

Soil Health and Organic Farming

Weed Management: An Ecological Approach



By Mark Schonbeck,
Diana Jerkins, Joanna Ory



**ORGANIC
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SOIL HEALTH AND ORGANIC FARMING

WEED MANAGEMENT: AN ECOLOGICAL APPROACH

**An Analysis of USDA Organic Research and
Extension Initiative (OREI) and Organic
Transitions (ORG) Funded Research from 2002-2016**

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Introduction

Organic farmers recognize healthy, living soils as essential for successful production. Perhaps the greatest soil health challenge relates to weed management, especially in annual crops. Without conventional herbicides, organic producers often use the practices of tillage and cultivation. Tillage and weed cultivation must be managed carefully, as they can disrupt soil life, degrade organic matter and tilth, and accelerate erosion. Organic farmers need sound, science-based information on weed management strategies that will not undermine their efforts to optimize soil health and fertility. Even with a substantial body of research completed to date on the challenge of controlling weeds organically without degrading the soil (Schonbeck, Jerkins, and Ory 2016), 67% of organic farmers still cite weeds as a high research priority (Jerkins and Ory, 2016).

The Natural Resources Conservation Service (NRCS) Soil Health Initiative (USDA-NRCS, n.d.) identifies four keys to soil health:

- Keep the soil covered.
- Maximize living roots in the soil profile.
- Minimize soil disturbance.
- Energize the system with biodiversity.

Organic systems minimize chemical soil disturbance (by excluding synthetic agrochemicals), yet they rely on physical disturbances for weed control. Organic reduced-till systems in which cash crops are no-till planted into residues of high-biomass cover crops exemplify all four NRCS keys to soil health, but do not consistently control weeds or sustain satisfactory yields.



Figure 1. Tillage, Dave Sandy, Penn State; Herbicide application, Jack Dykinga, USDA

**The challenge is
how to assemble
multiple practices
into an effective,
soil-friendly
integrated weed
management (IWM)
strategy.**

Several other practices widely used by organic producers can build soil health while reducing weeds: crop rotation, cover cropping, organic mulch, and best nutrient management. Research funded through USDA's Organic Research and Extension Initiative (OREI) and Organic Transitions Program (ORG) has helped producers refine these practices. In addition, research has supported advances in mechanical and thermal tactics that offer more weed control with less harm to the soil. The challenge is how to assemble multiple practices into an effective, soil-friendly integrated weed management (IWM) strategy. Collectively, today's organic farmers possess a treasure-trove of organic weed management knowledge, tools, and experience, yet many producers do not realize the full potential of organic IWM (Baker and Dyck, 2012). While more research is warranted, organic and transitioning farmers can benefit from better access to existing IWM information and tools, stronger farmer-farmer and farmer-scientist networks, and technical support in developing effective IWM strategies for their farms.

Challenges in Organic Co-Management of Weeds and Soil Health

Organic farmers devote substantial labor and financial resources to weed management, yet organic fields generally have higher weed pressure than conventional fields (Hooks et al., 2016). The challenges are especially acute in annual crop rotations, in which tilled, nutrient-enriched soils offer the ideal niche for many agricultural weeds. Although the National Organic Program has approved several vinegar- and essential-oil-based contact herbicides, these products have not proven cost-effective at a farm scale (Baker and Dyck, 2012). Organic producers have a wide range of tillage and cultivation tools designed for various crop and weed species, growth habits, and developmental stages. How-

ever, each cultivation degrades soil organic matter to some degree, and farmers often find themselves depleting the soil to save the crop.

Efforts to rebuild and maintain soil health and limit weed emergence through reduced tillage and increased use of cover crops have had mixed results. Organic no-till systems based on high biomass cover crops terminated by roll-crimping or mowing, can build soil and reduce annual weeds, yet often result in reduced crop yields and increasing populations of hard-to-manage perennial weeds like Canada thistle, bindweeds, and quack grass. The soil health/crop yield tradeoff can be particularly severe in colder regions with short growing seasons (Barbercheck et al., 2008; Caldwell et al., 2012; Delate, 2013; Shapiro, 2013; Silva, 2015) or semiarid regions where moisture constraints limit the use of cover crops (Menalled et al., 2016). The long growing seasons of the Southern region can facilitate cover cropping, reduced tillage, and diverse rotation; however, weed pressure is more intense and hotter climates accelerate the loss of soil organic matter. Thus, excellent soil, cover crop, and weed management are essential for successful organic reduced-till production (Chase et al., 2010; Morse et al., 2007).

Strategic rotations of cash, cover, and sod crops, varying dates and methods of tillage, planting, and other field operations, and other innovative strategies can reduce many weed problems and improve soil health. However, longer rotations, sod crops, and cover crops can mean foregone income, especially for small-acreage, high-value specialty crop operations.

Finally, organic co-management of weeds and soil health is inherently knowledge-intensive and site-specific, and the target is constantly moving. Different weeds have different ecological niches, and any change in strategy can cause some weeds to diminish and others to



Figure 2. Canada thistles, USDA



Crop rotation is probably the most important integrated weed management tool and should be the cornerstone of any weed management plan.”
(Hooks et al., 2016)



Short duration rotations with only corn and soybean production are detrimental to soil health ... inclusion of a perennial like alfalfa in organic crop rotations is critical for weed control and soil maintenance.”
(Sheaffer et al., 2007)



Anytime producers do the same thing year after year the Earth’s ecosystem finds a way around it to make it more diverse.”
(Beck, 2016)

increase. Organic farmers need to understand and apply this “niche concept” to respond effectively to the ever-evolving soil-crop-weed dynamics on their particular farms (Phelan et al., 2008).

Best Management Practices and Information Resources for Co-Management of Weeds and Soil Health in Organic Production

There are no formulas or recipes for soil-friendly organic weed management. A crop rotation, cultivation tool, or integrated strategy that works wonders for one producer may require modification or fail entirely at another farm with a different soil, climate, weed flora, land base, and production system. Select the best suite of practices for your farm based on your:

- Top five or ten weed species. Get to know their life cycles, when they emerge and flower, ecological niche and nutrient responses, and weak points that can be exploited.
- Soil type, texture and condition; topography; climate and rainfall regime.
- Land base, scale of operation, enterprise mix, equipment, labor, and other resources.
- Crop rotation opportunities and constraints based on production goals and market needs.

