Renewable Agriculture and Food Systems

cambridge.org/raf

To each their own: case studies of four successful, small-scale organic vegetable farmers with distinct weed management strategies

Bryan Brown[1,2] and Eric R. Gallandt[2]

[1]New York State Integrated Pest Management, 630 W. North St. Geneva, NY 14456, USA and [2]School of Food and Agriculture, University of Maine, Orono, ME 04469, USA

Preliminary Report

Cite this article: Brown B, Gallandt ER (2019). To each their own: case studies of four successful, small-scale organic vegetable farmers with distinct weed management strategies. *Renewable Agriculture and Food Systems* **34**, 373–379. https://doi.org/10.1017/S1742170517000576

Received: 19 November 2016
Revised: 12 October 2017
First published online: 28 November 2017

Key words:
Critical period; zero seed rain; mulch; organic farming; vegetable

Author for correspondence: Bryan Brown, E-mail: bryan.brown@cornell.edu

Abstract

Organic vegetable farmers execute weed management using many overall philosophies, including focusing management during the early-season critical period, managing the weed seedbank with a 'zero seed rain' strategy, or physically suppressing weeds with plastic or natural mulches. While these strategies vary in their ecological and economic implications, farmers' reasons for adopting specific weed management approaches, and the related practical implications of each approach remain unclear. To better understand farmer motivations and ecological impacts of broad weed management philosophies, we conducted case studies of four successful organic vegetable farmers with specialization in different management approaches. The farmers were interviewed about their experiences and soil samples were collected for weed community and soil organic matter (SOM) analysis. The farmer who controls weed seedlings primarily during the critical period has appreciated the associated weeding labor savings, but late-season weeds have contributed to a large weed seedbank (38,482 seeds m^{-2}), which is necessitating a change in his management. Conversely, the zero seed rain strategy of another farmer required a large amount of labor in the initial years, but weeding labor requirements have lessened every year due to decreased weed emergence from his diminishing weed seedbank (3065 seeds m^{-2}). Another farmer utilizes plastic mulch in many crops in order to reduce weeding labor during the busy spring planting season. Finally, the farmer that uses natural mulches has high labor costs, but they are offset by the benefits of weed suppression, soil moisture conservation and increases to SOM. The two farmers utilizing mulch had the greatest portion of monocotyledonous weeds, perhaps relating to their morphology allowing them to emerge through the mulch. In ranking management criteria based on their importance, the case study farmers generally valued the criteria that are benefited by their strategy, indicating a strong relationship between their priorities and their management. Overall, there was no 'best' weed management strategy, but farmers may benefit from the consideration of how their management priorities match the practical tradeoffs of each strategy.

Introduction

Organic farmers often have distinct approaches to weed management (Jabbour et al., 2014*b*; Dedecker et al., 2014). Among other strategies, farmers may focus on short-term control of weed seedlings, longer term weed seedbank management (Jabbour et al., 2014*a*, *b*) or weed suppression with mulch (Baker and Mohler, 2014). Motivations for each of these weed management strategies vary widely, likely related to farmers' agronomic beliefs (Wilson et al., 2009; Zwickle, 2011) and perception of risk (Slovic, 1987). For example, crop growth is most impacted by weeds in the early-season 'critical period' (Nieto et al., 1968; reviewed by Knezevic et al., 2002); thus, for farmers that consider labor as the main risk of weeds, they may limit weed control efforts to the critical period of each crop (Jabbour et al., 2014*a*, *b*). However, this strategy often allows late-season weeds to produce seeds, resulting in abundant 'seed rain' and a large weed seedbank (Norris, 1999; Jabbour et al., 2014*a*; Brown and Gallandt, 2017).

Conversely, farmers with strong awareness of the risks of weeds tend to have smaller weed seedbanks (Jabbour et al., 2014*a*), likely reflecting more weed-preventative practices. For example, preventing weeds from producing seeds can reduce the weed seedbank and lessen weed emergence in subsequent years (Norris, 1999). Such a 'zero seed rain' strategy attempts to reduce risks to both crop yields and labor management (Riemens et al., 2007; Gallandt, 2014).

Farmers may also use mulch to suppress weeds (Baker and Mohler, 2014; Brown and Gallandt, 2017), a strategy most frequently employed in high-value vegetable crops. In northern temperate regions, black plastic mulch is often used for its soil warming properties. Plastic mulch is also valued for weed suppression (Zwickle, 2011) and soil moisture retention (Lament, 1993), and it can increase yields in a variety of vegetable crops (Vavrina and Roka, 2000; Kaya et al., 2005; Zhang et al., 2007). Natural mulches, such as hay or tree leaves, may also be used to suppress weed growth. Application of natural mulch requires a large early-season investment in materials and hand labor, but there is a psychological boost to laborers in knowing that little subsequent weeding will be required (P. Arnold, personal communication). Among farmers, a major concern regarding natural mulches is the risk of weed seed contamination (Zwickle, 2011), but this can be mitigated by knowledge of the mulch source or on-farm mulch production allowing oversight of its quality.

