also known as occultation (Fortier, 2014), is the practice of using black plastic silage tarps applied to the soil for several weeks prior to planting as a method for stale seedbed preparation. Tarping can decrease subsequent weed seed germination (Standifer et al., 1984), but it is not always effective (Hunter, Callaway, Rayburn, & Coffman, 2016; Mudalagiriyappa, Nanjappa, & Ramachandrappa, 1999). The few studies that have compared solarization and tarping for weed control suggest that solarization is usually more effective than tarping (Abu-Irmaileh & Thahabi, 1997; Mudalagiriyappa et al., 1999; Singh, 2006), likely due to higher soil temperatures achieved under solarization (Horowitz et al., 1983). However, in one study conducted during the fall in Israel, tarping outperformed solarization (Rubin & Benjamin, 1983), perhaps because soil temperature during this relatively cool season was insufficient for weed control via solarization. In the Northeast USA, a single-year study found that tarping outperformed solarization as a method of cover crop termination (Lounsbury, Warren, Wolfe, & Smith, 2018), but we are aware of no prior studies comparing solarization and tarping for stale seedbed establishment in our region.

The primary objective of this study was to test whether solarization combined with flaming could improve the efficacy of stale seedbed establishment in the Northeast USA. A secondary objective was to compare the weed control efficacy of solarization to tarping. Field experiments were conducted in 2015-2017 to test the following hypotheses:

1. Springtime soil solarization will increase weed emergence;
2. Firming soil with a roller will further increase weed emergence;

3. The seedbank depletion resulting from solarization and rolling will reduce weed emergence in a subsequent stale seedbed created by flaming; and
4. During mid-summer, solarization will be more effective than tarping for stale seedbed establishment.

3.2. Materials and Methods

3.2.1. Solarization for an Improved Stale Seedbed

3.2.1.1. Site Description

To test Hypotheses 1 to 3, replicated field experiments were conducted over four site-years near Orono, Maine, USA (Table 3.1). Additional data were collected during two on-farm demonstrations in Winthrop and Harborside, Maine, USA in May to June of 2015. The monthly 30-year climate averages for the period were 14.7 °C mean temperature and 9.4 cm precipitation (NOAA, 2018).

3.2.1.2. Experimental Design

Field experiments included four treatments, arranged in a randomized complete block design with three replications per site-year. Treatments included:

- Tilled (control)
- Tilled + rolled (control)
- Tilled + solarized
- Tilled + rolled + solarized

Prior to establishment of each experiment, soils were rototilled to 15 cm soil depth, except for the Smith 2016 experiment in which the field was moldboard ploughed followed by cultivation with a Perfecta field cultivator (Unverferth Manufacturing Co., Inc., Kalida, Ohio, USA). In all experiments a 45.4 kg lawn roller was used to simulate cultipacking. This tool was appropriate to the scale of these experiments, but likely firmed soil more consistently than would a standard ring cultipacker. Prior to mulching, all plots were irrigated to approximate field capacity to increase heat conduction (Katan, 1981). Solarized treatments were covered with previously used 6-mil clear polyethylene film (hereafter referred to as plastic), salvaged from two greenhouses on the University of Maine campus. Previously used greenhouse plastic was chosen to represent likely grower management practices for our region. Plastic from the same source was used within blocks.

Plots were 3 m by 3 m with 0.6 m between plots. To secure plastic while keeping plots accessible for measurement during treatment, plastic edges were clipped to 3.3 cm diameter by 3.2 m long pieces of galvanized metal pipe laid in 10 cm deep trenches around plot perimeters. Plastic was removed after approximately two weeks of solarization (Table 3.1), after which stale seedbeds were prepared with no further soil disturbance by flaming all plots using a hand-held single burner propane torch, moving the end of the nozzle over the field at a height of 10 cm and a speed of 0.25 m s^{-1}. The effect of flaming was measured during the Rogers 2015 site-year by employing a split-plot design with presence/absence of flaming as subplot treatments. Two on-farm trials conducted in the spring of 2015 each consisted of a single replicate of the tilled and tilled + solarized treatments, following standard protocols.

Table 3.1. Information About Solarization Field Sites. Experiments were conducted at the University of Maine Rogers Farm and the UMaine Greens Project field (UMG) in 2015, and at Rogers Farm and the University of Maine Smith Farm in 2016. Soil series data are from NRCS (NRCS, 2018a); † OM = organic matter; ‡ year of soil test shown in parentheses. Weather data are from NOAA (NOAA, 2018). Dates show periods during which solarization treatments were applied in the field, and periods of observation of weed emergence following plastic removal.

Site-year	Location	Soils	Mean air temp (°C)	Total precip. (cm)	Dates
Rogers 2015	44°55'N 68°41'W	Pushaw-Boothbay complex; 4.6% OM† and 6.4 pH (2011)‡	16.0	15.9	Solarization: 27 May–12 June Observation: 12 June–30 June
UMG 2015	44°54'N 68°39'W	Peru-Tunbridge association; 6.6% OM and 6.1 pH (2012)	15.0	14.4	Solarization: 15 May–3 June Observation: 3 June–22 June
Rogers 2016	44°55'N 68°41'W	Pushaw-Boothbay complex; 3.7% OM and 6.2 pH (2014)	16.4	7.7	Solarization: 13 May–31 May Observation: 31 May–14 June
Smith 2016	44°54'N 68°41'W	Nicholville very fine sandy loam; 5.0% OM and 5.9 pH (2014)	16.9	6.3	Solarization: 18 May–1 June Observation: 1 June–15 June

3.2.1.3. Field Data Collection

Soil temperatures were logged hourly for the duration of solarization treatment using iButton temperature loggers (Maxim Integrated, San Jose, California, USA). One logger per plot was placed in a sealed 5 cm by 5 cm 4-mil plastic bag and buried at 5 cm soil depth. Volumetric soil moisture content was measured and averaged across three locations within each plot using a Delta-T soil moisture meter (HH2 version 4.0, Delta-T Devices Ltd, Cambridge, England) at the start of each experiment and concurrent with each weed census (described below).

Weeds were counted once every 2 to 7 days during solarization treatment, and approximately every 7 days for 2 weeks following solarization. Plastic was temporarily removed during census counts. During each census, weed seedlings were counted and pulled from permanent 0.25 m by 0.5 m quadrats during the solarization period, and from a new set of permanent quadrats during the period following solarization. The four weed taxa most abundant in each quadrat were identified and counted; remaining weeds were counted as other broadleaved or other grass-like. Weeds were identified to species level with the following exceptions: *Lolium* spp. and *Gnaphalium* spp. were identified to genus, and members of the Brassicaceae other than *Capsella bursa-pastoris* L. Medik. (likely *Brassica* and *Rorippa* spp.) were grouped as other brassicas. If few weeds were present, additional quadrats were added consecutively to the right of permanent quadrats and counts summed until ≥ 25 total weeds were counted or four quadrats sampled, whichever occurred first. Counts were adjusted for effective quadrat size, and summed to account for differences in number of censuses conducted at different site-years. Data representing weed emergence are thus reported as cumulative weed density m^{-2} in each plot during solarization and after solarization, respectively.

3.2.1.4. Statistical Analyses

All analyses were performed in R (R Core Team, 2016). Mixed effects models were constructed using the {nlme} package (Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2016), means separations performed using the {multcomp} package (Hothorn, Bretz, & Westfall, 2008), linear discriminant analyses performed using the {MASS} package (Venables & Ripley, 2002), and other multivariate analyses performed using the {vegan} package (Oksanen et al., 2016).

Response variables were square root transformed prior to analysis to improve normality and homogeneity of variances; statistical assumptions were met unless otherwise indicated below. The chosen significance level was $\alpha = 0.05$.

To determine whether solarized and rolled treatment effects were significant across site-years, we fit linear mixed effects (LME) models to the weed density data from all four site-years of experiments (Table 3.1) plus two on-farm trials. These models were chosen in part because they are appropriate for unbalanced designs (Crawley, 2013). Separate models were fit for the period during solarization, and the observation period after solarization, with cumulative weed density m^{-2} as the response, treatment as a fixed effect, and site-year as a random effect. Means were separated by Fisher's Protected LSD. The effects of flaming on solarization efficacy were tested using analysis of variance (ANOVA) and pre-planned contrasts.

To test for treatment effects on weed community composition, permutational multiple analysis of variance (PERMANOVA) models were fit for the period during solarization and the period after solarization, respectively, using Euclidean distances and 999 permutations (Anderson & Walsh, 2013). PERMDISP tests were performed using Euclidean distances and 999 permutations to test for homogenous dispersion among groups (Anderson & Walsh, 2013). These methods were selected because the data were not multivariate normal. Species observed in fewer than 10% of plots were dropped prior to analyses. The effects of treatment on the weed community were further explored through linear discriminant analyses (LDA) (Gotelli & Ellison, 2004). Separate analyses were conducted for the period during solarization and the period following solarization, with linear discriminant functions first constructed to discriminate weed communities by treatment. Classification using jackknifed discrimination matrices suggested these functions discriminated poorly, correctly classifying data in 36% and 29% of instances, respectively, for the periods during and after solarization, compared with 25% correct expected based on randomness. Because most misclassifications resulted from a poor ability of the functions to discriminate based on rolling, a second set of functions was created to discriminate between data pooled as solarized and non-solarized. These performed better, correctly classifying in 92% and 64% of instances, respectively, for the periods during and after solarization, with 50% correct expected based on randomness.

3.2.2. Comparing Solarization to Tarping

3.2.2.1. Site Description

To compare solarization to tarping, experiments (hereafter TARP) were conducted at the University of Maine Rogers Farm (44°55'N, 68°41'W) in July to September of 2016 and 2017. Soils were Pushaw-Boothbay complex (NRCS, 2018a) in both fields. The 2016 field had pH of 6.2 and 3.7% organic matter (2014 soil test); the 2017 field had pH of 5.8 and 3.0% organic matter (2017 soil test). The monthly 30-year climate averages for the period were 8.7 cm precipitation and 18.2 °C mean temperature (NOAA, 2018). During the eight week experimental periods, the mean air temperature and total precipitation were, respectively, 21.8 °C and 8.0 cm in 2016; 19.0 °C and 11.4 cm in 2017 (NOAA, 2018).

3.2.2.2. Experimental Design

Experiments consisted of seven treatments arranged in a randomized complete block design with three replications. Six mulched treatments consisted of factorial combinations of mulch (solarization, tarping) and treatment duration (2, 4, and 6 weeks); the seventh treatment was a nonmulched control. Plots were 1 m by 1 m with 0.6 m between plots, which was considered the minimum size needed to avoid strong edge effects (Yitzhak Mahrer & Shilo, 2012). The field was rototilled to 15 cm depth prior to experiment start dates, and irrigated prior to mulching. Solarization plots were covered with salvaged 6-mil clear polyethylene greenhouse plastic; tarping plots with 3-mil black plastic silage tarp (Belson Heavy Duty Plastic Tarp & Silo

Cap, #0000000068591, Mill's Fleet Farm, Appleton, Wisconsin, USA). Plastic edges were secured by burial. In 2016, mulch treatments were applied and the experiment begun on 14 July, and mulch was removed from 2, 4 and 6 week treatments on 28 July, 9 August, and 23 August, respectively. In 2017, the experiment was begun on 27 July, and mulches removed from 2, 4, and 6 week treatments on 9 August, 22 August, and 7 September, respectively. Plots were not flamed following plastic removal.

3.2.2.3. Field Data Collection

Following the methods detailed in section *2.1.3.*, soil temperature was logged hourly at 5 cm soil depth during treatment, and volumetric soil moisture measured prior to mulching and concurrent with weed censuses. Weeds were counted on days mulch treatment was terminated, and approximately 14 days after termination of each respective treatment. In 2016, census dates were 9 August, 23 August, and 9 September; in 2017, censuses dates were 22 August, 7 September, and 20 September. Censuses were performed in single 0.25 m by 0.5 m permanent quadrats located in the center of each plot. Control plots were censused concurrently with each mulch treatment census; to accommodate this design, weeds were not pulled during census counts. In 2016, weeds were identified as either broadleaved or grass-like. In 2017, weeds were counted by taxa following the methods in section *2.1.3.*

3.2.2.4. Statistical Analyses

Data were analyzed with analysis of covariance (ANCOVA) models and Welch's t-tests in R (R Core Team, 2016). Response variables were square root or $\log_{10}$ +1 transformed as necessary to meet assumptions. Means were separated by Fisher's protected LSD using the {multcomp} package (Hothorn et al., 2008). The nonmulched control treatment was excluded from analysis due to pseudoreplication in the experimental design and because this treatment was not essential to our objective of comparing solarization and tarping efficacy. Initial models suggested significant year effects, so years were analyzed separately. In both years, weed density was zero in tarped plots of any duration at plastic termination. To test whether weed density in solarized plots significantly exceeded these zero values, one-sided Welch's t-tests were performed for data pooled across treatment durations. Data from weed censuses performed 14 days after plastic termination were analyzed using ANCOVA with weed density as the response, and explanatory variables mulch treatment, duration (numeric), and treatment by duration interaction.

3.3. Results

3.3.1. Solarization for an Improved Stale Seedbed

In our spring experiments, soil temperatures were elevated under solarization, with maximum temperatures ranging from 32 to 47 °C at a depth of 5 cm in solarized plots, as compared with 29 to 38 °C in controls. Soil moisture was greater in rolled treatments (Table 3.2).

During treatment, there was 83% and 81% less weed density in tilled + solarized and tilled + rolled + solarized treatments, respectively, as compared with corresponding controls (Figure 3.1A). During 14 days of observation following plastic termination, weed density was 78% and 75% less in tilled + solarized and tilled + rolled + solarized treatments, respectively, as compared with controls (Figure 3.1B). These treatment effects were reasonably consistent across site-years both during ($R^2_{marginal} = 0.43$, $R^2_{conditional} = 0.73$, $X^2 = 81$, $P < 0.01$) and after solarization ($R^2_{marginal} = 0.28$, $R^2_{conditional} = 0.39$, $X^2 = 23$, $P < 0.01$).

Table 3.2. Temperature and Soil Moisture in Spring Solarization Experiments. Mean ± SD maximum and mean soil temperatures, exposure time to temperatures greater than 35 °C, and volumetric soil moisture measured during spring solarization experiments. Temperatures were measured at 5 cm soil depth; soil moisture was measured prior to solarization (start) and following plastic removal (end). Summary statistics calculated across four experimental site-years and two on-farm trials.

Treatment	Soil temp (°C)		Exposure time (h)			Soil moisture (%vol)	
	Max	Avg.	36-40 °C	41-45 °C	>45 °C	Start	End
Tilled control	32 ± 2	17 ± 1	< 1	0	0	21 ± 8	13 ± 3
Tilled + rolled control	32 ± 2	17 ± 1	0	0	0	29 ± 7	20 ± 4
Tilled + solarized	42 ± 4	24 ± 2	21 ± 12	12 ± 11	< 1	21 ± 7	13 ± 4
Tilled + rolled + solarized	42 ± 3	23 ± 3	20 ± 11	12 ± 12	< 1	27 ± 7	20 ± 4

Figure 3.1. Weed Density During and After Solarization. Mean cumulative weed density (A) during solarization and (B) after solarization across experimental site-years. Means were separated by Fisher's Protected LSD.

There was no significant difference in weed density between flamed and nonflamed subplots in either solarization treatment (tilled + solarized: t = -0.49, *P* = 0.63; tilled + rolled + solarized: t = -1.09, *P* = 0.29). Flaming significantly reduced weed density in the tilled control treatment (t = -2.85, *P* = 0.01), and caused a 32% reduction in weed density in the tilled + rolled treatment, though this difference was not statistically significant (t = -1.05, *P* = 0.31).

PERMANOVA models suggested non-significant effects of treatment on weed community composition during (R^2 = 0.09, $F_{3,48df}$ = 1.66, *P* = 0.09), and after solarization (R^2 = 0.09, $F_{3,48df}$ = 1.67, *P* = 0.06). Significant PERMDISP tests for the periods during ($F_{3,48df}$ = 5.84, *P* < 0.01) and after solarization ($F_{3,48df}$ = 6.76, *P* < 0.01) indicated differences in dispersion (beta diversity) between treatment groups (Anderson & Walsh, 2013). Linear discriminant analyses showed clear separation between solarized treatments and control treatments along the first linear discriminant function during the solarization period (Figure 3.2A). Rolling appeared to drive separation between control treatments but not solarized treatments during the period after solarization (Figure 3.2B). All weed species decreased in abundance under solarization (data not shown); however, LDA coefficients (Table 3.3) suggested that winter annuals (*Capsella bursa-pastoris*; *Stellaria media* (L.) Vill.; *Poa annua*) and *Trifolium repens* L. were disproportionately reduced during the solarization period, and *Poa annua* remained disproportionately reduced after solarization.

