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Organic Farmer Knowledge and Perceptions are Associated with On-Farm Weed Seedbank Densities in Northern New England

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Weed management remains a high priority for organic farmers, whose fields generally have higher weed density and species diversity than those of their conventional counterparts. We explored whether variability in farmer knowledge and perceptions of weeds and weed management practices were predictive of variability in on-farm weed seedbanks on 23 organic farms in northern New England. We interviewed farmers and transcribed and coded interviews to quantify their emphasis on concepts regarding knowledge of ecological weed management, the perceived risks and benefits of weeds, and the perceived risks and benefits of weed management practices. To characterize on-farm weed seedbanks, we collected soil samples from five fields at each farm (115 fields total) and measured germinable weed seed density. Mean weed seed density per farm ranged from 2,775 seeds m^{-2} to 24,678 seeds m^{-2} to a soil depth of 10 cm. Farmers most often reported hairy galinsoga and crabgrass species (*Digitaria* spp.) as their most problematic weeds. The proportion of the sum of these two most problematic weeds in each farm's seedbank ranged from 1 to 73% of total weed seed density. Farmer knowledge and perceptions were predictive of total seed density, species richness, and proportion of hairy galinsoga and crabgrass species. Low seed densities were associated with farmers who most often discussed risks of weeds, benefits of critical weed-free management practices, and learning from their own experience. These farmers also exhibited greater knowledge of managing the weed seedbank and greater understanding of the importance of a long-term strategy. Targeted education focusing on this set of knowledge and beliefs could potentially lead to improved application and success of ecological weed management in the future, thus decreasing labor costs and time necessary for farmers to manage weeds.

Nomenclature: Large crabgrass, *Digitaria sanguinalis* (L.) Scop. DIGSA; smooth crabgrass, *Digitaria ischaemum* (Schreb.) Schreb. ex Muhl. DIGIS; hairy galinsoga, *Galinsoga quadriradiata* Cav. GAQU.

Key words: Ecological weed management, farmer knowledge, mental model, organic agriculture, weed seedbanks.

Comparisons of weed communities between conventional and organic farming systems consistently show higher weed density and species diversity in organic farming systems (Hawes et al. 2010; José-María and Sans 2011; Roschewitz et al. 2005). Management factors such as timely implementation of fall tillage, growth of competitive crops, and increased use of preventive measures such as stale seedbed were associated with reduced weed densities on organic farms in the Netherlands (Riemens et al. 2010). Use of systems-based, seedbank management strategies can lead to reduced weed seed densities and subsequent seedling pressure (Liebman and Gallandt 1997), as well as less time spent weeding (Riemens et al. 2007). Organic farmers, however, widely report use of controls such as cultivation and handweeding (Jabbour et al., 2013), which are costly practices because of high time, labor, and/or fuel demands. Thus, there may be a disconnect between seedbank-based approaches promoted by researchers and seedling-focused practices used by growers.

A suite of factors inform the decisions that farmers make about weed management, including but not limited to knowledge, experience, and perceptions of weeds and weed management (Zwickle 2011). An individual's knowledge and experience inform their perceptions of a particular risk and this, in turn, influences what they deem an acceptable approach to mitigate that risk (Slovic 1987). In this study, we explored whether factors such as type of knowledge or perception were associated with on-farm weed seed density, a major risk on organic farms. We developed farmer

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"mental models" to quantify farmers' knowledge and perceptions regarding different topics relevant to organic weed management (Morgan et al. 2002). A mental model describes a farmer's network of knowledge, perceptions, and beliefs that inform their decision-making process.

Variability in the human dimension of management, here represented by mental models, could be associated with variability in the biological components of the managed system (Nowak and Cabot 2004). Three examples from distinct agricultural regions illustrate that farmer philosophy or knowledge can be related to biological metrics. In the Netherlands, grouping farmers according to philosophy showed that "market-oriented" farmers had greater weed densities than "crop-growth oriented" farmers (Riemens et al. 2010). Interviews with farmers in Ghana revealed that farmer assessment of soil quality based on qualitative metrics correlated to scientific measures of "fertile" and "non-fertile" soils (Dawoe et al. 2012). In Honduras, farmer awareness of insect natural enemies was associated with in-field abundance of these beneficial organisms as well as farmer awareness of alternatives to pesticides (Wyckhuys and O'Neil 2007). Thus, pest management decisions are in part influenced by farmer knowledge and perceptions.

We characterized farmer mental models based on interviews with 23 organic farmers in northern New England. Previously, we compared these farmer mental models, in aggregate, to an expert model based on interviews with scientists and extension professionals (Jabbour et al. 2013; Zwickle 2011). As a group, farmers exhibited knowledge of ecological weed management, discussing the major concepts mentioned by experts. Farmers emphasized the role of learning from their own experience more than learning from scientific research findings. Farmers and experts differed in their perceived risks of weeds, such that experts focused on the likelihood of crop yield loss, but farmers also considered the likelihood of increased time and labor as equally problematic when it comes to weeds. Farmers and experts were largely in agreement regarding risks and benefits of weed management strategies, most often discussing risks of cultivation and benefits of cover cropping (Jabbour et al. 2013).