Clearly, each of these weed management strategies have different ecological (Brown and Gallandt, 2017) and economic consequences; however, an applied understanding with respect to the impacts of each strategy on the management of working organic farms remains lacking. We hypothesized that the farmer motivations and practical implications related to each strategy would differ, thereby highlighting tradeoffs between each strategy. Therefore, we conducted case studies of farmers that have specialized in each strategy. We examined the factors that influenced the formation of their weed control strategy as well as the real-world implications of each strategy. Overall, it is our aim that the farmer experiences and perspectives presented in these case studies will resonate with other farmers (*in sensu* Rogers, 1988) to allow for more informed weed management decisions.

Methods

Farmers representing each weed management strategy (critical period weed control, zero seed rain, plastic mulch and natural mulch) were selected in July 2014 based on their involvement with previous studies (i.e., Jabbour et al., 2014*b*) and the authors' familiarity with their practices. The four participating farmers were all small-scale, organic, mixed vegetable growers located in northern New England. Each farmer had a minimum of 17 yr of experience and is highly regarded in the organic farming community. As reported by each farmer, their farms varied by soil type, number of workers, land area in cultivation, cover crop usage and seasonal workload (Table 1).

Farmers were interviewed in March 2015 after obtaining approval from the Institutional Review Board for the Protection of Human Subjects (IRB) (see online Supplementary Fig. S1). Following the interviews, permission from the farmers and IRB was granted to disclose identities. The four participants were each compensated US$250 for their time. Interviews were conducted by telephone and were around 1 h in duration. Digital voice recordings of the interviews were transcribed manually and checked for accuracy and consistency by the authors. Prior to publication, all interviewed farmers approved the final draft.

Interview questions were developed to expose key differences in the personal motivations and practical implications related to each weed management strategy. The same questions (see online Supplementary Table S1) were asked in all interviews in a semi-structured format (Bernard, 2011) that allowed for occasional follow-up questions. Topics included the benefits and drawbacks of their weed management strategy, as well as the required equipment, cropping choices, response to wet weather and likelihood to continue with their strategy under different circumstances. To further evaluate the farmers' motivations for adopting each strategy, they were also asked to rank the relative importance of four terms of management criteria following the Analytic Hierarchy Process (Saaty, 1982). Criteria included weeding labor, the weed seedbank, environmental sustainability and soil quality (see online Supplementary Table S1). Each possible pair of criteria were presented to farmers with the instruction to rank the pair on a scale of zero to ten with zero meaning the first term is extremely important and the second term has no importance, and *vice versa*. A rank of five would mean that the two terms are equally important. The weights of the individual criteria were calculated by creating a normalized comparison matrix, then dividing each value by the sum of its column, and finding the mean of each criteria row (Saaty, 1982).

To further depict the practical tradeoffs involved with each strategy, soil organic matter (SOM) and germinable weed seedbanks were assayed. In September 2014, ten soil cores were collected from each farm to a depth of 18 cm. Homogenized samples were sent to the University of Maine Soil Testing Service for SOM testing. An additional ten soil cores were obtained using a bulb planter (Yard Butler IBPL-6 Bulb and Garden Planter, Lewis Tools, Poway, CA, USA), with a diameter of 8 cm, inserted to a depth of 10 cm, to perform germinable weed seedbank assays (Gallandt et al., 1998). Following Ryan et al. (2010), soil was placed in 4 liter sealable plastic bags and transported in an insulated cooler to storage in dark conditions at −12°C. Bags were removed from storage on May 1, 2015 and allowed to thaw for 48 h before contents were spread on 51 × 51 cm flats over 2 cm of vermiculite. Flats were watered regularly to encourage germination. Common seedlings were identified to species or genus, while less common seedlings were recorded as 'other broadleaf' or 'other monocot'. Seedlings were removed after identification. When new emergence ceased, flats were allowed to completely dry so that the hardened soil could be lifted from the vermiculite, placed in a bucket, mixed, returned to the flat and watered to encourage a new cohort of germination. Five such cycles occurred during the assay period of May 1 to September 30, 2015.

Results and discussion

Farmer practices and motivations

The case study interviews highlighted distinct practical tradeoffs among the weed management strategies employed by the farmers, as well as the widely ranging factors influencing the formation of each farmer's weed management philosophy.

Mark Guzzi, critical period weed control

For most crops, Guzzi's weed management approach stresses a combination of mechanical cultivation and hand hoeing, often focusing these activities during the early critical period of his crops (*in sensu* Knezevic et al., 2002). He says, 'Crops can tolerate some weed pressure, especially later on in the season and so it becomes an issue of whether those weeds are going to interfere with harvest or not'. Regarding how Guzzi established his current weed management strategy, he recalled,

> 'It's very short term thinking … the [previous owner] had allowed the weed seedbank to grow and become a very significant problem. So when we got here … we got used to growing in very weedy fields. Our level of tolerance is no doubt higher than it should be … We created this farm business with all of these markets and expectations despite

Table 1. Summary of soil texture, farm size and land use for case study participants representing each weed management strategy (results were self-reported by each farmer)