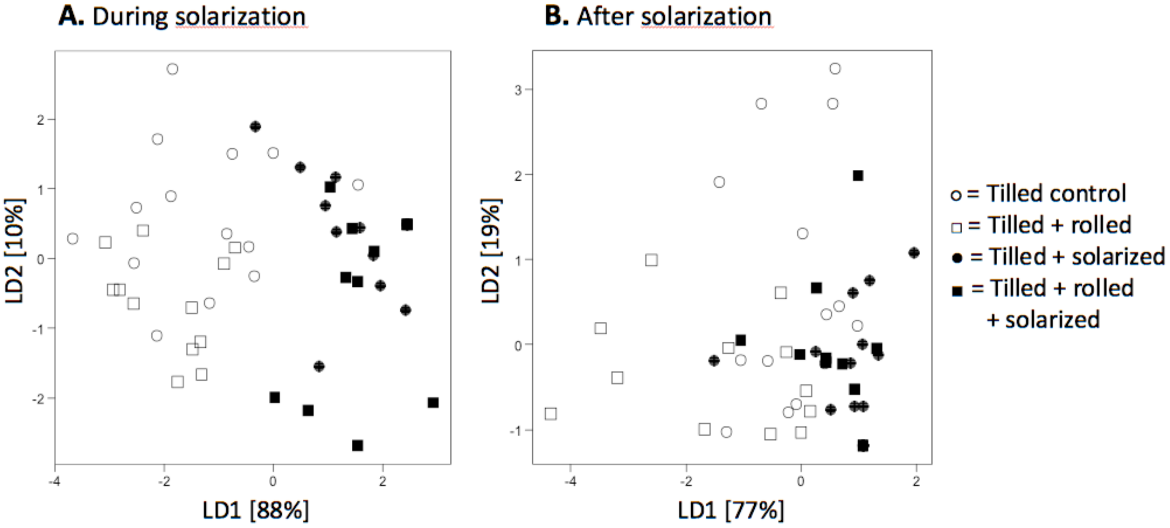


Figure 3.2. Impact of Solarization on the Weed Community. Linear discriminant analyses showing separation of weed communities by treatment along the first two of three linear discriminant (LD) functions (A) during solarization and (B) after solarization. Percent variation explained by each LD function (trace) shown in square brackets.

Table 3.3. Eigenvectors from LDA of Solarized Weed Communities. Coefficients of linear discrimination (eigenvectors) showing the contribution of weed species to overall community separation during and after two weeks of spring solarization. More negative values are associated with control plots; more positive values are associated with solarized plots. † = winter annual species.

Weed species	Common name	Eigenvectors	
		During solarization	After solarization
Elymus repens	Quackgrass	0.12	-0.03
Amaranthus retroflexus	Redroot pigweed	-0.04	-0.06
Ambrosia artemisiifolia	Common ragweed		-0.15
Capsella bursa-pastoris	Shepherd's-purse†	-0.47	-0.06
Chenopodium album	Common lambsquarters	-0.16	0.02
Digitaria sanguinalis	Large crabgrass	0.04	-0.07
Echinochloa crus-galli	Barnyardgrass	0.06	-0.06
Galinsoga quadriradiata	Hairy galinsoga	-0.06	-0.01
Panicum capillare	Witchgrass	-0.08	
Poa annua	Annual bluegrass†	-0.30	-0.31
Portulaca oleracea	Common purslane		-0.13
Stellaria media	Common chickweed†	-0.36	
Trifolium repens	White clover	-0.37	

3.3.2. Comparing Solarization to Tarping

Solarization resulted in higher maximum and average soil temperatures than did tarping (Table 3.4). In both years of our TARP study, weed density was zero at plastic termination in tarping treatments (Table 3.5). In 2016, weed density at termination of solarization treatments was very low and, across treatment durations, not significantly different than zero (Table 3.5; t = 2.29, $P = 0.05$). In 2017, weed emergence (density) was significant during solarization (Table 3.5; t = 6.00, $P < 0.01$). Our ANCOVA model for weed density following plastic termination in 2016 ($R^2 = 0.80$) included significant effects for treatment, duration, and treatment by duration interaction; specifically, solarization resulted in less subsequent weed density than tarping and was more effective with increasing treatment duration (Table 3.5), while tarping efficacy was lowest following 4 weeks of treatment. The corresponding model for 2017 ($R^2 = 0.83$) included significant effects for treatment only, with greater weed density following solarization than tarping (Table 3.5). Density of the most abundant species in our 2017 study system, *Portulaca oleracea* L., was higher in solarized plots than controls, while density of other broadleaved weeds was reduced by solarization (Figure 3.3).

Table 3.4. Temperature and Soil Moisture in TARP Experiments. Mean ± SD maximum and average temperatures, exposure time to temperatures greater than 35 °C, and volumetric soil moisture measured during TARP experiments. Soil moisture was measured prior to solarization (start) and following plastic termination (end). Data averaged across three replicate plots unless otherwise noted: nd signifies no data; †data from 2 replicates only.

Year	Treatment	Duration	Soil temp (°C)		Exposure time (h)			Soil moisture (%vol)	
		(weeks)	Max	Avg.	36-40 °C	41-45 °C	>45 °C	Start	End
2016	Control	2	35 ± 1	24 ± 0	< 1	0	0	36 ± 6	12 ± 1
		4	35 ± 1	23 ± 0	< 1	0	0	36 ± 6	10 ± 2
		6	nd	nd	nd	nd	nd	36 ± 6	23 ± 2
	Tarping	2	41 ± 2	28 ± 0	28 ± 11	3 ± 3	0	35 ± 5	18 ± 2
		4	41 ± 2	28 ± 0	71 ± 17	8 ± 12	0	38 ± 2	18 ± 2
		6	41 ± 3	27 ± 0	72 ± 55	11 ± 10	0	36 ± 5	17 ± 1
	Solarization	2	46 ± 3	31 ± 1	48 ± 11	30 ± 21	4 ± 8	33 ± 5	18 ± 3
		4	46 ± 3	31 ± 1	101 ± 12	64 ± 41	8 ± 11	33 ± 1	16 ± 3
		6	50 ± 1†	31 ± 0†	108 ± 2†	117 ± 2†	49 ± 8†	39 ± 3	17 ± 5
2017	Control	2	33 ± 4†	23 ± 1†	0†	0†	0†	22 ± 3	7 ± 1
		4	33 ± 4†	22 ± 1†	0†	0†	0†	22 ± 3	10 ± 1
		6	33 ± 4†	21 ± 1†	0†	0†	0†	22 ± 3	33 ± 4
	Tarping	2	39 ± 1†	25 ± 0†	16 ± 7†	0†	0†	30 ± 4	12 ± 0
		4	37 ± 0†	25 ± 0†	12 ± 1†	0†	0†	26 ± 5	15 ± 2
		6	39 ± 1	24 ± 0	31 ± 18	1 ± 2	0	29 ± 4	28 ± 6
	Solarization	2	46 ± 0†	29 ± 1†	32 ± 8†	33 ± 6†	5 ± 1†	29 ± 11	13 ± 5
		4	43 ± 3	27 ± 1	40 ± 14	17 ± 16	< 1	32 ± 6	14 ± 1
		6	45 ± 1	25 ± 1	51 ± 36	25 ± 6	1 ± 2	30 ± 2	28 ± 11

Table 3.5. Weed Density in TARP Experiments. Mean ± SEM total weed density measured during TARP experiments.

Year	Treatment	Duration (weeks)	Total weed density (no m^{-2})	
			Termination	Termination + 14
2016	Control	2	595 ± 114	803 ± 127
		4	803 ± 127	635 ± 46
		6	635 ± 46	680 ± 44
	Tarping	2	0	261 ± 67
		4	0	640 ± 130
		6	0	205 ± 69
	Solarization	2	5 ± 5	141 ± 14
		4	11 ± 7	16 ± 5
		6	5 ± 5	11 ± 5
2017	Control	2	56 ± 12	403 ± 101
		4	403 ± 101	320 ± 47
		6	320 ± 47	453 ± 107
	Tarping	2	0	32 ± 9
		4	0	0
		6	0	27 ± 16
	Solarization	2	419 ± 134	427 ± 130
		4	571 ± 50	288 ± 41
		6	224 ± 61	237 ± 80

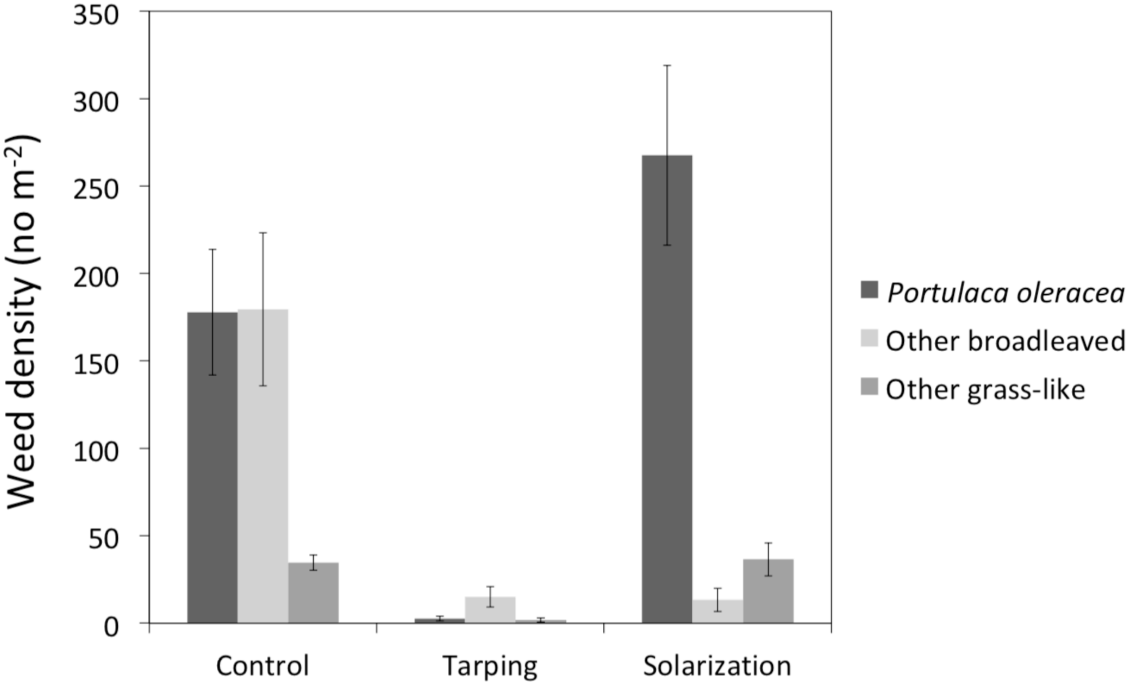


Figure 3.3. Density of Weed Taxa in 2017 TARP Experiment. Mean ± SEM density of *Portulaca oleracea*, other broadleaved weeds, and other grass-like weeds measured at 14 days after plastic termination in the 2017 TARP experiment. Data are shown pooled across treatment durations.

3.4. Discussion

3.4.1. Solarization for an Improved Stale Seedbed

Contrary to expectations (Hypothesis 1), but nevertheless a desirable weed management outcome, springtime soil solarization greatly reduced weed density during two weeks of treatment (Figure 3.1A). The weed-suppressive effect of solarization persisted after plastic was removed and plots were flamed. There was a trend toward increased weed density in rolled treatments, as expected (Hypothesis 2), but the magnitude of the solarization effect was greater and differences based on rolling were not significant (Figure 3.1). The finding that nonflamed subplots were not weedier than flamed subplots suggests that two weeks of solarization alone can create an excellent stale seedbed in our region, the Northeast USA.

The maximum temperatures and accumulated time under high temperature conditions measured at 5 cm depth during these experiments (Table 3.2) are less than published thresholds required for weed seed mortality in some species (Dahlquist, Prather, & Stapleton, 2007; Vizantinopoulos & Katranis, 1993). However, higher maximum temperatures were likely reached nearer the soil surface (Gamliel, Austerweil, & Kritzman, 2000; Ytzhaq Mahrer, 1980); data from our own methods development indicates that maximum temperatures may have been ≥ 5 °C greater at 1 cm as compared with 5 cm soil depth (Birthisel SK, unpublished data). Further, we observed dead white-thread stage weeds under the solarization plastic in some plots. These were not accounted for in our weed censuses, but their presence suggests that germination and subsequent seedling death was a mechanism of seedbank reduction in these experiments.

The pattern in our weed community data following solarization (Figure 3.2B), along with PERMDISP test results, suggests that solarization reduced beta diversity, or in-group dispersion, in comparison with control treatments. This is consistent with the hypothesis and findings of Chase (2007) and suggests that solarization can act as a filter shaping weed community composition (Booth & Swanton, 2002). Though winter annuals and *Poa annua* were disproportionately harmed during solarization (Table 3.3), the contributions of other weed species to the overall community were weakly impacted by solarization, and none strongly positively associated (Table 3.3). This suggests that solarization can be effective against many weeds present in the Northeast USA, consistent with Cohen and Rubin's review of species susceptibility to solarization (2007). Two susceptible weeds in particular, *Galinsoga quadriradiata* (Raf.) Blake and *Digitaria sanguinalis* (L.) Scop. (Vizantinopoulos & Katranis, 1993), are among the most problematic for regional organic farmers (Jabbour, Gallandt, et al., 2014).

Our decision to employ previously used greenhouse plastic in these experiments may have impacted results. There is a considerable body of research characterizing the effects of plastic optical properties on soil heating (Mahrer & Shilo, 2012), and specialized mulches designed to optimize efficacy have been tested (D'Anna, Lapichino, & D'Anna, 2012; Stevens, Khan, Wilson, Brown, & Collins, 1999; Yildiz, Benlioğlu, Boz, & Benlioğlu, 2010). We lacked the resources to quantify optical characteristics of the polyethylene used in these experiments. However, studies comparing the use of new and previously used polyethylene for solarization suggest that previously used polyethylene can work as well or better than new (Avissar, Naot, Mahrer, & Katan, 1985; Yildiz et al., 2010), so we do not necessarily expect that efficacy was diminished. Specialized solarization films (Chase, Sinclair, & Locascio, 1999) or modifications such as the use of bubble film for solarization (Oz, Coskan, & Atilgan, 2017) could perhaps improve efficacy, though the increased soil heating from the use of specialized films does not always translate to improved weed control outcomes (Chellemi, Olson, Mitchell, Secker, & McSorley, 1997; Yildiz et al., 2010).

Solarization is a promising strategy for improving the efficacy of stale seedbed preparation in the Northeast USA and warrants further study. We hope future work in our region will measure the impact of solarization on weed seedbank depletion (Gallandt, 2006), assessing its potential to cause long-term reductions in weed pressure. Growers in our region have asked whether the in-season weed control benefits of solarization offset labor and opportunity costs, resulting in economic returns. Solarization was economically advantageous in California strawberries (Stapleton, Molinar, Lynn-patterson, Mcfeeters, & Shrestha, 2005); however, a study in California organic vegetables found that flame weeding was more cost-effective (Deese, 2010). An economic assessment specific to small and mid-sized vegetable growers in the Northeast USA could aid in the creation of local farm management recommendations. Growers have also asked about the impacts of solarization in the Northeast USA on beneficial soil microbiota, which we address elsewhere (Chapter 4).

3.4.2. Comparing Solarization to Tarping

We had expected solarization to result in higher soil temperatures and better weed control outcomes than tarping (Hypothesis 4). Results of our 2016 TARP experiment (Table 3.4; Table 3.5) support this hypothesis, corroborating a majority of published experiments on the topic (reviewed in Birthisel, Gallandt, & Souza Cunha, 2018). In our 2017 experiment, however, tarping was more effective than solarization (Table 3.5). The abundance of *Portulaca oleracea* in our 2017 study site was likely an important factor influencing this result; emergence of this species was apparently promoted by solarization (Figure 3.3). Consistent with this finding, Dahlquist et al. (2007) report that *P. oleracea* readily germinated at temperatures of 42 and 46 °C. Though we did not collect weed species data at the plot level in 2016, when solarization proved more effective (Table 3.5), we noted that the four most abundant species in the field were *Amaranthus retroflexus*, *Chenopodium album*, *Galinsoga quadriradiata*, and *Echinochloa crus-galli*, all annuals that were well controlled in our other experiments (Figure 3.3; Table 3.3). Another factor that may have contributed to the discrepancy in results between site-years is soil temperature: overall, hotter temperatures and greater accumulations of time at high temperatures were measured in 2016 than in 2017 (Table 3.4).

We had expected the efficacy of both solarization and tarping to increase with treatment duration, but our data offer weak and inconsistent support for this idea. Treatment duration was not a significant factor in 2017. In 2016, solarization efficacy did increase with treatment duration (Table 3.5). However, weed density following tarping was unexpectedly 146% greater in the 4 week treatment as compared with the 2 week treatment (Table 3.5). The timing of rainfall during this atypically dry summer may explain this result: 43 mm of rain fell during the period of observation following plastic removal in the 4 week treatments, whereas only 13 mm and 8 mm of rain fell during the observation periods following the 2 week and 6 week treatments, respectively (NOAA, 2018). Since moisture cues are typically required for germination (Baskin & Baskin, 1998) and weeds at the seedling stage may be especially sensitive to desiccation, greater density might have been expected following 2 weeks of tarping if conditions had been more favorable to germination and establishment. The fact that weed emergence did not appear to be stimulated by rainfall in the 4 week solarization treatment (Table 3.5) suggests that this treatment may have been effective in depleting the germinable weed seedbank.

Overall, these results suggest tradeoffs between solarization and tarping that should be more thoroughly characterized before either strategy is advocated as a “better” approach for farmers in the Northeast USA and areas of similar climate. Solarization applied as a stale seedbed technique to susceptible species under good conditions may result in greater seedbank depletion than tarping (Standifer et al., 1984) thereby offering longer-term benefits. However, the light blocking effect of tarping may make it more suitable under marginal conditions, or in situations where the intended purpose is simply to prevent weed emergence for a period of time rather deplete the seedbank. Research comparing these practices over a wider range of soil, weather, and seedbank conditions could aid in the development of guidelines to help growers select practices that align with their situations and goals. We advocate as well that further studies follow Lounsbury et al. (2018) in examining the utility of solarization and tarping for terminating cover crops prior to organic no-till or strip-till plantings. Recent work on ‘biosolarization’ (Stapleton et al., 2016) indicates that incorporation of crop residues (Mallek, Prather, & Stapleton, 2007) and other organic amendments (Achmon et al., 2017; Gamliel et al.,

2000) prior to treatment can increase the weed control efficacy of solarization. Given farmer interest in organic reduced tillage, this could be a fruitful area for future work.

