

Principles of Sustainable Weed Management in Organic Cropping Systems

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An Ecological Understanding of Weeds

Weeds are the most costly category of agricultural pests, causing more yield losses and added labor costs than either insect pests or crop disease. Because organic farming excludes the use of synthetic herbicides, most organic farmers consider effective organic weed control a top research priority. In particular, weeds are a constant fact of life in annual row crops, vegetables, and other horticultural crops. With a little diligence, home gardeners can turn their weeds into beneficial organic matter. However, weed control costs really add up in a one-acre market garden, and a weedy vegetable field at the 10-100 acre scale can spell a crop failure.

Yet, if it weren't for weeds, the world would have lost more topsoil than it has to date, and humankind might have suffered mass starvation by now. Why? Because weeds are pioneer plants that do a vital job: they protect and restore soil that has been left exposed by natural or human-caused disturbance. Watch any recently burned or logged forest area, and you will see precious topsoil washing away in each heavy rain – until the brambles, greenbrier, pokeweed, poison ivy and other brushy weeds cover the ground with their impenetrable tangle. These pioneer plants initiate the process of ecological succession that, if left uninterrupted, will eventually restore the climax forest or other plant community native to the region.

In agriculture and horticulture, humans replace the native climax vegetation with a suite of domesticated plant species chosen for their value as food, forage, fiber, or fuel, or for aesthetic purposes. Annual crop production entails regular soil disturbance or clearing by tillage cultivation and/or herbicides, which elicits a “weed response” from nature. Agricultural fields present different environments from those left by a natural disaster or a forest clear cut, one characterized by repeated soil exposure and relatively high levels of available nitrogen (N), phosphorus (P), potassium (K), and other essential plant nutrients. Agricultural weeds are those pioneer plant species that can emerge rapidly, exploit the readily available nutrients, and complete their life cycle before the next tillage or herbicide application terminates their growth.

Weeds are a normal and natural occurrence in vegetables and other annual cropping systems. Serious weed *problems* develop when a susceptible crop, a large weed seed bank in the soil (including both true seeds and vegetative propagules of perennial weeds), and a favorable environment for weed growth occur together.

Our most troublesome *annual* weeds reproduce through prolific seed production, and their seeds often germinate in response to cues that competing vegetation has been removed. These cues include light (exposure to a brief flash of daylight during tillage is sufficient), increased fluctuations in soil temperature and moisture, improved aeration, or accelerated release of soluble N and other nutrients. These weeds are most prevalent in frequently-tilled fields, but some can also thrive in annual cropping systems managed no-till. Examples include common lambsquarters, pigweeds, galinsoga, common purslane, velvetleaf, morning glories, foxtails, and crabgrass.

Our most troublesome *perennial* weeds are those that can regenerate new plants from small fragments of root, rhizome, stolon or other underground structures. These weeds may or

may not also reproduce by seed. They plague both annual and perennial crops, and tend to increase when tillage is reduced or eliminated. Examples include purple and yellow nutsedges, bermudagrass (wiregrass), quackgrass, johnsongrass, Canada thistle, milkweeds, and field and hedge bindweeds.

Successful organic weed control – managing the land's natural “weed response” to cultivation – begins with an ecological understanding of weeds and their roles in the farm or garden ecosystem. Whereas annual crops and weeds have similar growth requirements – ample NPK, full sun, prepared seedbed, etc. – subtle differences exist that can be exploited to the crop's advantage. For example, the emerging seedling of a small-seeded weed like galinsoga or pigweed requires available nutrients from the soil almost immediately to survive and grow. In contrast, an emerging corn, bean, or rye seedling can draw nutrients from reserves in its large seed for a couple of weeks before it becomes dependent on soil nutrients. Furthermore, some weeds, such as lambsquarters, common ragweed, and foxtails, respond dramatically to high levels of soluble N, and their growth rate continues to increase with fertilizer application rates well beyond the point at which corn – one of the heaviest-feeding crops – levels off. Thus, farmers can avoid overstimulating weeds by using slow-release sources of N and other nutrients, applied at rates sufficient to meet crop needs but no more.

Weeds – a Working Definition

The term “weed” has been defined as a “plant out of place,” an “unwanted plant,” or a plant that is a pest in that it interferes with crop or livestock production. The word is typically applied to any plant species that often becomes a pest, such as common chickweed, pigweeds or crabgrass. However, weed manuals also list plants such as clovers, fescue, hairy vetch, and Jerusalem artichoke – valued as forage, cover, or food crops when grown in the right context – as potential weeds. Indeed, “volunteer crops” such as buckwheat, rye, Japanese millet, corn, or soybean can become weeds when they self-seed and emerge in another part of the crop rotation when they are no longer wanted.

Thus, “weed” is in part a *human value judgment* of certain plant species as interfering with the desired use of a particular field at a particular time. Weeds are also a *human creation*. We turn plant species into “weeds” by providing open niches for unwanted plants to grow, and by importing new plant species into a region or continent.

In practice, any vegetation that comes up in a field or garden that the grower did not plant is often collectively called “weeds,” regardless of whether it is causing problems. Trying to eradicate all volunteer vegetation is hard on farm budgets, gardeners' backs, soils, agro-ecosystems, fuel supplies, and the wider environment. Managing a weed to protect crops usually does not require exterminating the weed altogether. Thus a working definition might be:

A weed is any plant not intentionally sown or propagated by the grower that requires management to prevent it from interfering with crop or livestock production.

Sustainable weed management recognizes the ecological role of weeds as well as their pest potential. Some innovative

farmers utilize certain weeds as nutritious food or fodder, habitat for natural enemies of insect pests, or cover crops.

The goal of sustainable organic weed management is to minimize the adverse impacts of weeds on crops, and sometimes to reap the benefits of weeds.

What are Weeds Doing in My Field?

Weeds are nature's way of covering soil that has become exposed by fire, flood, landslide, windstorms, clear-cutting, clean tillage, herbicides, overgrazing, or other disturbance. Bare soil is hungry and at risk. The soil life, so vital to soil fertility, goes *hungry* because the normal influx of nourishing organic compounds from living plant roots has been cut off for the time being. The exposed soil surface is *at risk* of erosion by rain or wind, especially if root systems have also been removed or disrupted. Pioneer plants – weeds – are those species that can rapidly cover bare soil and begin performing a number of vital ecological functions:

- Protect the soil from erosion.
- Replenish organic matter, feed and restore soil life.
- Absorb, conserve, and recycle soluble nutrients that would otherwise leach away.
- Absorb carbon dioxide from the atmosphere.
- Restore biodiversity.
- Provide habitat for insects and animals.

At the same time, agricultural weeds hurt crop yields or increase costs of production by:

- Competing for light, nutrients, moisture, and space.
- Releasing natural substances that inhibit crop growth (allelopathy).
- Physically hindering or smothering crop growth (e.g., morning glories and bindweeds).
- Hosting pests or pathogens that may attack crops.
- Promoting disease by restricting air circulation around the crop.
- Interfering with or contaminating crop harvest.
- Reproducing prolifically, resulting in a greater weed problem next year.
- Parasitizing crops directly (e.g., dodder, witchweed).

Annual vegetable and row cropping creates empty ecological niches – bare, unoccupied soil with unutilized moisture and nutrients – for part of each season. Open niches may occur in *time*, between harvest of one crop and establishment of the next; and in *space*, between rows until the crop canopy has closed. Weeds emerge, grow, and reproduce in these open niches – until they are stopped by cultivation, pulling, mowing, herbicides, or direct competition from crops.

One key sustainable strategy for dealing with weeds is to *minimize open niches for weeds in cropping systems*, while maintaining satisfactory crop yields. In annual cropping systems and less-competitive perennials like asparagus and cut flowers, some open niches are unavoidable, whereas others can be eliminated through cover cropping, tighter crop rotations, closer row spacing, and intercropping. Well-managed pasture, forage, orchard, permaculture, and agroforestry systems are generally more “closed,” and usually require less intensive weed control efforts.

The Menace of Invasive Exotic Plants

Plant species that have been introduced into our region from abroad often become serious weeds, spreading unchecked in the absence of their natural enemies. Unlike most pioneer plants that promote ecological succession back to native forest or prairie after a disturbance, some introduced species, known as “invasive exotic plants,” actively smother or supplant native vegetation. Kudzu – those enormous vines that cover and kill large trees – is perhaps the most dramatic example in our region. A recent study has shown that kudzu does its damage, not just by shading, but also through a powerful allelopathic effect. That is why no winter-hardy grasses, forbs, or wildflowers ever emerge through the tangle of dead kudzu vines in early spring. Ailanthus (“tree of heaven”) also supplants native forest trees by allelopathy as well as aggressive growth. A small (1 – 3 ft) herbaceous invader called garlic mustard has been shown to hurt forest trees by killing off their vital mycorrhizal fungal symbionts.

Some of the South's worst agricultural weeds have also been introduced from abroad. Purple nutsedge, native to the Old World tropics, is a small (4-24 inches) perennial sedge that can stunt sugarcane and coffee trees through intense competition and allelopathy. It causes substantial crop losses in the Deep South. Other exotic weeds include common bermudagrass, barnyardgrass, tropical soda apple, crabgrass, Johnsongrass, and jungle rice. Two recent invaders of concern in the South are Bengal dayflower and deep-rooted sedge.

Nationwide or regional coordinated eradication efforts are often directed at invasive exotic plants. Musk thistle, spotted knapweed and purple loosestrife are three invasive exotics in the upper South that have been successfully managed through *classical biological control*, the introduction of specific insects that feed on those weeds in their areas of origin.

The Organic Grower's Dilemma

Because organic farmers do not use synthetic herbicides, they rely more heavily than conventional growers on tillage and cultivation for weed control, especially in annual vegetable crops. Unfortunately, while cultivation takes out existing weeds, it also stimulates additional weed seeds to germinate. This can lead to a “cultivation treadmill” with which many vegetable growers are all too familiar.

Furthermore, organic farmers seek to maintain a healthy, living soil rich in organic matter with good physical structure (tilth). Frequent tillage and cultivation can burn up soil organic matter, degrade soil structure, disrupt beneficial soil organisms like earthworms and mycorrhizal fungi, and leave the soil more prone to erosion, compaction, and crusting. This creates a dilemma for organic growers:

How can I control weeds without tilling the soil to death?

The answer is that ecological weed management combines *planning* and *prevention* with *control*. Cultural practices such as crop rotation, cover cropping, mulching, and maintaining optimum growing conditions for crops lessen weed pressure on the crop. These practices also help build soil quality, and reduce the intensity and frequency of cultivation needed to accomplish adequate weed control.

Beyond Tillage and Cultivation

Controlling weeds in annual cropping systems without herbicides almost always entails some tillage and cultivation. However, organic weed control does not simply substitute steel for herbicides. Experienced growers develop site-specific systems for their farms, selecting materials and tactics from a large weed-management toolbox (see sidebar), which continues to expand with ongoing research and experimentation by farmers and scientists.