Farmer	Weed management strategy	Soil texture	Seasonal workers (No.)	Land in cultivation (ha)	Land in summer cover crop (%)	Land in winter cover crop (%)	Overall busiest time for farm operations
Mark Guzzi	Critical period weed control	Silt loam	10	10	28	40	All season
Tom Honigford	Zero seed rain	Sandy loam	2	4	14	75	August–September
Dave Colson	Black plastic mulch	Loam	5–7	4	50	90	May and September
Tom Roberts	Natural mulch	Clay loam	3–12	2	15	20	August–September

the fact that we were totally contaminated with weeds. I recognized … the smart thing to do would be to have done a Nordell-type approach where we would have taken that ground and exhausted the weed seedbank before expanding production … [Now] there is a psychological barrier that I feel to scaling back and going to the Nordell approach.'

Guzzi is referring to Eric and Anne Nordell, who helped popularize weed seedbank management approaches (Nordell and Nordell, 2009; Gallandt, 2014). Guzzi's explanation also mentions short-term decisions, which have been found to be correlated with large weed seedbanks (Jabbour et al., 2014*a*).

Tom Honigford, zero seed rain

Honigford has a very low tolerance for weeds. He uses mechanical cultivation every 10–14 days until crops grow too large to be cultivated. Shortly after each mechanical cultivation, scuffle hoeing (also called stirrup hoeing) is used to control remaining weeds. In this process, weeds in close proximity to the crop are pulled by hand, and any crop plants that were buried by cultivation are uncovered. After crops grow too large for tractor cultivation, he continues to control weeds with hand tools. Weeding efforts may cease if there is no chance of weed seed production before the crop is harvested and tilled. Prevention of weed seed production has led to a dramatic reduction in weed emergence, which has lessened the requirement for hand weeding. When asked how he developed such a low weed threshold he joked,

> 'Probably because I'm German. *There will be order!* I just like the look of a clean field. [Weeds] never get that big in my operation. I nail those little [expletive] as soon as they come out of the ground … After a while I said 'Hey, wait a minute, this is actually working! … I worked [hard] those first few years, killing all those weeds … [Now] every year I find that I weed less than I did the year before because I don't have any weed seed rain anymore.'

Dave Colson, plastic mulch

In addition to a diverse array of ecologically based weed management practices, Colson uses black plastic mulch for many of his crops. Plastic mulched beds are generally not hand weeded. Exceptions include some long-season crops, which may require

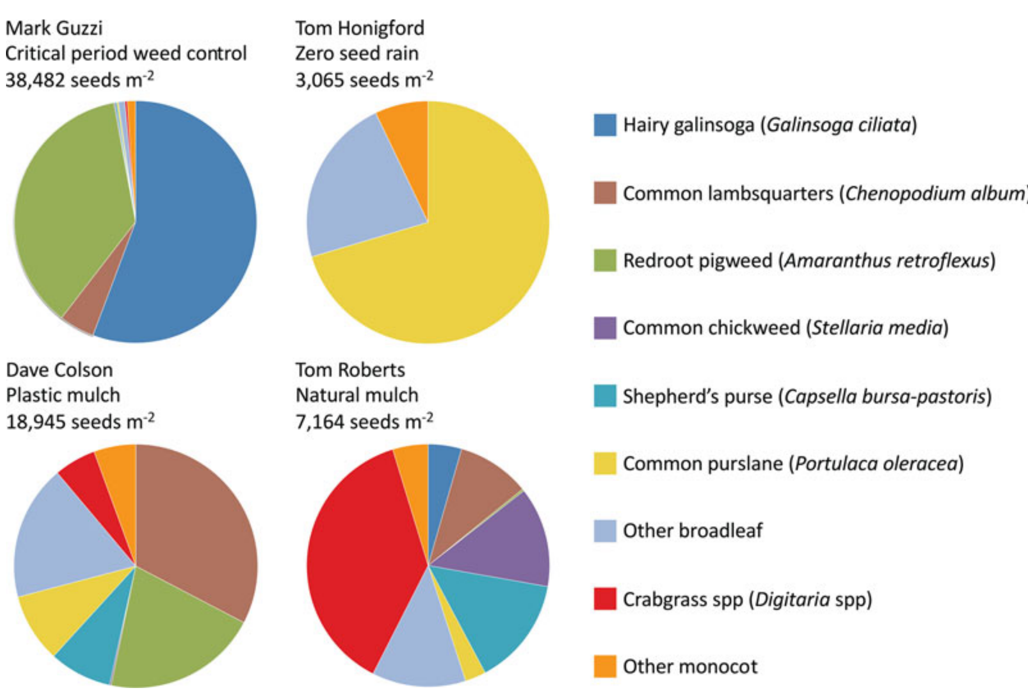

Fig. 1. Weed species composition determined from germinable seedbank assays of soil samples from each participating farmer. Listed below each farmer's name is the weed management strategy that they represent and their total weed seedbank density.