3.5. Conclusions

Across replicated experiments, two weeks of springtime soil solarization followed by flaming created a stale seedbed with 78% less subsequent weed density than a control stale seedbed prepared with flaming only. Nonflamed subplots established during one site-year suggested that solarization alone, without flaming, can created an effective stale seedbed. Soil temperatures measured under solarization may have contributed to thermal inactivation of some species of weed seed, and fatal germination of others. Multivariate weed community analyses indicate that solarization may act as an ecological filter shaping weed community composition. We hope future studies of solarization will more thoroughly characterize its impacts on weed seedbanks, and evaluate whether the practice is economically advantageous to growers in our region. Additional experiments compared the efficacy of solarization to tarping with black plastic. Solarization outperformed tarping in one year of study, but the opposite was true the following year. Higher temperatures in our first year experiment, and high density of the relatively heat-tolerant weed *Portulaca oleracea* (purslane) in our second, may explain these discrepant results. Overall, solarization and tarping are promising organic stale seedbed preparation techniques, but more work is needed to evaluate their relative efficacy over a range of conditions and applications relevant to growers in humid continental climates like the Northeast USA.

CHAPTER 4

EFFECTS OF FIELD AND GREENHOUSE SOLARIZATION ON SOIL MICROBIOTA AND WEED SEEDS ON MAINE FARMS

4.1. Introduction

Soil solarization is the practice of controlling pests by covering irrigated soil with clear plastic tarps, using solar energy to heat soils to lethal temperatures (J Katan et al., 1976). Solarization has long been known to kill weeds (Cohen & Rubin, 2007; Horowitz et al., 1983) and soilborne pathogens (Katan, 1981; McGovern & McSorley, 2012) in warm, sunny climates. It was thought to be inconsistently effective in cooler regions (Walters & Pinkerton, 2012), but recent work by our group demonstrated that two weeks of spring solarization in the humid continental climate of Maine, USA prepared an excellent stale seedbed (Chapter 3). These promising results prompted questions from organic farmers in our region about mechanisms and best practices for solarization, as well as concerns about impacts on soil microbiota, nutrient cycling, and soil health. The experiments described herein sought to build on existing knowledge (Kapulnik & Gamliel, 2012) and address a lack of necessary (Chellemi et al., 1997) region-specific data on these topics.

The mechanisms through which solarization causes weed suppression in our region have yet to be fully elucidated. Solarization may cause thermal inactivation (Dahlquist, Prather, & Stapleton, 2007) or fatal germination of some species, while enforcing dormancy in others (Marenco & Lustosa, 2000). The temperature thresholds required for thermal seed death may be altered by environmental factors including soil moisture (Egley, 1990) and soil organic content (Stapleton et al., 2016). From a seedbank management standpoint, direct mortality of seeds or seedlings is a more desirable outcome than forcing seed dormancy (Gallandt, 2006).

Although solarization is considered a ‘mild’ soil treatment in comparison to other disinfestation techniques including steaming (Runia, 2012), it nonetheless affects the soil ecosystem beyond the control of target pests. Solarization often increases dissolved organic matter (Chen, Katan, Gamliel, Aviad, & Schnitzer, 2000; M. A. Khan et al., 2012) and plant available nutrients including inorganic nitrogen (Khan et al., 2012; Oz et al., 2017; Sofi, Tewari, Razdan, & Koul, 2014). Gelsomino & Cacco (2006) report that solarization in Italy altered microbial community composition during treatment. Scopa et al. found that soil respiration rates decreased non-significantly during field solarization (Scopa & Dumontet, 2007), but significantly under solarization within a greenhouse (Scopa, Candido, Dumontet, & Miccolis, 2008). It is well established that survival or rapid recolonization of the rhizosphere by beneficial mesophilic microbiota following solarization can induce soil suppressiveness against pathogens (Katan & Gamliel, 2012), which can positively impact crop growth. We are aware of no prior studies exploring the effect of solarization in the Northeast USA on beneficial soil microbiota.

Variations on solarization that are of interest to organic farmers in our region include greenhouse solarization and tarping. Conducting solarization within a greenhouse (Gullino & Garibaldi, 2012) or covering fields with multiple plastic layers (Barakat & Al-masri, 2012) typically results in higher soil temperatures than single-layer solarization, and can improve pest control efficacy (Garibaldi & Tamietti, 1983; Stevens et al., 1999). Tarping, also known as occultation, utilizes black plastic or heavy-gauge silage tarps to block sunlight from reaching the soil for several weeks prior to planting (Fortier, 2014). Black plastic results in lower soil temperatures and less consistently effective weed control than solarization in warmer regions (Horowitz et al., 1983; Standifer et al., 1984). The impacts of greenhouse solarization and tarping on soil microbiota have not been previously studied in the Northeast USA.

We conducted paired experiments in a field and a greenhouse to measure solarization impacts on soil microbiota, assessed via plate counts and soil biological activity, and on weed seeds and soil available nitrogen. In a separate field experiment, we compared the effects of solarization and tarping on soil biological activity at three soil depths. The hypotheses guiding these experiments were as follows:

1. Solarization will reduce all including beneficial soil microbiota during treatment, but the beneficial microbes will return to control levels following treatment;
2. Soil available nitrogen will increase as a result of solarization;
3. Solarization will cause mortality of buried weed seeds;
4. Greenhouse solarization will achieve higher temperatures and be more lethal to microbiota and weed seeds than field solarization;
5. Tarping will be less lethal to microbiota than field solarization; and
6. The impacts of field solarization and tarping on soil microbiota will decrease with increasing depth from the soil surface.

4.2. Materials and Methods

4.2.1. Field and Greenhouse Solarization

4.2.1.1. Site Description

Paired experiments were conducted during June to August of 2016 in an open field (hereafter FIELD experiment) and an adjacent greenhouse (GHOUSE experiment). The site (44°54'N 68°39'W) had been in sod for decades before construction of a 33 m by 8 m double layered 6 mil polyethylene high-tunnel, in-field greenhouse in 2012; the open field was added to production in 2014. Prior to these experiments, the field was left fallow in 2015, and amended with compost in April of 2016. The greenhouse had been planted to organic salad greens in the fall of 2015 and spring of 2016. Soils were Peru-Tunbridge association. The field had 17.9%

organic matter, 6.6 pH, and N-P-K of 21 ppm–406 kg ha^{-1}–2660 kg ha^{-1}; the greenhouse 9.2% organic matter, 6.2 pH, and N-P-K of 90 ppm–97 kg ha^{-1}–1644 kg ha^{-1} (June 2016 soil tests). The high organic matter at these sites, an artifact of past management, likely introduced a 'biosolarization' effect (Stapleton et al., 2016) into these experiments, potentially increasing the efficacy of solarization in comparison to what would be expected at lower organic matter levels.

Air temperatures over the course of these experiments averaged 19.7 °C with a total rainfall of 20 cm (NOAA, 2018). The 30-year historical averages for temperature and rainfall for the months June through August were 19 °C and 26 cm, respectively (NOAA, 2018).

4.2.1.2. Experimental Design

The FIELD and GHOUSE experiments were each arranged as a randomized complete block design with four replicates of three treatments: solarized for 2 weeks, solarized for 4 weeks, and unsolarized control. Plots were 1.5 m by 3.0 m with 0.3 m rows. Soils were rototilled to 15 cm depth 1 to 2 days prior to the experiment start date, 22 June 2016. To begin the experiment, all plots were irrigated to approximate field capacity, and solarization treatments covered with previously used 6 mil polyethylene greenhouse plastic, the edges of which were secured by burial. Previously used plastic was chosen in order to reflect likely grower practices in our region (Chapter 3). Plastic was removed from 2-week treatments on 6 July, and from 4-week treatments on 20 July.

4.2.1.3. Field Data Collection

Soil temperatures were logged hourly during treatment using iButton temperature loggers (Maxim Integrated, San Jose, CA). One logger per plot was placed in a sealed 5 cm by 5 cm 4 mil plastic bag and buried at 10 cm soil depth. Soil moisture was measured and averaged across three locations per plot using a Delta-T soil moisture meter (HH2 version 4.0, Delta-T Devices Ltd, Cambridge, England) on every date that samples were collected.

Bulk soil samples, later sub-divided for measurement of microbial colony forming units (CFU), soil biological activity, and available nitrogen, were collected prior to irrigation and plastic application on 22 June 2016, directly after plastic termination (removal), and five or six days following termination (2-week treatments: 11 July; 4-week treatments: 25 July). Additional samples were collected for soil biological activity measurement at 14 days after termination of 4-week treatments (2 August) and 28 days after termination of 4-week treatments in the GHOUSE experiment only (16 August). Baseline samples collected at the start of experiments consisted of 10 soil cores per block. Subsequent samples, each consisting of 5 soil cores, were taken at the plot level. Soil cores were collected to 10 cm depth using a sterilized 7.6 cm diameter bulb planter (Yard Butler IBPL-6 Bulb and Garden Planter, Lewis Tools, Poway, CA), placed in plastic bags, mixed well, and refrigerated prior to processing.

To test for treatment effects on weed seed viability, seed bags were constructed by sewing a total of 30 weed seeds into polypropylene tea bags (dimensions 6.5 cm by 8 cm; mesh gauge ≤ 200 μm), consisting of 10 seeds each of the following endemic species: *Sinapis arvensis* L., *Digitaria sanguinalis* (L.) Scop., and *Chenopodium album* L. Seeds were purchased in 2016 from Azlin Seed Service (Leland, MS, USA, 38756). One seed bag was buried at 1 cm depth near the center of each control and 4-week treatment plot prior to plastic installation. Seed bags were exhumed at termination of 4-week treatments and refrigerated prior to processing.

4.2.1.4. Laboratory Analyses

The impact of solarization on soil microbial communities was measured by dilution plating and enumeration of colony forming units (CFU) following the methods of Meng et al. (2012). Four selective media were used: 1/10 strength tryptic soy agar + 100 mg L^{-1} cyclohexamide ($TSA_{+1/10}$) to isolate general bacteria; Rose Bengal Chloramphenicol (RBC) to isolate general fungi; Gould's S1 (Tarnawski, Hamelin, Locatelli, Aragno, & Fromin, 2003) to isolate fluorescent pseudomonads, and full strength tryptic soy agar amended with 100 mg L^{-1} cyclohexamide (TSA_+) with samples heated to 80 °C for 30 min to isolate *Bacillus* spp. Suspensions of 10 g well-mixed soil in 90 mL sterilized phosphate-buffered saline solution were shaken for 20 min at 300 rpm and serially diluted. Two replicate plates of each media were inoculated with 100 µL of diluted sample and incubated at room temperature prior to enumeration: 2 days for general bacteria, fluorescent pseudomonads, and *Bacillus* spp.; 3 days for general fungi. Plate counts were standardized using the following equation:

$$\text{CFU g}^{-1}\text{ soil} = N * D / V$$

where N is number of colonies plate^{-1}, D is the dilution factor (10^1 to 10^5), and V is the volume of culture plated (100 µL). Standardized counts from replicate plates were averaged.

Soil biological activity, an indicator of microbial biomass, was measured through CO_2 evolution assays following the methods of Franzlubbers (2016). Soil samples were dried for 3 days at 55 °C, passed through a 4 mm sieve, and 100 g or 50 g soil placed in a beaker and re-wetted to approximated 50% water-filled pore space. Re-wetted samples were incubated at 25 $^{\circ}$C for 3 days in 0.95 L jars alongside two open 25 mL vials: one containing 10 mL 1M NaOH (889573, Carolina Biological Supply Company, Burlington, NC) to trap evolved CO_2, the other containing 10 mL H_2O for humidity. A blank was included with each set of samples. Following incubation, vials of NaOH were mixed with ≤ 5.25 mL 1M $BaCl_2$ (LC116052, LabChem, Zelienople, PA) to form a precipitate, and 2 to 3 drops phenolphthalein color indicator added. NaOH solutions were titrated against 1M HCl (867843, Carolina Biological Supply, Burlington, NC) until color changed from pink to clear. Soil biological activity was calculated as:

$$CO_2 - \text{C mg kg}^{-1}\text{ soil} = (\text{mL}_{[\text{blank}]} - \text{mL}_{[\text{sample}]}) * N * M/S$$

where N is the normality of acid (1 mol L^{-1}), M is the mass conversion from cmol_c to g C (6000), and S is the soil weight.

In preparation for available soil nitrogen (NO_3^- and NH_4^+) testing, samples were dried at room temperature, passed through a 2 mm sieve, and 3.0 g shaken with 30 mL 2.0M KCl (P217-10, Fisher Scientific, Fair Lawn, NJ) at 320 rpm for 1 h, centrifuged at 2700 x g for 20 min, and the supernatent passed through 2 µm filter paper (Ahlstrom 642, Ahlstrom Corporation, Helsinki, Finland). Samples were frozen prior to transferral to the University of Maine Analytical Lab and Maine Soil Testing Service for measurement of NO_3^- and NH_4^+.

Weed seed viability was measured using tetrazolium assays. Within 48 h of exhumation, seeds were removed from mesh bags, placed on moistened filter paper (P8, Fisher Scientific, Pittsburgh, PA, USA, 15275) in 100 mm x 15 mm Petri dishes and left to imbibe at room temperature overnight. Germinated and decayed seeds were removed and counted as viable and non-viable, respectively. Remaining seeds were placed on dry filter paper, bisected longitudinally, and stained with 1 to 2 drops triphenyl tetrazolium chloride solution (1% by weight: T8877-10G, Sigma Life Science, St. Louis, MO, USA, 63013). Seeds were incubated for 24 h, after which seeds stained pink were counted as viable, and seeds remaining unstained were counted as non-viable. Percent seed viability was calculated as:

$$\% \text{ viability} = (V_r / T_r) * 100$$

Where V_r is the number of viable seeds recovered and T_r is the total number of seeds recovered after burial.

4.2.1.5. Statistical Analyses

Data were analyzed with analysis of variance (ANOVA), analysis of covariance (ANCOVA), and multivariate analysis of variance (MANOVA) (Crawley, 2013; Gotelli & Ellison, 2004) in R (R Core Team, 2016). Response variables were $\log_{10} + 1$ or square root transformed as appropriate to improve normality and homogeneity of variances. The chosen significance level was $\alpha = 0.05$. Multivariate analyses were performed using functions from 'Biostats R' (McGarigal, 2000), and packages {energy} (Rizzo & Szekely, 2017) and {vegan} (Oksanen et al., 2016). The {multcomp} package (Hothorn et al., 2008) was used for multiple comparisons, and {pgirmess} (Giraudoux, 2013) for permutation tests. The {gdata} package (Warnes et al., 2017) was used for some aspects of data cleaning. Separate models were fit for FIELD and GHOUSE experiments in all cases. Statistical assumptions were met unless otherwise noted.

To test for solarization impacts on soil microbial communities, MANOVA models were fit with average CFU g^{-1} soil of the four microbial taxa (general bacteria, general fungi, *Bacilli*, fluorescent pseudomonads) as response variables, and explanatory variables: treatment, duration (numeric), and treatment by duration interaction. Separate models were fit for measurements at termination and 5 days post termination. Missing data (8% of observations) were replaced with median values. Neither model adhered to the assumption of multivariate normality; Pillai's trace was therefore chosen as the test statistic because it is considered robust to modest violations of MANOVA assumptions (Gotelli & Ellison, 2004).

To test whether solarization affected soil biological activity, ANCOVA models were fit for termination and termination + 5 day measurements, respectively, with soil biological activity (CO_2 – C mg kg^{-1} soil) as the response, and explanatory variables: treatment, duration, and their interaction. ANOVA models were fit for termination + 14 and termination + 28 day data.

To test for solarization effects on available nitrogen, MANOVA models were fit using available nitrogen (NO_3^-, NH_4^+) as responses, with explanatory variables: treatment, duration, and their interaction. Separate models were fit for termination and termination + 5 day measurements. Missing data (1% of observations) were replaced with median values. Pillai's trace was used as the test statistic due to modest violations of MANOVA assumptions (Gotelli & Ellison, 2004).

To test whether four weeks of solarization resulted in direct mortality of buried weed seeds, ANOVA models were fit with percent seed viability as the response, and explanatory factors: treatment, seed species, and their interaction. This GHOUSE model violated the assumption of normality, so a permutation test (permutations = 1000) was used to obtain simulated P-values (Crawley, 2013; Giraudoux, 2013).

4.2.2. Comparing Solarization to Tarping

To compare the effects of solarization and tarping on soil biological activity, measurements were taken during a 2016 experiment (hereafter TARP), which is described in full in Chapter 3. This TARP experiment was conducted at the University of Maine Rogers Farm (44°55'N, 68°41'W) on Pushaw-Boothbay complex soils (NRCS, 2018a) with 6.2 pH and 3.7% organic matter (2014 soil test). Soil samples for biological activity analysis were collected prior to application of clear and black plastic mulches (14 July 2016), on the day plastic was removed after four weeks of treatment (9 August), and 14 days after plastic termination (25 Aug). Prior to sample collection, soil was gently firmed by stepping on a 23 cm by 23 cm board placed on the soil surface. Samples were collected from three depth strata (0-2 cm, 2-5 cm, and 5-10 cm) using a series of 7.5 cm diameter cylinders inserted into the soil. To obtain sufficient soil volume for analysis, three samples from each depth strata were collected per plot and bulked. Samples were refrigerated prior to processing. Laboratory measurement of soil biological activity followed the methods described in section 2.1.4. above (Franzluebbers, 2016).

To test for treatment and soil depth effects, ANCOVA models were fit for termination and termination + 14 day data, respectively, with soil biological activity as the response and explanatory variables: treatment (control, solarization, tarping), sample depth (numeric: 2, 5, 10), and their interaction. Means were separated by Fisher’s protected LSD.