Here, we expanded on this work to consider the variability amongst individual New England farmer mental models, and the relationship between farmer mental models and on-farm weed seedbanks. We hypothesized that mental models would predict seed densities as follows: (1) knowledge in congruence with the scientific expert model, in particular, would be strongly associated with lower seedbank densities; (2) farmers who most often discussed the knowledge categories of systems thinking and ecological complexity, those most emphasized by scientific experts (Jabbour et al. 2013), would have lower on-farm seedbank densities; and (3) those farmers who exhibited greater awareness of the risks of weeds, the risks of seedling-focused management practices, and the benefits of seedbank management practices would have lower seedbank densities because of a focus on long-term management strategies. These hypotheses were driven by our overall assumption that farmers who understand ecological systems and the risk-benefit tradeoffs required for seedbank management will have lower seedbank densities. We recognize that most farmers will not be at such extremes in understanding or practice, and will fall along this spectrum, employing both seedling and seedbank-focused approaches.

Materials and Methods

For each participating farm, soil samples were collected in spring 2010 to measure germinable weed seed density. Farmers were interviewed in fall 2010 to quantify farmer knowledge and perceptions regarding organic weed management. Details of the interview methods were reported previously (Jabbour et al. 2013) and are described in brief below.

Farmer Participants. A large pool of potential farmer participants was contacted by email based on recommendations from Maine Organic Farmers and Gardeners Association (MOFGA) and Northeast Organic Farming Association (NOFA) personnel. The email described the research project, farmers' involvement, and projected outcomes. The 23 participating farmers were those who responded affirmatively to the initial email solicitation, in addition to several farmers who learned about the research project in newsletter postings. Farmers from Maine (n = 12), New Hampshire (n = 5), and Vermont (n = 6) participated in this study, and each farm was assigned a random identification number from 1 through 23. These farms were categorized as enterprises growing primarily mixed vegetables (n = 19 farms) or field crop/dairy enterprises (n = 4 farms). Farm and farmer demographics including gross income, gender, and years of experience farming were recorded.

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Farmer Interviews. Farmers were interviewed in November and December 2010. The interview protocol was organized based on concepts in an expert model of organic weed management, developed through interviews and focus groups with expert scientists, Extension professionals, and farmers (Zwickle 2011). The experts concluded that farm and farmer attributes informed perceptions of weeds and weed management. In turn, these perceptions will inform a farmer's decision to implement a given weed management practice. For example, a farmer with knowledge of ecological complexity (farmer attribute) may perceive weeds as beneficial as food for wildlife (perception) thus delaying fall tillage to allow granivorous animals to reduce weed seed densities on the soil surface. Cognitive hierarchy models of human behavior indicate that individual attributes tend to explain differences in values; values in turn explain differences in beliefs/perceptions, which then explain differences in behavior (Fulton et al. 1996; Stern 2000). We were not able to include details on the actual management practices implemented on each participant's farm, but based on the model of cognitive hierarchy we expect that attributes, beliefs, and perceptions will indirectly influence the outcomes of weed management behaviors (e.g., seed bank densities). We used a semi-structured, open-ended interview strategy such that all farmers received the same initial prompts, but farmers were asked to clarify or provide more information about the concepts important to them. Interviews were conducted to uncover farmer knowledge, perceptions, and experiences in a way that minimized the influence of the interviewer and provided farmers as much freedom of expression as possible (Jabbour et al. 2013; Zwickle 2011).

The interviews were independently transcribed and entered into the qualitative software program MAXQDA (MAXQDA, Software for Qualitative Data Analysis 2012). Each interview was coded separately according to a coding schematic developed from the expert model. Coding has been defined as "the analytic process through which concepts are identified" (Corbin and Strauss 2008). Specifically, farmer responses during the interview were assigned a concept, identifying what that particular response was about. If a farmer discussed a concept not found in the expert coding schematic, it was added and marked as a unique farmer response. Coding the frequency of each individual concept is important in mental models (Morgan et al. 2002). The more often a farmer mentioned a concept, the greater the importance in their decision making process.

Rather than asking a farmer directly about the general aspects of weed management that experts emphasized, responses were coded when one of the principles was inherent in a farmer response. For example, Farmer 9 discussed the importance of rotating row crops with forage crops to utilize grazing as a way to reduce weed seed density. This discussion was coded in the knowledge area "Managing Weed Seedbank." Specifically, Farmer 9 said:

> With forage—with the cows grazing it, they're eating up the seeds before they even become viable. If I can mix a forage rotation in there I can really reduce the amount of weed seeds for the next year.

We tested whether 14 coded concepts from the interviews were associated with weed seedbank densities: six related to knowledge, two related to learning, and six related to perception. Each specific concept varied based on the frequency of mention by each individual farmer, essentially turning each coded concept into a variable for data analysis. See Supplementary Table 1 (http://dx.doi.org/10.1614/WS-D-13-00098.TS1) for specific examples discussed by farmers within each of these concepts. The six knowledge variables represented farmer understanding of ecological weed management, in particular: recognizing opportunities to manage weeds, managing the weed seed bank, ecological complexity of organic systems, systems thinking, the importance of long-term strategy for successful weed management, and weed/soil interactions. These knowledge variables originated from the scientific expert model as describing the most important concepts to successfully manage weeds organically. In aggregate, these 6 variables represent "knowledge of ecological weed management," and demonstrate farmer understanding of these concepts, and overall consistency with the expert model. The two learning variables indicated farmer emphasis on: learning from personal experience and learning from other sources (including other farmers, science and research, field days, print media, and the Internet). The six perception variables represented farmer emphasis on: perceived risks of weeds, perceived benefits of weeds, perceived risks and benefits of critical-weed free management practices, and the perceived risks and benefits of seedbank management practices.