https://doi.org/10.1017/S1742170517000576 Published online by Cambridge University Press

hand weeding of the planting holes, but this can often be done during harvesting operations. He mostly uses mechanical cultivation for the paths with the addition of hand hoeing to control edges of plastic mulched beds. For crops in the Cucurbitaceae family, he uses natural mulch for the paths in between the plastic to suppress weeds and to keep the fruit cleaner and easier to find. Colson recounted the factors involved with his increased use of plastic:

> 'We started using black plastic because we wanted to get more heat units on heat-loving crops. The problem is in the spring, you're so busy getting so much planted that by the time you hit June you're ready to go back and start doing maintenance on the stuff you've put in. A lot of stuff we wouldn't have thought about putting plastic on [would be] filled with weeds, like those early brassicas … The reason for putting them in plastic was so we could put the hand weeding time into things like [planting or weeding the direct seeded crops].'

Tom Roberts, natural mulch

Roberts applies hay or tree leaf mulches to most crops. Mulch applications are performed by hand, after crops have grown large enough to avoid being smothered. He uses a flail mower to cut hay before it produces seeds and applies the resulting finely chopped mulch around delicate or closely spaced crops, like onions. He uses a string trimmer to harvest irregular areas inaccessible to the flail mower, and uses this mulch, which includes longer pieces, on crops less prone to being smothered. He also uses municipally collected tree leaves as mulch. Whole leaves are used in paths but are shredded for use in beds to avoid matting, which could produce anaerobic conditions. While many of his crops are mulched immediately after transplanting, some crops require additional growth prior to mulching, necessitating hand weeding until mulch applications can be completed. Some hand weeding may also be necessary to control weeds that emerge through the mulch. Roberts explained the factors that led him to using natural mulch:

> 'Several things, one is we have mulch available and if something is available to boost our organic matter we ought to be using it. It also retains water … We don't have a lot of water available to us … So that water retention is really important to us. The fact that it suppresses weeds is a real bonus … It's not just for weed suppression, if that's all it did, the cost of the hand labor would be hard to justify.'

Ancillary benefits of each strategy

For Guzzi, labor management and cost savings are the primary benefits of a critical period strategy; however, he also hypothesized a secondary benefit of soil improvement derived from the annual incorporation of weed biomass as a green manure. Additionally, he has suggested that the presence of weeds on his farm may be an indicator of soil health, and further provide other agroecosystem benefits through the provision of food and habitat to birds, mice and beetles that could predate both weed seeds and other pests. While the ecosystem services provided by weeds are well documented (Marshall et al., 2003; Petit et al., 2010), the concept of weeds acting as an indicator of soil health remains controversial (Kopittke and Menzies, 2007; Tilman et al., 1999).

Honigford has also recognized additional benefits of his zero seed rain approach beyond the reduced labor requirements associated with decreased weed emergence. Due to the lack of weed competition with his crops, Honigford is able to omit applications of mid-season fertilizer. He also believes that the lack of weed competition is reflected by his customers' satisfaction with the taste of his produce.

The mulch-based weed management approaches of Colson and Roberts also provide ancillary benefits to their farms. Colson mentioned that the plastic mulch conserves soil moisture and that weeds likely germinate and die under the mulch, thereby reducing the weed seedbank. Likewise, Roberts noted that increased water conservation due to the natural mulch is one of the main benefits. He also values the addition of the mulch to SOM. Roberts believes his high SOM buffers the pH, decreases nutrient leaching and improves the soil structure. Roberts is gradually reducing the amount of compost he applies with the expectation that the high SOM will be sufficient to provide most of his fertility. Indeed, for every 1% of SOM, 22–34 kg N ha^{-1} can become available during the growing season (Grubinger, 2005). Overall, Roberts valued the ancillary benefits of his strategy more than the other farmers.

Drawbacks of each strategy

Each case study farmer noted distinct drawbacks related to their weed management strategy. Guzzi noted that the increased weed emergence resulting from critical period management is detrimental in several ways. He explained,

> 'In some crops [like carrots, onions, and salad mix] that have less tolerance to weed pressure—and those are valuable crops that we want to keep in the mix—we would make more money off them if we didn't have to spend [so much time] weeding them … [Also] the weeds themselves create competition but they also do other things, they can reduce airflow in the crop resulting in disease problems, they can host insects, they can provide habitat for rodents.'

Honigford recognized that the frequent cultivation used in his system could negatively impact soil quality. However, he was also optimistic that the shallow disturbance resulting from cultivation would not be as detrimental as more aggressive tillage practices. He also cited his ample long-term profitability as evidence that frequent cultivation is economically sustainable. This reflects previous studies showing that organic farmers using extensive cultivation often minimize consideration of risks to their soil (Riemens et al., 2010; Jabbour et al., 2014*a*). Colson spoke of the environmental costs of plasticulture, saying, 'If I didn't have to use it, I wouldn't. I don't like using a petroleum product and having all of that to throw away every year'. He also mentioned the extra management required to track which beds have been covered with plastic mulch and are ready for transplanting. Roberts highlighted soil cooling as a drawback of the mulch; but for crops that thrive in heat, like tomatoes, the mulch is applied in early July when the soil is sufficiently warm and increased moisture retention is necessary. Roberts indicated that the greatest drawback of his natural mulching approach is the labor required to grow, harvest and apply the mulch. He also estimated that growing the mulch requires five to ten times as much land area as the mulched area, indicating that perhaps natural mulching is best used on a small scale.