4.3. Results

4.3.1. Field and Greenhouse Solarization

Maximum temperatures were greater in solarized treatments than non-treated controls, and greater in the GHOUSE experiment as compared with the FIELD experiment (Table 4.1). Accumulated time at temperatures greater than 35 °C was zero in controls for both experiments, increased under FIELD solarization, and more than doubled under GHOUSE solarization as compared with FIELD solarization (Table 4.1). Baseline mean ± SD soil moisture values (%vol) were 22 ± 5 in the FIELD experiment and 20 ± 8 in GHOUSE. Conditions were quite dry in the GHOUSE soils by the end of treatment (Table 4.1).

Baseline counts of mean ± SD CFU g^{-1} soil for the FIELD experiment were general bacteria 6.8 ± 0.2, general fungi 5.8 ± 0.2, bacilli 5.9 ± 0.1, and fluorescent pseudomonads 5.6 ± 0.1 (data reported on a $\log_{10} + 1$ transformed scale). Solarization treatment did not greatly impact FIELD microbial populations at either the time of plastic termination or 5 days post termination (Table 4.2). Duration of treatment was a significant term in the 5-day-post-termination model (Table 4.2). Baseline GHOUSE populations (CFU g^{-1} soil) were general bacteria 7.3 ± 0.4, general fungi 5.7 ± 0.1, bacilli 6.5 ± 0.1, and florescent pseudomonads 5.0 ± 0.1 (data reported on a $\log_{10} + 1$ transformed scale). Treatment was a significant factor affecting the microbial community at termination and 5 days post termination (Table 4.3). Specifically, fluorescent pseudomonad populations were reduced in solarized plots as compared with non-treated controls; other taxa were weakly or inconsistently impacted (Table 4.3). Duration of treatment was a significant term in both models, though an overarching pattern was not apparent (Table 4.3).

Table 4.1. Temperature and Soil Moisture in FIELD and GHOUSE Experiments. Mean ± SD maximum and average temperatures, exposure time to temperatures above 35 °C, and volumetric soil moisture in FIELD and GHOUSE experiments. Temperatures were measured at 10 cm soil depth and means calculated across four replicates unless otherwise noted: † data from 3 replicates; ‡ data from one replicate. Soil moisture was measured in three locations per plot at plastic termination.

Experiment	Treatment	Duration (weeks)	Soil temp (°C)		Exposure time (h)			Soil moist. (%vol)
			Max	Avg	36-40 °C	41-45 °C	>45 °C	
FIELD	Control	2	31 ± 1†	22 ± 1†	0†	0†	0†	11 ± 1
		4	32 ± 2†	23 ± 1†	0†	0†	0†	11 ± 3
	Solarization	2	39 ± 3	28 ± 1	28 ± 22	4 ± 4	0	14 ± 8
		4	38 ± 5	27 ± 3	39 ± 31	10 ± 20	0	12 ± 3
GHOUSE	Control	2	33‡	27‡	0‡	0‡	0‡	1 ± 1
		4	35‡	27‡	0‡	0‡	0‡	1 ± 1
	Solarization	2	44 ± 1	34 ± 0	74 ± 9	48 ± 5	0	3 ± 1
		4	46 ± 3	34 ± 1	123 ± 20	87 ± 16	19 ± 28	2 ± 1

Table 4.2. Colony Counts and MANOVA Results from FIELD Experiment. Mean ± SD microbial colony counts from FIELD experiment and corresponding MANOVA results. Models were constructed to test the effects of solarization treatment and duration on soil microbiota for the day treatments were terminated, and 5 days after termination. † nd = no data. *P*-values significant at an α = 0.05 level are denoted with an asterisk (*).

Colony counts (CFU g^{-1} soil)	Termination				Termination + 5 days			
	Control		Solarization		Control		Solarization	
	2 week	4 week	2 week	4 week	2 week	4 week	2 week	4 week
General bacteria	7.3 ± 0.5	7.7 ± 0.5	7.6 ± 0.6	7.6 ± 0.4	7.2 ± 0.2	7.4 ± 0.4	7.5 ± 0.7	7.5 ± 0.2
General fungi	5.1 ± 0.4	4.8 ± 0.9	5.1 ± 0.5	5.3 ± 0.8	5.7 ± 0.1	5.1 ± 0.3	6.0 ± 0.2	5.7 ± 0.3
Bacilli	6.4 ± 0.4	6.7 ± 0.2	6.5 ± 0.4	6.6 ± 0.4	nd†	6.1 ± 0.3	nd	6.5 ± 0.4
F. pseudomonads	5.4 ± 0.3	4.4 ± 0.2	4.8 ± 0.6	4.7 ± 0.8	5.5 ± 0.3	4.8 ± 0.5	5.5 ± 0.5	5.0 ± 1.1
MANOVA	DF	Pillai's	F	*P*	DF	Pillai's	F	*P*
Treatment	1	0.05	0.11	0.98	1	0.61	3.53	0.05
Duration	1	0.36	1.24	0.36	1	0.75	6.66	<0.01*
T x D	1	0.29	0.93	0.49	1	0.33	1.11	0.41
Residuals	12				12			

Table 4.3. Colony Counts and MANOVA Results from GHOUSE Experiment. Mean ± SD microbial colony counts from GHOUSE experiment and corresponding MANOVA results. Models were constructed to test the effects of solarization treatment and duration on soil microbiota for the day treatments were terminated, and 5 days after termination. † nd = no data. *P*-values significant at α = 0.05 are denoted with an asterisk (*).

Colony counts (CFU g^{-1} soil)	Termination				Termination + 5 days			
	Control		Solarization		Control		Solarization	
	2 week	4 week	2 week	4 week	2 week	4 week	2 week	4 week
General bacteria	7.8 ± 0.4	7.1 ± 0.2	7.2 ± 0.4	7.2 ± 0.7	7.5 ± 0.3	8.0 ± 0.6	7.4 ± 0.3	7.8 ± 0.7
General fungi	5.6 ± 0.3	5.9 ± 0.5	4.3 ± 0.4	5.7 ± 0.6	5.5 ± 0.4	5.6 ± 0.2	5.2 ± 0.6	5.7 ± 0.6
Bacilli	7.0 ± 0.2	6.6 ± 0.6	6.9 ± 0.1	6.5 ± 0.4	nd†	6.5 ± 0.3	nd	6.5 ± 0.2
F. pseudomonads	4.9 ± 0.6	0.9 ± 1.8	4.1 ± 0.8	0.0 ± 0.0	5.0 ± 0.3	4.4 ± 0.8	1.0 ± 2.0	1.3 ± 1.6
MANOVA	DF	Pillai's	F	*P*	DF	Pillai's	F	*P*
Treatment	1	0.69	4.96	0.02*	1	0.87	15.09	<0.01*
Duration	1	0.94	35.87	<0.01*	1	0.63	3.84	0.04*
T x D	1	0.56	2.84	0.09	1	0.14	0.37	0.83
Residuals	12				12			

Baseline soil biological activity ($CO_2 - C$) mean ± SEM values in FIELD and GHOUSE experiments were 185 ± 3 mg kg^{-1} soil and 153 ± 10 mg kg^{-1} soil, respectively. In the FIELD experiment, solarization did not significantly reduce biological activity during treatment (Figure 4.1A; F = 4.90, $P = 0.05$). Subsequently, there was a significant reduction at 5 days (Figure 4.1B; F = 7.13, $P = 0.02$) but not 14 days after plastic removal (Figure 4.1C; F = 2.24, $P = 0.18$). In the GHOUSE experiment, solarization reduced soil biological activity during treatment (Figure 4.1D; F = 20.86, $P < 0.01$), and differences persisted through 28 days of subsequent measurement (Figure 4.1E-G). Duration of solarization and treatment by duration interaction were not significant terms ($P \geq 0.05$). R^2 values underpinning FIELD models were: termination = 0.36, 5 days post termination = 0.49, and 14 days post termination = 0.27; R^2 values for GHOUSE models were termination = 0.68, 5 days post termination = 0.71, 14 days post termination = 0.82, and 28 days post termination = 0.87.

In the FIELD experiment, baseline soil available nitrate and ammonium mean ± SEM values were 2.2 ± 1.0 NO_3^--N mg L^{-1} soil and 1.3 ± 0.1 NH_4^+-N mg L^{-1} soil, respectively. Available nitrogen was elevated in solarized treatments as compared with controls at termination and 5 days thereafter (Figure 4.2). Duration of treatment and treatment by duration interaction were not significant terms ($P \geq 0.05$).

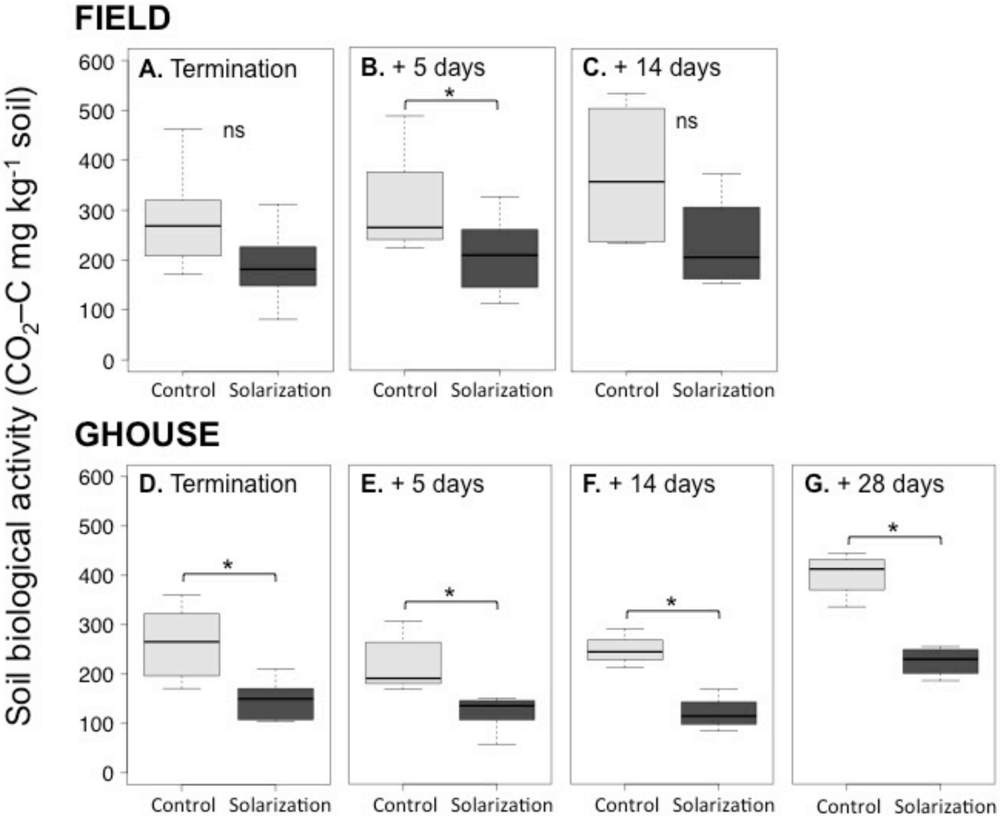


Figure 4.1. Soil Biological Activity in FIELD and GHOUSE Experiments. Biological activity measured in the FIELD experiment at (A) plastic termination, (B) termination + 5 days, and (C) termination + 14 days, and in the GHOUSE experiment at (D) termination, (E) termination + 5 days, (F) 14 days post termination, and (G) 28 days post termination. Data are shown pooled across treatment durations. Asterisks (*) indicate significant difference at α = 0.05, and ns indicates no significant difference.

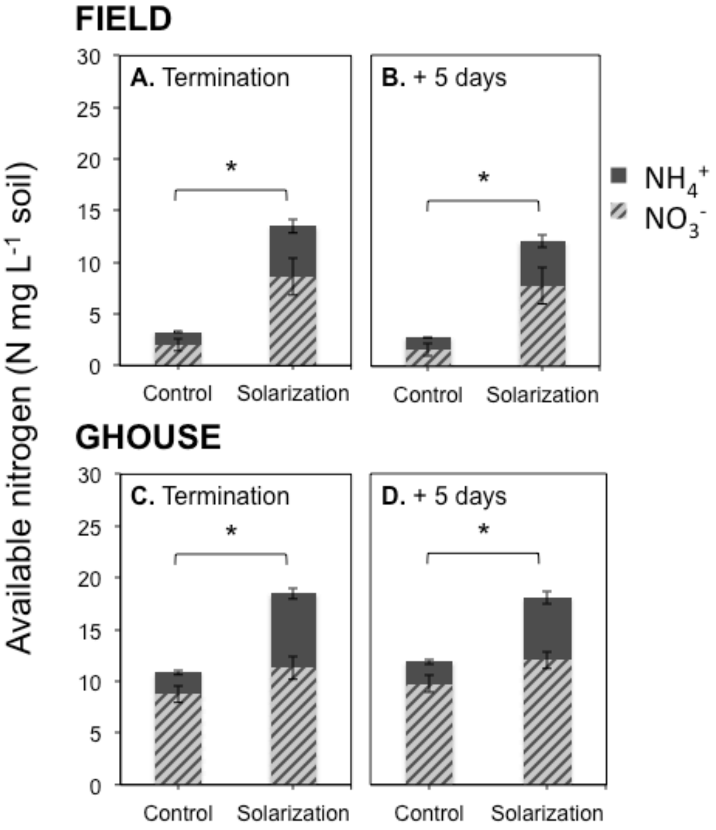


Figure 4.2. Available Nitrogen in FIELD and GHOUSE Experiments. Mean ± SEM available nitrogen in the FIELD experiment (A) at plastic termination and (B) five days after termination, and in the GHOUSE experiment (C) at termination and (D) five days after termination. Data are shown pooled across treatment durations. Asterisks (*) denote statistically significant treatment effects at $\alpha = 0.05$.

Weed seed viability was reduced under solarization in both FIELD and GHOUSE experiments (Figure 4.3). There was a significant species effect in the FIELD model, but no significant treatment by species interaction (Figure 4.3A; Table 4.4). All weed species were greatly reduced following GHOUSE solarization (Figure 4.3B) with no significant species or interaction effects (Table 4.4). R^2 values for these models were 0.47 in FIELD and 0.87 in GHOUSE.

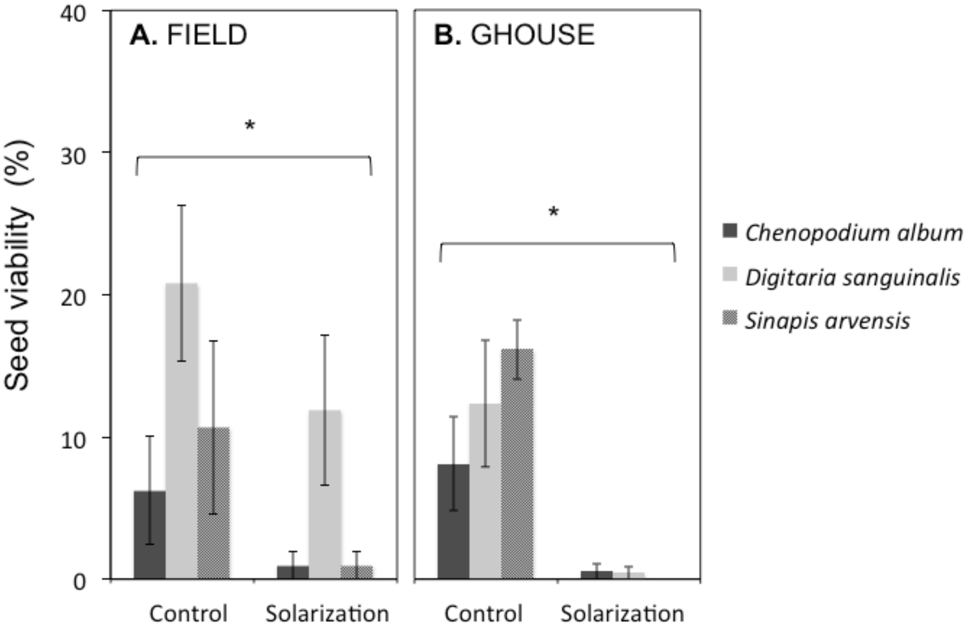


Figure 4.3. Weed Seed Viability in FIELD and GHOUSE Experiments. Mean ± SEM seed viability of three weed species after four weeks of burial in non-treated control and solarization treatments in (A) FIELD and (B) GHOUSE experiments. Asterisks (*) denote statistically significant treatment effects at α = 0.05.

Table 4.4. FIELD and GHOUSE Weed Seed Viability ANOVA Tables. Models were constructed to test the effects of solarization treatment and seed species on weed seed viability after four weeks of solarization. *P*-values significant at the α = 0.05 level are shown with an asterisk (*). Due to non-normality of residuals in the GHOUSE model, simulated *p*-values calculated via permutation test are presented.

	FIELD			GHOUSE		
	DF	F	*P*	DF	F	*P*
Treatment	1	5.85	0.03*	1	122.73	<0.01*
Seed Sp.	2	4.81	0.02*	2	1.60	0.24
T X Sp.	2	0.20	0.82	2	3.57	0.07
Residuals	18			18		

4.3.2. Comparing Solarization to Tarping

In the TARP experiment, soil biological activity was evaluated at three soil depths during and after four weeks of field solarization and tarping treatment. Soil depth and treatment by depth interactions were not significant ($P \geq 0.05$). Treatment did not impact soil biological activity at plastic termination (Figure 4.4A), but 14 days thereafter, soil biological activity was reduced in the solarized treatment as compared with the non-treated control (Figure 4.4B). R^2 values were 0.21 and 0.61 for termination and 14-day-post-termination models, respectively.