Perceived risks and benefits of management strategies were grouped according to whether they primarily allowed for a critical weed-free crop period (generally mechanical strategies targeting seedlings) or to manage the seedbank (Gallandt 2006). The following were grouped as critical weed-free period strategies: cultivation and tillage, hand weeding, organic herbicide use, flaming, mowing, and grazing. Seedbank management strategies included crop rotation, cover crop use, mulch use, nutrient management, and crop seeding rates.

Weed Seedbank Sampling. Soil samples for seedbank characterization were collected in the spring of 2010, between April 15 and June 2. At each farm, we collected samples from a 10 m^{-2} region in the centers of 5 different fields, yielding a total of 115 seedbank samples. Seedbank samples were collected from land used for row crop production; however, some of these fields were rotated through pasture or sod in years prior to sampling. Each seedbank sample was comprised of 10 cores (8 cm diameter) collected to a depth of 10 cm using a bucket auger. Germinable weed seedbank densities were estimated using greenhouse germination assays. See Gallandt et al. (1998) for details on the method used to estimate the germinable seedbank. Briefly, soil was sieved, laid on damp vermiculite in the greenhouse, and watered daily. Each seedling was identified to species, counted, and removed. When possible, unknowns were grown out to adult plants to accomplish identification; however, because of limited labor, there were still unidentified weeds, which were categorized as ''unknown grass'' or ''unknown broadleaf'' weeds. Flats were dried in August and October to accomplish 3 cycles of weed seed germination.

Data Analysis. *Seedbank Variables*. Mean seedbank density values per farm were calculated as an average of the five fields sampled per farm. Seedbank density was log-transformed to achieve normality. The proportion of hairy galinsoga and crabgrass in the seedbank was calculated based on farmer reports of these species being the most problematic to manage (Jabbour et al. 2013). We used two measures to describe weed diversity: species richness (the total number of species per farm) and evenness (relative abundance of species). Evenness was calculated using the index E_{var} (Smith and Wilson 2009).

Associations between farmer demographics and seedbank variables. We used a series of one-way ANOVAs to test whether farmer years of experience (0 to 4, 5 to 9, 10 to 14, 15+), gender, gross income ($0 to 100,000; $100,000 to 249,000; $250,000 to 499,000; and $500,000 or more), or state (Maine, New Hampshire, or Vermont) predicted seedbank density, species richness, evenness and the proportion of hairy galinsoga and crabgrass in the seedbank.

Associations between knowledge congruent with experts and seedbank variables. Throughout the coding process, farmer responses were assigned to concepts either found in the expert coding schematic or added and marked as a unique farmer response. We tallied the frequency of mentions coded as part of the expert coding schematic across all six knowledge variables, thus signifying overall knowledge of concepts congruent with the expert group. We then used linear regression to test whether the frequency of mentions of knowledge congruent with experts was predictive of seedbank density, species richness, evenness and proportion of hairy galinsoga and crabgrass in the seedbank. To aid with interpretation, we calculated the proportion of mentions congruent with experts within each of the six knowledge variables as well.

Associations between farmer interview and seedbank variables. Fourteen interview variables described farmer knowledge, learning, and perceptions concepts. Several of these variables were positively correlated with one another, and thus were not independent (Supplemental Figure 1; http://dx.doi.org/10.1614/WS-D-13-00098.FS1). For example, learning from experience was positively correlated with awareness of risks of weeds. Given the correlated interview variables, we used the multivariate analysis technique principle component regression to determine if the interview variables predicted seedbank variables. We used the 'pls' package (Mevik and Wehrens 2007) in R 2.12.0 (R Development Core Team 2012).

First, we created ''latent'' variables in the form of principle components (PCs) from the 14 interview variables. We used the first seven PCs, which explained 85.9% of the variance in the interview variables, as the independent variables in a standard multiple regression with backward selection. PCs are uncorrelated with one another, thus solving the issue of multicollinearity of interview variables (Graham 2003). PCs primarily represent the predictors with the loading, or weight, of greatest magnitude, and we interpreted PCs based on loadings 0.35 or greater. We completed PC

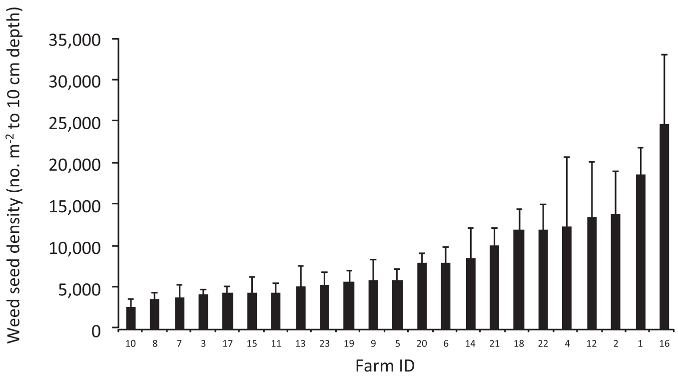

Figure 1. Total germinable weed seed density (mean and S.E. of five fields at each farm) of the 23 farms sampled in northern New England.

regression to test for the effect of the interview variables on seedbank density, species richness, evenness, and the proportion of hairy galinsoga and crabgrass in the seedbank.