For more information, please see Table 1 (Pg. 13): Resources on ecological weed management: 1 2, 7, and 15. For weed profiles see 1, 2, 14, and 15.

Rotate Crops and Field Operations to Keep the Weeds Guessing and Build Soil Health

The USDA National Organic Standards require a good crop rotation to support soil health and biodiversity and manage nutrients, weeds, and other pests. In addition to alternating crops from different plant families, design the cropping system to minimize open niches that weeds can exploit, and avoid offering the same seasonal niches year after year. Some rotation strategies that support co-management of weeds and soil health include:

- Incorporate in the rotation three or more crops with contrasting and complementary growth habits, rooting patterns, nutrient needs, and cultural requirements.
- Add crops that will compete effectively against the most troublesome weeds present.
- Vary dates of planting, harvest, and other field operations.
- Vary depth, intensity, and method of tillage and cultivation; till only when necessary.
- Minimize bare soil periods in the rotation.
- Integrate a perennial sod or forage crop (1-3 years or longer) into the rotation.
- Harvest/mow forages several times a year to deplete perennial weeds like Canada thistle.
- Interseed, overseed or frost-seed clovers, grasses, and/or annual cover crops into standing cereal grains or other production crops when practical.

Where the land base is sufficient, rotating cropland into perennial sod for two or more years is an excellent and proven strategy to enhance soil health, reduce weed pressure, deplete annual weed seed banks,

Farmer Innovation in Crop Rotation for Weed Management

Grain farmers in Ohio have encountered severe problems with giant ragweed in the soybean phase of a diverse four-year rotation of corn-soybean-cereal grain-hay. An Ohio State University research team conducted replicated trials to evaluate an innovation by one of the project's farmer participants, Ed Snavelly (Stinner and Phelan, 2008). Adding a fifth year to the rotation after corn and before soybean, consisting of early season cultivated fallow and midsummer planting of buckwheat (for grain or green manure) substantially reduced ragweed in soybean (Ed Snavelly, March 2016, personal communication). He subsequently added livestock enterprises and extended the rotation to seven years with emphasis on feed grains and forages for on-farm use, and realized a further reduction in weed pressure.



Cover crops ... serve as integral components of organic farming systems"
(Treadwell, 2009)



Cover crops slow erosion, improve soil, smother weeds ... you'll reap dividends on your cover crop investments for years, because their benefits accumulate over the long term."
(Clark, 2007)

and improve yields. On-farm livestock enterprises or nearby markets for forages can make the sod phase pay more directly. Small-scale operations such as peri-urban farms or high tunnels require a different approach, which can include intensive tactics, such as multi-cropping, intercropping, weed mat, hoeing, manual weeding, and NOP-allowed herbicides.

For more information, please see Table 1 (Pg. 13): Resources on crop rotation for weed management: 1, 2, 5, 6, 7, 12, 13, and 17.

Use Cover Crops Effectively

Cover crops in the rotation can displace weeds that would otherwise dominate fallow periods, disrupt weed life cycles, deter weed emergence, and encourage weed seed consumers. They also reduce erosion and compaction, add organic matter, support soil life, fix nitrogen (N), scavenge nutrients, and support beneficial insects. Organic farmers often use cover crops to perform two or more of these functions. When planting cover crops for weed management:

- Select cover crop species with rapid early growth and canopy closure.
- In multi-functional mixes, include one or two species with these properties.
- Use the right cover crops for the season and use optimum planting dates.
- Provide adequate soil nutrients, pH, and moisture for rapid early establishment.
- For late summer plantings of slower-starting, winter hardy covers, add a fast-growing species (buckwheat, radish, oats) that will cover the ground quickly, then winterkill.

- Combine legumes with cereal grains or other grasses for better weed suppression and N fixation. A low rate of the grass (e.g., 20 – 30 lb/ac cereal grain) can be sufficient.
- Time cover crop planting and termination to interdict (with tillage and/or closed cover crop canopy) peak emergence of the major weeds present.
- To protect soil quality and allow weed seed consumption by ground beetles, leave frost-killed cover crop residues on the soil surface over winter rather than fall-till.
- Sorghum-sudangrass planted in early summer can suppress Canada thistle. Mowing when the grass is 3-4 feet tall and thistle is at pre-bloom stage greatly enhances efficacy.

For more information, please see Table 1 (Pg. 13): Resources on cover crops for weed management: 1, 2, 3, 4, 6, 8, 9, 11, and 17, and the report, Cover Crops: Selection and Management.

Manage Nutrients to Feed the Crop, not the Weeds!

Vegetables, corn, and some other field crops are heavy feeders and need sufficient nutrients to thrive. However, surplus levels of soluble soil nitrogen (N), phosphorus (P), and potassium (K) can intensify emergence, growth, and aggressiveness of annual weeds such as pigweed, ragweed, lambsquarters, and foxtails. To keep crops ahead of weeds in nutrient utilization:

- Optimize soil food web function (soil health) to provide a slow, steady release of nutrients that favors crops over “nutrient responder” weeds.
- Obtain a soil test to determine actual nutrient needs of your crops on your soil.
- Obtain a nutrient analysis of any compost or manure inputs to be used.
- Do not over-apply N, P, or K – even as compost.
- Use poultry litter products in moderation, and only if warranted by soil test.
- If supplemental nutrients are needed, apply in the crop row (e.g., in-row drip fertigation).
- Maintain low available soil N for soybean and other strong N fixers.

For more information, please see Table 1 (Pg. 13): Resources on nutrient management to favor crops over weeds: 1, 2, and 7 and the report, Nutrient Management: Crops, Soil, and the Environment.