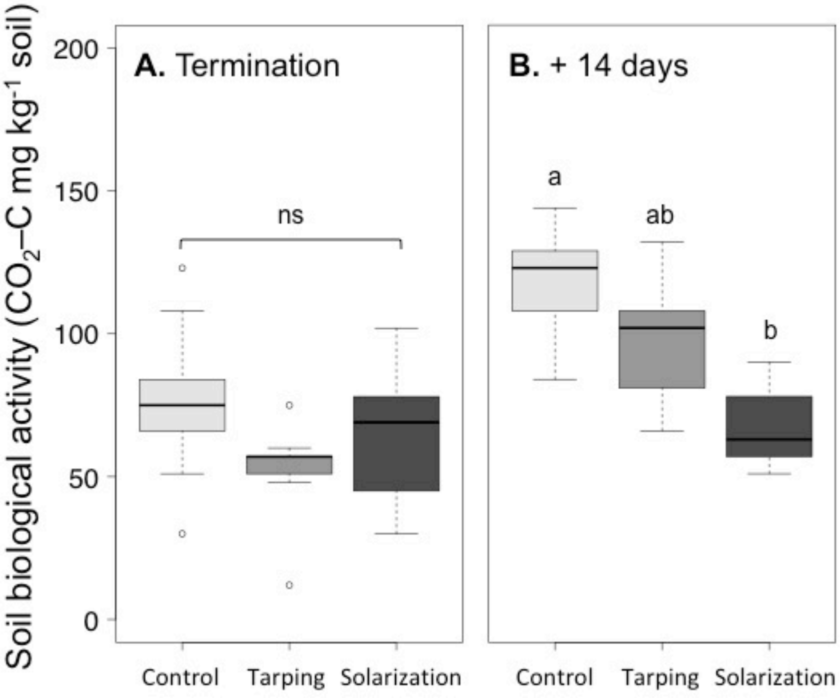


Figure 4.4. Soil Biological Activity in 2016 TARP Experiment. Soil biological measured (A) at plastic termination, and (B) 14 days after plastic termination in non-treated control, tarping, and solarization treatments. Data are shown pooled over treatment depths. Connecting letters reflect means separated by Fisher's protected LSD at α = 0.05; ns indicates no significant difference.

4.4. Discussion

4.4.1. Field and Greenhouse Solarization

Soil solarization is an established method of pest control (Cohen & Rubin, 2007; McGovern & McSorley, 2012) that can create an effective stale seedbed in the Northeast USA (Chapter 3); however, its effects on soil health in our humid continental climate have not been previously reported. Microbial communities are important to agroecosystem function (Wall, 2013), and many organic farmers prioritize the maintenance of soil health (Baker & Mohler, 2015); thus questions of solarization's non-target impacts are of relevance to growers.

Based on the assumption that most soil microbiota at our study site would be adapted to ambient temperatures, we hypothesized that overall, beneficial microbe populations would be reduced during treatment, but would quickly re-colonize from lower soil layers thereafter (Hypothesis 1) (Katan & Gamliel, 2012). The data indicated that solarization in our FIELD experiment had transient effects on soil biological activity (Figure 4.1A-C), and population of the four taxa we measured were not significantly impacted (Table 4.2). This suggests that many species present in our soils, including generally beneficial rhizosphere bacteria of the *Bacillus* and *Pseudomonas* genera (Kloepper, Ryu, & Zhang, 2004; Mazurier, Corberand, Lemanceau, & Raaijmakers, 2009; Santoyo, Orozco-Mosqueda, & Govindappa, 2012), were resilient to field solarization. In the case of bacilli, this is unsurprising given their known ability to form spores (Baril et al., 2012) that allow survival at temperatures exceeding 80 °C. Though our findings offer weak support for Hypothesis 1, they are nonetheless consistent with past studies. Scopa & Dumontet found that soil biological activity was reduced, but not significantly, during field solarization in southern Italy (2007), while numerous studies have concluded based on plate counts that field solarization did not permanently harm beneficial microbiota (Jaacov Katan & Gamliel, 2012).

Available nitrogen (NO_3^- and NH_4^+) was elevated during and after solarization (Figure 4.2), consistent with our expectation (Hypothesis 2) and the results of past studies (Khan et al., 2012; Oz et al., 2017; Sofi et al., 2014). Mechanisms of available nitrogen increase may include increased mineralization (Rubin, 2012) or breakdown of microbial cells. Katan and Gamliel (2012) note that the growth of crop plants is often stimulated following solarization, due at least partially to increased soil nutrient availability. Thus, solarization in the Northeast USA could provide additional benefits beyond weed control, and might be well suited as a stale seedbed treatment prior to sowing heavy-feeding crops.

Weed seed viability overall was greatly reduced by solarization (Figure 4.3), supporting Hypothesis 3. Under the conditions in our FIELD experiment (Table 4.1), *Digitaria sanguinalis* appeared to suffer less mortality than other species (Figure 4.3A), though this was not reflected statistically. The time and temperature requirements for weed seed thermal death are known to vary by species (Dahlquist, Prather, & Stapleton, 2007) due to traits such as seed coat hardness (Baskin & Baskin, 1998; Egley, 1990). Weed seed mortality may have been elevated in this study due to high soil organic matter. The 17.9% organic matter measured in our FIELD experiment, though still within the range found on operating organic farms in our region (Brown BJ, unpublished data), is quite high. Incorporation of organic amendments prior to solarization, termed biosolarization, is known to decrease the time needed for thermal inactivation of weed seeds (Achmon et al., 2017) and can lead to enhanced control of soilborne pathogens as well (Díaz-Hernández, Gallo-Llobet, Domínguez-Correa, & Rodríguez, 2017; Ozyilmaz, Benlioglu, Yildiz, & Benlioglu, 2016; Stapleton et al., 2016). Though the practice is promising, more work evaluating the impact of biosolarization on beneficial soil microbiota is advised; Kanaan et al. found that soil biological activity was reduced during and for four weeks following solarization integrated with compost application (2016).

We expected greenhouse solarization to result in higher soil temperatures and greater mortality of microbes and weed seeds than field solarization (Hypothesis 4). Consistent with this hypothesis, soil biological activity (Figure 4.1D-G), microbial populations (Table 4.3), and weed seed mortality (Figure 4.3B) were reduced by greater magnitudes or with more consistency by solarization in our GHOUSE as compared with our FIELD experiment. Congruent with these results, greenhouse solarization reduced biological activity during treatment in a study by Scopa et al. (2008). The reduction in fluorescent pseudomonads we measured during greenhouse solarization (Table 4.3) is consistent with previously reported temperature sensitivity of this taxon (Seong, Hofte, Bolens, & Verstraete, 1991) (Table 4.1). However, fluorescent pseudomonads have been shown to quickly re-colonize after treatment: Gamliel & Katan (1991) reported that fluorescent pseudomonads were reduced during solarization, but two days after sowing tomatoes *in vitro*, rhizosphere populations were higher in solarized soils than controls. It is possible that dry soil conditions (Table 4.1) or an absence of vegetation (Laffley A, unpublished data) in our GHOUSE experiment slowed expected recolonization. Viability of buried weed seeds was reduced by 98% in our GHOUSE experiment, with all three species well controlled (Figure 4.3B), demonstrating that greenhouse solarization in the Northeast USA can result in substantial weed seedbank depletion at shallow depth.

4.4.2. Comparing Solarization to Tarping

Results of our TARP experiment offered little support for the hypothesis that tarping is less lethal to microbiota than field solarization (Hypothesis 5). Despite higher soil temperatures under solarization as compared with tarping (Chapter 3), soil biological activity was not affected by treatment at the time of plastic removal (Figure 4.4A), and a trend toward less biological activity following solarization as compared with tarping was not significant (Figure 4.4B). Overall, this provided little support for Hypothesis 5, suggesting rather that solarization may not pose an increased risk to soil microbes as compared with tarping in our system. The hypothesis that impacts of treatment on soil biological activity would decrease with increasing soil depth (Hypothesis 6) was also unsupported. Differences by depth might have been detected if we had included soil strata deeper than 10 cm (Mahrer & Shilo, 2012).

We were surprised that soil biological activity showed a delayed negative response to solarization, evident in the significant difference between solarized and non-treated control plots measured 14 days after plastic termination (Figure 4B). Following the logic of Hypothesis 1, we had expected the opposite temporal trend: that biological activity would be reduced during treatment, but would return to control levels rapidly thereafter. Though we do not have a mechanistic explanation for this result, potential contributing factors include changes in microbial community composition (Gelsomino & Cacco, 2006; Ozyilmaz et al., 2016) or the soil chemical environment (Chen et al., 2000; Khan et al., 2012; Oz et al., 2017; Sofi et al., 2014) during and after solarization.

4.4.3. Potential for Plant Pathogen Control

Solarization can contribute to effective soilborne pathogen control in warmer climates (McGovern & McSorley, 2012), but we are aware of no studies examining its efficacy in our region. We compared temperature maxima and accumulated thermal time measured in our FIELD and GHOUSE experiments (Table 4.1) to published thermotolerance thresholds of common soilborne pathogens that impact vegetable and horticultural crops in Maine (Table 4.5). Solarization would theoretically reduce populations of nearly half of these pathogens under conditions measured in our FIELD experiment, and over two-thirds of species under GHOUSE conditions. Only *Botrytis cinera*, the fungus causing noble rot or gray mold in horticultural crops including grape, was expected to be stimulated by solarization (Le Bihan, Soulas, Camporota, Salerno, & Perrin, 1997). This brief review is limited to the theoretical effects of temperature on regionally important vegetable and horticultural pathogens, and does not account for other environmental aspects influencing pathogen survival. Nonetheless, this provides indication that field and, especially, greenhouse solarization have the potential to contribute to plant pathogen reduction in the Northeast USA.

Table 4.5. Expected Pathogen Responses to Solarization. Expected responses of some plant pathogens common in the Northeast USA to temperature conditions obtained in our FIELD and GHOUSE experiments. Responses are categorized as reduced in number due to treatment (+), not affected by treatment (0) or stimulated by treatment (-). All cited studies measured pathogen response at temperatures equal to or less than those achieved at 10 cm soil depth in our FIELD and GHOUSE experiments. † Field study; ‡ *in vitro* study

Pathogen species	Common name	Expected response		Source
		FIELD	GHOUSE	
Alternaria cucumerina	*Alternaria* leaf blight	+	+	(Vakalounakis & Malathrakis, 1988)‡
Alternaria Solani	Early blight	0	+	(Abu-Gharbieh, Saleh, & Abu-Blan, 1988)†
Botrytis cinera	Noble rot	-	-	(Le Bihan et al., 1997)†
Fusarium solani f. sp. *cucurbitae*	*Fusarium* rot	0	+	(Abu-Gharbieh, Saleh, & Abu-Blan, 1988)†
Pectobacterium atrosepticum	Blackleg	+	+	(Tsror et al., 2009)‡
Pectobacterium carotovorum	Soft rot	0	0	(Smadja et al., 2004)‡
Phytophthora erythroseptica	Pink rot	0	+	(Pinkerton, Ivors, Reeser, Bristow, & Windom, 2002)†
Phytophthora infestans	Late blight	+	+	(Drenth, Janssen, & Govers, 1995)‡
Plasmodiophora brassicae	Club foot	0	0	(Chellemi, 1994)†
Rhizoctonia	Belly rot	0	+	(Pinkerton et al., 2002)†
Sclerotinia sclerotiorum	White mold	+	+	(Cartia & Asero, 1994)†
Verticillium dahliae	*Verticillium* wilt #1	0	+	(Pullman, DeVay, Garber, & Weinhold, 1981)†
Verticillium albo-atrum	*Verticillium* wilt #2	+	+	(Smith, 1965)‡

4.5. Conclusions

Populations of culturable beneficial soil microbiota were not affected by field solarization, but soil biological activity was transiently reduced. Solarization resulted in seed mortality in both field and greenhouse, but the high (98%) weed seed mortality measured in our greenhouse experiment came with a potential ecological tradeoff: populations of florescent pseudomonads and soil biological activity were reduced and remained suppressed following greenhouse solarization for the duration of our measurements. Available nitrogen increased during and after solarization in both the field experiment and the greenhouse experiment. Temperatures in these experiments were theoretically sufficient for the reduction of some regionally problematic soilborne pathogens. In a separate field experiment, solarization reduced soil biological activity following plastic removal, while the similar practice of tarping with black plastic did not, though differences between these mulching practices were not significant. Future research is needed to determine whether results from these experiments can be generalized over a broader range of soil and environmental conditions, to determine whether solarization in our region results in improved crop yields and is economically viable, and to explore the potential of solarization to contribute to plant pathogen control in the Northeast USA.

CHAPTER 5

WEEDUCATOR: A NOVEL APPROACH TO ORGANIC WEED MANAGEMENT EDUCATION

5.1. Introduction

Maine is home to a growing number of young and beginning farmers; the number of farmers in Maine under the age of 34 increased by 46% in the decade leading up to USDA NASS' most recent Agriculture Census (2012). Many of these beginning farmers choose to grow organically. Organic farming practices are typically more environmentally sustainable than conventional practices (Reganold & Wachter, 2016; Tuomisto, Hodge, Riordan, & Macdonald, 2012); however, economic sustainability remains a challenge for Maine organic farmers (Percy, 2015) including beginning farmers (Gillespie & Johnson, 2010).

Farmers who grow organically typically rely on a diverse array of non-chemical tactics used in combination to manage weeds, including different tools, mulches, and crop rotations (Baker & Mohler, 2015; Chapter 1). Beginning farmers face a steep learning curve in mastering the many techniques that contribute to successful organic weed control, and interviews with established farmers suggest that much of the knowledge they eventually acquire comes through time-consuming trial and error (Jabbour, Zwickle, et al., 2014).

In a review of contemporary beginning farmer training initiatives, Niewolny and Lillard (2010) cite participatory learning methods and forums to reach the “digitally aware” beginning farmer audience as recommended areas for research and program development. The purpose of this project was to explore the potential for an interactive digital tool to help beginning farmers lessen the learning curve they face related to weed management. To this end, we developed a prototype digital learning tool, WEEDucator, with input from focus groups of farmers and agriculture students. Subsequently, we administered an educational intervention to a group of students recruited from University of Maine sustainable agriculture courses that was designed to test the following hypotheses:

1. Interacting with the WEEDucator tool will increase users' factual knowledge of weed ecology and management; and
2. Users will like the look and feel of this tool, find it fun to use, and prefer it to other methods through which they might learn this content.

5.2. Materials and Methods

5.2.1. Tool Development

We began the tool development process by studying existing weed management decision aids (e.g., Lindsay et al., 2017; Pannell et al., 2004). While these had value in providing users the ability to interactively explore effects of different weed management approaches, we generally did not find their user interfaces engaging, and we wondered if an attempt to further 'gamify' this kind of educational resource by employing new media technology and design principles could result in a product that was more fun to use. Gamification has been used extensively in other disciplines to promote participant engagement (reviewed in Dicheva, Dichev, Agre, & Angelova, 2015). The only prior attempt to gamify weed management education of which we are aware is a soybean management game developed in the early 1990s (Wiles, Wilkerson, & Coble, 1991).

We developed a concept for an organic weed management simulator game, and convened a focus group of organic vegetable farmers to give input on our ideas. Farmers were recruited through the MOFGA listserv and given an honorarium for their participation. Participating farmers (N=11) ranged in experience from 5 to 15 years. Based on feedback from this group, we revised our game design to be modular, including a scaled-back version of the management simulator, as well as other information farmers indicated they wish they had known when they began farming. Our revised designs were further honed through a second focus group conducted with sustainable agriculture students from a nearby community college.

We constructed a prototype game-like digital tool, WEEDucator, consisting of three learning modules (Figure 5.1). This tool was built using the Unity game engine (Unity Technologies, 2018), in collaboration with new media artists. The Management Sim module of this tool (Figure 5.1) is underpinned by a simple simulation model, the structure of which is outlined in Appendix B; for a review of past approaches to modeling weed populations, see Holst et al. (2007). Other modules were developed based on a variety of published sources, which are referenced within the tool itself. Though this WEEDucator prototype is not a 'finished product,' it was considered sufficiently functional to allow play-testing and measurement of learning outcomes. It is freely available for download and use (Birthisel, Rimkunas, & Sullivan, 2017; https://skbirthisel.weebly.com/outreach.html).

5.2.2. Tool Evaluation

WEEDucator's effectiveness as a teaching tool was measured and feedback about user experience gained via an educational intervention with paired pre- and post-assessments. Participants were recruited through announcements made during fall semester 2017 in two University of Maine sustainable agriculture courses. This test population may not be representative of a broader beginning farmer audience (Niewolny & Lillard, 2010), but was assumed to have some level of specialized knowledge in agriculture. Participation was incentivized by offering snacks or extra credit points according to the preference of the course instructor. The University of Maine Institutional Review Board approved the study protocol and all participants provided informed consent to participate.

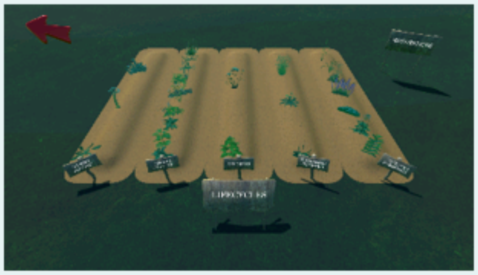
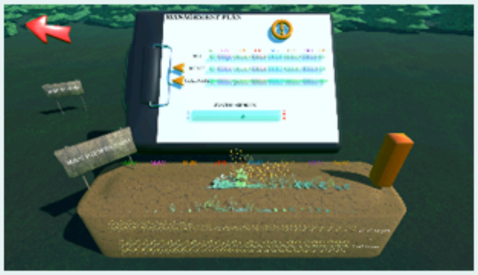
	Module Name	Description
	**Lifecycles**	An interactive 'guidebook' containing 35 common weed species that illustrates aspects of weed biology relevant to farmer management decisions.
	**Toolshed**	A collection of videos and infographics providing information about various weed management tools and tactics.
	**Management Sim**	An interactive simulation model that allows the user to create a weed management plan and see possible impacts of their choices on weed pressure and the weed seedbank.

Figure 5.1: Modules Included in the WEEDucator Prototype.