A Sustainable Weed Management Toolbox

Major Tools:

The Grower's Mind – observation, planning, ingenuity
Vigorous Cash Crops
Crop Rotation
Cover Crops
Mulches – organic, black plastic film, and weed barrier
Indigenous Weed Seed Predators – ground beetles, etc.
Livestock – to graze weeds after crop harvest
Tillage and Cultivation Tools
Flame Weeders
Mowers and other Cutting Tools
Rollers and Roll-crimpers – for cover crop management

Minor and Experimental tools:

Clear plastic mulch - soil solarization
Classical biological controls for specific weeds
Management of the soil microflora
Specific crop-weed allelopathic interactions
OMRI certified organic herbicides
Bioherbicides – specific fungal pathogens

A Note on "Sustainable" and "Organic"

All the practices discussed here are allowed under the USDA Organic Standards, except where otherwise specified. They are "sustainable" to the extent that they reduce crop losses to weeds while protecting or improving soil health and environmental quality. The information presented is intended to assist both organic and non-organic producers develop effective, ecologically sound weed management strategies.

Twelve Steps to Sustainable Weed Management

Ecological weed management integrates multiple preventive (cultural) and control (weed-killing) tactics into strategies tailored to each region, cropping system and farm. Agroecologist Matt Liebman and weed scientist Eric Gallandt recommend using "many little hammers," including "indirect controls" such as crop variety, planting date, and nutrient management, rather than relying only on the "large hammers" of cultivation and herbicides. In their words:

"The use of a combination of methods can lead to (i) acceptable control through the additive, synergistic or cumulative action of tactics that may not be effective when used alone; (ii) reduced risk of crop failure or serious loss by spreading the burden of protection across several methods; and (iii) minimal exposure to any one tactic and consequently reduced rates at which [weeds] adapt and become resistant." (Liebman & Gallandt, 1997, p 326).

The following outline offers a conceptual framework for developing a site-specific weed management strategy, based on an understanding of the web of relationships among crops, weeds, soils, insects, micro-organisms, and the producer on a particular farm. Not a linear sequence, the steps are employed together in an integrated manner. For example, Step 6 (cover crops) furthers Step 2 (minimize niches for weeds), and Step 1 (know the weeds) provides vital information for other steps, particularly 3 (design system, select tools), 4 (keep the weeds guessing), and 7 (manage the weed seed bank).

There is nothing "set in stone" about the number of steps or the framework itself. Use this or another suitable framework (such as those offered by Liebman and Gallandt, 1997; Grubinger, 1997; and Sullivan, 2003, listed in Resources), to select and assemble a set of "many little hammers" that, working together, keep your farm's particular weed flora from causing major problems.

Pre-season Planning

Step 1 – Know the weeds on your farm.

Step 2 – Plan cropping systems to minimize open niches for weeds.

Step 3 – Design the cropping system and select tools for effective weed control.

Preventive (Cultural) Practices

Step 4 – Keep the weeds guessing with crop rotation.

Step 5 – Grow vigorous, competitive crops.

Step 6 – Put the weeds out of work – grow cover crops.

Step 7 – Manage the weed seedbank – minimize "deposits" and maximize "withdrawals."

Control Tactics

Step 8 – Knock the weeds out at critical times.

Step 9 – Utilize biological processes to enhance weed control.

Step 10 – Bring existing weeds under control before planting weed-sensitive crops.

Enhancing and Fine-tuning the Weed Management Strategy

Step 11 – Keep observing the weeds, and adapt management practices accordingly.

Step 12 – Experiment, and keep up with new developments in organic weed management.

Step 1 – Know the Weeds on your Farm

Obtain correct identification of the *major* weeds present on the farm, and any new weedy arrivals that could cause problems if allowed to spread. A definitive ID may not be needed for minor, uncommon, or non-troublesome species. Use a good key or field manual, and ask your Extension agent or other resource person for help if you get stuck.

Two weeds that look similar may have very different life cycles, growth habits, and susceptibility to control tactics. For example, giant foxtail and johnsongrass are two tall, vigorous summer grasses with large, fairly wide leaves. However, while the foxtail is an annual whose reproduction can be stopped by a single mowing soon after head emergence, johnsongrass is a perennial that reproduces through heavy, winter-hardy rhizomes that will survive mowing and regenerate the weed. More aggressive measures, such as vigorous tillage followed by fast-growing cover crops, or

running hogs in the field to root out the rhizomes, are needed to control johnsongrass.

Learn each major weed's life cycle (see sidebar), growth habit, seasonal pattern of development and flowering, modes of reproduction and dispersal, seed dormancy and germination triggers, and impacts on crop production. Find the weed's weak points – the stages in its life cycle that are most vulnerable to control tactics, crop competition, and other stresses that can be exploited in your management strategy.

“Know the weeds” is listed first because it informs most of the succeeding steps. At the same time, gaining a thorough knowledge of the farm's weed flora is an ongoing process over many seasons, and is important for fine-tuning the farm's weed management system.

The more you know about the weeds in your fields, the more precisely you can design effective strategies. Some questions to consider:

- What are the five to ten most common or most troublesome weeds in the farm's primary crops?
- Which ones are predominant at different seasons?
- What fields or beds have the worst weed pressure? What is their management history?
- Which fields are least weedy? What is their history?

Monitor fields regularly throughout the season and year after year, and record your observations. In addition to providing more information on the existing weed flora and how it responds to prevention and control measures, careful monitoring can detect the arrival of new weed species before they spread and become major problems.

Step 2 – Plan Cropping Systems to Minimize Open Niches for Weeds

Plan the crop rotation to keep the soil covered with desired vegetation or mulch as much of the season as possible. Schedule plantings of each cash or cover crop as soon as practical after the preceding crop is finished – or sooner! Eliot Coleman, Maine farmer and author of *The New Organic Grower*, has developed an eight-year crop rotation for vegetable production in northern New England, in which clovers or other hardy cover crops are interplanted or overseeded between rows of established vegetable crops. When the vegetable is harvested, the cover crop is already established and rapidly covers the ground. This minimizes the bare soil period at the vegetable → cover crop transition. Different cover crops may be better adapted to the warmer climates in the South, and our longer growing season may expand opportunities for cover crop overseeding at different seasons.

No-till planting of vegetables or row crops into mowed, rolled, roll-crimped, undercut, or winterkilled cover crops eliminates the bare soil period at the cover crop → vegetable transition. Whereas *continuous* no-till is not currently feasible in organic crop production, tillage can be reduced, thereby minimizing soil degradation and flushes of weed germination. The no-till cover crop strategy works best when weed populations are moderate, and the primary weeds are annuals, especially small-seeded annual broadleaf weeds, which are readily blocked by the mulch.

Knowing the Weeds: Life Cycle Categories

Summer Annual Weeds, such as pigweeds, smartweeds, common cocklebur, morning glories, sicklepod, crabgrasses, foxtails and goosegrass, grow rapidly during the frost-free season, reproduce through prolific seed production (thousands to hundreds of thousands per plant), and usually die with the first fall frost. Their seeds often come up in “flushes” after tillage or cultivation. Management tactics include timely *shallow* cultivation (the shallower the disturbance, the fewer additional seeds are stimulated to germinate), mulching (most effective for small seeded broadleaf weeds), and roging out late-season “escapes” to interdict seed formation. Rotating to summer cover crops and cool-season vegetables can disrupt their lifecycles and thereby reduce weed pressure.

Winter Annual Weeds, such as common chickweed, deadnettles, shepherd's purse, wild mustards and annual sowthistle, also reproduce prolifically by seed, and emerge in response to tillage or light stimulus. They are winter hardy, emerge in early fall or early spring, flower and set seed in late spring, and die back in summer. They are troublesome for garlic, salad greens, and other cool season vegetables, and can host pathogens and insect vectors of summer vegetables, such as tomato spotted wilt virus carried by thrips. Timely shallow cultivation, winter cover crops, and rotating to late-planted summer vegetables help keep winter annual weeds in check.

Simple or “Stationary” Perennial Weeds, such as dandelion, broadleaf dock, pokeweed, and tall fescue, arise each year from winter hardy taproots, root crowns, or sturdy fibrous root masses. They reproduce mainly by seed, and newly emerging seedlings can be controlled by timely shallow cultivation. These weeds are more troublesome in pasture and perennial crops than in annual crops. Light or local infestations can be dug out. Repeated close mowing can slowly weaken rootstocks, and vigorous tillage alternating with heavy smothering cover crops can reduce more widespread infestations.

Biennial Weeds, such as burdock, prickly lettuce and wild carrot share characteristics of both winter annual and simple perennial weeds. They come up during spring through late summer, overwinter as rootstocks, then emerge, bolt, and set seed the next spring. Timely mowing, undercutting, or digging just before flowering can interrupt propagation.

Invasive or “Wandering” Perennial Weeds, such as quackgrass, bermudagrass, johnsongrass, nutsedges, Canada thistle, and bindweeds, are generally the most serious. They form extensive underground perennial structures – roots, rhizomes, bulbs, or tubers – from which they propagate and spread, often over a wide area. Many of these weeds can regenerate from a one-inch fragment of rhizome buried several inches deep in the soil. Thus, a single disking or rotary tillage that chops up the rhizomes will propagate the weed. However, *repeated* tillage whenever regrowth reaches the 3–4 leaf stage can weaken these stubborn weeds. Competitive cover crops such as buckwheat, sorghum-sudangrass, or winter rye planted after tillage will counteract the damaging effects of the soil disturbance and help suppress weed regrowth. Mowing every four weeks to a short stubble height can slowly weaken invasive perennials, and may be the best option in pastures other non-tilled situations.

Strategies to reduce weed niches in space (between crop rows) include intercropping (companion planting), relay cropping (including cover crop overseeding), alley cropping, agroforestry systems, strip tillage, and living mulches.

Permaculture is a system for designing highly diverse communities of food producing and other useful plants that leave little room for unwanted plants. Permaculture begins with a careful analysis of the site, on which a site-specific design is based. Most permaculture designs emphasize the use of perennial plant species and limits tillage for annual crops to a minor percentage of the landscape. Similarly, some indigenous cultures in Mexico and other developing countries maintain multi-tier food gardens with tree, shrub, and annual herb canopies containing as many as 75 useful plant species growing together, including a few that US farmers might consider weeds.

Organic mulches such as straw, old hay (preferably seed-free), or chipped brush restrict niches for weed growth by blocking light stimuli and offering physical hindrance to emerging weed seedlings. These mulches are most effective against annual weeds. Black plastic mulch or landscape fabric (weed barrier) can block out many perennial weeds, although some weeds emerge through planting holes, and nutsedges and a few other weeds can penetrate the mulch itself.

With the exception of the synthetic mulches, *all* of these strategies to minimize weed niches also add organic matter, build soil quality, and/or enhance farm biodiversity.

Bio-Intensive and Bio-Extensive Organic Weed Management Systems

Gardeners and growers with limited land area usually implement *bio-intensive* methods to close off weed niches in their crop rotations. Vegetables are spaced close together for rapid canopy closure, cover crops are used intensively and cut to generate mulch or composting materials, and each crop is planted immediately after the preceding crop is harvested.

Some farmers with more land area alternate several years in cultivated annual vegetable crops with several years in a perennial grass-legume sod, often managed as pasture or hay land. At Elmwood Stock Farm in central Kentucky, growers John Bell, Ann Bell Stone and Mac Stone grow vegetables for three years, then rotate to pasture for five years. These rotations help limit the buildup of annual weeds such as pigweed, lambsquarters, galinsoga, crabgrass, and foxtails.