Individual case studies of low seedbank density and high seedbank density farmers. We summarized seedbank and interview data for the three farmers with the lowest and the highest seedbank densities in our study to highlight key patterns, both in agreement or divergent from the results of the regression.

Results and Discussion

Seedbank Variables. On-farm germinable weed seedbank density varied widely, from 2,775 seeds m^{-2} to 24,678 seeds m^{-2} (Figure 1). Crabgrass and hairy galinsoga, the species named by farmers as most problematic, were the most abundant species detected in weed seedbanks (Table 1). Evenness of weed communities was negatively correlated with seedbank density ($r = -0.533$, $P = 0.009$), and there was a trend towards increased species richness with higher seedbank density ($r = 0.37$, $P = 0.076$). The proportion of hairy galinsoga and crabgrass in the seedbank was not correlated with total seedbank density, evenness, or species richness ($P > 0.1$). Given the close correlation between evenness and seedbank density, we chose not to explicitly test for associations between interview variables and evenness.

Are Farmer Demographics Associated with Seedbank Variables? Differences were not detected in total seedbank density, species richness, or proportion of hairy galinsoga and crabgrass according to years of experience farming, gender, gross farm income, or state ($P > 0.1$). Seedbank data from a longitudinal study in Germany (Albrecht 2005) showed increasing weed seedbank densities in the first 3 yr of conversion from conventional to organic production, followed by a decrease in seedbank density from the fourth to sixth years. Although our farmers varied in years of experience, we only had one farmer with fewer than 5 yr of experience. Our sample may not have fully captured the contrast between beginning and experienced farmers. Geographical location (state) may not have had an effect on seedbank variables because of the similar farming operations and climatic conditions found throughout northern New England. Seedbank variables did not differ according to gross farm income, which likely reflects the many other dimensions of a farming operation beyond weed management that result in income.

Does Knowledge Congruent with Experts Affect Associations with Seedbank Variables? Throughout the coding process, farmer responses were assigned to concepts that existed in the expert coding schematic, which we described as knowledge congruent with experts, or were coded as a unique

Table 1. Most abundant species in New England farm weed seedbanks.

Common name	Scientific name	Weed seed density[a]
Crabgrasses	*Digitaria* spp.[b]	2,456 ± 738
Hairy galinsoga	*Galinsoga quadriradiata*	840 ± 372
Common lambsquarters	*Chenopodium album*	789 ± 155
Redroot pigweed	*Amaranthus retroflexus*	545 ± 141
Barnyardgrass	*Echinochloa crus-galli*	390 ± 136
Marsh yellowcress	*Rorippa islandica*	292 ± 87
Common purslane	*Portulaca oleracea*	284 ± 111
Mustards	*Brassica* spp.	271 ± 140
Yellow woodsorrel	*Oxalis stricta*	262 ± 64
Chickweed	*Stellaria media*	239 ± 79

[a] No. m^{-2} to 10 cm depth.
[b] Mixture of *D. sanguinalis* and *D. ischaemum*.

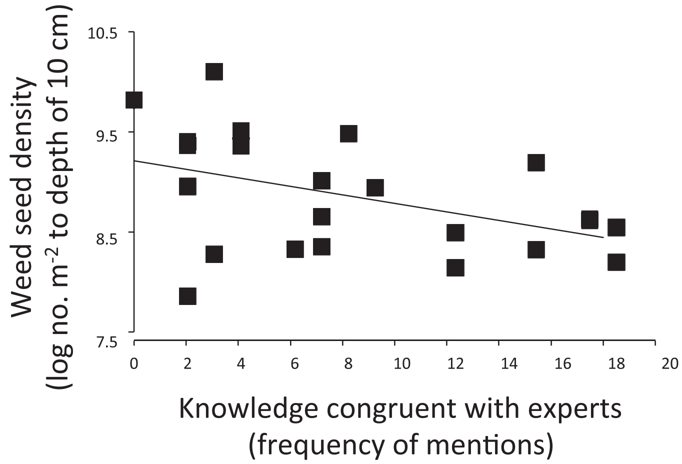

Figure 2. Relationship between knowledge congruent with experts and weed seed density, with best-fit regression line (R^2 = 0.19, P = 0.035), for 23 participating farmers. Congruency indicates frequency of mention of knowledge categories identified as important by scientific experts.

farmer response. The frequency of mentions of knowledge congruent with experts predicted both lower total seedbank density (Figure 2, $R^2 = 0.19$, P = 0.035) and lower proportion of the seedbank comprised of hairy galinsoga and crabgrass (R^2 = 0.29, P = 0.008), supporting our hypothesis. Knowledge congruent with experts was not associated with species richness ($R^2 = 0.01$, P = 0.913).

The expert model framework featured the concepts that scientific and Extension professionals, along with expert farmers, deemed the most important for successful organic weed management (Zwickle 2011). Our results support the value of this framework as an educational resource for ecological weed management. However, the proportion of knowledge codes congruent with experts was not the same within each knowledge variable (Table 2). The weed-soil interactions variable had the lowest proportion of mentions congruent with expert knowledge. This pattern resulted from unique, detailed farmer discussion of this topic such that they discussed different concepts regarding weed-soil interactions than experts. The other knowledge variables were dominated by mentions of knowledge congruent with experts. The topic of weed-soil interactions was an area that farmers would like to know more about, and experts also expressed the need for more research to address farmer questions (Jabbour et al. 2013). According to the expert understanding of this perception, farmers use weeds to "read" what type of nutrients are missing from the soil profile and use this knowledge to design nutrient management strategies that will negate the cause of that particular

Table 2. Frequency of mentions in each knowledge category coded as congruent with expert schematic or unique to farmers. The final column reports the proportion of total mentions in each category congruent with experts.