Educational interventions and assessments were administered in-person. Participants were read a script informing them of the study's purpose and terms, including that participation was voluntary and assessment responses would be kept anonymous. Pre-assessments were then administered, after which participants were instructed to open the WEEDucator program on provided computers and explore the tool at their own pace for up to 45 minutes. They were advised that this might not be sufficient time to fully explore the tool's functionality, and it was acceptable to move between modules of the tool according to their own interests. After 45 minutes, or when participants indicated they were 'done' (whichever occurred first), participants were asked to close WEEDucator and complete a post-assessment matched to their pre-assessment by randomly-assigned numbers.

Pre-assessments consisted of nine factual questions (see Appendix C for assessment text), each worth a minimum of zero and a maximum of two points for a total of 18 possible points. After each question, students were prompted to select a level of confidence in their given answer. Pre-assessments also asked participants for some background information including their major and year in school. Post-assessments consisted of the same nine questions and confidence level prompts, followed by a section designed to solicit user feedback, including a question asking participants to rank WEEDucator in comparison to other educational methods (Appendix C). Assessments were graded according to a pre-determined rubric, with partial credit given for partially-correct answers. To test whether participants' knowledge and confidence in their answers changed following the educational intervention, mean pre- and post- assessment scores for knowledge and confidence, respectively, were compared using Welch's t-tests. To test for significant differences in participants' ranking of educational methods, we used ANOVA with Fisher's protected LSD for means separation. Analyses were performed in R (R Core Team, 2016). Assumptions were validated for all statistical methods.

5.3. Results and Discussion

5.3.1. Learning Outcomes

Nineteen students participated in formalized pre- and post-assessments designed to evaluate the WEEDucator prototype's effectiveness as a teaching tool. Just over half of participating students were majoring in plant science-related fields (Sustainable Agriculture, Environmental Horticulture, or Forestry); other participants were from a variety of majors. Eight participants were first year students, three were graduate or non-traditional students, and the rest were upper-class undergraduates.

Mean knowledge scores were 58% higher in the post-assessment as compared with the pre-assessment (t = -4.57, $P < 0.01$; Figure 5.2A). Participant confidence scores were 107% higher in the post-assessment as compared with the pre-assessment (t = -6.95, $P < 0.01$; Figure 5.2B). For all individual questions, mean difference scores between assessments (post minus pre) were positive, indicating that WEEDucator improved mean knowledge scores for every survey question. These results provide support for Hypothesis 1, which states that interacting with WEEDucator will increase users' factual knowledge of weed ecology and management. The fact that confidence scores increased by a greater magnitude than knowledge scores is interesting, and worthy of note based on the possibility that exposure to this tool might have empowered users to feel over-confident in relation to their actual level of knowledge.

Limitations to this study include the small sample size (N=19), and the fact that same-day pre- and post-assessments do not indicate how well participants retain information over time. While these are clear limitations, our study is not unique in featuring a sample of this size (e.g., George & Cole, 2018) nor in using same-day pre- and post-assessments to gauge learning outcomes (Fishel, 2008). Another point worthy of note is that the use of identical questions in the pre- and post-assessments (Appendix C) may have contributed to the positive learning outcomes measured (Figure 5.2A), as exposure to the pre-assessment may have operated similarly to a 'think-pair-share' exercise in priming students to be interested in finding answers to these questions (Cooper & Robinson, 2000). Despite these limitations, these results are promising, suggesting that WEEDucator was effective in conveying knowledge related to its learning objectives.

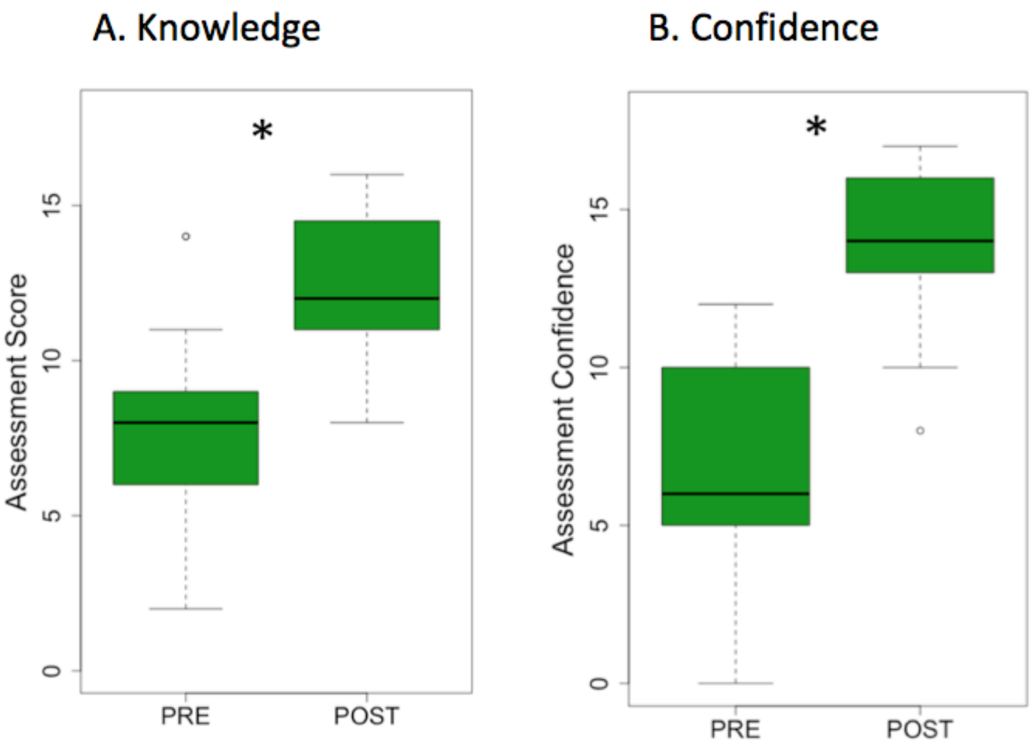


Figure 5.2. Pre- and Post-Assessment Knowledge and Confidence Scores. Scores for factual knowledge of weed ecology and management (A) and participant confidence in their answers (B). The maximum number of points in either category was 18.

5.3.2. User Feedback

Assessment participants ranked 'games like WEEDucator' as their most preferred way to learn this material, followed by activities in lab and lecture, watching YouTube videos, classroom lectures, and reading a textbook ($R^2 = 0.37$, $F = 11.49$, $P < 0.01$; Figure 5.3). There was no significant difference in participant preference between WEEDucator and activities in lab and lecture, but WEEDucator was significantly preferred to the other methods of learning included in this comparison (Figure 5.3).

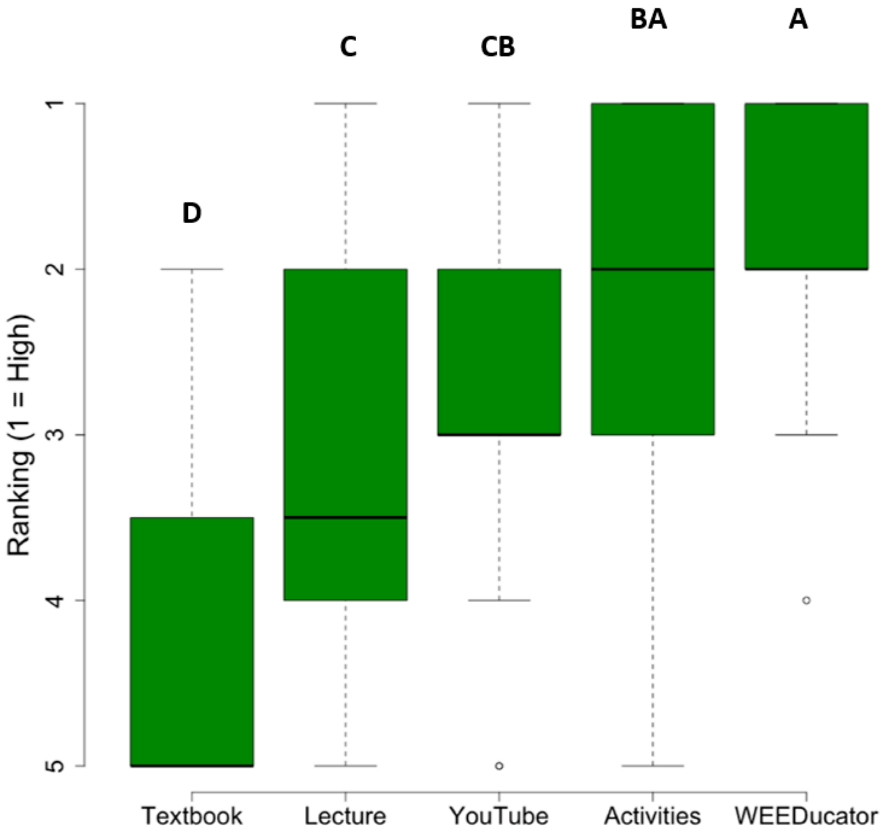


Figure 5.3. Participant Ranking of Learning Methods. Participant rankings of educational methods they might use to learn the content provided in WEEDucator. Connecting letters reflect means separated by Fisher's protected LSD at α = 0.05.

A majority of participants indicated that WEEDucator was both helpful and fun to use (Table 5.1). The Toolshed, which featured videos and infographics about organic weed management tactics (Figure 5.1), was the most liked module, with nine respondents indicating that they liked this module the most and three indicating that they liked it least. Several respondents who liked the Toolshed most indicated that they found it informative, with comments including "Solid info given, expanded my knowledge!" Those who liked this module least commented that they wished it had been more interactive. Five participants indicated that they liked the virtual guidebook Lifecycles (Figure 5.1) the most and three that they liked this module least, citing a variety of reasons for their preferences. Six participants indicated that they liked Management Sim (Figure 5.1) the most and nine participants indicated that they liked this module least. Several of those who liked this module the most cited its interactive nature, while those who liked it least commented that they found it confusing or wished for more instruction; in the words of one respondent, “If there were clearer directions, I think it would be more enjoyable.”

Table 5.1. Some Participant Feedback About WEEDucator. Number of participants responding true/false or omitting response to survey questions asking if they found WEEDucator helpful and fun to use.

Survey text	Responses (No.)		
	True	False	No answer
Overall, I found WEEDucator helpful	18	0	1
Overall, WEEDucator was fun to use	17	0	2

In response to the prompt ‘Anything else you’d like us to know?’ eight respondents identified bugs in the program. Other frequent responses (mentioned by >5 respondents) included positive comments about the tool being useful or informative, positive comments about the tool being interesting, and miscellaneous suggestions for improvements to the interface.

Overall, this feedback (Figure 5.3; Table 5.1) provides support for our hypothesis that users will like WEEDucator, find it fun to use and prefer it to other methods of learning this content (Hypothesis 2). Participants were verbally prompted to provide critical feedback and identify bugs in the program that should be fixed, so the number of comments on these points is unsurprising, but nonetheless reinforces that the current iteration of WEEDucator is a prototype that would need revision before it could be considered a finished product.

5.4. Conclusions

WEEDucator is a functional proof-of-concept for how simple games may contribute to effective teaching of weed ecology principles and practices. In an educational intervention (N=19), exposure to the tool resulted in improved student ability to correctly answer factual questions about weed ecology and management, and a majority (>90%) of participating students indicated that they found the tool helpful and fun to use. Students ranked 'tools like WEEDucator' highly among methods through which they might learn this kind of information. It remains an open question whether similar results would be obtained with a broader population of beginning farmers, but these findings do suggest that interactive digital tools like WEEDucator can effectively engage agriculture students in learning about ecological weed management.

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APPENDIX A: LISTS OF RARE WEED SPECIES AND MAPS OF SITE OCCUPANCY

The following pages in this appendix contain lists of relatively rare weedy (WSSA, 2018) species identified our spring 2013 seedbank sampling of 30 farms in Maine (Table A.1) and our subsequent 2015 survey sampling (Table A.2). Maps showing transect occupancy of species of agronomic concern (risk) found during our 2015 surveys are also included (Figure A.1). Species found in seedbank samples were considered rare when they were found in the seedbank on only one farm, or when the sum of emerged seedlings across all 30 farms was less than 100 seeds per 30 m^2. Species found during survey sampling were considered rare based on expert opinion of the surveyors, or if they had previously been identified as such during seedbank sampling.

Table A.1. Weed Species Classified as Rare in Seedbank Samples. † Species also reported in survey sampling (Table A2).

<100 seeds	Only one farm	Only one farm & <100 seeds
Tanacetum vulgare L. (common tansy)	*Scirpus cyperinus* (L.) Kunth (woolgrass bulrush)	*Agrostemma githago* L. (corn cockle)
Elymus repens (L.) Gould (quackgrass) †	*Tussilago farfara* L. (coltsfoot)	*Avena sativa* L. (common oat) †
Erigeron annuus (L.) Pers. (fleabane)	*Physalis philadelphica* Lam. (tomatillo)	*Chaenorhinum minus* (L.) Lange (dwarf snapdragon)
Lobelia siphilitica L. (blue cardinal flower)		*Euphorbia maculata* L. (spotted spurge) †
Lythrum salicaria L. (purple loosestrife)		*Erigeron canadensis* L. (horseweed)
Matricaria discoidea DC. (pineapple weed) †		*Deschampsia flexuosa* (L.) Trin. (crinkled hair grass)
Fallopia convolvulus (L.) (wild buckwheat) †		*Houstonia caerulea* L. (bluets)
Rumex crispus L. (curly dock) †		*Panicum capillare* L. (witchgrass) †
Urtica dioica L. (stinging nettle)		*Panicum dichotomiflorum* Michx. (fall panicum) †
Verbascum thapsus L. (common mullein)		*Potentilla simplex* Michx. (oldfield cinquefoil)
Medicago sativa L. (alfalfa) †		*Trifolium incarnatum* L. (crimson clover) †
		Trifolium pratense L. (red clover) †

Table A.2. Rare Weeds Identified in Surveys. † Species also reported in seedbank sampling (Table A1); ‡ Species found outside of transects.

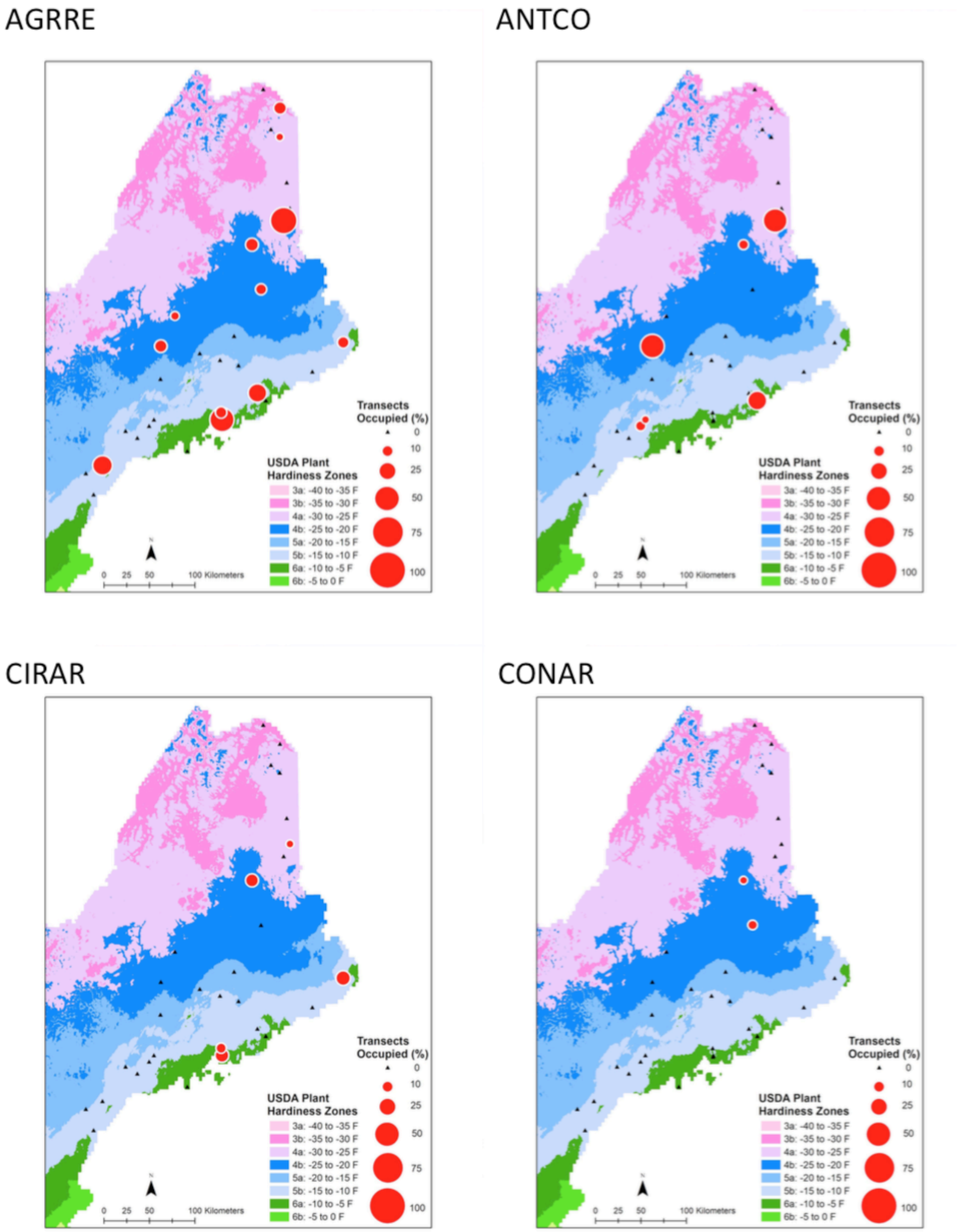
Species	Bayer Code
Acalypha rhomboidea Raf. (rhombic copperleaf)	ACCRH
Achillea millefolium L. (yarrow)	ACHMI
Agrostis gigantea Roth (redtop)	AGSGI
Agrostis perennans (Walter) Tuck. (autumn bentgrass)	AGSPE
Anthemis cotula L. (mayweed chamomile)	ANTCO
Anthoxanthum odoratum L. (sweet vernalgrass)	AOXOD
Arctium minus (Hill) Bernh. (burdock)	ARFMI
Artemisia vulgaris L. (mugwort) ‡	ARTVU
Asclepias syriaca L. (common milkweed)	ASCSY
Avena fatua L. (wild oat)	AVEFA
Avena sativa L. (common oat) †	AVESA
Barbarea vulgaris W. T. Aiton (yellow rocket)	BARVU
Calystegia sepium (L.) R. Br. (great bindweed)	CAGSE
Cerastium glomeratum Thuill. (sticky chickweed)	CERGL
Cirsium arvense (L.) Scop. (Canada thistle)	CIRAR
Cirsium vulgare (Savi) Ten. (bull thistle)	CIRVU
Convolvulus arvensis L. (field bindweed)	CONAR
Cyperus esculentus L. (yellow nutsedge)	CYPES
Daucus carota L. (wild carrot)	DAUCA
Elytrigia repens (L.) Desv. ex Nevski (quackgrass) †	AGRRE
Equisetum arvense L. (field horsetail)	EQUAR
Eragrostis minor Host (little love grass)	ERAPO
Eragrostis pilosa (L.) P. Beauv. (India lovegrass)	ERAPI
Erechtites hieraciifolius (L.) Raf. ex DC. (pilewort)	EREHI
Euphorbia maculata L. (spotted spurge) †	EPHMA
Fagopyrum esculentum Moench (buckwheat)	FAGES
Fallopia convolvulus L. (wild buckwheat) †	POLCO

Table A.2. Continued.