Eric and Anne Nordell of Trout Run, PA have developed a *bio-extensive* approach to weed management in their organic vegetables. Their motto is *weed the soil, not the crop*. In each rotation block, they grow only one production crop every two years. The rest of the rotation schedule consists of high-biomass cover crops, and a short (six week) fallow period during the summer of the non-production year. Frequent, shallow tillage during the fallow period draws down the weed seed bank, while the heavy cover crops on either side of the fallow choke out emerging perennial and annual weeds, and provide plenty of organic matter to compensate for the six weeks of soil disturbance. The result? Their crops require very little cultivation or manual weeding; in the Nordells' words, "We substitute land for labor."

Step 3 – Design the Cropping System and Select Tools for Effective Weed Control

Once a crop rotation has been planned that minimizes opportunities for weed growth, the next step is to design the system to facilitate weed control throughout the season. Develop control strategies to address anticipated weeds in each major crop, and select tools for pre-plant, between-row, and within-row weed removal. Plan bed layout, row spacing, and plant spacing to facilitate precision cultivation. Choose irrigation methods and other cultural practices that are compatible with planned weed control operations.

Because row spacings may vary from four inches to six feet in a diversified rotation, matching cultivation tools and row spacing can be challenging. Use row spacings that are multiples of one another and are compatible with equipment dimensions to facilitate mechanized cultivation.

Consultant Josh Volk (2008) recommends a simple 3-2-1 system, in which smaller vegetables (e.g., lettuce) are planted on three rows per bed, medium-size crops (e.g., broccoli) are planted in the two outer rows only, and large crops (e.g., tomato) are planted in the center row only. Cultivation is done with two toolbars. The first carries four sweeps set to run between rows and in the alleys behind the tractor tires. The second carries three sweeps that can be raised to leave crop rows untouched, or lowered to cultivated unoccupied rows in one-row and two-row plantings. In this and other systems, precise spacing of crop rows and of cultivation equipment is essential to optimize weed control and avoid crop damage. Both mechanical and computer-based optical guidance systems have been developed to keep tractor-drawn cultivation implements "on course" with respect to the crop.

Farmers, researchers, and agricultural engineers have developed a wide range of tools for precision cultivation, flame weeding, and other weed control operations in many different vegetable and row crops. Some of these are described in *Steel in the Field* by Greg Bowman (1997). The toughest weeds to manage are those within the crop row. The simplest approach, effective on small weeds (less than one inch) in established crops (6–18 inches tall) is to adjust shovel, sweep, or rolling cultivators to throw just enough soil into the row to bury and smother the weeds. Several within-row implements, including finger weeders, torsion weeders, tine weeders, and "spiders" have been designed to uproot or sever weeds seedlings while leaving larger crop plants intact. Computer guided weeders have been designed to recognize the crop and move out of the row, then back in to get between-plant weeds. These implements are not as dependent on the crop-weed size differential. They cost \$30,000 or more, yet can pay for themselves in time saved within a year or two on a mid-scale vegetable farm.

Most cultivation implements work best in soils with good crumb structure (tilth), and become less effective in killing weeds if the soil is cloddy, crusted, or compacted. Wet soil will clog many implements. Brush hoes may be a good choice for frequently wet fields. In stony soils, sturdy implements, and implements equipped with spring mechanisms, such as a springtooth harrow, function best, and are least likely to become damaged by impacts with stones.

For homestead and market gardens managed with hand tools, a great diversity of hoes and weeders have been developed for every need, ranging from light weight collinear hoes and trapezoid hoes to take small weeds out of young crops, to oscillating (stirrup) hoes, and heavy-duty standard hoes suitable for larger weeds. Earth Tools, Inc (see Resources) is an excellent source for high quality hand tools.

Before investing in new equipment, evaluate tools and other resources already on hand to determine what additional weed control implements are needed. Consider crops being grown, cultural methods, main weeds and when they become problematic, soil conditions, climate, farm scale, and budget.

For example, suppose edamame soybean is a major crop on a 20-acre vegetable farm, and summer annuals dominate the weed flora. The farmer has found that removing weeds from within crop rows improves yield, but hand weeding is impractical at this scale, and within-row weeds can get too large for the farm's torsion weeder if cultivation is delayed a few days. Soybean is a crop that can be blind cultivated with a rotary hoe just before emergence, a practice that increases the crop-weed size differential, and thereby widens the time window for effective use of the torsion weeder. Thus, a rotary hoe may be a wise investment for this farm.

Other crops such as sweet corn, Irish potato, and broccoli tolerate and even benefit from hilling-up once they are established. For these crops, a simple, inexpensive between-row cultivation system with sweeps or rolling cultivators can be adjusted to throw soil into crop rows. The implement simultaneously severs between-row weeds and buries weeds within and near the row.

A flame weeder can be a good investment for crops such as corn that can tolerate a brief blast of heat at certain stages of development. Also, flame weeding just before emergence of small-seeded, slow-germinating crops like carrot, parsley, and beet can wipe out emerging weed seedlings, and thereby allow the crop to emerge in a clean seedbed.

Multi-acre organic production of weed-sensitive crops like carrot and onion may require sophisticated strategies. Researchers working with organic carrot farmers in Italy developed an integrated weed control system that yielded substantial net savings in labor costs (Peruzzi et al., 2007). The growers' standard production system was to seed carrots in five 3-inch-wide bands spaced 12 inches apart (center to center) on a 6-foot wide bed, flame-weed pre-emergence, tractor-cultivate between crop bands, and hand-weed within bands. The experimental strategy changed the planting pattern to ten rows spaced 7 inches apart, and utilized an innovative precision cultivating machine that combined 3.5-inch between-row sweeps with vibrating tines and torsion weeders for weeds near and within crop rows. This system reduced total weed control labor costs and often enhanced carrot yield.

Many organic farmers use black polyethylene film (black plastic) mulch as their main weed management tool in tomato, pepper, melon, and other high value crops. Black plastic can block emergence of many grass and perennial weeds that can penetrate organic mulch, and its soil-warming effect is especially advantageous when an early harvest is desired.

Plastic does not add organic matter to the soil, and must be removed at the end of the season (required for USDA certified organic farms) and hauled to a landfill, labor and

environmental costs that should be taken into account. Biodegradable plastic mulches have been developed that give good weed control and do not require disposal; however these are not currently allowed in certified organic production.

In a plastic-mulched crop, weeds emerging through planting holes need to be pulled. Alleys between plastic-covered beds also require cultivation or other weed control measures. A few weeds, notably nutsedges, can puncture and grow through plastic mulch. Black plastic can even *accelerate* the spread of purple nutsedge by warming the soil. Vining weeds like morning glories and bindweeds grow toward planting holes and climb the crop. Despite these limitations, many growers consider plastic mulch highly cost-effective.

Organic mulches such as hay or straw can be effective against annual weeds in tomato and many other vegetables. They are often used to control weeds down alleys between plastic-mulched beds. Organic mulch cuts off weed seed germination stimuli, hinders weed emergence, conserves soil moisture, adds organic matter and nutrients, and harbors some beneficial organisms. However, hay mulch can itself be a source of weed seeds or damaging herbicide residues (see sidebar), so check your sources!

Because spreading organic mulch by hand becomes costly at the multiacre scale, some growers invest in a bale chopper to mechanize application of small rectangular bales. Others use a flail mower and forage wagon to harvest, transport, and unload mulch grown on-farm; or a crimp-roller to convert cover crops into an *in situ* mulch. However, perennial weeds can readily penetrate organic mulches or rolled cover crops, so get the perennial weeds well under control before investing in capital equipment for organic mulching systems.

Herbicide Hazards in Hay Mulch

Several pyridine carboxylic acid herbicides commonly used to control pasture weeds can persist for up to three years, leading to severe damage in tomato, squash, and other vegetables mulched with hay harvested from treated fields. These include *clopyralid* (product trade names include Curtail, Scorpion, Reclaim, Confront, Stinger, and Accent Gold); *plicloram* (Grazon, Torden), and *aminopyralid* (Milestone, Forefront), and a newly released pyrimidine carboxylic acid, *aminocyclopyrachlor*. Another related herbicide, *triclopyr* (Crossbow, Garlan, Remedy), can persist for 3-12 months.

One CSA farmer in Virginia suffered a near-total crop loss from plicloram-contaminated hay, and was saved from bankruptcy by a loyal CSA membership, who helped remove the bad hay and shared the financial loss for the season. Even the following cover crop showed moderate herbicide injury.

In addition to incurring crop losses, a USDA certified organic farmer may temporarily lose organic certification until herbicide residues subside.

Even compost made from the manure of animals that had grazed fields or consumed hay from fields treated with clopyralid or aminopyralid has caused serious crop losses to organic vegetable growers in the Pacific Northwest and in the United Kingdom.

Take-home lesson: **always check your source before purchasing mulch hay or straw from another farm.** Better yet – grow your own mulch!

Step 4 – Keep the Weeds Guessing

Each weed species is adapted to the patterns of soil disturbance, other stresses, and available resources that characterize the particular crops or farming systems in which that weed thrives. This pattern – or weed niche – is shaped by: crops grown; seasonal timing of tillage, planting, cultivation, mowing, and harvest; methods and depth of tillage and cultivation; timing, types, and amounts of fertilizers; irrigation method and schedule; climate; soil type and soil conditions. When the same crops are planted and the same practices are used year after year, the populations of certain weeds can explode. Conversely, a complex crop rotation that varies timing of field operations as well as plant family creates a more changeable environment that can “keep the weeds guessing.”

For example, continuous corn or a simple corn-soy rotation, in which fields are moldboard-plowed every spring before planting, is known to promote velvetleaf, cocklebur, and other aggressive, large-seeded summer annual weeds that can emerge from several inches depth. In addition, certain weeds can proliferate in more diverse rotations if the soil is tilled on a predictable schedule each year. Vegetable farmers who rototill before each crop to prepare the seedbed are often plagued by heavy populations of small seeded annual weeds like pigweeds, lambsquarters, galinsoga, purslane, and foxtails. A four-year rotation of sweet corn, snap beans, cucurbit family, and tomato family, with winter cover crops each year, can allow these weeds to build up, as they germinate in response to late spring tillage ahead of vegetable planting. Adding cool season vegetables and competitive summer cover crops to the rotation shifts timing of field operations, and can slow the buildup of these weeds.

Rotating fields into perennial cover for two or three years (e.g., orchardgrass + red clover) can be especially effective in disrupting the life cycles of annual weeds. Perennial cover removes the tillage stimulus for weed germination, and provides continuous habitat for ground beetles and other consumers of weed seeds, thereby reducing weed populations.

Another strategy is to plant a field or bed in a succession of salad greens, radishes, and other quick maturing crops for a year. Seedbed preparation for each crop knocks out weeds before they can propagate, and can thereby draw down populations of weeds that become problematic in longer-season vegetables like melon or tomato.

Crop diversity also impacts weeds directly. Various crops compete against weeds by rapidly forming a dense, low canopy within crop rows (snap bean, Irish potato) or across the field (sweet potato, cucurbits, cowpea); by growing tall (corn, tomato); by forming extensive root systems that “grab” soil moisture and nutrients (sorghum-sudangrass); or not much at all (onion, carrot). Thus, common purslane might die out under a sweet potato canopy, grow slowly in established sweet corn without affecting yield, and compete severely against summer-sown carrot.