Equipment required for each strategy

When speaking about the required equipment for their weed management strategies, Guzzi cited several cultivators, including a Reggie weeder (Univerco, Quebec, Canada), which is a powered,

https://doi.org/10.1017/S1742170517000576 Published online by Cambridge University Press

rotating set of tines that a rear operator can move in and out of the crop rows. Honigford mentioned his six different cultivators, which are each suited to different conditions (Bowman, 2002), thereby allowing him to respond to a range of soil, weed and crop situations. Colson's main piece of necessary equipment was a single-bed plastic mulch applicator. He also has a toolbar with sets of sweeps to cultivate the pathways. Roberts initially used a rotary mower to cut his hay mulch; however, he transitioned to a flail mower, as it allowed for the production of a finer mulch that more precisely could be applied in thinner layers around the crop while still maintaining a stable mat in windy conditions.

Effects of each strategy on crop rotation and cover cropping

Guzzi adjusts his crop rotation to avoid planting weed-sensitive crops in areas of abundant seed rain from the year before. In years of extensive seed rain, he sometimes uses a moldboard plow to bury weed seeds deeply. At greater soil depth, germination may be inhibited (Holm, 1972; Stoller and Wax, 1973) but seed decay may be slowed (reviewed by Mohler, 1993), meaning buried weed seeds would likely remain problematic if returned to the surface. Honigford makes use of short-term cover crops in order to ensure that they are incorporated before any weeds can produce seeds (*in sensu* Mirsky et al., 2010). Colson's crop rotation depends on the agronomic goal for that field. If the aim is to reduce the weed seedbank prior to the planting of a weed-sensitive crop, he can increase the number of bare fallow periods in the 1–2 yr prior to planting; conversely, if the weed seedbank is sufficiently low, building fertility may become the primary goal, with a focus on legume-based crop rotations to increase available nitrogen. Every 4 yr, Roberts uses a mix of summer cover crops and bare fallow periods to reduce the weed seedbank. Roberts rarely uses winter cover crops because of the sufficient cover provided by the mulch.

Effects of wet weather on operations

Most farmers stressed that cultivation is typically not effective in wet weather, a phenomenon that is well documented in the literature (Terpstra and Kouwenhoven, 1981; Cirujeda and Taberner, 2004; Evans et al., 2012). Guzzi noted that wet weather can cause him to miss the opportunity to cultivate while weeds are small. This was also the main perceived risk of cultivation described by previously interviewed organic farmers in this region (Jabbour et al., 2014*b*). Honigford has a high post-harvest refrigeration capacity, which allows him the flexibility to cultivate during the dry part of the week and harvest during the wet part of the week. Colson typically prepares beds and delays applying the plastic until after a rainfall in order to trap moisture in the soil under the mulch. However, with the recent wet springs experienced on his farm, he has had to postpone plastic application until field fields were sufficiently dry. Roberts mentioned that while he was concerned about mulched crops becoming oversaturated in recent wet years, it did not emerge as an issue impacting production.

Weed seedbank data

Guzzi had the largest weed seedbank (Fig. 1), which likely reflects the use of a critical period weed control strategy (Norris, 1999). Two competitive and fecund broadleaf weeds, hairy galinsoga (*Galinsoga ciliata*) and redroot pigweed (*Amaranthus retroflexus*) dominated his weed seedbank. Honigford had the smallest weed seedbank (Fig. 1), as expected for a zero seed rain system (Riemens et al., 2007). The most abundant weed in Honigford's seedbank was common purslane (*Portulaca oleracea*), which he attributes to its ability to produce seeds after he had assumed it was killed by cultivation. Indeed, common purslane can produce viable seeds if flowering occurs prior to disturbance (Miyanishi and Cavers, 1980) or spread vegetatively from stem cuttings (Proctor et al., 2011). To address this problem, Honigford now transports common purslane out of his fields by hand. Aside from common purslane, Honigford's seedbank was extremely low (736 seeds m^{-2}), similar to the 550 seeds m^{-2} at Eric and Anne Nordell's Beech Grove Farm (Gallandt, unpublished). Colson's moderately high weed seedbank (Fig. 1) likely reflects the difficulty of controlling weeds on the margins of the plastic or in the planting holes (Brown and Gallandt, 2017). Although grasses were not as abundant as broadleaf weeds in the seedbank data (Fig. 1), Colson noted his difficulty in managing summer annual grasses that form thick clumps in the alleyways, which often allows them to survive cultivation. Roberts' seedbank was surprisingly small (Fig. 1), perhaps demonstrating the effectiveness of his mulching and the lack of weed seed contamination in his mulch. Roberts had the greatest portion of monocotyledonous weeds, possibly due to their morphology allowing for more successful emergence through the mulch (Brown and Gallandt, 2017). Most of the farmers highlighted crabgrass (*Digitaria* spp) and hairy galinsoga as their most problematic species, consistent with previous interviews of northern New England organic growers performed by Jabbour et al. (2014*a*). However, Roberts noted that hairy galinsoga seeds have a short half-life; thus, an effective application of mulch in the year following seed rain will cause many of the seeds to perish. Overall, each farmer demonstrated knowledge of the weed seedbank, but their actual seedbank densities varied widely. Indeed, farmer emphasis on long-term management may be a better predictor of weed management success (Jabbour et al., 2014*a*) than farmer knowledge (Zwickle, 2011).