Draw Down the Weed Seed Bank

Keeping the number of weed propagules (seeds, rhizomes, tubers) in the soil at a low level is essential to successful weed management without herbicides or excessive tillage, yet many organic fields have very large weed seed banks that frustrate efforts at soil-friendly weed control. Several key practices include:

- Avoid importing or spreading weeds. Compost manure and other residues before spreading, use weed-free organic mulch, and weed-free crop seeds.
- Till, mow, or pull weed escapes before they bloom to prevent adding to the weed seed bank.
- Use stale seedbed or false seedbed technique to deplete the weed seed bank.
- Rotate to perennial sod for 2-3 years to deplete the weed seed bank.
- Provide plant cover or residues for ground beetles and other weed seed consumers.

For more information, please see Table 1 (Pg. 13): Resources on weed seed bank management: 1, 8, 10, 13, 14, and 22.

Till and Cultivate Strategically

When cultivation is necessary to deal with weeds, select tools, working depths, and timings to obtain the most weed control and least harm to the soil. Several key practices include:

- Select the right tool for the crop, weeds, soil conditions, and management system.
- Use high-residue cultivators to control weeds without completely burying residues.
- Use blind cultivation (rotary hoe, tine weeder) when weeds are in “white thread” and crops are un-emerged or at a growth stage least prone to damage.
- Use timely, shallow cultivation when weeds are small.
- If creeping perennial weeds are disked, plowed, or otherwise broken up by tillage, till again when re-growing fragments have 3 leaves, then plant aggressive cover crops.
- If a heavy “weed seed rain” occurs, turn-plowing can bury seeds below emergence depth. Do not plow again for several years to avoid bringing still-viable seeds to the surface. This tactic is not recommended for larger or long-lived weed seeds.

For more information, please see Table 1 (Pg. 13): Resources on effective cultivation, tools, and tactics: 2, 6, 8, 10, 12, 13, and 15.

Use Complementary Tactics to Enhance Efficacy of Weed-Soil Co-Management

Crop rotation, cover crops, organic mulches (rolled cover crop or applied materials), and careful nutrient management will support soil health and can reduce but not eliminate weeds. The following complementary tactics can enhance efficacy and reduce the need for cultivation:

- Flame weeding [1 and 15 (video clips) in Table 1].
- Timely mowing between crop rows or in field borders.
- Livestock grazing and crop-livestock integration (1 in Table 1).
- Weed mat/cover for two weeks after roll-crimping to stop weeds or cover crop regrowth in no-till vegetables - practical for small scale operations (9 in Table 1).
- Mechanical weed pullers, directed hot-water spray (safer than flame in mulched crops), and air-propelled abrasive grits applicators are in research and development.



Figure 3. Flame weeding, ATTRA Sustainable Agriculture

Select Crop Cultivars and Management Practices for Weed Tolerance

Crop varieties differ in their ability to thrive and yield in the presence of weeds, and to outcompete or suppress weeds. Weed competitive crops can also build soil health by adding more above-ground and below-ground biomass. Choose cultivars that:

- Adapt to your region, climate, microclimate, and soil.
- Emerge and establish rapidly, and cover the ground quickly.
- Emerge and establish well in non-optimum conditions (e.g., cool, wet soil).
- Grow tall and/or form a dense vegetative canopy.
- Utilize nutrients efficiently and can thrive and yield on slow-release organic N sources.

Optimize the performance of all cultivars by using fresh, high-vigor seed and optimizing planting date, nutrients, moisture, and cultural practices. Many vegetable crops can be transplanted, giving them a head start on weeds.

For more information, please see Table 1 (Pg. 13): Resources on weed-tolerant crop varieties: 6 and 7, and the report, Plant Genetics: Plant Breeding and Variety Selection.

Take Practical Steps Toward Reducing Tillage

Continuous no-till is generally not practical for farm-scale organic production of annual crops. However, soil health improvement does not require an entirely no-till system, and a good crop rotation with judicious tillage can build soil organic matter. No-till seeding or transplanting into roll-crimped or mowed cover crop in a rotational no-till system can be successful when weed populations are low and growing seasons are long and warm enough to accommodate a high biomass cover crop prior to the production crop. Other reduced-till options include:

- Strip tillage (narrow strip worked up for each crop row; alleys untilled).
- Ridge tillage (residues cleared from ridge tops just before crop planting).



Figure 4. Strip tillage, USDA

- Shallow mulch tillage (disrupts weeds but leaves some residue on the surface).
- High-residue cultivators (after conservation primary tillage that leaves residues).
- Spading machines (manages cover crops and weeds without pulverizing soil).
- Chisel plow (does not invert soil profile) in lieu of moldboard plowing.
- Overseeding cover crops into standing cash crops (eliminates post-harvest tillage).
- Late summer or fall cover crops that winterkill (less tillage required for spring planting than live covers or winter weed growth).

For more information, please see Table 1 (Pg. 13): Resources on weed management in organic reduced-till systems: 6, 9, and 1, and the report, Practical Conservation Tillage.

Manage Weeds and Soil Health During Establishment of Perennial Fruit Crops

Clean cultivation in perennial fruit crops eliminates weed competition and facilitates nutrient and organic amendment applications, but compromises soil and likely crop health. Producers and researchers have developed several soil-friendly alternatives, including wood chip or other organic mulches, living mulches, grass or grass-legume sod alley with “mow-and-blow” to mulch and feed the crop, weed mat (woven synthetic landscape fabric), and various combinations of these practices. Effective weed management in and near crop rows is especially important during the establishment years. Some tips for co-manage-

Farmer Innovation Simplified Soil and Weed Management in Berry Crops

Oregon State University research on organic blueberry and blackberry production systems found weed mat most effective for controlling weeds and promoting crop establishment, but the mat limited options for subsequent applications of compost and other organic materials to feed the soil. One farmer participant suggested a simple innovation: lay the weed mat as two strips on either side of the crop row, overlapping in the center (Schonbeck et al., 2016). This “zipper” arrangement allows the grower to pull the mat back to apply compost, nutrients, and/or organic mulch and then replace it to maintain weed control. Project co-PI Dr. Dave Bryla noted that many organic and conventional berry farmers in the Pacific Northwest have adopted this “win-win” solution for feeding the soil and the crop while maintaining good weed control (Schonbeck et al., 2016).

ment of soil health, weeds, and fruit crop nutrition during this critical period include:

- Lay weed mat for best weed control, in a “zipper” arrangement to facilitate amendment applications (see Sidebar).
- Organic mulch such as wood chips or straw enhance soil organic matter and soil health; plan on some hand weeding or mowing, and replenish mulch periodically.
- In blueberry production, pine bark or pine straw can help maintain required soil acidity.
- Plant alleys in mowed sod, including legumes for N, grasses for organic matter and weed suppression, and flowers for beneficial insects. Mow sod and blow it into crop rows.
- Ensure that organic inputs deliver sufficient but not excess nutrients to the crop.