Each plant species (crop, weed, or native plant) gives off a unique mixture of natural substances that retard (or occasionally promote) the growth of certain other plant species. This phenomenon is called allelopathy. In a diverse crop rotation, most weed species are exposed to significant crop competition or allelopathy sometime during the rotation.

Some tips for designing crop rotations to keep weeds guessing include:

- Vary timing of operations as well as plant family.
- Include warm- and cool-season crops, and short- and long-season crops.
- Vary depths and methods of tillage.
- If weed pressure is moderate, include no tillage cover crop management at some points in the rotation.
- After several years in annual crops, rotate the field into perennial cover for 1-3 years.

Finally, remember that weeds are constantly adapting and responding to weed management tactics, both at the species level (genetic changes), and at the community level (changes in weed flora). As a result, using the same strategy year after year will eventually select for weeds that can thrive despite the stresses imposed. For example, conventional agriculture is now plagued by herbicide-resistant weeds. Weeds can also adapt to non-chemical tactics, so avoid relying on one weed control tool, tactic, or strategy, no matter how successful it initially appears.

Step 5 – Grow Vigorous, Competitive Crops

In organic weed management, crop vigor is the first line of defense against weeds. Whereas timely cultivation knocks the weeds back, the most economical and soil-friendly way to keep crops ahead of the weeds is to optimize the health and vigor of the crop itself. Vegetables that emerge, establish, and grow rapidly get through their “critical weed-free period” early in the season. Crops that quickly form a closed canopy (completely shading the field or bed) can hinder weed growth and reproduction in a manner similar to cover crops.

The challenge for organic vegetable farmers is that most annual crops are vulnerable to weeds early in the season when the crop is small. Some vegetables, such as carrot and onion, grow slowly and may not fully occupy the space even at maturity. However, optimal crop management can make any vegetable more weed-tolerant and weed-competitive.

Following are several management practices that can enhance crop competitiveness toward weeds.

- Choose vigorous, locally-adapted crop varieties.
- Use high-quality seed.
- Grow and set out vigorous transplants when appropriate.
- Maintain healthy, living soil.
- Optimize crop nutrition.
- Choose optimum planting dates whenever practical.
- Adjust row and plant spacing to shade out weeds.
- Maintain optimum crop growing conditions.
- Feed and water the crop, not the weeds.

Crop varieties that are well suited to the farm’s climate, rainfall patterns, and soils will grow more vigorously than varieties bred for warmer, cooler, wetter, drier or more fertile conditions. Find out from neighboring farmers and local seed suppliers what varieties seem to work best in your locale.

Crop varieties vary in height, spread, and density of canopy. Tall or long-vine varieties with dense foliage compete more effectively against weeds than shorter varieties with less foliage. Some older, heirloom crop varieties compete better against weeds than modern varieties. For example, in the southern Appalachian region, ‘Danvers’ carrot produces a

large, dense top that shades out weeds by the middle of its growth cycle, while 'Nantes' forms less top growth and requires more weeding, and some modern, specialty cultivars like 'Minicor' and 'Cosmic Purple' have small, thin tops, and must be weeded regularly until maturity. Recent studies have shown that pea and potato varieties with heavier foliage compete better against weeds. Note that heavy canopy can be a disadvantage in situations where fungal diseases pose a significant threat to the crop (e.g., *Alternaria* in carrot).

Use high quality seed that will germinate and grow rapidly. Discard old, slow-germinating, partially-viable seed, unless you are salvaging a hard-to-replace heirloom variety or breeding line. Thin, slow-starting stands may require several times as much weed control labor as a good stand!

Transplanting gives vegetables a head start on weeds. Sow seeds in a good, weed-free greenhouse mix to produce vigorous "starts." Lettuce, tomato family, brassicas and onion family transplant especially well. Some organic growers also transplant cucurbits, corn, pea, bean, and even spinach, chard, beet, and turnip, in order to beat the weeds.

Maintain a healthy, living soil to promote crop vigor. Fine-tune nutrient levels and soil conditions to match the needs of each crop. For most vegetables, slow-release sources of nitrogen (N), such as compost, residues of a grass + legume cover crop, or feather meal match crop needs best, and are less likely to "over-amp" N-responsive weeds like lambsquarters, pigweeds, ragweed, and quackgrass than faster-release N sources like blood meal or a succulent, all-legume green manure. However, don't hesitate to fertilize a "hungry" crop with the appropriate organic fertilizer, as an underfertilized vegetable is vulnerable to weeds that tolerate lower fertility.

Plant each crop when temperatures and moisture levels are favorable to that crop, and are likely to remain so until harvest. Trying to stretch the season for a given crop by planting earlier or later than usual can make the crop less vigorous and more prone to weeds. Utilize season extension techniques to maintain more favorable conditions for the crop, and plan on a little extra labor for weed management.

Temperatures above 95°F cause stress and reduce quality in most food crops, while certain weeds, notably Palmer amaranth and purple nutsedge, attain their peak growth in such heat. When it gets this hot, plant aggressive, heat-loving cover crops, and take a break! Many vegetable farmers in Florida and across the Deep South suspend production during the heat of summer, and resume in the fall (see sidebar).

In crops and locations where disease is not a concern, use plant and row spacings to promote early canopy closure without overcrowding the crop. Some vegetables can be planted in double or multiple rows on raised beds to speed canopy closure and facilitate between-bed cultivation. Use in-row drip irrigation or fertigation to water and feed the crop but not the weeds. *Subsurface* drip irrigation (line installed several inches below the surface in crop row) is especially effective, providing water to established crops while leaving near-surface weed seeds within the row dry and dormant.

Grow the least competitive vegetables (carrot, onion, etc.) on fields with a recent history of low weed populations or effective weed control. Plant weedier fields to competitive crops like potato, sweet potato, winter squash, and cowpea.

Avoid the Weeds – Take the Summer Off

Milagro ("Mila") Berhane, community gardener and Extension Specialist in Horticulture at Southern University in Baton Rouge, LA, describes weeds as "a struggle and a significant barrier to successful organic vegetable farming." Her worst weeds include johnsongrass, bermudagrass, other grasses, yellow nutsedge, and morning glories.

Mila grows two acres of variety trials (sweet corn, cowpea, cucumber) as well as a large community garden. She manages weeds successfully through strategic crop timing, use of transplants, and cultivation with a wheel hoe equipped with stirrup hoe attachments. She avoids plastic mulch because it is easily penetrated by the nutsedge, requires end-of-season pickup, and entails environmental costs.

Mila has learned when different vegetables grow best in her part of Louisiana (hardiness zone 8b). Broccoli, collard, turnip, and other brassicas thrive when transplanted late in August so that they grow as summer heat subsides. Carrot, beet, and spinach do not establish well when temperatures are above 80°F, so she plants them in November or December.

Regarding warm-season vegetables like summer squash and snap bean, Mila notes that "the weeds start in April and are worst in summer, so we start planting in March, and do our last spring planting in May." Tomato and pepper planting is delayed until August to avoid weed and disease pressure. "Peppers do great in the fall, producing until December."

When the soil begins to warm up in February, Mila tills and shapes beds by tractor, waits for several weeks (stale seedbed), tills again, and immediately transplants spring crops to get the jump on the April flush of weeds. Whenever a bed become vacant in late spring or summer, she tills, does another stale seedbed, then plants cowpea to compete with the weeds. "I plant cowpeas anytime the soil is warm, from May on, sometimes to pick peas, and sometimes as a cover crop only."

Additional strategies include straw mulch after last cultivation, in-row drip irrigation, and manual removal of weeds to prevent seed set. She has reduced pigweed and curly dock populations to non-troublesome levels, and is working on similarly reducing the morning glory seed bank. Her experience shows that good Integrated Weed Management that includes a strategy of taking the summer off, can give good weed control without herbicides, plastic, or an aching back, even in a hot, moist climate with intense weed pressure.

Step 6 – Put the Weeds Out of Work – Grow Cover Crops!

Cover crops do the same job as weeds, only better. Cover crops are domesticated plant species that grow vigorously with relatively little care, and are used to prevent soil erosion during fallow periods. They perform many of the same ecosystem functions as weeds: cover and protect bare soil, feed the soil life, conserve and recycle nutrients, enhance biodiversity, and harbor beneficial insects.

Cover crops suppress weeds in several ways. First, cover crops occupy the space and limit weed growth through direct competition for light, nutrients, and moisture.

Second, many cover crops and their residues release allelochemicals into the soil that prevent or hinder weed seedling growth. Winter rye, oats, barley, sorghum-

sudangrass, buckwheat, forage radish, subterranean clover, and sunflowers have been shown to exert allelopathic effects against certain weeds.

Third, a vigorous cover crop can change the environment for weed seeds on and in the soil. Whereas a brief flash of unfiltered daylight stimulates weed seed germination, the dim green light under a heavy crop canopy can actually inhibit germination. The canopy also reduces thermal stimuli by lowering soil temperature and dampening daily fluctuations. Sometimes, weed seed germination remains inhibited for a period of time after the cover crop is terminated, thereby reducing weed populations in a subsequent vegetable crop.

Finally, cover crops can enhance the vigor, and therefore weed-competitiveness, of the following cash crop, by providing N (legumes), enhancing availability of other nutrients, or improving soil conditions.

Whenever a bed or field becomes vacant, put the weeds out of a job - plant a cover crop immediately so that it can begin the vital restorative work that nature does with weeds. Innovative farmers have developed many weed management strategies in which cover crops play a major role (see sidebar).

Whereas the long, hot growing seasons of the South promote rank weed growth, they also expand opportunities for cover cropping. Warm-season crops like forage soybean, sorghum-sudangrass, and Japanese, pearl, and foxtail millets, choke out weeds, and produce tremendous biomass within 50-70 days after planting. Buckwheat and cowpea form especially heavy, shading canopies, and are excellent weed deterrents for short summer fallow periods.

During the cooler part of the year, cereal grains can be grown with hardy annual legumes. Bicultures generally give better weed suppression and soil building than either grain or legume alone. Rye, wheat, hairy vetch, crimson clover, and Austrian winter pea can be grown over winter throughout the South. Oats, barley, field pea, common vetch, bell bean, and berseem clover grow vigorously in the milder winters of the Deep South. Daikon and forage radishes are especially weed-suppressive and are frost hardy to about 20°F.

Cover crops will not solve all weed problems or eliminate the need for cultivation. Yet, cover cropping is one of the more important "little hammers" of ecological weed management, as they can reduce weed control costs and limit weed seed set while fields are not in production. In addition, cover crops replenish organic matter, feed soil life, add nitrogen (legumes), make other nutrients more available, prevent erosion, and providing habitat for natural enemies of insect pests. Take these benefits into account when evaluating the economics of cover cropping as a weed management tool.

Use good planting technique, sufficiently high seeding rates, and high quality seed, in order to obtain a dense, weed-suppressive cover crop. Don't hesitate to water or feed a cover crop seeding (compost, aged manure, or amendments based on a soil test) if needed to get it off to a good start.