SOM data

Although variation in SOM is likely related to pre-existing soil conditions, weed management strategies also may have impacted SOM based on the relative mix of soil disturbance and residues applied. Honigford had the lowest SOM, at 3.8%, which may relate to his frequent cultivation, twice-annual tillage and more coarsely textured soil (Table 1). Roberts had the highest SOM, at 21.0%, perhaps reflecting his regular applications of natural mulch. Furthermore, SOM was 30.5% on Roberts' no-till perennial crops. Guzzi and Colson had SOM of 6.0 and 4.8%, respectively.

Importance of criteria related to management

Based on pairwise comparisons of criteria related to management, Guzzi placed most importance on the amount of weeding labor of his operation (Fig. 2), which aligns with the ability of critical period weed control to maximize yield while minimizing in-season control efforts (Knezevic et al., 2002). The weed seedbank was also valued by Guzzi, although this may represent a more recent change in his priorities. Honigford placed the most importance on the weed seedbank, which provides insight into his rationale

https://doi.org/10.1017/S1742170517000576 Published online by Cambridge University Press

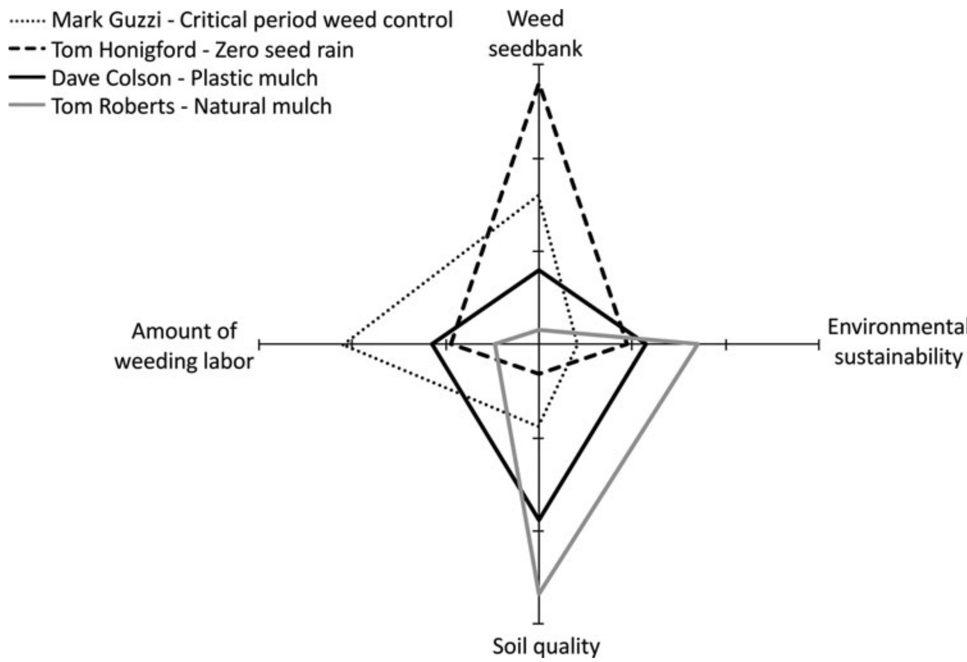

Fig. 2. Radar plot of the importance of four criteria related to management to case study farmers representing each weed management strategy. Values were derived by normalizing pairwise comparison rankings of all four criteria by each farmer.

for a zero seed rain approach. Colson was well balanced in his valuations, which he also demonstrated in the interview by mentioning, 'There is always this juggling act between cutting down on the weeds, … planning [crop rotation], and keeping an eye on soil fertility and soil health at the same time'. Finally, Roberts placed most importance on soil quality, followed by environmental sustainability of his farm. Natural mulch satisfies both those concerns since the mulch likely improves SOM, provides much of his fertility, and is mostly harvested from his low-input haying operation.