Knowledge variable	Congruent with experts	Unique to farmers	Congruent proportion
Recognizing opportunities	37	4	0.90
Managing weed seedbank	55	14	0.80
Weed-soil interactions	12	55	0.18
Ecological complexity	21	1	0.95
Systems thinking	41	5	0.89
Long-term strategy	24	9	0.73

weed's presence in the field (Zwickle 2011). There is no peer-reviewed research to support this farmer-based observation, but its unique presence in the farmer model shows farmers' desire to use heuristics, or short cuts, in order to simplify complex decisions (Kleindorfer 1999). If using the "weeds as indicators" heuristic leads to greater weed management problems in the future, as this research suggests, then outreach efforts must bring these decision biases to farmers' attention in order to show how they may be compromising overall seedbank reduction. Both research and education efforts need to take place to effectively develop and apply weed management knowledge in this area.

Are Types of Farmer Knowledge and Perceptions Associated with Seedbank Variables? Principle component (PC) regression was used to regress the seedbank response variables of seedbank density, species richness, and the proportion of hairy galinsoga and crabgrass in the seedbank on the measured interview variables, represented by the PCs (Table 3). We tested the first 7 PCs as predictors; each of these explained at least 5% of variance of the interview variables. Loadings for only the first 5 PCs are presented in Table 3, because PC6 and PC7 were not included in any of the final models following backward selection, as described below. We present results for the reduced regression models below.

Based on the highest loadings on each PC, we have indicated what each of these components primarily represented, for ease of interpretation. PC1 represented "experience and perceptions," with highest loadings from mentions of farmers learning from their own experience, risks of weeds, and the benefits of critical weed-free management. This PC explained 30.9% of the variance of the 14 interview variables. PC2 represented "long-term, seedbank management knowledge" because of high loadings from those two knowledge variables as well

Table 3. Principle components (PCs) of farmer interview variables were regressed against variables describing on-farm weed seedbanks.

		Principle component loadings				
		PC1	PC2	PC3	PC4	PC5
Knowledge	Recognizing opportunities	0.28	−0.10	**0.40**[b]	−0.34	
Knowledge	Managing weed seedbank	0.20	**0.49**			**−0.41**
Knowledge	Ecological complexity	0.26	−0.26			−0.29
Knowledge	Systems thinking		0.34	**0.40**	0.26	0.27
Knowledge	Long-term strategy		**0.40**	**0.46**	−0.14	
Knowledge	Weed-soil interactions	0.23		0.10		**0.70**
Learning	From own experience	**0.41**	0.10			
Learning	From other sources	0.20	0.14		**0.61**	−0.12
Perceptions	Risks of weeds	**0.38**	0.20	−0.25		
Perceptions	Benefits of weeds		−0.33	**0.45**	−0.18	**−0.37**
Perceptions	Benefits of CWF[a] management	**0.40**	0.13		−0.20	
Perceptions	Benefits of SB[a] management	0.32	−0.25	0.25	0.26	
Perceptions	Risks of CWF management	0.23		−0.31	**−0.44**	0.12
Perceptions	Risks of SB management	0.30	**−0.36**	−0.16	0.30	0.13
				% variance explained		
Seedbank density		22.4**	12.6*	0.8	2.5	15.1*
Species richness		0.1	2.9	22.4*	4.9	2.1
Proportion of *G. quadriradiata* and *Digitaria* spp.		10.5	15.6*	16.2*	5.2	0.0

[a] Abbreviations: CWF, critical weed-free; SB, seedbank.
[b] Bold values denote loadings higher than 0.35, those that most associate with a given PC.
** P < 0.01.
* P < 0.05.

as awareness of risks of seedbank management practices. PC3 also represented knowledge, ''broad, systems-based knowledge,'' because of high loadings of knowledge of long-term strategy, systems thinking, and recognizing opportunities to manage weeds, along with awareness of benefits of weeds. PC4 primarily represented ''learning from other sources.'' PC5 represented ''alternative knowledge,'' because of loadings indicating high knowledge of weed-soil interaction and low knowledge of managing the weed seedbank. As indicated earlier, knowledge of weed-soil interactions was the only knowledge category for which most of the concepts mentioned were unique to farmers rather than in agreement with experts (Table 2).

The reduced regression model explained 50.1% of the variance in seedbank density, including the following predictors: PC1 (22.4% variance explained, P = 0.009), PC5 (15.1% variance explained, P = 0.027), and PC2 (12.6% variance explained, P = 0.041) (Table 3). Lower seedbank densities occurred on farms whose farmers placed more emphasis on ''experience and perceptions'' (PC1), less emphasis on ''alternative knowledge'' (PC5), and more emphasis on ''long-term, seedbank management knowledge'' (PC2).