One limitation of cover cropping can arise when the cover crop is incorporated into the soil as a green manure. This tillage reopens the niche for weeds until the subsequent production crop becomes established and occupies the soil. Decomposing cover crop residues can inhibit, not affect, or stimulate weeds, depending on cover crop species, biomass, and maturity, soil and weather conditions, and weed species

present in the field. As a result, green manures may or may not reduce weed pressure in a subsequent cash crop.

Many annual cover crops can be killed by mowing or rolling after full bloom to create mulch in place. This eliminates soil disturbance and bare soil periods between the cover crop and the next cash crop. Whereas these "organic no-till systems" can be challenging to manage, an increasing number of farmers have adopted them, especially for summer vegetables after winter cover crops.

See Resources section for references on cover crops, cover crop management and reduced tillage systems.

Beating the Weeds with Innovative Cover Cropping and Cultivation

David Stern, an organic grower in the Finger Lakes region of New York, has developed an innovative, integrated weed management strategy for his 40-acre vegetable farm. In addition to winter cover crops of rye + vetch and oats + peas, he intercropped vegetables with other widely-available, low-cost cover crops. Red clover is overseeded into winter squash. This hardy, shade-tolerant clover gets established under the squash foliage, rapidly covers the ground after harvest, and is allowed to grow through the following season to reduce annual weeds and rebuild the soil. David sows buckwheat between plastic-mulched rows of sweet potatoes. Just before the sweet potatoes vine out, he mows the buckwheat to produce mulch in place and suppress weeds. He overseeds proso millet (birdseed – low cost!) into spring shell and snap peas; and oats into fall brassicas. Late Irish potato is planted in alternate beds with sorghum-sudangrass, which is mowed periodically to generate mulch for the potato crop.

When it is time to roll out the steel, David combines the efficiency of mechanization with the fine precision of the human eye and hand. He has designed tractor drawn platforms from which workers can comfortably hand weed or operate tractor-mounted wiggle hoes while the tractor moves slowly down the row. He also has a range of tractor drawn implements, from Buddingh basket weeders for tiny weeds to more aggressive Lilliston rolling cultivators and Regi weeders for larger weeds in established crops.

Step 7 – Manage the Soil Weed Seed Bank: Minimize Deposits and Maximize Withdrawals

The reason so many weeds come up soon after tillage is that most soils have a large *weed seed bank* – millions of viable, dormant weed seeds per acre, waiting for the right stimuli (such as the light flash, improved aeration, or accelerated N mineralization associated with tillage; or the wider temperature fluctuations under exposed soil) to germinate and emerge. The weed seed bank is the reserve of viable weed seeds present in the soil, and consists of new weed seeds recently shed and older seeds that have persisted from previous years. The weed seed bank also includes the tubers, bulbs, rhizomes, and other vegetative structures through which invasive perennial weeds propagate.

Every year, weed seed germination, seed decay, and seed consumption by soil organisms draw down the weed seed bank. Then, when the current season's weeds shed their seeds,

they replenish the weed seed bank. Another source for the weed seed bank is the inadvertent arrival of new weed seeds in organic amendments or crop seeds brought onto the farm, in soil carried on footwear or farm equipment, or via wildlife, irrigation, or floodwaters. These “seed imports” tend to be small in numbers, but potentially serious if a new, aggressive weed species is introduced onto the farm.

It is especially important for organic farmers to pay close attention to the weed seed bank. Good organic weed management depends on effective measures to limit weed seed set, as herbicides cannot be used to kill a heavy flush of weeds. Also, the efficacy of mechanical cultivation declines as weed population density increases. A small percentage of weeds will escape even the best cultivation tools, and a small percentage of a high weed population can still hurt yields.

Managing the weed seed bank entails *encouraging “withdrawals”* and *minimizing “deposits.”* Seed inputs can be reduced by cutting or pulling weeds before they set seed, and by mowing or tilling fields as soon as crop harvest is complete. “Walking the field” to remove large weeds from established crops before the weeds set seed is a good way to reduce seed bank deposits. Some growers find that the added labor is a good investment, even on multi-acre fields. Note that large weeds in full bloom can sometimes form mature seeds after being severed or uprooted; they should be chopped fine (e.g., with flail mower), or removed from the field.

Competitive cash and cover crops can reduce weed seed deposits, since a small weed that grows and matures in the shade of a crop may produce 100–10,000-fold fewer seed than a large weed of the same species growing in full sun.

Good sanitation – measures to prevent the introduction of new weed species on the farm – can go far toward preventing future weed problems. When using mulch hay from off farm sources, try to get seed-free hay if possible. Compost manure at high temperatures (140°F for a week, turn to be sure all parts of pile reach this temperature) before spreading. Remove soil from boots, tractor tires, tiller tines, and other equipment before entering the field, especially if the soil comes from another farm. Power-wash shared or rented equipment before and after use. Check crop seed sources to verify that they are free of “noxious weed seeds.” Filter irrigation water before applying to fields, if it comes from rivers that might transport weed seeds from upstream.

It can be virtually impossible to eliminate *all* off-farm sources of weed seeds. Wildlife, floodwaters and other factors beyond the farmer’s control can bring new weed species to the farm. Be vigilant – regular field monitoring can detect a new infestation while it is still small and local enough to eradicate.

On the other side of the ledger, try to make some hefty withdrawals from the weed seed bank. One excellent technique is *stale seedbed*. Till the soil several inches deep several weeks before crop planting, watch closely, and cultivate when a flush of weeds emerges. Cultivate again immediately before planting, this time going *very shallowly* (0.5-1 inch) to avoid stimulating more weed seeds to sprout with the crop. If the final flush of weeds is mainly broadleaf species, you can flame weed to avoid further soil disturbance.

Encourage weed seed predation. Ground beetles, crickets and some other ground-dwelling insects eat weed seeds. Birds, some species of field mice (not the voles that damage crops)

and even slugs (which can damage crop seedlings) glean newly-shed weed seed from the ground. Research has shown that weed seed predation can reduce the current season’s deposits by 50–90% (Menalled et al., 2006). Mow fields promptly after harvest to stop further weed seed formation, but consider delaying tillage to give the “cleanup crew” a few weeks to eat weed seeds already shed. Cover crops can sometimes be interseeded into production crops, or no-till drilled after harvest, to allow both weed seed predation and prompt cover crop establishment.

Provide year round habitat for ground beetles and other weed seed predators by keeping at least part of the field covered by living vegetation or organic mulches as much of the season as possible. Reduce tillage if practical, in order to lessen disruption of habitat for weed seed consumers.

Step 8 – Knock the Weeds Out at Critical Times

The “control” part of organic weed management aims to remove weeds that threaten current or future production at the least possible cost in labor, fuel, machinery, and soil quality. Trying to eliminate every weed on the farm would likely lead to red ink and defeat efforts to build healthy soil. Thus, the farmer must continually evaluate when weed control operations are necessary or most advantageous. Generally, the critical times for weed control are:

- When the crop is planted.
- When flushes of weed seedlings are just emerging.
- During the crop’s minimum weed-free period.
- When perennial weed reserves reach their minimum.
- Before weeds form viable seed or vegetative propagules.

The weeds that do the most damage to crops are those that emerge before or with the crop. Thus, it is vital to plant into a clean seedbed. A seedbed prepared several days before planting may look clean, yet have millions of germinating weed seeds per acre, already getting a head start on the crop to be planted. Whenever possible, plant immediately after the final step in preparing the soil – whether that step is harrowing, rototilling, incorporating amendments, shaping the beds, or strip-tilling the crop rows. When in doubt, lightly stir the soil surface with your fingertips or a rake and look for the “white threads” of germinating weeds.

For many crops, blind cultivation can be used to keep the seedbed clean until the crop is up. Larger-seeded vegetables can be rotary-hoed to give them a head start. Weed seedlings that emerge ahead of slow-germinating crops like carrot can be flamed. Some farmers time this operation by covering a small patch with a pane of glass. When the crop first emerges under the glass, the field is flame-weeded. The rest of the crop then emerges a day or two later, in a clean field.

Timely cultivation, flame weeding, mowing, manual pulling, or mulching can make the difference between success and failure. Early in the season, when the crop is just getting established, get the weeds while they are small. Cultivate shallowly when weeds are just emerging and in the white thread stage. Timely shallow cultivation makes lighter work for the gardener, saves fuel for the farmer, reduces soil disturbance, and destroys millions of weeds per acre before they cause trouble.

In flame weeding, the flamer should move over the ground at a speed and height that briefly scalds emerged weeds, rather than charring them. Properly flamed weeds may take a few hours to show visible signs of damage, then die overnight. Overflaming wastes fuel, and may damage soil life or increase fire hazards. Broadleaf weed seedlings with exposed growing points are most readily killed by flaming. Grass weeds, whose growing points remain underground for the first few weeks of growth, and larger, tougher weeds of any species, may lose foliage to the heat, but then regrow.

Keep the vegetable crop weed-free through its “minimum weed-free period” – usually the first one-third to one-half of the crop’s growing season. Weed-free periods for vigorous summer crops like corn, squash, or transplanted tomato might be 4–6 weeks, and slower-starting crops like eggplant, carrot or onion may require 10 weeks weed-free. Weeds that are allowed to grow during this time are likely to reduce yields significantly, by 10–100 percent. Later-emerging weeds usually have little direct impact on crop yield. After this point, some weed growth may even help by protecting soil and providing beneficial insect habitat. However, weeds that harbor diseases or pests of the crops being produced, promote disease by hindering air circulation, or interfere with crop growth and harvest by climbing and twining plants, should be eliminated throughout the crop’s life cycle.

Invasive perennial weeds that multiply through rhizomes, tubers, and other vegetative structures are the toughest to manage, but even they have a window of vulnerability. When the underground structures have been chopped up by tillage, each fragment regenerates a new shoot, and initially expends its reserves in doing so. Once it has four or more new leaves, the weed begins to replenish its reserves, so cultivate again at the 3–4 leaf stage, making sure that shoot growth is severed. Repeated operations, combined with competition from cover or production crops will eventually exhaust even the most stubborn perennial weeds.

Remove weeds before they multiply. Cultivate, mow, or pull flowering weeds to prevent seed set. Some weeds can mature seeds after they have been uprooted, so get them before blooms open to prevent seed set. Invasive perennial weeds like bermudagrass and Canada thistle can propagate underground any time they are allowed to grow continuously for more than four weeks, or attain a foot or more in height. Perennial weed infestations may require periodic cultivation, chopping, or mowing throughout the cropping cycle.

Timely application of organic mulch can enhance control of many annual weeds. Once the crop is established, hoe or cultivate shallowly early on a clear, hot day, let the uprooted weeds die in the sun, then spread hay or straw mulch that evening or the next day to conserve moisture and discourage additional weed emergence. This strategy often gives equal or superior weed control for fewer cultivation passes.

In plastic-mulched crops, monitor planting holes for emerging weeds, and remove them while still small enough to pull easily. Usually, one weeding is sufficient, after which the crop shades out later-emerging weeds. Control alley weeds sufficiently to prevent weed propagation, maintain air circulation around the crop, and facilitate harvest.