Likelihood of adhering to each strategy under different circumstances

When asked how his strategy would change if he was given land with a smaller weed seedbank, Guzzi spoke of how he has used nearby hayfields with small weed seedbanks to grow vegetables. He mentioned that due to the peripheral location of these fields, he grows crops like winter squash, which can yield well with minimal weeding. Growing these crops likely increases the weed seedbank but he can cover crop or fallow that land for subsequent years to reduce the seedbank before growing vegetables again. Guzzi is also moving toward more of a mulch-based system for many of his crops, which seems to be an effective way to suppress emergence from his sizable weed seedbank. Contrastingly, Honigford already has a low weed seedbank and is satisfied with his current strategy. He also indicated that if he had to start farming land with a large weed seedbank, he would continue with a zero seed rain approach due to the long-term benefits. Colson indicated that he would continue using plastic mulch even if his weed seedbank was very small. He also mentioned that the plastic mulch benefits his sandy loam soil (see Table 1) by improving water retention. Likewise, Roberts would also continue using natural mulch even if his soil had a near-zero weed seedbank. He explained,

> 'It's not just a weed suppressor, it's about keeping the water in the soil … if you don't use mulch, you are in fact mulching with the top inch of soil because it dries to the extent that plants cannot use the nutrients. The fungal hyphae that are feeding the plant roots can't grow in it. So when mulching, suddenly the soil is an inch deeper because plants can use that top layer … Sometimes, I'll pull the mulch aside and find tomato roots right at the surface loving that initial decomposition of organic matter.'

Roberts added that conditions are often sufficiently weed-free to transplant into overwintered mulch that was not incorporated, perhaps allowing for a no-till system. However, for small direct-seeded crops like carrots or beets, he uses tillage to prepare a fine seedbed.

Conclusions

The farmer motivations and practical implications related to each strategy differed greatly. However, one similarity between three of the case study farmers is that their strategies are implemented to reduce labor demands. Indeed, labor costs are often considered the key risk of weeds by organic farmers (Jabbour et al., 2014*b*). For example, Guzzi appreciates the labor savings of a critical period approach; Honigford's zero seed rain strategy reduced weed emergence over time, which now allows him to use fewer full-time laborers (Table 1); and Colson's main interest in expanding his use of plastic mulch was to save weeding labor during his busy planting season. In contrast, Roberts acknowledged that natural mulching requires more labor than other weed management strategies, but he continues to use natural mulch because of its benefits to the soil.

Overall, we found no single 'best' weed management strategy, but rather, tradeoffs between reducing management costs, improving soil health, and decreasing the weed seedbank. Many of the ecological and economic tradeoffs of the weed management strategies discussed by case study farmers were reflected in our related systems comparison field experiments (Brown and Gallandt, 2017). Through the related field experiments as well as the case study farmer perspectives of each strategy presented herein, we aim to allow for more informed farmer decisions related to weed management. While we have investigated each strategy separately, farmers may employ each strategy simultaneously based on individual field or crop goals, thereby incorporating successful aspects of each strategy into their management.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1742170517000576

Acknowledgements. The authors are grateful to the four farmers who participated in these case studies. Funding for the work reported here was provided by a Graduate Student Grant from the USDA Northeast Sustainable Agriculture Research and Education Program, entitled *Balancing economy and ecology: A systems comparison of leading organic weed management strategies*, project GNE14-072-27806, with Principle Investigator (PI) Bryan Brown and co-PI Eric Gallandt. This project was supported by the USDA National Institute of Food and Agriculture, Hatch (or McIntire-Stennis, Animal Health, etc.) project number H-1-00473-11 through the Maine Agriculture & Forest Experiment Station.

References

Baker BP and Mohler CL (2014) Weed management by upstate New York organic farmers: strategies, techniques and research priorities. *Renewable Agriculture and Food Systems* **30**, 1–10.

Bernard HR (2011) *Research Methods in Anthropology—Qualitative and Quantitative Approaches*, 5th edn., Oxford, UK: AltaMira Press.

Bowman G (2002) *Steel in the Field: A Farmer's Guide to Weed Management Tools*. Beltsville, MD: Sustainable Agriculture Network.

Brown B and Gallandt E (2017) A systems comparison of contrasting organic weed management strategies. *Weed Science* 1–12. doi: 10.1017/wsc.2017.34.

Cirujeda A and Taberner A (2004) Defining optimal conditions for weed harrowing in winter cereals on *Papaver rhoeas* L. and other dicotyledonous weeds. In 6th EWRS Workshop on Physical and Cultural Weed Control. Lilliehammer, Norway.

DeDecker JJ, Masiunas JB, Davis AS and Flint CG (2014) Weed management practice selection among Midwest U.S. organic growers. *Weed Science* **62**, 520–531.

Evans GJ, Bellinder RR and Hahn RR (2012) An evaluation of two novel cultivation tools. *Weed Technology* **26**, 316–325.

Gallandt ER (2014) Weed management in organic farming. In Chauhan BS and Mahajan G (eds). *Recent Advances in Weed Management*. New York: Springer, pp. 63–85.

Gallandt ER, Liebman M, Corson S, Porter GA and Ullrich SD (1998) Effects of pest and soil management systems on weed dynamics in potato. *Weed Science* **46**, 238–248.

Grubinger V (2005) Managing nitrogen on organic farms. The University of Vermont Extension. Available at https://www.uvm.edu/vtvegandberry/factsheets/managingNorganic.html (Verified 3 October 2016).

Holm RE (1972) Volatile metabolites controlling weed germination in soil. *Plant Physiology* **50**, 293–297.