For more information, please see Table 1 (Pg. 13): Resources on weed-soil co-management in perennial fruit: 18, 19, 20, and 21.

TABLE 1. INFORMATION RESOURCES AND TOOLS FOR ORGANIC WEED MANAGEMENT

1. **Integrated Weed Management: Fine-tuning the System**, (Michigan State University Extension, 2008, 131 pp). Excellent manual with examples from working farms; crop rotation, cover crops, grazing, flame weeding, and manure/compost management. Order hard copy at: <http://www.msuweeds.com/publications/extension-publications/iwm-fine-tuning-the-system-e-3065/>.
2. **Risk Management Guide for Organic Producers**, 300 pp (K. Moncada and C. Sheaffer, 2010) Chapters on soil health, crop rotation, weed ecology, weed management, and individual weed species profiles. Available at <http://organicriskmanagement.umn.edu/>
3. **Cover Cropping to Suppress Weeds in Northeast US Farming Systems**, (B. Curran & M. Ryan, 2012). Webinar. <http://articles.extension.org/pages/30856/cover-cropping-to-suppress-weeds-in-northeast-us-farming-systems-webinar>.
4. **Using Cover Crop Mixtures to Achieve Multiple Goals on the Farm**, (Mary Barbercheck et al., Penn State, 2014). Webinar, integrating weed management with other cover crop goals. <http://articles.extension.org/pages/71186/using-cover-crop-mixtures-to-achieve-multiple-goals-on-the-farm-webinar>. Also Finding the Right Mix: Multifunctional Cover Crop Cocktails for Organic Systems <http://agsci.psu.edu/organic/research-and-extension/cover-crop-cocktails>
5. **Weed Management, Environmental Quality, and Profitability In Organic Feed and Forage Production Systems**, (Penn State). <http://agsci.psu.edu/organic/research-and-extension/organic-forage>.
6. **Organic Weed Management in Organic Grain Cropping Systems**, (Reberg-Horton, C., North Carolina State U, 2012), listed in: Carolina Organic Commodities and Livestock Conference 2012: Selected Live Broadcasts. Cultivation, rotation, variety selection, cash and cover crop management, reduced till <http://articles.extension.org/pages/61970/carolina-organic-commodities-and-livestock-conference-2012-selected-live-broadcasts>.

7. **Managing weeds in vegetables organically**, (Hooks, C., A. Leslie, and G. Chen, 2016)* Rotation, nutrient and water management, crop variety, transplanting, crop management. [https://extension.umd.edu/sites/default/files/_images/programs/mdvegetables/OrganicWeedMgntVeg21May2016\(1\).pdf](https://extension.umd.edu/sites/default/files/_images/programs/mdvegetables/OrganicWeedMgntVeg21May2016(1).pdf).
8. **Managing the Weed Seedbank with Cover Crops and Tillage**, (Buchanan, A., G. Chen, and C. Hooks, 2014)*. <https://extension.umd.edu/learn/managing-weed-seedbank-cover-crops-and-tillage>.
9. **Organic Weed Control in No-Till Systems**, (Brust, G., 2014)* https://extension.umd.edu/sites/default/files/_docs/articles/OrganicWeedControlUsingNo-till_3-2014_0.pdf. Laying weed mat (landscape fabric) on roll-crimped cover crop for two weeks suppressed weeds and cover crop regrowth for eight weeks after removal.
10. **The Stale Seedbed Technique: A Relatively Underused Alternative Weed Management Tactic for Vegetable Production**, (Hooks, C., A. Buchanan, and G. Chen, 2014)* <https://extension.umd.edu/learn/stale-seedbed-technique-relatively-underused-alternative-weed-management-tactic-vegetable>.
11. **Offing Cover Crops for Weed Suppression: Featuring the Roller Crimper and Other Mechanical Contraptions**, (University of Maryland, 2014)* <https://extension.umd.edu/learn/offing-cover-crops-weed-suppression-featuring-roller-crimper-and-other-mechanical-contraptions>.
12. **Northern New England Local Bread Wheat Project**, Several videos and articles on weed management in organic cereals. <https://extension.umaine.edu/localwheat/>.
13. **Cultivation and Seedbank Management for Improved Weed Control Webinar**, (Gallandt, E., 2012, U Maine). Grains and vegetables, comparison of weed seed banks in different rotations. <http://articles.extension.org/pages/62445/cultivation-and-seedbank-management-for-improved-weed-control-webinar>.
14. **Manipulating Weed Seed Banks to Promote their Decline**. (Brainard, D., C. Mohler, and M. Schonbeck. 2013). Stale seedbed, germination responses of 19 weed species. <http://articles.extension.org/pages/18528/manipulating-weed-seed-banks-to-promote-their-decline>.