Step 9 – Utilize Biological Processes to Further Reduce Weed Pressure

Biological controls play a major role in insect pest management in organic and sustainable farming systems. Beneficial insect releases and beneficial habitat plantings (farmscaping, or conservation biological control) often form the foundation of organic insect pest management. What about biological weed control? Considerable research has been conducted on biological control of weeds with herbivorous or seed-eating insects, specific microbial pathogens of weeds (“bioherbicides”), and soil microorganisms that suppress weed germination, emergence, or growth. At this time, however, few organic vegetable growers utilize weed biocontrol agents. Although ongoing research may expand the future role of weed biocontrol products, they may not ever achieve the prominence of the many biological insect pest controls that are now widely used. Why is this so?

Most insect pest outbreaks involve one or two insect species attacking a specific crop. Often, the pests can be controlled through conservation or augmentative release of their specific natural enemies. In contrast, many different weed species appear each year in the field. A specialist biocontrol agent that knocks out one or two species may not significantly reduce overall weed growth, while a generalist agent that attacks most or all of the weeds present would likely damage the crop as well. Furthermore, the efficacy of experimental bioherbicides depends greatly on weather, soil, and other factors that vary widely from farm to farm and from year to year. However, specific weed-eating insects have been used successfully against several invasive exotic weeds in rangeland and natural ecosystems (see sidebar next page).

Although organic farmers rarely use biological *products* or *agents* in weed control, weeds can be impacted by several biological *processes*, including:

- Herbivory – consumption by livestock, wildlife, or insects
- Weed seed predation and decay
- Disease caused by bacteria, fungi, or other agents
- Plant–soil–microorganism interactions that modify the competitive relationship between crop and weed
- Allelopathy by cover crops or production crops

Understanding these processes and how various cultural practices and weed control measures influence them can lead to improved organic weed management strategies. Much of this is still in the “research and discovery” phase.

Weed seed *predation* by ground beetles and other macroscopic organisms has been shown to reduce weed seed banks significantly under field conditions (Menalled et al., 2006). Maintaining organic mulches or vegetative cover year round in part of the field provides habitat for seed predators. Management strategies to promote weed seed *decay* by soil micro-organisms have not consistently shortened the half-life of the weed seed bank. Claims that organic farming or particular approaches to organic farming directly reduce weed populations or weed aggressiveness by enhancing soil life or changing the soil nutrient balance (e.g., higher calcium levels) have not been validated through controlled trials. However, good organic practices and healthy soils can enhance crop vigor (Step 5 above), thereby reducing weed problems.

Classical Biological Control of Weeds

The introduction of insects to combat weeds usually takes the form of classical biological control or inoculative release. Relatively small numbers of an insect that feeds on a specific weed species, or a closely related group of weed species, are released at several points within the weed's range. When the releases are successful, the insects multiply and spread over a number of years, gradually bringing the weed under control over a wide geographic area.

This approach is most often used against an invasive exotic weed that has become a major problem in pastures, rangeland, other agroecosystems, waterways, or native plant communities over a wide region, and is not easily suppressed by other means.

Classical biocontrol of an exotic weed normally entails a cooperative effort of professionals from several disciplines, such as entomology, ecology, native plant conservation, weed science, and range management. Investigators go to the weed's region of origin to identify, collect, and evaluate its natural enemies as potential biocontrol agents. Often, two or three different species are utilized simultaneously to enhance control of the target weed. Potential biocontrol insect(s) are carefully evaluated in quarantine for a year or more to ensure that they will attack only the target weeds, and not become pests of crops, native plants, or other nontarget vegetation.

In the United States, the USDA has worked in cooperation with land grant universities to tackle several exotic weeds through classical biological control, such as:

- Alligator weed in TX, MS, LA, and FL
- Musk thistle, plumeless thistle, and Canada thistle in VA, AR, TN, TX, and KY
- Klamath weed, tansy ragwort, spotted knapweed and several exotic thistles in rangeland in western states
- Purple loosestrife in VA, TN, and AL, as well as parts of the Northeast and Midwest
- Water hyacinth in FL, TX, and AL
- Puncturevine in TX, OK, and FL

This approach is rarely used in croplands, where many unrelated kinds of weeds occur, and routine tillage, cultivation, and pesticide use in crops generally interfere with the biocontrol agents. However, classical biological control may play an effective role in removing one of the above-listed invasive plants from pastures, conservation buffers, or field border habitat plantings, especially on organic farms that use fewer and less-persistent insecticide sprays. See Resources section for a source of weed biocontrol agents.

In addition, diversified farming systems that include livestock and/or poultry in addition to vegetables and other annual crops offer expanded weed management options. For example, if a field that has been devoted to annual crop production becomes too weedy, rotating the field into perennial grass-legume pasture or hay for a few years can break the life cycle of the "weeds of cultivation" and reduce their seed banks. Good rotational grazing practices and haying practices can enhance weed control and prevent the buildup of perennial pasture weeds during this period. Many farmers who use such rotations report enhanced yields and reduced weed pressure when the field is returned to vegetable production.

Grazing livestock in fields immediately after vegetable harvest can help curtail weed growth and weed seed production, and poultry will consume weed seeds on the soil surface. Livestock can be useful in removing diseased crop residues that might otherwise require composting, burning, or burial by inversion tillage for disease control.

Livestock can also be used to graze down understory vegetation in orchards, Christmas trees, and other tree plantings (silvopasture), a practice that can accomplish weed management, livestock nutrition, and fertilization (manure) simultaneously. Repeated intensive grazing can clean up a weed-infested field for future crop production. The weeds should be grazed to the point of severe defoliation at short intervals to deplete underground reserves of perennial weeds. Hogs can be especially effective against perennial weeds, as they root out and consume fleshy roots, rhizomes, and tubers.

Weeder geese are certain African and Chinese varieties of geese that have been used for centuries to remove young grasses and other weeds from established crops, including berry plantings, vineyards, and orchards. Weeder geese require water, shade, and fencing for containment and protection from predators while they are working in the fields. They control weeds most effectively during their first year of life, and should be introduced to the fields at the age of six to eight weeks. Older, second-season geese weed much less actively, so it is common practice to utilize the geese for weed control for one season, and then finish them for meat.

In utilizing farm animals for weed management, be sure to consider what weeds are present, and the grazing needs and preferences of the livestock. Grazing for weed control works best on weeds that provide high quality forage, such as johnsongrass, bermudagrass, quackgrass, crabgrass, pigweed, and lambsquarters. It will not work for unpalatable species like horsenettle or thistles, and grazing large amounts of succulent but toxic weeds such as docks and St. Johnswort (=Klamath weed) can endanger livestock health.

One limitation of livestock for weed control is that most animals do not digest all the seeds they consume. As a result, their manure can carry or spread weed seeds from field to field. Thus, they control weeds most effectively when they graze before the weeds set seed.

Finally, it is important to protect food safety when utilizing livestock, poultry, or weeder geese to manage weeds in food crops. Under USDA Organic Standards, uncomposted manure may not be applied to the field within 120 days prior to harvest of organic food crops that have contact with soil or soil particles, or 90 days for crops like sweet corn or tree fruit that have no contact with soil. This rule applies to droppings left by livestock, poultry, or weeder geese, as well as manure applications, and is a good guideline for protecting food safety on all farms. Running livestock after vegetable harvest and just before cover crop planting, and during the pasture/sod phase of a long term rotation, are effective ways to utilize animals to manage weeds and build soil fertility without compromising food safety or organic certification status.

Crop allelopathy against weeds can also be considered a biological effect. In addition to cover crops, a few vegetable varieties have been shown to exert significant allelopathic activity against weeds, especially weed seedlings. Many allelopathic relationships are quite specific. For example,

sunflower root exudates inhibit seedling growth of wild mustard and other broadleaf weeds, but have little effect on grasses. Sweet potatoes strongly inhibit yellow nutsedge and velvetleaf, but have relatively little effect on pigweed, morning glory, and coffee senna. In no-till field trials, rye residues are strongly allelopathic against pigweed and lambsquarters, but not ragweed.

Recently killed rye mulch is highly suppressive against lettuce and other small-seeded vegetables, much less so for large-seeded vegetables like snap bean, and not at all on transplanted tomato, pepper, cucurbits or brassicas. Transplants and large seeds are inherently less susceptible to allelopathic suppression. Furthermore, the allelochemicals given off by cover crop mulch are concentrated near the soil surface. Transplants and large seeds are planted deep enough so that their roots escape the zone of high allelochemical concentrations. This tolerance is often utilized in fields whose weed floras are dominated by small-seeded annuals that germinate from near the soil surface. For example, tomato and other transplanted summer vegetables often do well in a killed rye + vetch mulch, which usually provides several weeks' selective control of many summer annual weeds.

As specific allelopathic relationships become better understood, crop rotations and cover cropping practices can be designed to give crops an edge over certain weeds.

Step 10 – Bring existing weeds under control before planting weed-sensitive crops

Healthy soil, optimum nutrition, appropriate planting dates, and best cultural practices enhance the ability of most vegetables to deal with weed pressure. However, some crops are inherently weed-sensitive and require extra attention to protect them from weed competition even in the best of circumstances. Factors that make a crop especially vulnerable to weeds include slow early growth, a long establishment period, and cultural requirements that limit options for managing weeds with tillage and cultivation.

Weed control in perennial horticultural crops like asparagus, cane fruit, young or dwarf fruit trees, and some cut flowers can be quite difficult, especially when perennial weeds dominate the weed flora. Bring existing weed pressure under good control through strategic tillage and intensive cover cropping before planting perennial vegetable, fruit or ornamental crops. Continue with diligent weed control during the first few years after planting in order to get the crop well established. Asparagus, some perennial herbs, and perennial cut flowers do not compete well against weeds, and may continue to need intensive weed management throughout their lifetimes. Invasive rhizomatous or tuber-forming perennial weeds pose especially severe problems in perennial crop production. Try to avoid these weeds through site selection and site preparation for perennial crops.

Site preparation can include tillage methods that will effectively control existing weeds, cover cropping, sheet mulching (a layer of cardboard or several layers of newsprint plus several inches of organic mulch), soil solarization (covering the soil with clear plastic for a few weeks during hot weather to kill weed seeds and propagules in the top few inches of soil), or manual spot-weeding. Many farmers grow

and till in a series of highly competitive cover crops before setting out asparagus crowns, young berry bushes, or fruit trees. Cover crops that become infested with invasive perennial weeds or large numbers of other weeds should be mowed, tilled in, and immediately followed by another cover crop.

Soil pH, nutrient levels, and physical condition should be carefully assessed and adjusted through appropriate amendments to optimize growing conditions for the desired crop. Good site preparation and pre-plant weed control can save the grower many days of backbreaking labor digging and pulling weeds out of the new planting, and can make the difference between success and failure.

Other weed-sensitive crops with shorter life cycles, such as strawberry, onion, leek, garlic, carrot, and parsnip, require essentially weed-free conditions for at least several months after planting. Growers often place these in their rotations following highly weed-competitive cover crops, “cleaning crops” that facilitate weed control and reductions in the weed seed bank, or both. Cleaning crops include vegetables like potato, sweet potato, corn, cabbage, and broccoli that can be cultivated vigorously and hilled up early in their life cycle, and compete well against weeds later on. The wide spaces between rows of winter squash can be cultivated several times to flush out weeds before the vines spread out; however later-emerging weeds often set seed during the crop's long maturation period. For vegetables like carrot and onion, growers often employ fallow cultivation or stale seedbed for a few weeks before planting to draw down the weed seed bank.