PC1, a significant predictor of seedbank density, indicated that awareness of risks of weeds and benefits of critical weed-free strategies are associated with low seedbank densities. PC2, primarily indicating ''long-term, seedbank management knowledge'' also had high loading from the variable of risks of seedbank management practices. These results support our hypothesis that awareness of risks of weeds may be an important predictor of seedbank density; however, the importance of management perceptions was counter to our expectations. Our results indicated that managers who emphasize benefits of critical weed-free, seedling-focused strategies and the risks of seedbank management are also capable of achieving low seedbank densities. Finally, we reject our hypothesis that the knowledge variables of systems thinking and ecological complexity, those most important to scientific experts, predict low seedbank densities. Knowledge of ecological weed management was important, but rather because of the variables of long-term strategy and managing the weed seedbank.

A bi-plot of PC1 and PC2 was created to illustrate the associations among the interview variables and individual farm samples included in the regression (Figure 3). As indicated by the circled numbers, high seed density farms (solid circles) clustered closely together in comparison to low seed density farms (dashed circles). The clustering indicates that the interview variables represented

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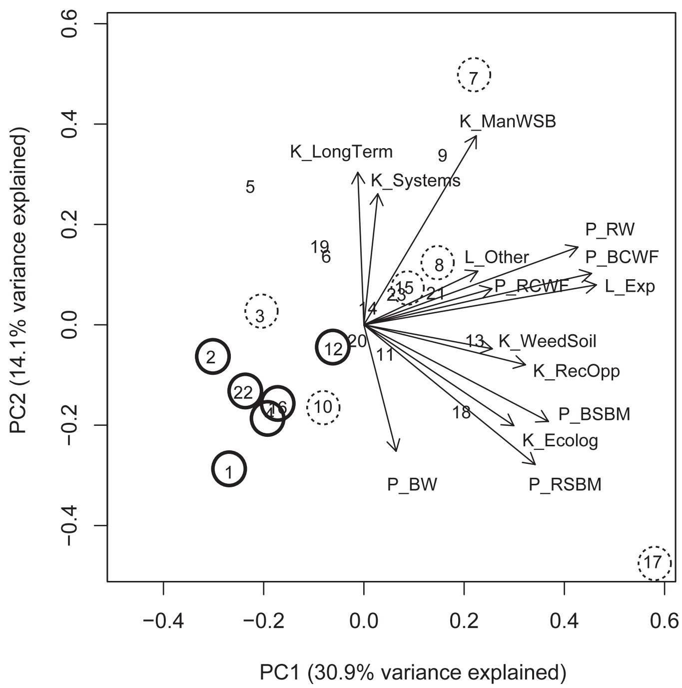

Figure 3. Principle component analysis of farmer interview variables, indicated by the vectors. Knowledge variables are indicated with the prefix "K," learning variables with the prefix "L," and perceptions variables with the prefix "P." Farm replicates are indicated by their identification number, 1 through 23. The six farms with the highest seedbank densities are indicated by solid circles, and the six farms with the lowest seedbank densities are indicated by dotted circles.

by the first two PCs varied less amongst high seed density farms than amongst low seed density farms. Interviews of low seed density farmers yielded more diverse responses than those of high seed density farmers, which were more consistent. In other words, there appear to be a diversity of mental models that can lead to low seed density farms, whereas high density farms are uniformly predicted by mental models defined by low levels of both "experience and perceptions" (PC1) and "long-term, seedbank management knowledge" (PC2).

In addition to weed seed density, we tested for associations between interview PCs and the diversity metric of species richness. The reduced model to predict species richness consisted solely of PC3 (22.4% variance explained, P = 0.023), which indicated that higher species richness was associated with higher levels of "broad, systems-based knowledge."

Finally, we tested for associations between interview PCs and the proportion of the seedbank comprised of hairy galinsoga and crabgrass. The farmers interviewed considered these species to be most problematic (Jabbour et al. 2013). The proportion of these species in the seedbank varied widely across farms, from 1 to 73% of total seed density, with a mean of 32%. The reduced regression model explained 47.5% of the variance in the proportion of hairy galinsoga and crabgrass in the seedbank, including PC3 (16.2% variance explained, P = 0.030), PC2 (15.6% variance explained, P = 0.033), PC1 (10.5% variance explained, P = 0.075), and PC4 (5.2% variance explained, P = 0.201). Lower proportions of these problematic weeds were associated with farms who operators exhibited high levels of both "broad, systems-based knowledge" (PC3) and "long-term, seedbank management knowledge" (PC2). Hairy galinsoga and crabgrass are both summer annuals that exhibit protracted emergence periodicity, and, based on observation, their seedlings have greater root/shoot ratios than those of many common species (e.g., common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.)), a trait that would result in reduced sensitivity to cultivation relative to other species. Based on their biology and ecology, we expect critical weed-free managers to have higher densities of these species.

The importance of farmer learning from experience and trial and error is widely recognized in recent literature (Eckert and Bell 2005, 2006; Leitgeb et al. 2012; Macé et al. 2007; Turner et al. 2007) and had the highest loading on PC1 "experience and perceptions." Many farmers offered specific examples of learning from experience, regarding particular types of weeds, crops, and management strategies. Farmer 7 offered a broad view of his management approach in relation to this topic:

> To manage weeds, first observation. No sense going out and spending diesel if you don't have weeds out there – observation. Then, experience. Turning that observation into a matter of judgment as to whether this is going to be a problem…Then, just refinement – implementation of a protocol – farmers don't use the word protocol but that's what it is…If it's a well designed protocol, you shouldn't have to modify it too much. That's the benefit of experience. When you're new, then there's no protocol, there's no experience, there's no judgment…It's kind of a crap shoot. So you start from that point and then you develop through experience, a pattern, and then that pattern becomes recognized and there's a lot of common sense in there. Common sense is not common. Common sense really comes from experience.