15. **eXtension Organic Agriculture, Weed Management**, Articles on ecological weed management, a few weed profiles, and videos on cultivation tools and farmer innovations. <http://articles.extension.org/pages/61887/weed-management-topics>
16. **Crop Rotation on Organic Farms – a Planning Manual**, (Mohler, C. L. and S. E. Johnson, editors, 2009. Cornell University Natural Resource, Agriculture, and Engineering Services, 156 pp). Available at www.sare.org.
17. **Managing Cover Crops Profitably, 3rd Edition**, (Clark, A., editor, 2007, Sustainable Agriculture Network, 244 pp). Available at www.sare.org.
18. **Organic Blueberry Production Webinar**, (Stik, B., H. Larco, and D. Bryla. 2012). <http://articles.extension.org/pages/26115/organic-blueberry-production-webinar>.
19. **Organic Blackberry Production: Tips Learned from an Ongoing Research Study**, (Strik, B., D. Bryla, and L. Valenzuela, 2014). <http://articles.extension.org/pages/70279/organic-blackberry-production:-tips-learned-from-an-ongoing-research-study>.
20. **Alternative Orchard Floor Management Strategies**, (Rowley, M., B. Black, and G. Cardon, 2012) Utah State University Extension bulletin Horticulture/Fruit/2012-01pr (4 pp). <https://extension.usu.edu/productionhort/htm/organic/organic-stone-fruit-production>.
21. **Organic Fruit Production**, page on eXtension, including orchard floor and weed management. <http://articles.extension.org/pages/59501/organic-fruit-production-systems>.
22. **Composting to Reduce Weed Seeds and Pathogens**, (Zaborski, E., 2015) <http://articles.extension.org/pages/28585/composting-to-reduce-weed-seeds-and-plant-pathogens>.

* Access via <https://extension.umd.edu/mdvegetables/organic-vegetable-production>.

Current Science on Soil Friendly Organic Weed Management, An Analysis of USDA OREI and ORG Funded Research from 2002-2016

Many of the research findings related to organic weed management strategies and tactics vary from project to project, depending on region, climate, soil, farming system, and experimental methodology. However, several common themes emerged, as well as some robust and relevant findings that relate to a particular region or farming system.

Crop Rotation

Farmers and researchers have documented significant soil health and weed management benefits from integrating two or three years of perennial sod or forage crops into annual field crop or vegetable rotations. (Sheaffer et al., 2007, Reberg-Horton, 2012, Michigan State University Extension, 2008, Moncada and Sheaffer, 2010, Pennsylvania State University, undated). Annual weed seed banks decline because weed reproduction is prevented and seed predators increase in undisturbed sod, while mowing the perennial sod helps deplete perennial weed reserves. Measures of soil health, such as soil organic C and N, increase and subsequent cash crop yields often improve. In a vegetable cropping system in Washington State, a two-year pasture break reduced weed seed banks, though soil health parameters did not respond as much as they did to the addition of compost (Cogger et al., 2013).

Comparisons of alternative management strategies during the three-year transition period to organic production have shown lower weed populations, better soil quality, and higher yields after grass-legume sod than after cultivated crops or tilled fallow during transition (Hulting et al., 2008). In Ohio, a “native prairie mix” during the three-year transition suppressed weeds better than tilled fallow, vegetable rotation, or annual smother crops (Cardina et al., 2011). An Illinois study compared an intensive vegetable rotation (with frequent tillage and cultivation, mulching and manual weeding), a lower-intensity field crop rotation, and undisturbed grass-legume perennial ley during the transition (Eastman et al., 2008). With cover crops in the annual rotations, all three systems improved soil quality, but the perennial sod treatment had the lowest weed populations at the end of the transition, and highest tomato, pepper, and edamame soybean yields in the following two years (Rosa and Masiunas, 2008, Eastman et al., 2008). In small-scale intensive vegetable cropping systems, where a perennial sod break may not be economically practical, adding a cereal grain or cover crop

to the vegetable rotation can reduce weed pressure and improve the soil quality (Hooks et al., 2016).

During transition to organic dryland grains in the Palouse region of Washington State, forage- and green manure-intensive rotations reduced wild oats and other weeds compared to other systems. Field pea as a winter green manure suppressed weeds and fixed N, while spring plantings of the same crop failed because weeds gained the upper hand (Gallagher et al., 2006).

Frost-seeding of clovers into standing winter cereals in the late winter or early spring has worked well in many locations across the eastern and central United States (Michigan State University Extension, 2008). In addition to allowing establishment of a legume after a grain planting without tillage, clover planting has improved soil quality, contributed N to the following crop, and occupied a niche that would otherwise be invaded by weeds soon after grain harvest. One exception appears to be in the coldest parts of the North Central region, such as Minnesota, where spring weather is warm enough to promote clover germination and is often followed by freezes to 0° Fahrenheit or colder, which kills the clover seedlings (K. Moncada, University of Minnesota, personal communication, 2016).

Nutrients, Manure, and Compost

Long-term cropping system trials at Rodale Institute in central Pennsylvania have shown higher corn yields and less weed pressure in organic systems than in conventional systems with high inputs (Ryan et al., 2008). A major factor in this outcome appears to be the slower release of nutrients in the organic system that favor the crop over weeds. However, other studies have shown that many agricultural weeds

A Special Case: Small Scale with Intensive Weed Management

In a study of organic transition strategies in a peri-urban agricultural setting in Ohio, Kleinhenz et al., (2008) reported a 50% reduction in weed seed banks after three year transitions with frequent tillage (multi-crop vegetables with winter cover, or cultivated summer fallow and winter cover) compared to perennial grass-legume sod. Annual applications of dairy manure compost at 7.5 t/ac substantially enhanced soil organic matter and N availability (Briar et al., 2011), without increasing weed pressure (Kleinhenz et al., 2008). While the frequently-tilled treatments stimulated weed emergence, the small scale of the trial (2,000 square feet plots) allowed diligent removal of weeds before seed set, and thus a drawdown of the weed seed bank.

respond to readily available soil N and sometimes P or K, *including nutrients from organic sources*. For example, in field trials in Ohio, poultry dung deposited from moveable chicken tractors stimulated the growth of “weed grasses at the expense of clovers” in alleys between production beds (Lilburn et al., 2015).



Figure 5. Chicken tractor, USDA

300 lb/ac (Cornell U, 2015; Mohler et al., 2008). Corn planted after red clover plowdown did not respond to compost, indicating that the legume alone met corn N needs (Caldwell et al., 2012). In another study, lambsquarters and Powell amaranth showed greatly increasing growth rates at 730-5800 lb/ac poultry litter compost (N-P₂O₅-K₂O ~ 5-4-3); while foxtail, velvetleaf, and lettuce showed moderate increases, and neither lacinato kale nor field corn responded at all (Little et al., 2012). Equivalent rates of N (blood meal) or K (potassium sulfate) applied singly did not elicit the same responses. *Thus, more compost may grow more weeds rather than increasing crop yield*, especially when high-analysis poultry litter compost is used. Researchers in Beltsville, MD are currently conducting trials to determine whether reduced rates of poultry litter can maintain or improve organic grain yields in both weedy and weed-free conditions in the mid-Atlantic region (Cavigelli, 2015).