Species	Bayer Code
Fragaria virginiana Duchesne (wild strawberry)	FRAVI
Galium aparine L. (catchweed bedstraw)	GALAP
Gamochaeta purpurea (L.) Cabrera (purple cudweed)	GNAPU
Holcus lanatus L. (common velvetgrass)	HOLLA
Hypericum punctatum Lam. (spotted St. John's wort)	HYPPU
Hypochaeris radicata L. (common catsear)	HRYRA
Juncus bufonius L. (toad rush)	IUNBU
Lactuca serriola L. (prickly lettuce)	LACSE
Lepidium campestre (L.) W. T. Aiton (field pepperweed)	LEPCA
Lolium perenne L. ssp. multiflorum (Lam.) Husnot (Italian ryegrass)	LOLMU
Matricaria discoidea DC. (pineapple weed) †	MATMT
Medicago lupulina L. (black medic)	MEDLU
Medicago sativa L. (alfalfa) †	MEDSA
Melilotus officinalis (L.) Lam. (sweetclover)	MEUOF
Nuttallanthus canadensis (L.) D. A. Sutton (Canada toadflax)	LINCA
Oenothera laciniata Hill (cutleaf evening primrose)	OEOLA
Panicum capillare L. (witchgrass) †	PANCA
Panicum dichotomiflorum Michx. (fall panicum) †	PANDI
Pastinaca sativa L. (wild parsnip) ‡	PAVSA
Persicaria maculosa Gray (ladysthumb)	POLPE
Persicaria pensylvanica (L.) M. (Pennsylvania smartweed)	POLPY
Phalaris arundinacea L. (reed canarygrass)	TYPAR
Phleum pratense L. (timothy)	PHLPR
Physalis heterophylla Nees (clammy groundcherry)	PHYHE
Physalis longifolia Nutt. (longleaf groundcherry)	PHYSU
Poa pratensis L. (kentucky bluegrass)	POAPR
Ranunculus acris L. (meadow buttercup)	RANAC
Reynoutria japonica Houtt. (Japanese knotweed)	POLCU
Rhinanthus crista-galli L. (yellow rattle) ‡	RHIMI

Table A.2. Continued.

Species	Bayer Code
Rorippa sylvestris (L.) Besser (creeping yellowcress)	RORSY
Rumex crispus L. (curly dock) †	RUMCR
Sagina procumbens L. (birdseye pearlwort)	SAIPR
Scorzoneroides autumnalis (L.) Moench (fall dandelion)	LEBAU
Secale cereale L. (rye)	SECCE
Senecio vulgaris L. (common groundsel)	SENVU
Setaria viridis (L.) P. Beauv. (green foxtail)	SETVI
Silene latifolia Poir. (white campion)	MELAL
Silene vulgaris (Moench) Garcke (bladder campion)	SILVU
Sisymbrium officinale (L.) Scop. (hedge mustard)	SSYOF
Solanum physalifolium Rusby (hairy nightshade)	SOLPS
Solanum ptychanthum Dunal (eastern black nightshade)	SOLPT
Sonchus arvensis L. (perennial sowthistle)	SONAR
Sonchus oleraceus L. (annual sowthistle)	SONOL
Stellaria graminea L. (little starwort)	STEGR
Thlaspi arvense L. (field pennycress)	THLAR
Tragopogon dubius Scop. (western salsify)	TRODM
Trifolium arvense L. (rabbitfoot clover)	TRFAR
Trifolium aureum Pollich (hop clover)	TRFAU
Trifolium fragiferum L. (strawberry clover)	TRFFR
Trifolium incarnatum L. (crimson clover) †	TRFIN
Trifolium pratense L. (red clover) †	TRFPR
Trifolium repens L. (white Clover)	TRFRE
Tripleurospermum inodorum (L.) Sch. Bip. (scentless chamomile)	MATIN
Triticum aestivum L. (common wheat)	TRZAX
Veronica serpyllifolia L. (thymeleaf speedwell)	VERSE
Vicia villosa Roth (hairy vetch)	VICVI
Viola arvensis Murray (European field pansy)	VIOAR


AGRRE

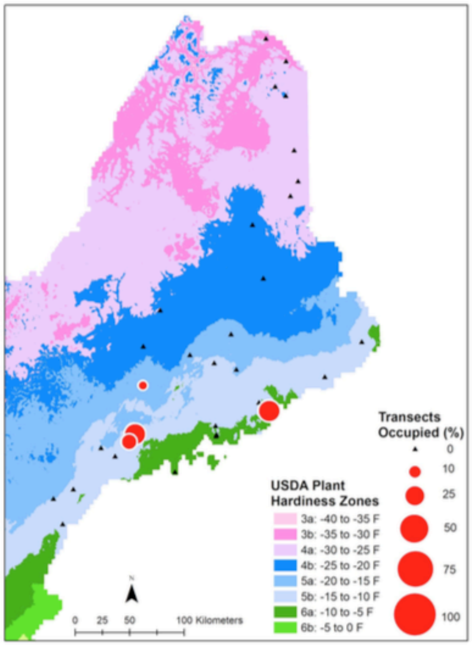
ANTCO

CIRAR

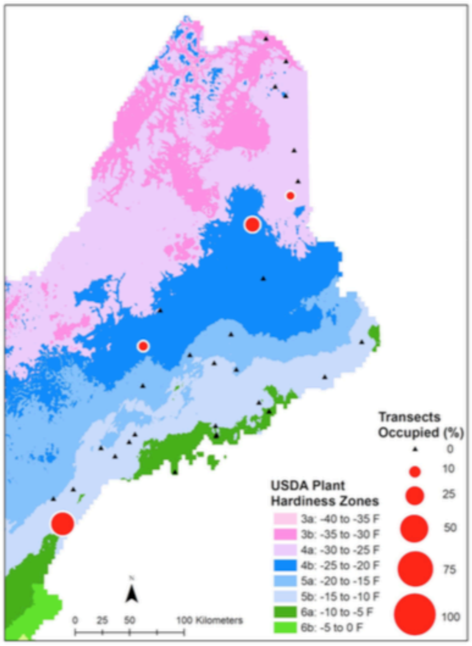
CONAR

Figure A.1. Site Occupancy Maps for Species of Likely Agronomic Risk. Percent of transects occupied at 32 farms in Maine for 19 rare weed species determined to be of high potential agronomic risk. Each panel corresponds to one species, identified by Bayer code (see Table A.2 for key). Figure continues onto subsequent pages.

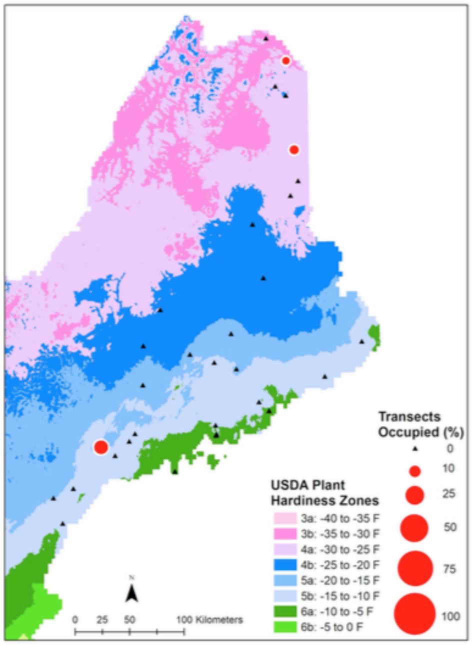
CYPES



GALAP



LOLMU



PANCA

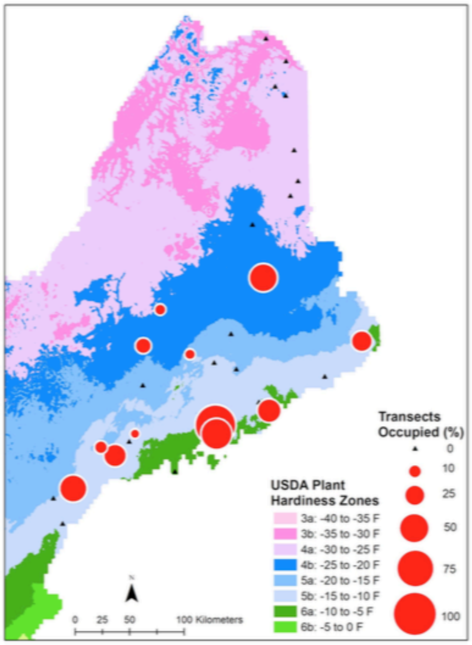


Figure A.1. Continued.

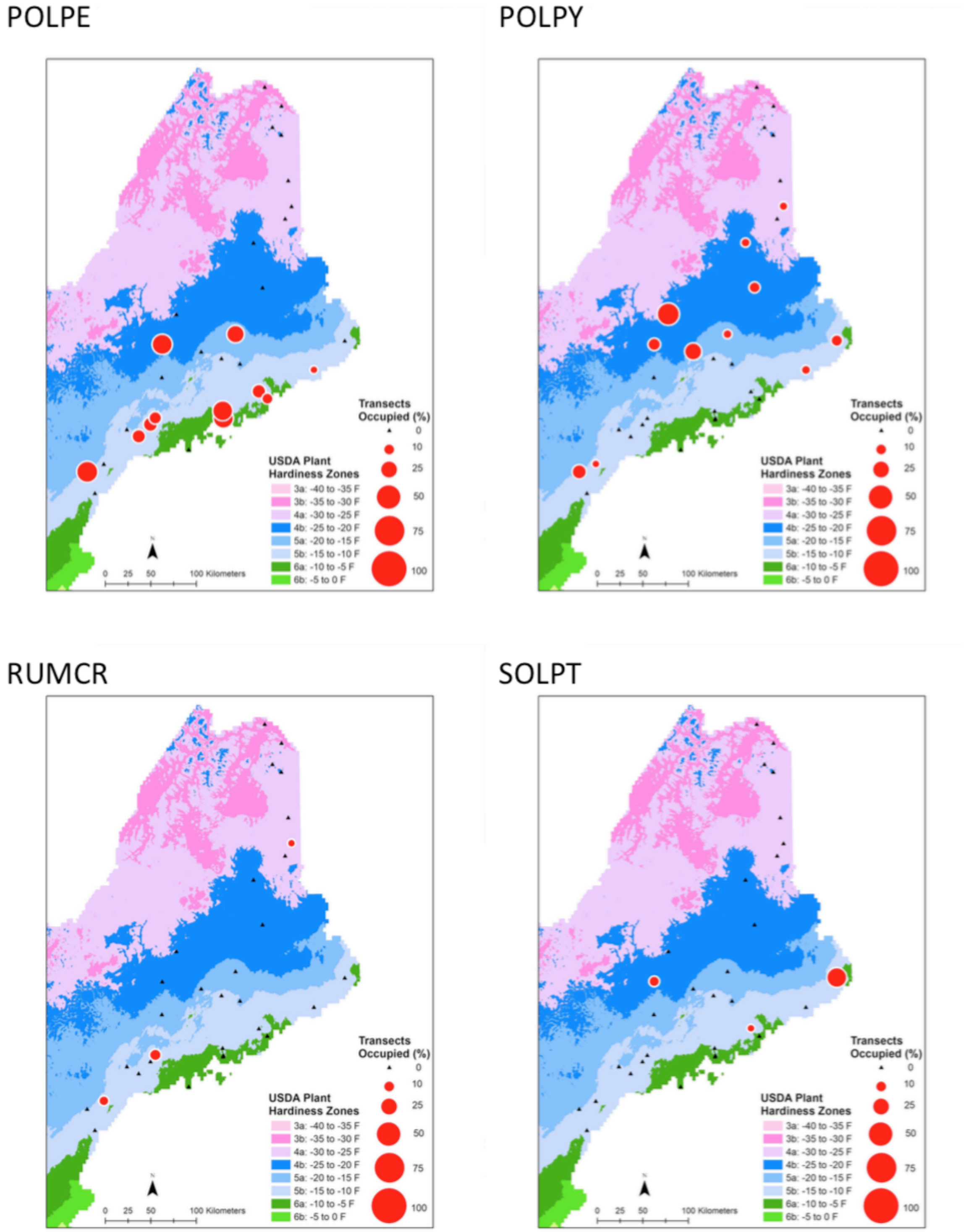


Figure A.1. Continued.

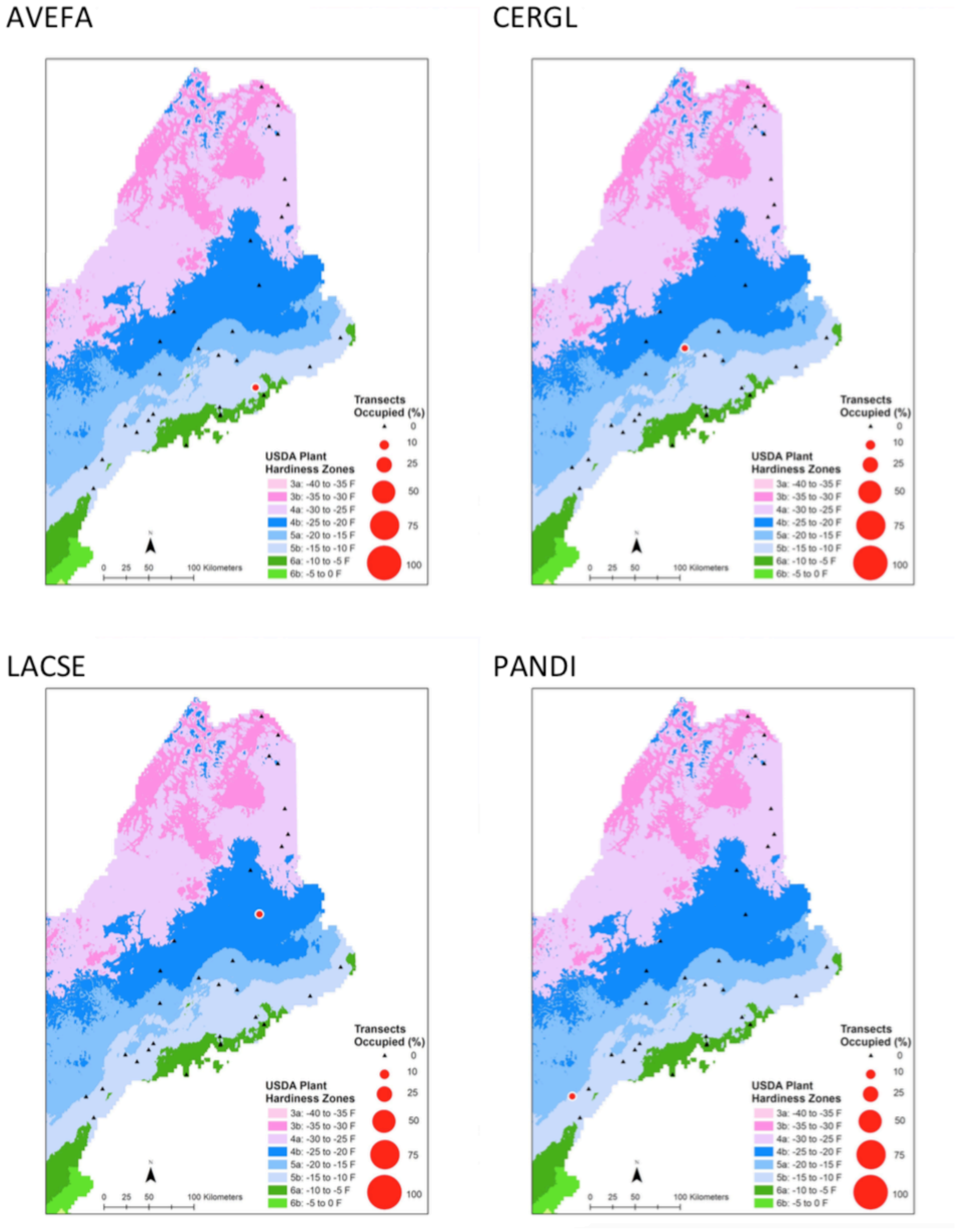
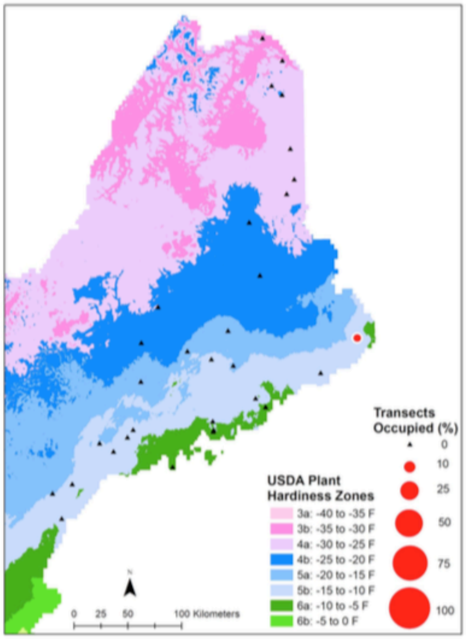
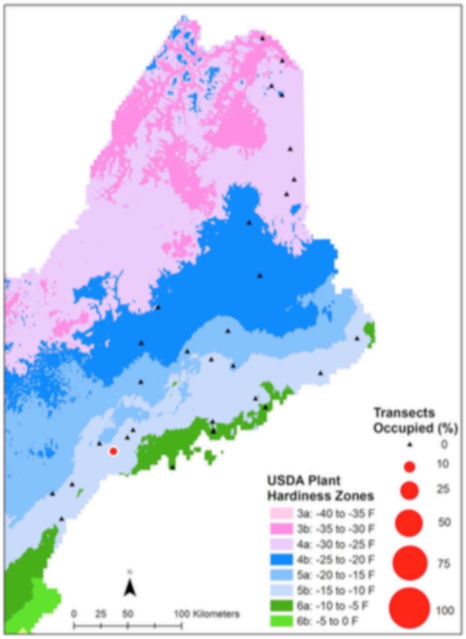


Figure A.1. Continued.