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Awareness of the risks of weeds and the benefits of critical weed-free management strategies were the perceptions with high loadings on PC1. Farmers generally perceived weeds as high risk and low benefit (Table 4; Jabbour et al. 2013; Wilson et al. 2008). This finding is consistent with research that identifies perceived risks and benefits as inversely related (Alhakami and Slovic 1994; Finucane et al. 2000), specifically where negative feelings toward a hazard lead to high perceived risk and low perceived benefit. In a similar but reverse example, conventional farmers in Ohio generally perceived herbicides as a high benefit and low risk management tool, again likely because of the positive feelings associated with herbicides in conventional agriculture (Wilson et al. 2008). The authors concluded that these farmers are thus unlikely to perceive the need to minimize the risks of herbicides such as herbicide resistance.

Organic farmer perceptions of critical weed-free management practices differed from the Ohio conventional herbicide case. Discussion of critical weed-free management practices by these organic farmers was dominated by cultivation, handweeding, and flaming. Although farmers acknowledged the benefits of critical weed-free management, farmers also readily recognized the risks associated with these practices, often discussing risks more often than benefits (Table 4). However, it was awareness of the economic and agricultural benefits of critical weed-free practices (e.g., the working rate of a tractor or the precision of handweeding) that distinguished the mental models of low and high seedbank farmers (Figure 3), whereas all farmers were aware of the risks (Table 4). This finding supports work on technology acceptance which poses that understanding what influences an individual to accept a new technology (e.g., critical weed-free practices), requires an understanding of both the perceived risks and benefits of that technology so both may uniquely contribute to acceptance (Siegrist 2000). In addition, research in a variety of environmental and natural resource contexts points to the importance of perceived benefits for motivating changes in attitudes and behavior (Ascher et al. 2012; Paveglio and Carroll 2009; Slagle and Zajac 2013).

Knowledge of ecological weed management was represented by "long-term, seedbank management" PC2, "broad systems-based knowledge" PC3, and "alternative knowledge" PC5. Knowledge of managing the weed seedbank, which had high loadings on both PC2 and PC5 (Table 3), included farmer discussion of use of appropriate tillage tactics, crop rotations, and pre-empting weed seed rain. PC5 primarily separated farmers according to their levels of knowledge of weed-soil interactions. Farmers who discussed "alternative knowledge" of weed-soil interactions at length tended to discuss managing the weed seedbank less often, and had higher weed seedbank densities. PC3 and PC2 explained the most variation in the proportion of hairy galinsoga and crabgrass species in the seedbank. Farmer knowledge has been shown to be associated with other on-farm biological indicators of insects and soil quality (Dawoe et al. 2012; Wyckhuys and O'Neil 2007). Here, we demonstrate that knowledge of ecological weed management principles was predictive of both lower overall weed density as well as the proportion of the weed community that is comprised of particularly problematic species.

How Do These Patterns Compare to Particular Case Studies of Low Seedbank Density and High Seedbank Density Farmers? We summarized seedbank and interview data for the three farmers with the lowest and the highest seedbank densities in our study (Table 4). We also present the summary statistics for all 23 farmers in the final column for context. Low-seedbank farmers generally exhibited high levels of knowledge, although farmer 10 is a notable exception. Farmer 10, with the lowest seedbank density of all farmers, also had low levels of knowledge of ecological weed management. However, in other areas of his mental model, Farmer 10 aligned with other low seedbank farmers, emphasizing learning from his own experience, mentioning risks of weeds more often than benefits, and discussing both the benefits and risks of critical weed-free management.

When considering all farmers interviewed, farmers discussed risks of critical weed-free management practices more often than benefits, and discussed benefits of seedbank management practices more often than risks (Table 4), indicating a general negative affect or regard for critical weed-free management, and a general positive affect or regard for weed seedbank management (Finucane et al. 2000). This pattern differed between low and high-weed seedbank farmers. Low-seedbank farmers were more aware of the benefits of critical weed-free management practices such as cultivation, handweeding, and flaming than high-seedbank farmers who focused solely on the risks of these practices. Farmer 10 described his management strategy of "calendar" weeding, every 2 wk, using a tractor, hand hoes, or handweeding (in order of preference),

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Table 4. Profiles for farms with the lowest (farms 10, 8, and 7) and highest (farms 2, 1, and 16) weed seedbank densities sampled. To place these data in broader context, summary statistics (mean, minimum and maximum values) of all 23 farms are also included.