In long term organic grain and vegetable cropping systems studies at Cornell University (NY), the “high input” system (poultry litter compost at rates commonly used by organic farmers in the region), had higher weed populations than lower-input systems (Mohler et al., 2009). Growth of common ragweed, Powell amaranth, lambsquarters, and foxtails increased with poultry compost rates up to 6 tons/ac (2X recommended), while corn yields plateaued at 1.5 tons and soybean yield at just

Legume green manures can also promote weed growth through N enrichment. Planting red clover before dry beans increased soil nitrate-N and weed numbers and biomass compared to planting rye or winterkilled radish before dry beans (Heilig and Hill, 2014; Hill, 2015). Clover also accelerated mortality in lambsquarters seed experimentally buried in the topsoil. The team recommended planting red clover before a heavy N user like field corn.

Greenhouse and field experiments showed that adding high C:N ratio organic amendments (sugar, sawdust, or straw) to reduce soluble soil N availability can suppress weeds and enhance soybean yield (Stinner and Phelan, 2008). Organic soybeans have been successfully grown no-till in rolled winter rye in Illinois (University of Maryland, 2014) and Missouri (Clark, 2016). Soybeans drilled into a roll-crimped, rye planted at a rate of four tons per acre have given yields commensurate with full tillage and cultivation in North Carolina (Reberg-Horton, 2012). Soybeans and other strong N-fixers can thrive in soils with low soluble N. This presents an opportunity to exploit crop-weed niche separation through nutrient management. Other nutrient-based niche differentiations are currently under investigation (Phelan et al., 2008).

Selecting and Managing Cover Crops for Weed Control in Different Regions

Successful weed suppression by cover crops depends on many factors, including the cover crop species or mix, planting and termination dates, seeding rates and proportions of components in a mix, and soil condition; in addition, region and climate exert an overarching influence on outcomes with different cover crops, planting dates and rates. In Pennsylvania, timely planting and sufficient soil fertility influenced the ability of a rye cover crop to prevent weeds, and delaying spring termination of the cover crop (with or without tillage) until after the main flush of lambsquarters, velvetleaf, and foxtail emergence reduced these weeds in the subsequent crop (Curran and Ryan, 2012). Fall legumes (red clover, field pea) alone allowed considerable weed growth, but including just 28 lb/ac rye in the mix suppressed weeds as effectively as rye alone at 140 lb/ac (Barbercheck et al., 2014). Based on multiple trials, the team recommends that, for weed suppression, fall planted mixes should contain at least one species that will provide fast ground cover in the fall, even if that species eventually winterkills (e.g. radish, oat). Other researchers have found that radish cover crops planted at least six weeks before fall frost form a dense canopy that suppresses winter weeds completely through the following March or April (Gruver et al., 2016).

In upstate New York, comparative weed-suppressiveness of cover crops planted in July were buckwheat > sorghum-sudangrass > Japanese millet > flax, while crimson clover was the most suppressive of several annual legumes (Drinkwater and Buckley, 2010). Cover crop mixtures did not always enhance weed suppression. Buckwheat mixtures were more effective than other mixes, but buckwheat also suppressed the legume component and reduced N fixation.

Surprisingly, in multiple site trials over two seasons, mixing several cultivars of a single cover crop species consistently improved weed suppression over a single cultivar of the same crop (Drinkwater and Walter, 2014). This trend held for all six cover crops tested of hairy vetch, winter pea, rye, wheat, and ryegrass (Bjorkman et al., 2014) determined optimum planting windows for late-summer cover crops in the Great Lakes region (MI, IL, NY). Buckwheat and sudangrass must be sown by early August, and mustard by late August, to obtain sufficient biomass to benefit soil health and suppress weeds; a delay of 7 to 10 days can cut biomass by half. In the same region, grasses (Japanese millet, sorghum-sudangrass) or grass-legume mixtures suppressed weed growth and seed production much more effectively than legumes (cowpea, soybean) alone (Brainard et al., undated). In Ohio, sorghum-sudangrass and tef cover crops provided greater weed control in two- or three-species mixes including soybean or sunflower than as single species covers (Cardina et al., 2011).

In Florida and the Virgin Islands, cover crops competed well with weeds, but did not reduce weeds in subsequent cash crops, and the weed seed banks remained unchanged (Chase et al., 2010). The team recommended no-till cover crop termination or supplemental organic or synthetic mulch for weed management. Even with tight, diverse rotations including cover crops, soil fertility and organic matter tended to decline over time, which illustrates the soil health challenges faced by vegetable producers in hot climates. The project team is continuing to explore the soil health and weed management challenges in these regions (Chase et al., 2015).

Managing Cover Crop Residues and Weed Seeds

Leaving weed seeds at the soil surface can promote their destruction caused by weathering and weed seed predators like ground beetles (Reberg-Horton, 2012). Multiple studies demonstrate the importance of undisturbed vegetation or residue to allow ground beetles to complete their life cycle and consume more weed seeds (Gibson et al., 2015). No-till planting of fall cover crops has also been recommended to enhance weed

seed exposure to predation (Gallandt, 2012). Bjorkman et al. (2014) found that leaving frost-killed cover crop residues on the soil surface reduced spring weeds and improved subsequent bean crop yields compared to fall tillage.

Moldboard plowing can bury weed seeds so they cannot emerge, but then the producer must avoid additional deep or inversion tillage until the seeds lose viability, which can take 3-5 years (cocklebur, purslane, pigweed) or much longer (velvetleaf, lambsquarters, Johnsongrass) (Reberg-Horton, 2012).