SENVU



SETVI



SOLPS

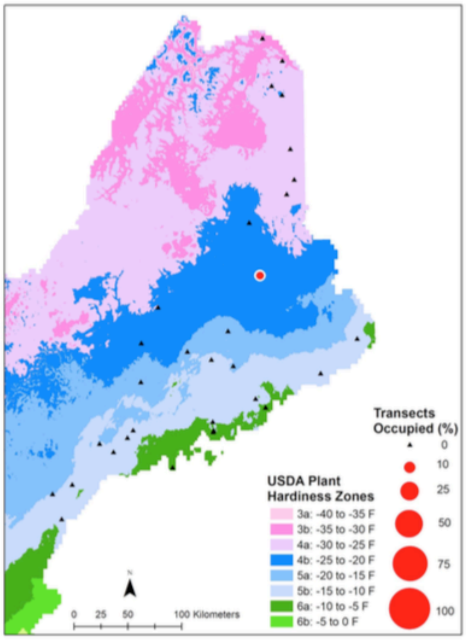


Figure A.1. Continued.

APPENDIX B: OUTLINE OF SIMULATION MODEL UNDERPINNING THE WEEDUCATOR MODULE 'MANAGEMENT SIM'

The following R code and data input file (Table B.1) were sent to a collaborator who used the underlying logic and parameter values to create WEEDucator's Management Sim module using C#. This is a discrete time model operating on a weekly time step that simulates emergence, growth, and reproduction of an aggregate population of summer annual weeds throughout one growing season, given a user-defined management regime. The WEEDucator interface allows users to change parameter values iteratively via radio buttons and sliders. The coding for these interactive elements is not outlined below; rather, default parameter values are included, with alternate choices specified in the comments (following "#" symbols).

This model, and its interactive implementation in WEEDucator (which can be found under Birthisel, Rimkunas, & Sullivan, 2017), are intended for educational purposes and operate at a heuristic level. Model assumptions may not hold true across real-world settings. Abbreviations are defined and citations used in choosing parameter values are included at the end of this appendix (Table B.2).

B.1. Simulation Model R Code

```
### Model to underpin WEEDucator management sim (summer annual weeds)
### Sonja Birthisel, Spring 2017

#User-entered parameter values
SBstart=2250 #can range from 100 to 5000 seeds per square foot to 4 inches depth
mulchtype="rye" #alternative: mulchtype ="black"
mulchheight_user=3 #can range from 0 to 6 inches for users
tool="scuffle" #alternatives: "wheel", "tine", "sweeps"

#Loop for selecting mulch specifications
if(mulchtype=="rye"){
  mulchheight=mulchheight_user
} else if (mulchtype=="black"){
  mulchheight=6
}
```

```
if(tool=="scuffle"){
  culteffbig=0.5; culteffsm=0.9
} else if(tool=="wheel"){
  culteffbig=0.3; culteffsm=0.8
} else if(tool=="tine"){
  culteffbig=0.1; culteffsm=0.4
} else if(tool=="sweeps"){
  culteffbig=0.2; culteffsm=0.5
}

#User-defined management regime
numSteps=30
till=cult=mulch=rep(0,numSteps+1)
#The three lines below were for my own testing purposes; these are user-selected
#till[c(5,10,15,20,25)]=1 #set tillage regime
#cult[c(13,14)]=1 #set cult timing
#mulch[c(6:10)]=1 #set mulch regime

#Initialize vectors and starting vals
p1=p2=p3=p4=p5=rep(0,numSteps+1); t=rep(0,numSteps+1)
p3[1]=SBstart*0.2; p4[1]=SBstart*0.8

inputs=read.csv("mat&em.csv")
mat=inputs$mat; em=inputs$em; sr=inputs$sr
matReset=inputs$matReset[1:23]; sp=0.56

#Main loop
for (i in 1:numSteps){
  if (till[i]==1){
    p1[i+1]=p2[i+1]=0
    p3[i+1]=0.2*(p3[i]+p4[i])
    p4[i+1]=0.8*(p3[i]+p4[i])
    p5[i+1]=p5[i]
    if (i>10){
      mat=c(mat[1:i],matReset) #uses R's built-in concatenate function, c()
    }
  } else if (cult[i]==1){
    p1[i]=p1[i]+mat[i]*p2[i]
    p1[i]=p1[i]-culteffbig*p1[i]
    p1[i+1]=min(p1[i],10)
    if (p1[i]<10){
      p2[i]=p2[i]-mat[i]*p2[i]
      p2[i]=p2[i]+em[i]*p3[i]
      p2[i+1]=p2[i]-culteffsm*p2[i]
      p3[i+1]=p3[i]-em[i]*p3[i]
      } else {
      p2[i]=p2[i]-mat[i]*p2[i]
      p2[i+1]=p2[i]-culteffsm*p2[i]
```

```
    p3[i+1]=p3[i]
    }
  p4[i+1]=p4[i]
  p5[i+1]=p5[i]+sr[i]*(1-sp)*p1[i+1]
 } else if (mulch[i]==1){
  p1[i]=p1[i]+mat[i]*p2[i]
  p1[i+1]=min(p1[i],10)
  if (p1[i]<10){
   p2[i]=p2[i]-mat[i]*p2[i]
   p2[i+1]=p2[i]+em[i]*p3[i]*exp(-0.021*mulchheight/25.4)
   p3[i+1]=p3[i]-em[i]*p3[i]*exp(-0.021*mulchheight/25.4)
  } else{
   p2[i+1]=p2[i]-mat[i]*p2[i]
   p3[i+1]=p3[i]
  }
  p4[i+1]=p4[i]
  p5[i+1]=p5[i]+sr[i]*(1-sp)*p1[i]
 } else {
  p1[i]=p1[i]+mat[i]*p2[i]
  p1[i+1]=min(p1[i],10)
  if (p1[i]<10){
   p2[i]=p2[i]-mat[i]*p2[i]
   p2[i+1]=p2[i]+em[i]*p3[i]
   p3[i+1]=p3[i]-em[i]*p3[i]
  } else{
   p2[i+1]=p2[i]-mat[i]*p2[i]
   p3[i+1]=p3[i]
  }
  p4[i+1]=p4[i]
  p5[i+1]=p5[i]+sr[i]*(1-sp)*p1[i]
 }
 t[i+1]=t[i]+1
}

#Plot results, specifying axes
par(mfrow=c(2,3))
plot(t,p1,type='o',main='mature weeds')
plot(t,p2,type='o',main='immature weeds')
plot(t,p3,type='o',main='top 2 cm of seedbank')
plot(t,p4,type='o',main='lower 8 cm of seedbank')
plot(t,p5,type='o',main='new seeds (assumed dormant)')
plot(t,t,type='o',main='nothing here to see')
```

Table B.1. Parameter Vectors for Simulation Model. This table includes contents of the file entitled “mat&em.csv” referenced in the R code above. Abbreviations are defined in Table B.2.

week	mat	em	sr	matReset
15-Apr	0	0.001	0	0
22-Apr	0	0.001	0	0
30-Apr	0	0.01	0	0.05
7-May	0	0.025	0	0.1
14-May	0	0.025	0	0.2
21-May	0	0.05	0	0.3
28-May	0	0.05	0	0.4
4-Jun	0	0.1	0	0.5
11-Jun	0	0.1	0	0.6
18-Jun	0	0.1	0	0.7
25-Jun	0.05	0.1	18	0.7
2-Jul	0.1	0.05	118	0.7
9-Jul	0.2	0.05	218	0.7
16-Jul	0.3	0.01	318	0.7
23-Jul	0.4	0.01	418	0.6
30-Jul	0.5	0.01	518	0.5
6-Aug	0.6	0.001	618	0.4
13-Aug	0.7	0.001	718	0.3
20-Aug	0.7	0.001	818	0.2
27-Aug	0.7	0.001	918	0.1
3-Sep	0.7	0.001	818	0.05
10-Sep	0.7	0.001	718	0
17-Sep	0.6	0.001	618	0
24-Sep	0.5	0.001	518	
1-Oct	0.4	0	418	
8-Oct	0.3	0	318	
15-Oct	0.2	0	218	
22-Oct	0.1	0	118	
29-Oct	0.05	0	18	
5-Nov	0	0	0	
12-Nov	0	0	0	

Table B.2. Simulation Model Abbreviations and Citations. Abbreviations used, corresponding simulation model parameters or definitions, and (as applicable) citations used in determining parameter estimates included in simulation model code and Table B.1 above.

Abbreviation	Parameter / definition	Citation
SBstart	Seedbank at start of simulation	(Jabbour, Gallandt, et al., 2014)
mulchtype	Type of mulch	
mulchheight	Thickness of rye mulch	(Teasdale & Mohler, 2000)
tool	Tool used for hand weeding or cultivation	
culteffbig	Cultivation efficacy for large weeds	(Gallandt, Brainard, & Brown, 2018)
culteffsm	Cultivation efficacy for small weeds	(Gallandt, Brainard, & Brown, 2018)
numSteps	Number of steps (weeks) in simulation	
till	Week(s) of season in which tillage occurred	
cult	Week(s) of season in which cultivation or hand weeding occurred	
mulch	Week(s) of season in which mulch was in place	
p1	Density of mature weeds	
p2	Density of immature weeds	
p3	Density of seeds in top 2 cm of seedbank	
p4	Density of seeds in lower 8 cm of seedbank	
p5	New seed rain	
em	Vector of weekly rates at which weeds emerge	(Cordeau et al., 2017)
mat	Vector of weekly rates at which weeds mature	(Liebman et al., 2001)
sr	Vector of weekly seed rain values	(Davis & Raghu, 2010)
matReset	Vector used to re-set maturation counter after tillage	
sp	Weekly seed predation rate	(Birthisel, Gallandt, Jabbour, & Drummond, 2015)

APPENDIX C: PRE- AND POST- ASSESSMENTS USED TO EVALUATE WEEDUCATOR'S EFFICACY AS A TEACHING TOOL AND GAIN STUDENT FEEDBACK

Participant #________

WEEDucator Pre-Assessment

*** Please answer honestly – your responses will be kept anonymous and will not affect your course grade.

Background Information

What year are you in school?

- ☐ First year
- ☐ Second year
- ☐ Third year
- ☐ Fourth year
- ☐ Graduate student
- ☐ Other_______________

What is your major?___________________

How would you rate your knowledge of weed ecology and management? (1 = LOWEST)

1 2 3 4 5 6 7 8 9 10

Knowledge Pre-Assessment

1. At what time of year do most **winter annuals** drop their seed?

____
____
____
____

Please check the box that most closely relates to your confidence with your answer:

- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

2. **Biennial** weeds flower and set seed:
    - ☐ The year after they germinate
    - ☐ For many years after they germinate
    - ☐ The first year they germinate
    - ☐ Just before they germinate

Please check the box that most closely relates to your confidence with your answer:
- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

3. How might knowledge of weed **lifecycles** help a farmer?

____
____
____
____

Please check the box that most closely relates to your confidence with your answer:
- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

4. For optimal weed management, when should **cover crops** be terminated?

____
____
____
____

Please check the box that most closely relates to your confidence with your answer:
- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

5. What is a **stale seedbed** and why might a farmer use this technique?

____
____
____
____

Please check the box that most closely relates to your confidence with your answer:
- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

6. Weeds can most easily be killed by cultivation at what **growth stage**:
    - ☐ In the seed stage
    - ☐ In the white thread stage
    - ☐ Just before flowering
    - ☐ While seeds are maturing on the mother plant

    Please check the box that most closely relates to your confidence with your answer:
    - ☐ I am 100% confident in my answer
    - ☐ I have some doubt
    - ☐ I completely guessed

7. What is a **weed seedbank**?

    ____
    ____
    ____
    ____

    Please check the box that most closely relates to your confidence with your answer:
    - ☐ I am 100% confident in my answer
    - ☐ I have some doubt
    - ☐ I completely guessed

8. Do **seedbanks** impact farm management? If so, how?

    ____
    ____
    ____
    ____

    Please check the box that most closely relates to your confidence with your answer:
    - ☐ I am 100% confident in my answer
    - ☐ I have some doubt
    - ☐ I completely guessed

9. Which of these practices is likely to be **most helpful** in depleting the weed seedbank:
    - ☐ Cultivation
    - ☐ Mulching

    Please check the box that most closely relates to your confidence with your answer:
    - ☐ I am 100% confident in my answer
    - ☐ I have some doubt
    - ☐ I completely guessed

Participant #________

WEEDucator Post-Assessment

*** Please answer honestly – your responses will be kept anonymous and will not affect your course grade.

Knowledge Post-Assessment

10. At what time of year do most **winter annuals** drop their seed?

____
____
____
____

Please check the box that most closely relates to your confidence with your answer:

- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

11. **Biennial** weeds flower and set seed:

- ☐ The year after they germinate
- ☐ For many years after they germinate
- ☐ The first year they germinate
- ☐ Just before they germinate

Please check the box that most closely relates to your confidence with your answer:

- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

12. How might knowledge of weed **lifecycles** help a farmer?

____
____
____
____

Please check the box that most closely relates to your confidence with your answer:

- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

13. For optimal weed management, when should **cover crops** be terminated?

Please check the box that most closely relates to your confidence with your answer:
- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

14. What is a **stale seedbed** and why might a farmer use this technique?

Please check the box that most closely relates to your confidence with your answer:
- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

15. Weeds can most easily be killed by cultivation at what **growth stage**:
- ☐ In the seed stage
- ☐ In the white thread stage
- ☐ Just before flowering
- ☐ While seeds are maturing on the mother plant

Please check the box that most closely relates to your confidence with your answer:
- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

16. What is a **weed seedbank**?

Please check the box that most closely relates to your confidence with your answer:
- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

17. Do **seedbanks** impact farm management? If so, how?

____

____

____

____

Please check the box that most closely relates to your confidence with your answer:
- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

18. Which of these practices is likely to be **most helpful** in depleting the weed seedbank:
- ☐ Cultivation
- ☐ Mulching

Please check the box that most closely relates to your confidence with your answer:
- ☐ I am 100% confident in my answer
- ☐ I have some doubt
- ☐ I completely guessed

Feedback & Suggestions

Overall, I found WEEDucator helpful

- ☐ True
- ☐ False

Comments______________________________

____

____

Overall, WEEDucator was fun to use

- ☐ True
- ☐ False

Comments______________________________

____

____

I would prefer to learn the content in WEEDucator (rank in order of preference, 1 = HIGHEST)
- _ By reading a textbook
- _ In a classroom lecture
- _ Through activities in lab or lecture
- _ By interacting with a tool like WEEDucator
- _ By watching YouTube videos
- _ Other_________________________________

What part(s) of WEEDucator did you like most?

Comments______________________________

☐ Lifecycles ____
☐ Toolshed ____
☐ Management sim

What part(s) of WEEDucator did you like least?

Comments______________________________

☐ Lifecycles ____
☐ Toolshed ____
☐ Management sim

What platform(s) would you prefer to use for accessing educations tools like WEEDucator?

☐ Smartphone app
☐ Downloadable computer app
☐ Web-based app
☐ Other____________________

Anything else you'd like us to know?

____
____
____
____
____

BIOGRAPHY OF THE AUTHOR

Sonja Katharine Birthisel was born in Clinton, Wisconsin in June of 1988. She grew up homeschooled in Wisconsin and Maine. She attended Luther College in Decorah, IA and graduated *magna cum laude* in 2010 with a Bachelor of Arts degree in Biology and a minor in Mathematics. Prior to attending graduate school she worked as a Resident Counselor at the Illinois Mathematics and Science Academy. Sonja graduated from University of Maine in 2013 with a Master of Science degree in Ecology and Environmental Sciences, after which she devoted a year to public service with FoodCorps/Americorps. She returned to the University of Maine in 2015 to begin doctoral studies. In her spare time, Sonja enjoys dancing, reading, and attempting to make the world a better place. Sonja is a candidate for the Doctor of Philosophy degree in Ecology and Environmental Sciences from the University of Maine in December 2018