	Lowest seed densities			Highest seed densities				
	F10	F8	F7	F2	F1	F16	Mean	(Min, Max)
Seedbank variables								
Seedbank density	2,775	3,658	3,857	13,830	18,722	24,678	8,600	
Proportion of *G. quadriradiata* and *Digitaria* spp.	0.44	0.56	0.01	0.38	0.54	0.62	0.32	(0.01, 0.73)
Species richness	16	17	21	20	24	39	24.35	(16, 39)
Evenness	0.21	0.16	0.24	0.12	0.15	0.19	0.18	(0.12, 0.24)
Interview variables								
Knowledge mentions (total)	3	15	22	6	0	6	12.1	(0, 23)
Recognizing opportunities	0	1	0	0	0	3	1.8	(0, 6)
Managing weed seedbank	1	8	11	4	0	0	3.0	(0, 11)
Ecological complexity	2	2	0	0	0	0	1.0	(0, 4)
Systems thinking	0	3	5	2	0	0	2.0	(0, 10)
Long-term strategy	0	1	1	0	0	1	1.4	(0, 4)
Weed-soil interactions	0	0	5	0	0	2	2.9	(0, 14)
Expert-align knowledge	2	12	18	4	0	3	8.3	(0, 18)
Farmer-only knowledge	1	3	4	0	0	3	3.8	(0, 14)
Learning mentions (total)	15	14	31	8	5	11	17.2	(5, 35)
From own experience	9	7	13	8	4	4	8.7	(3, 16)
From other sources	6	7	18	0	1	7	8.6	(0, 19)
Risk: benefit of weeds	4.7	9.0	23.0	1.7	0.6	1.5	4.6	(0.6, 23)
Risks of weeds	14	27	23	10	7	12	16.4	(7, 27)
Benefits of weeds	3	3	1	6	12	8	7.0	(1, 16)
Management perceptions								
Benefits of CWF[a] management	3	4	5	0	1	0	2.3	(0, 5)
Risks of CWF management	5	7	13	4	8	8	9.1	(1, 20)
Benefits of SB[a] management	0	12	7	0	4	5	4.6	(0, 28)
Risks of SB management	6	5	0	0	2	0	3.0	(0, 14)

[a] Abbreviations: CWF, critical weed-free; SB, seedbank.

depending on the crop type and situation. During his interview, he clearly stated that he has zero tolerance of weeds, and defined a management strategy as successful "if I kill them…eradication."

The risks of critical weed-free practices most often discussed by farmers were damage to soils. In the Netherlands, organic farmers who often considered risks to their soil when making weed management decisions had higher weed densities than those who never or sometimes considered risks to soils (Riemens et al. 2010). Farmer 16, with the highest weed seed densities sampled of all farms, prioritized soil quality over weed management, as described here:

> If we try to keep [the soil] dry and cultivated with tillage equipment, it just gets hard packed and nasty. I don't like it. It looks dead to me, you know? So even if the weeds are covering it, at least the soil is a lot more friable and a lot nicer underneath. You know there is something going on under there [in the soil].

Farmers 8 and 10 both highlighted the weed management benefits of stale seedbed and bare fallow practices, but discussed the importance of coupling such management with efforts that improve soil quality. Farmer 10 clarified that he uses cover crops to "build up soil and protect from erosion," not to manage weeds, because he does not "think [cover crops] work" as a weed management strategy. We did not measure any indicators of soil quality on these farms, but we propose future research should certainly explore whether such tradeoffs occur (e.g., weed control vs. soil quality) and how they relate to farmer mental models.

Although all farmers discussed risks and benefits of weeds (Table 4), low-seedbank farmers generally mentioned risks of weeds more often and benefits of weeds less often than average. Low-seedbank farmers mentioned risks of weeds anywhere from 4.7 to 23 times more often than benefits of weeds, whereas high-seedbank farmers mentioned risks of weeds 0.6 to 1.7 times more often than benefits of weeds. The three highest seedbank farmers each discussed the benefit of weeds serving as a cover crop, for example, according to Farmer 2:

> If we don't have time to plant something, and the weeds are there, they will cover the ground…they're soaking up nutrients. They are preventing erosion… And as long as you get on the field quickly enough so that you get them when they are still in a vegetative state, you can eventually control them when you get ready to farm it. I think any time that a weed is growing it is providing some benefit.

Low-seedbank farmers mentioned risks in four major categories (agricultural, economic, ecological, and social), with a focus on agricultural and economic risks of weeds. These farmers mentioned risks of weeds more often during their interviews, demonstrating increased awareness.

Overall, farmer knowledge, perceptions, and experience aligned with low weed seedbank densities in the expected direction. The relationship between knowledge congruent with experts and low seedbank densities demonstrates the relevance of research and Extension efforts to organic weed management success. Educators, however, should recognize the importance of farmer experience and perceptions, in addition to scientifically-based knowledge, as influential to weed management as well. There is great variation in the knowledge and perceptions that guide farmers, even amongst the low-density exemplars in our farmer sample of New England. Yet what these farmers share in common is a focused effort to manage weeds, potentially dependent on distinct strategies, that has proven successful for them based on their own experiences. Farmer 10, whose farm had the lowest seed density, said,

> I really think that what I'm doing is working, and I don't understand why everybody doesn't do it. I'm not saying I always have the best attack strategies, but this whole idea of letting weeds go is just a terrible thing to do. I think people rationalize it by saying, 'Well, weeds work for me.' Weeds never work for you.

Although other successful weed managers, including those within this study, certainly have philosophies distinct from Farmer 10, the aim of researchers and educators should be to help farmers gain the knowledge and experience necessary to enable them to develop a plan that works for them and their operations. The low-seedbank farmers featured here are not "celebrity" farmers. They are regular people whose focused efforts, whether in designing an effective crop rotation or knowing when to use or not use cover crops, for example, have allowed them to succeed at achieving low weed seed densities on their farms. Future research should explore requisite knowledge, skills, and relative cost/benefits of management practices along a continuum from seedling-focused to seedbank-focused management.

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