Canada Thistle

Management of Canada thistle is a top research priority among organic farmers, and several OREI projects have addressed this challenge. Canada thistle is an invasive, creeping perennial weed that spreads by seed and by creeping roots sending up new shoots, and is a major weed in organic grain and organic reduced-till vegetables. Sudangrass and sorghum-sudan hybrids suppress Canada thistle. Summer mowing when Canada thistle is tall but not yet flowering can set it back (root reserves are near their minimum at this time). In Illinois, a sudangrass cover crop was mowed when it was several feet tall and thistle plants had 7-10 leaves. This treatment resulted in a 98% reduction in Canada thistle in a soybean crop the following year, whereas neither buckwheat cover nor mowing alone reduced thistle in the soybean crop (Bicksler and Masiunas, 2008). Sudangrass regrows aggressively after mowing and releases an allelochemical (sorgoleone), thereby compounding the impacts of mowing on the weed. Similarly, sorghum-sudangrass has suppressed Canada thistle in Ohio (Cardina et al., 2011).

In a comparison of four organic grain/forage crop rotations in Pennsylvania, Canada thistle populations remained low in conventionally tilled annual crops or reduced till with a two-year alfalfa phase, but increased several-fold where reduced till was attempted without the sod phase (Pennsylvania State University, n.d.). Similarly, Canada thistle contributed to substantial yield losses in organic minimum-till annual grain rotations in Iowa (Delate, 2013). However, a four-year soy-oat-alfalfa-corn rotation in which the alfalfa was mowed several times effectively reduced Canada thistle in Minnesota (Sheaffer et al., 2007). In the latter study, summer annual covers of pearl millet, buckwheat, or pea suppressed the weed only temporarily.

Together, these findings suggest an integrated strategy for dealing with a Canada thistle infestation: a crop rotation that includes a perennial phase mowed periodically for forage harvest, and an annual phase that includes a sudangrass or sorghum-sudan cover sown in early summer and mowed when the grass is well established and thistles are at the seven leaf to pre-bloom stage.

The Weed Aspect of the Organic Reduced-Tillage Challenge

Many USDA funded projects have tackled the challenges of “organic no-till” systems for soil health and weed control. The higher the cover crop biomass, the better suppression of annual weeds. However, heavy residues can complicate planting and reduce stands and yields because of inadequate seed-soil contact (Reinbott, 2015, Curran et al., 2014). Increased weight on no-till planters and other equipment modifications can help (Curran et al., 2014), and some crops can be planted into standing cover crops before rolling (Clark, 2016, Reinbott, 2015, University of Maryland, 2014). In Wisconsin, roll-crimped cover crops with three to five ton/ac aboveground biomass reduced early season weed biomass 50-80% in vegetable crops, but the mulch complicated manual weeding so that total labor requirement increased (Silva, 2015).

Insufficient cover crop biomass, especially N-rich, low-residue legumes, can enhance weed growth in organic no till (University of Maryland, 2014), and producers are advised to terminate cover crops by tilling when biomass is insufficient (Reinbott, 2015). Appropriate fertilizer applications can enhance cover crop growth and biomass, though poultry litter may also increase weed growth with the cover (University of Maryland, 2014). As noted earlier, a four ton/ac rye cover crop gave good weed control and crop yields in no-till organic soybean (Reberg-Horton, 2012).

Reduced tillage, cover crops, and legume interseeding reduced weed pressure in dryland organic wheat in the interior Pacific Northwest, though perennial weeds remained problematic (Burke et al., 2014). Shallow cultivation with rotary harrow and rotary hoe provided sufficient control of moderate populations of annual weeds and protected soil health by leaving residues on the surface in organic dryland grain production in Washington (Gallagher et al., 2006).

One innovative approach, explored over multiple seasons in the High Plains region of Montana, is to integrate sheep into organic dryland grain, pulse, and oilseed production (Menalled et al., 2016). Efforts to replace all tillage with targeted sheep grazing to manage green manures and weeds led to severe (45-90%)

yield reductions in wheat and dry pea, mostly owing to heavy infestations of field bindweed, Canada thistle, and other aggressive perennial weeds (Menalled et al., 2016). Farmers in this region cite field bindweed as a leading barrier to organic cereal grain production, and the research team is now evaluating a modified strategy that integrates sheep grazing with a 50-60% reduction in tillage frequency over a 5-year crop rotation, a biocontrol agent (bindweed gall mite) and weed-competitive crops prior to winter wheat (Menalled, 2016). The reduced till crop-livestock integrated system first year gave more encouraging results in 2016, with little yield reduction in wheat and a 30% reduction in lentil (Menalled, 2016).

While strict no-till (especially continuous no-till) still appears impractical for organic annual cropping, other forms of reduced tillage show promise. Examples include the ridge tillage system in vegetable production with cover crops and low-inputs and the rotation developed by Anne and Eric Nordell in Pennsylvania. In the Nordell rotation, one year of ridge till vegetable production alternates with a year of high biomass cover crops and a short (six week) period of stale seedbed (cultivated fallow) to draw down weed seed banks (Drinkwater et al., 2009). In Maryland, researchers concluded that “strip-tillage is a very promising and practical tool for organic vegetable production, especially if other weed management tactics such as stale seedbed are combined.” This system improved soil quality and gave satisfactory weed control and good yields, while in Hawaii, green onions grown in a no-till system of rolled sunhemp out-yielded onions in either bare ground or plastic mulch (Chen et al., 2015).

Interseeding grass-legume cover crop mixtures into standing soybean and corn crops is another approach to reducing frequency of tillage and enhancing year-round ground coverage and plant biomass that is being explored at several sites in the Northeast region (Ryan et al., 2015)

Weed Management in Grains

A University of Maine research team focused on organic cereal grain production in northern New England has tried various strategies for weed management. Narrow rows (four inches) and/or increased seeding rates can reduce weed growth, but do not always increase yield or net return. Wide rows (nine inches) with inter-row cultivation in addition to the standard practice of blind cultivation (rotary hoe or tine weeder) also reduced weed growth and more often improved yields (Kolb, 2012; Darby, 2012). Frost seeding clovers into winter grains also suppressed weeds, but vigorous clover growth sometimes reduced yield or interfered with harvest.