What is “Organic No-Till,” and is it Practical?

Organic no-till usually refers to mechanically killing a high biomass cover crop without tillage (usually roll-crimping or flail mowing), followed by no-till planting of transplanted or large-seeded vegetable or row crops. Production crop can also be planted no-till into winterkilled cover crop residues. Examples of this practice include tomato and pepper transplanted into roll-crimped winter rye + hairy vetch, fall brassicas planted into flail-mowed summer foxtail millet + soybean, and early spring vegetables planted into winter-killed oats + peas. Because *continuous* no-till is not practical in organic production, fields are normally tilled after vegetable harvest before planting the next cover crop, and the system is properly known as “rotational no-till.”

Whereas these reduced-tillage systems can enhance soil quality, reduce flushes of annual weeds, and give good vegetable yields, they commonly fail when perennial weeds are present or overall weed pressure is high. Nutsedges, quackgrass, bermudagrass, johnsongrass, Canada thistle, bindweeds, and even small clumps of fescue, timothy, and clover left from recently turned sod crops will readily grow through the heaviest of cover crop mulches and compete severely with no-till planted vegetables. High populations of annual weeds or a large seed bank of annual weeds can also spell trouble.

Rotational organic no-till should be considered a “weed-sensitive system,” and existing weeds should be brought under control first before attempting no-till cover crop management.

Weed Management Checklist for Perennial and Other Weed-Sensitive Crops

- Choose production sites carefully before setting out asparagus crowns, strawberry plants, and other perennials. Consider site topography, aspect, air circulation, and microclimate; soil quality, fertility, and pH; and existing vegetation, especially weeds.
- If possible, avoid sites with aggressive weeds, especially invasive perennials.
- Choose vigorous varieties well-adapted to your climate and soil conditions. This is especially important for perennial crops.
- Get a good soil test and amend the soil to optimize growing conditions for your crop.
- Devote one full season to site preparation prior to planting – more if perennial weed pressure is heavy. Use tillage and cover cropping practices that target the weeds present. Incorporate organic and natural mineral amendments as needed during this time.
- Continue whole-field weed reduction and soil improvement through cultivation and cover crops right up until planting time.
- Lay out crop rows and irrigation lines to facilitate ongoing weed management during crop establishment.
- Plan within-bed weed control measures to eliminate competition against the young crop. Use organic mulch, landscape fabric, or timely manual weeding.
- For weed-sensitive annual vegetables and strawberries, choose those fields with the lowest weed pressure.
- Design crop rotations to facilitate reduction in weed pressure during the year(s) preceding a weed sensitive crop. Select cover crops that fight weeds effectively, yet are easy to manage prior to vegetable planting.
- Precede early spring onion and carrot with a late-summer, weed-suppressive cover crop that will winter-kill and thereby facilitate seedbed preparation.
- Utilize stale seedbed or cultivated fallow to reduce the weed seed bank just before sowing a weed-sensitive crop.
- Consider soil solarization to reduce weed populations before planting perennials or other high-value, weed-sensitive crops.
- Employ no-till and minimum-till cover crop management systems only in fields with light weed pressure and few perennial weeds.
- When rotating a field out of sod crops (pasture or hay) into vegetables, till down cover crops during the first year of production before attempting no-till.

Step 11 – Keep Observing the Weeds and Adapt Management Practices Accordingly

Nothing in this information sheet can tell you as accurately how to manage the weeds on your farm, as your own observation! Keep watching the weeds through the season and year after year. What tactics work best? What crops or rotation sequences seem to suppress – or encourage – certain weeds, or to lessen or increase weed control labor?

Some weeds may indicate certain soil conditions, such as nutrient imbalances, compaction, or poor aeration. There is a lot of traditional lore on this subject – some well substantiated and some less so. Several books have been written on this topic, but again your observations are probably the best guide.

In general, increasing problems with *annual* weeds may result from frequent tillage on a “predictable” schedule, so reduce tillage or vary timing and method, and consider rotating weedy fields into perennial cover or pasture for a few years. Also try overseeding cover crops into established vegetable or row crops at the time of last cultivation.

Some annual weeds, including pigweeds and foxtails, have adapted to no-till systems, and will emerge in untilled fields, especially when the soil is mostly bare. Increase ground coverage or till strategically to address the problem.

If *summer annual weeds* get bad in warm season vegetables, rotate to cool season vegetables and competitive summer cover crops. If *winter annual weeds* become a problem in cool season vegetables, rotate to summer vegetables and vigorous winter cover crops.

If you use the moldboard plow or other inversion tillage regularly, and *large seeded annual weeds* such as velvetleaf, common cocklebur and morning glories are your biggest headache, consider switching to shallow, non-inversion tillage. On the other hand, if you rely on the rototiller, and *small-seeded weeds with short lived seeds*, such as galinsoga are building up to unmanageable populations, a one-time pass with the moldboard plow may bury much of the weed seed bank to a depth from which seedlings cannot emerge, and at which the seeds gradually die. This strategy has even been used with fair success against moderately long-lived seeds, such as pigweed. Be sure to keep subsequent tillage quite shallow for a few years after plowing to avoid exhuming the seeds while they are still viable.

Increasing problems with *invasive perennial* weeds may indicate a need for increased tillage for a period of time to bring these problem weeds under control. Consider the root / rhizome structure and specific vulnerabilities of the target weed when choosing tillage implements. For example, a chisel plow can effectively bring quackgrass, bermudagrass, or nutsedge rhizomes to the surface to dry out or freeze, but can be ineffective or even counterproductive for deeper-rooted invasive perennials like Canada thistle. Follow tillage with vigorous, weed-smothering cover crops to minimize soil degradation and to enhance weed suppression. If an asparagus bed or berry patch has become infested with these weeds, consider tilling it up and rotating the area into annual crop production. Transplanting the perennial crop root crowns to a clean site before destroying the weeds may or may not be cost effective, depending on crop vigor and size of planting.

Carefully observe the *timing* of heaviest weed emergence and growth, and consider shifting planting schedules so that your crops miss the most intense weed competition. Many growers delay planting for a couple of weeks to allow the late spring flush of weeds to come up, to be destroyed during seedbed preparation. The long growing seasons in the South allow considerable flexibility in adjusting planting date to avoid times of peak weed emergence. In comparison delaying planting in the upper Midwest or Northeast may result in a yield reduction because of the short season..

Step 12 - Experiment, and Watch for New Developments in Organic Weed Management

When dealing with weeds organically, don't be afraid to try something new! You may read about a new weed control tool, NOP-allowed herbicide or bioherbicide, cover crop, or crop rotation strategy in a farm magazine that sounds like it might be worth trying on a tough weed problem on your farm. You might think of a novel way to use, combine, modify or fabricate cultivation implements to better match your cropping system or weed complex. Or, you might come up with an entirely new strategy to give the crop the advantage. Try out any of these ideas by conducting a simple on-farm experiment. Farmer innovation and on-farm trials are the time-honored way that humankind has made advances in farming and food production.

If a certain cover crop or vegetable variety seems to have outcompeted a problem weed that has been generally difficult to control, it might simply be a "chance" occurrence related to weather or soil variations, or it might be a "real" effect. Similarly, an unusually good result with a variation on normal practices could be a lead. Try it again next year and see what happens.

University of Vermont Extension Specialist Vern Grubinger (1997) offers a few words of advice on realizing the most benefit and the least risk when experimenting with new weed management tactics:

"Start on a small scale with tools and techniques that are new to your farm

"Identify your most problematic weeds and compare different combinations of rotations, cover crops and cultivation tools to see how effective they are in providing control

"Keep an eye out for new tools, or new ways to use old tools.

"Leave a control row or section untreated, so you can see the effectiveness of your tactics."

In addition watch for new developments in ecological weed management. Researchers and farmers continue to develop new tools and tactics to manage weeds without herbicides. Peruse farming magazines and publications for practical applications of their work, from new cultivation tools to new strategies for particularly stubborn weed problems.

Some cutting edge areas of research may take longer to yield practical results, yet bear watching and possible integration into a farm's weed management strategy. These range from classical biological controls against new invasive species, to specific weed-crop allelopathic relationships, and manipulation of weed-crop-soil-microbe interactions to give the crop a competitive edge over certain weeds. For example, recent findings suggest that fall-planted, winter-killed radish cover crops can suppress spring weeds and at the same time enhance spinach yields (see sidebar on next page).

While none of these endeavors is likely to yield a "big hammer" to replace herbicides or steel, they can contribute additional "little hammers" to reduce the amount of tillage and cultivation needed. In particular, emerging information about specific allelopathic and plant-soil-microbe interactions may help hone and refine the preventive tools of crop rotation, cover cropping, and soil management.

Following are a few examples of experimental weed control practices, with a brief summary of field results to date.

Nighttime Cultivation

Because tillage exposes weed seeds to a light flash, cultivation to remove existing weeds is often followed by a new flush of weeds. This can result in a soil-exhausting "cultivation treadmill" if the soil's weed seed bank is large. Some growers and researchers have experimented with cultivating at night or with an opaque cover over the tillage implement. This eliminates the light stimulus, and has reduced subsequent weed emergence, usually by 20–70 percent.

Soil Solarization

Covering the soil surface with clear plastic mulch during hot sunny weather can raise the temperatures of the top few inches of soil sufficiently to kill vegetative propagules (e.g., rhizomes of johnsongrass) and some weed seeds. A few growers use this method on a small scale to prepare beds for high value specialty crops. Soil solarization is not so effective on dormant or "hard" weed seeds, or on any seeds or propagules buried at a depth of six inches or more.

Nutsedge tubers are quite heat tolerant (to about 120°F) and difficult to kill by solarization; however solarization induces wide fluctuations in soil temperature that break nutsedge tuber dormancy (Chase et al., 1999). Tips of emerging shoots open, become trapped, and are heat-killed under the plastic, which can significantly weaken the tubers, and facilitate control by subsequent cultivation.

Biological Weed Controls and Organic Herbicides

Several organic (OMRI approved) herbicides based on plant allelochemicals or essential oils are commercially available. They are fairly expensive and are most practical for spot applications such as clearing weeds from around a farmstand or dealing with a localized infestation of a noxious weed.

Researchers have also developed bioherbicides based on specific plant pathogens. Two products – DeVine against strangervine in citrus, and Collego against northern jointvetch in rice and soybeans, achieved commercial success in the 1980s. These products are now off the market because the target weeds were largely eliminated, and demand for the products dried up. Other bioherbicide agents against pigweeds, hemp sesbania, and sicklepod have shown promise in research trials, but are not yet commercially available.

Classical biological control with herbivorous insects was discussed on page 13. Researchers continue to seek new biocontrol agents for new invasive exotic weed problems.

Crop–Weed–Soil–Microbe Interactions

Some fascinating research has been done into the role of soil and root-zone microorganisms in plant–plant interactions and the so-called "rotation effect." Microbes play a role in many specific crop–weed interactions, forming beneficial symbioses with some plants while inhibiting or parasitizing others. For example, mycorrhizal fungi are highly beneficial to legumes, grains, onion family, cotton, strawberry, and many other crops; but are mildly parasitic to weeds and crops in the amaranth, buckwheat, chenopod (spinach, beet, lambsquarters), and purslane families, purple and yellow nutsedges, and a few weedy grasses like annual bluegrass.