Jabbour R, Gallandt ER, Zwickle S, Wilson RS and Doohan D (2014*a*) Organic farmer knowledge and perceptions are associated with on-farm weed seedbank densities in northern New England. *Weed Science* **62**, 338–349.

Jabbour R, Zwickle S, Gallandt ER, McPhee KE, Wilson RS and Doohan D (2014*b*) Mental models of organic weed management: comparison of New England US farmer and expert models. *Renewable Agriculture and Food Systems* **29**, 319–333.

Kaya C, Higgs D and Kirnak H (2005) Influence of polyethylene mulch, irrigation regime, and potassium rates on field cucumber yield and related traits. *Journal of Plant Nutrition* **28**, 1739–1753.

Knezevic SZ, Evans SP, Blankenship EE, Van Acker RC and Lindquist JL (2002) Critical period for weed control: the concept and data analysis. *Weed Science* **50**, 773–786.

Kopittke PM and Menzies NW (2007) A review of the use of the basic cation saturation ratio and the 'ideal' soil. *Soil Science Society of America Journal* **71**, 259–265.

Lament WJ (1993) Plastic mulches for the production of vegetable crops. *HortTechnology* **3**, 35–39.

Marshall EJ, Brown VK, Boatman ND, Lutman PJW, Squire GR and Ward LK (2003) The role of weeds in supporting biological diversity within crop fields. *Weed Research* **43**, 77–89.

Mirsky SB, Gallandt ER, Mortensen DA, Curran WS and Shumway DL (2010) Reducing the germinable weed seedbank with soil disturbance and cover crops. *Weed Research* **50**, 324–352.

Miyanishi K and Cavers PB (1980) The biology of Canadian weeds. 40. *Portulaca oleracea* L. *Canadian Journal of Plant Science* **60**, 953–963.

Mohler CL (1993) A model of the effects of tillage on emergence of weed seedlings. *Ecological Applications* **3**, 53–73.

Nieto HJ, Brondo MA and Gonzales JT (1968) Critical periods of the crop growth cycle for competition from weeds. *PANS (C)* **14**, 159–166.

Nordell A and Nordell E (2009) Weed the soil, not the crop. *Acres USA* **40**, 21–28.

Norris R (1999) Ecological implications of using thresholds for weed management. *Journal of Crop Production* **2**, 31–58.

Petit S, Boursault A, Guilloux ML, Munier-Jolain N and Reboud X (2010) Weeds in agricultural landscapes. A review. *Agronomy for Sustainable Development* **31**, 309–317.

Proctor CA, Gaussoin RE and Reicher ZJ (2011) Vegetative reproduction potential of common purslane (*Portulaca oleracea*). *Weed Technology* **26**, 694–697.

Riemens MM, Groeneveld RMW, Lotz LAP and Kropff MJ (2007) Effects of three management strategies on the seedbank, emergence and the need for hand weeding in an organic arable cropping system. *Weed Research* **47**, 442–451.

Riemens MM, Groaneveld RMW, Kropff M, Lotz LAP, Renes R, Sukkel W and van der Weide RY (2010) Linking farmer weed management behavior with weed pressure: more than just technology. *Weed Science* **58**, 490–496.

Rogers EM (1988) *Social Change in Rural Societies: An Introduction to Rural Sociology*, 3rd edn., Englewood Cliffs, NJ: Prentice Hall.

Ryan MR, Smith RG, Mirsky SB, Mortensen DA and Seidel R (2010) Management filters and species traits: weed community assembly in long-term organic and conventional systems. *Weed Science* **58**, 265–277.

Saaty TL (1982) *Decision Making for Leaders: The Analytical Hierarchy Process for Decisions in A Complex World*. Belmont, CA: Lifetime Learning Publications.

Slovic P (1987) Perception of risk. *Science* **236**, 280–285.

Stoller EW and Wax LM (1973) Periodicity of germination and emergence of some annual weeds. *Weed Science* **21**, 574–580.

Terpstra R and Kouwenhoven J (1981) Inter-row and intra-row weed control with a hoe-ridger. *Journal of Agricultural Engineering* **26**, 127–134.

Tilman EA, Tilman D, Crawley MJ, Johnston AE (1999) Biological weed control via nutrient competition: potassium limitation of dandelions. *Ecological Applications* **9**, 103–111.

Vavrina CS and Roka FM (2000) Comparison of plastic mulch and bare-ground production economics for short-day onions in a semitropical environment. *HortTechnology* **10**, 326–330.

Wilson RS, Hooker N, Tucker M, LeJeune J and Doohan D (2009) Targeting the farmer decision making process: a pathway to increased adoption of integrated weed management. *Crop Protection* **28**, 756–764.

Zhang TQ, Tan CS and Warner J (2007) Fresh market sweet corn production with clear and wavelength selective soil mulch films. *Canadian Journal of Plant Science* **87**, 559–564.

Zwickle S (2011) *Weeds and organic weed management: investigating farmer decisions with a mental models approach*. M.S. thesis. Ohio State University, Columbus, OH. 171 p.