Weed/Soil Co-Management During Establishment of Perennial Fruit Crops

In university and on-farm trials in the Pacific Northwest, weed mat (woven landscape fabric) gave the best weed control, crop establishment, and early yields in organic blueberry and blackberry, though it sometimes reduced root volume and increased the need for irrigation (Strik et al., 2011, 2014, 2015). In the southeastern US, weed mat, pine straw, and pine bark all provided good weed suppression during the first two years of rabbiteye blueberry establishment, after which weed growth required manual pulling and/or re-application of organic mulch (Andersen et al., 2010). In this study, plants grew best in the organic (pine) mulches.

In orchard floor management studies in Arkansas (Rom 2012), California (Ingalls, 2012), and Utah (Reeve 2012, Rowley et al., 2012), representing warm-humid, warm-dry, and cold-dry regions, respectively, weed mat and wood chip mulch, alone or with other organic nutrient sources such as compost, have shown the greatest promise for weed control, soil health, and tree growth. In Utah, perennial legume cover in alleys with mow-and-blow provided N to trees and enhanced soil health. However, some treatments delivered excess N or other nutrients, indicating a need to fine-tune the system. Living mulches and cover crops enhance soil quality but can compete against young trees or small fruit for moisture and nutrients at critical seasons. In the Great Lakes, the critical time for sweet cherries is early in the season, and weed mat during spring and early summer followed by late season sorghum-sudangrass cover optimized biomass input to the soil and tree growth in organic high tunnel sweet cherry production (Lang et al., 2014).

Complementary, Soil-Friendly Weed Control Tactics

Because crop rotation, cover crops, nutrient management, and reduced tillage have not fully solved the organic weed management dilemma, researchers are evaluating various non-tillage or minimal soil-disturbing weed control tactics that can be integrated with these practices to enhance soil, weed, and crop yield outcomes. An air-propelled abrasive-grits applicator under development at University of Illinois (Wortman, 2015) can also be used to deliver in-row nutrients (granular organic fertilizer as grits). A University of Missouri team is evaluating between-row mowing, mechanical weed pullers, or directed hot water sprays (safer than flame in the presence of residues) to manage weeds in corn and soybean no-till planted just before roll-crimping winter covers (Clark, 2016). Soybeans planted no-till into a winter rye cover crop showed highest yields and fewest weeds in the mowing treatments.

Many organic vegetable growers find black plastic film mulches to be highly effective, affordable, and labor-efficient for controlling weeds without cultivation. However, many growers are concerned about the use of a fossil fuel based material that must be removed at the end of the season, and are seeking more sustainable alternatives (K. Moncada, U Minnesota, personal communication, 2016). Ongoing research and development of fully biodegradable film mulches is making steady advances, and in 2012 the National Organic Standards Board has recommended that NOP develop rules for their use; but NOP had not yet approved any biodegradable film mulch products as of 2015 (Corbin et al., 2012, 2015).

A biological seed treatment that has promoted corn emergence from cool, wet soil (Goeser et al., 2008) could enhance the crop's weed tolerance.

Potential for Plant Breeding for Weed Tolerance and Competitiveness in Organic Systems

Cultivar evaluations have indicated good genetic potential to breed for increased ability to maintain yield in the presence of weed pressure, and/or compete more vigorously against weeds in corn, soybeans, and dry beans (Seidel, 2008, Orf, et al., 2015, Renner et al., 2015), carrot (Simon et al., 2015, Turner, 2015), rice (Zhou, 2016), and wheat (Jones et al., 2011). Heritable traits include rapid emergence and early growth, canopy spread or density, deep or extensive root systems, and tolerance to cultivation. At least one food grade soybean cultivar with superior canopy and weed suppression has been released (Kate Moncada, personal communication).

Putting it All Together: Decision Support Tools in the Pipeline

As noted earlier, selection of the best strategy or suite of practices for co-management of weeds and soil management in organic crop rotations is highly site-specific and cannot be prescribed by formula or computer models. The objective of this report is to provide practical tools and a synopsis of recent research findings to help each producer to develop the best system for her/his organic, transitioning, or sustainable farming operation. Several ongoing USDA funded projects are developing new tools for organic farmers:

- An Ohio State University team is refining a Decision Support Framework to help producers develop ecological weed management strategies (Wilson, 2015).
- A Cornell University team is developing a weed management strategy decision tool, integrating advanced mechanical weed control tactics (synergistic combinations of several cultivation tools on the tractor toolbar) with cover crop based reduced till systems (Rangarajan et al., 2016).
- The University of Minnesota will soon post a “one-stop-shop” website to support producers making a transition to organic with learning modules and decision case studies (based on actual working farms) on a range of topics including soil health and fertility, weed biology, weed management, and decisions related to crop rotation, cover crops, strategies for Canada thistle control, and other weed management practices (Sheaffer, 2015).

Questions for Further Research in Soil-Friendly Organic Weed Management

Controlling weeds organically while building and maintaining soil quality remain top research priorities for organic farmers. While much has been learned by scientists and farmers alike, continued investment in developing improved options for soil-friendly weed management is essential. Some specific topics for further study include:

- Weed seed mortality related to soil biological activity and soil health; practical guidelines on managing soil life to reduce weed seed banks without hurting crop seed germination.
- Integrated weed/soil health co-management strategies for specific regions that have been under-represented in studies to date (e.g. Southern region) or that pose especially great challenges (e.g., dryland farming in the semiarid interior Western region).
- Continued and expanded efforts to develop cultivars with enhanced weed tolerance, weed competitiveness, and ability to thrive and yield in soil with low soluble nutrient levels.
- Practical, regionally adapted strategies for integrating soil health/weed co-management (crop rotation, cover crops, etc.) with soil-friendly weed-control tactics (flaming, mowing, and newer technologies like weed pullers and abrasive grits applicators).
- Further development of practical, reduced-till strategies and practices for different crops and cropping systems in each major agricultural region.
- Further development of nutrient/weed co-management guidelines, including which weeds can be controlled by specific nutrient management practices.
- More information or guidelines in selecting cover crops and designing mixes for optimum weed suppression and soil health, tailored to each major agricultural region.

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Notes



**ORGANIC
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P.O. Box 440
Santa Cruz, CA 95061
831.426.6606
info@ofrf.org
www.ofrf.org