Studies have shown that high populations of mycorrhizae in the soil can slow the growth of some of these “non-host” plants, which suggests that mycorrhizae could give “strong-host” crops like grains, legumes and onion family an edge over non-host weeds like pigweeds, lambsquarters, and nutsedges. This possibility merits further investigation.

Brassicas (cabbage, broccoli, turnip, Asian greens, radishes, cultivated and weedy mustards) defend themselves against most fungi, including mycorrhizae, through release of allelopathic glucosinolate and isothiocyanate compounds.

Whereas some researchers are attempting to give crops an edge over weeds by adding certain microbes to the soil, the existing microbiota in most soils is likely to overwhelm the added inoculant. Direct inoculation of the roots of strong-host crops with the correct mycorrhizal symbionts may be an exception, and has sometimes shown promising results. One future practical application of soil microbiology research may be to fine-tune crop rotations, soil amendments, and management practices to optimize soil microbiota for the crop and thereby give it an advantage over weeds.

Spinach Thrives after Radish Cover Crop

by Mark Schonbeck

In 2006, Dr Ron Morse and I observed much better yields of spring spinach after August-planted, winterkilled radish cover crops than after oats, pearl millet, or legumes (also winterkilled). Whereas the radishes suppressed weeds well into April despite leaving little surface residue as of the beginning of March, it seemed to promote establishment of spinach, possibly by preventing damping-off in the seedlings. We tried it again in 2007, with both daikon (edible white cylindrical root) and fodder radish (inedible, woody, red taproot). That year, with a drier spring, the radishes suppressed weeds into May, and again doubled spinach stands and yields. Thinking it might still be a fluke, or a site-specific phenomenon, I hesitated to shout about it too far and wide.

In 2009, a former student of Dr. Ray Weil, world class soil scientist at University of Maryland, contacted me to share similar results from Maryland, including a photo of the experimental field showing taller, thicker spinach wherever radish had been grown and winterkilled. Then, during an interview at Grassroots Farm, farmer Joe Tessauro mentioned that spring spinach planted after winterkilled daikon had also done unusually well at nearby Moon Indigo Farm and Full Circle Farm, and that this planting sequence has “become part of vegetable growing lore in Floyd County [Virginia].”

Although I was not able to reproduce this beneficial radish-spinach effect in my own garden a few years ago, this one negative result can be attributed to an unusually mild winter that did not fully winterkill the radish, followed by poor care for the spinach crop on my part. So, that leaves five strong successes out of six trials, which is an unusually pronounced and consistent pattern for a “rotation effect” like this. Try it in your fields and see if it works for you.

Caution: to avoid building up clubroot and other persistent brassica diseases, do not plant any brassica family crops for three years after the radish.

Based on article in Virginia Biological Farmer, Vol. 32, No. 4 (4th Quarter 2009), p 8), www.vabf.org.

Resources for Organic Weed Management

Ecological Weed Management Principles and Practices

C. A. Chase, T. R. Sinclair, and S. J. Locascio. 1999. Effects of soil temperature and tuber depth on *Cyperus* spp. *Control. Weed Science* 47: 467-472.

Denise M. Finney and Nancy G. Creamer. 2008. Weed Management on Organic Farms. Chapter within the *New Organic Production Guide* published by the Center for Environmental Farming Systems, 33 pp. Available at <http://www.cefs.ncsu.edu/resourcesorganicproduction.htm>.

Vern Grubinger, 1997. 10 Steps Toward Organic Weed Control. *American Vegetable Grower*, Feb. 1997, pp 22-24.

Matt Liebman and Eric R. Gallandt, 1997. Many little hammers: ecological approaches for management of crop-weed interactions. In L.E. Jackson, ed., *Ecology in Agriculture*, pp 291-343. Academic Press, San Diego, CA.

Fabian D. Menalled, Matt Liebman and Karen Renner. 2006. The ecology of weed seed predation in herbaceous crop systems. ed. p. 297-327 In *Handbook of Sustainable Weed Management*. H. P. Singh, D. R. Batish and R. K. Kohli Eds. Binghamton, NY: Haworth Press.

Anne and Eric Nordell, *A Whole-Farm Approach to Weed Control*. A compilation of articles by the Nordells, published in the *Small Farmers Journal*, on their "weed the soil" system. Approximately 50 pp. Available for \$10 by mail order, Eric and Anne Nordell, 3410 Rt. 184, Trout Run, PA 17771.

Preston Sullivan. 2003. *Principles of Sustainable Weed Management for Croplands*. ATTRA Publication #PO39, 15 pp. National Sustainable Agriculture Information Service. Excellent overview with extensive resource list, available at www.attra.org/attra-pub/weed.html.

On-line resources on Ecological Weed Management

IPM for Organic Crops, an on-line training curriculum for Extension and also open to the public, includes several modules on organic weed management.* Currently available at: <http://campus.extension.org/course/view.php?id=92>.

Organic Agriculture Resource Area on eXtension, the Extension Service's on-line information database available to the public. The eOrganic project has recently posted a body of practical information, including about twenty articles on weed management in vegetable systems,* and will be expanding and improving this information over the next few years. Visit www.extension.org and click on the link for the Organic resource area.

Weed Identification – Books, CD's and Web Sites

Charles T. Bryson, Michael S. DeFelice, ed. 2009. *Weeds of the South*. Photography by Arlyn W. Evans. Excellent and beautifully illustrated field manual covering about 400 weed species of the southern region. Includes key to plant families.

Georgia Cooperative Extension Service, Bulletin 761, 1995. *Weeds of the Southern United States*. 45 pp. Field guide to

120 major weeds of the South. Available for \$3; to order, call Georgia Cooperative Extension at 706-542-8999 or -8575.

S. Hagoood. 2008. *Virginia Tech Weed Identification Guide* [Online]. Department of Plant Pathology, Physiology and Weed Science. Virginia Polytechnic Institute and State University. This resource covers 324 weeds of the southeastern United States, arranged alphabetically by common name and by scientific name. Each entry includes photos of seedling and mature phases, and close-ups of leaves and/or flowers, plus verbal descriptions of life cycle, growth habit, leaves, flowers, and specific identifying characteristics. An interactive key to grass weeds is included to assist the user with this large family of hard-to-identify species. Available at: <http://www.ppws.vt.edu/weedindex.htm>.

R. Old. 2008. *1,200 Weeds of the 48 States and Adjacent Canada: An interactive identification guide* [DVD]. XID Services, Inc., Pullman, WA. This DVD includes a database and an interactive key to 1,200 agricultural weeds throughout the continent. Instead of moving through dichotomous categories in a set sequence, the user can select from a wide range of vegetative and reproductive characteristics, using the most obvious traits of the specimen at hand to narrow down the list of possibilities. Available at: <http://xidservices.com/>.

Radford, A. E., H. E. Ahles, and C. R. Bell. 1968. *Manual of the vascular flora of the Carolinas*. University of North Carolina Press, Chapel Hill. Most common weeds of the southeastern US will be included in this flora.

Jon M. Stuckey, Thomas J. Monaco & A.D. Worsham. 1994. *Identifying Seedling and Mature Weeds Common in the Southeastern United States*. North Carolina Agricultural Research Service & NC Cooperative Extension Service.

United States Department of Agriculture, Natural Resources Conservation Service. *PLANTS Database*. Available at: <http://plants.usda.gov/>

USDA, Agricultural Research Service, 1971. *Common Weeds of the United States*. Dover Publishing, Inc., New York, NY.

Richard H. Uva, Joseph C. Neal and Joseph M. DiTomaso, 1997. *Weeds of the Northeast*. Cornell University Press, Ithaca, NY. 297 pp. Covers 299 weeds, with excellent photos and descriptions, includes majority of agricultural weeds of the upper South.

Weed Science Society of America. *Photo Gallery* [Online]. Weed Science Society of America. Has photographs of many weeds, including close-ups of leaves and flowers that can aid in identification. No verbal descriptions at this site. Available at: <http://www.wssa.net/Weeds/ID/PhotoGallery.htm>.

Cultivation Tools and Methods

Greg Bowman, ed. 1997. *Steel in the Field: a Farmer's Guide to Weed Management Tools*. Sustainable Agriculture Network, National Agricultural Laboratory, Beltsville, MD. 128 pp. Order at www.sare.org.

A. M. Peruzzi, A., M. Ginanni, M. Fontanelli, M. Raffaelli, and P. Barberi. 2007. Innovative strategies for on-farm weed

management in organic carrot. *Renewable Agriculture and Food Systems* 22: 246–259.

Josh Volk. 2008. Basic tools for mechanical cultivation. *Growing for Market* 17: 7–10.

Recommended Vendors of Cultivation tools

Bezzerrides Brothers (559-528-3011, www.bezzerrides.com).

Bigham Brothers (www.bighambrothers.com/lilliston.htm, 806-745-0384).

Brillion Farm Equipment (www.brillionfarmeq.com, 800-409-9749).

Buddingh Weeder Co. (616-698-8613).

Earth Tools, Inc., Joel Dufour, manager, 1525 Kays Branch Road, Owenton, KY 40359, www.earthtoolsbcs.com, 502-484-3988. This company offers a wide range of excellent hand tools and walking (two-wheel) tractor implements for weed control at the market garden scale.

Vendor of Classical Biological Controls of Invasive Exotic Weeds

Biological Control of Weeds, Inc., 1418 Maple Drive, Bozeman, MT 59715; tel. 406-586-5111; www.bio-control.com/products.asp.

Cover Cropping and Reduced Tillage

George Kuepper, 2001. Pursuing Conservation Tillage Systems for Organic Crop Production. National Sustainable Agriculture Information Service (ATTRA). Available at www.attra.org/attra-pub/organicmatters/conservationtillage.html.

Preston Sullivan, 2003. Overview of Cover Crops and Green Manures. National Sustainable Agriculture Information Service (ATTRA) publication #IP024, 16 pp. Available at www.attra.org/attra-pub/covercrop.html.

Sustainable Agriculture Network. 2007. *Managing Cover Crops Profitably, 3rd Edition*. National Agricultural Library, Beltsville, MD. 2007. 244 pp. \$19.

Virginia Association for Biological Farming offers a series of four information sheets on cover crops and reduced tillage by Mark Schonbeck and Ron Morse, entitled:

Cover Cropping: On-farm, Solar-powered Soil Building
Cover Crops for All Seasons
Using Manually-Operated Seeders for Precision Cover Crop Plantings on the Small Farm
Reduced Tillage and Cover Cropping Systems for Organic Vegetable Production

These are available at www.vabf.org.

Appendix: Scientific (Latin) Names of Weeds and Crops Mentioned in Text

Weeds

Alligatorweed – *Alternanthera philoxeroides*
Bermudagrass – *Dactylon cynodon*
Bindweed, field – *Convolvulus arvensis*
Bindweed, hedge – *Calystegia sepium*
Brambles – *Rubus* spp.
Burdock – *Arctium minus*
Carrot, wild (= Queen Anne’s lace) – *Daucus carota*
Chickweed, common – *Stellaria media*
Cocklebur, common – *Xanthium strumarium*
Crabgrasses – *Digitaria* spp.
Dandelion, common – *Taraxicum officinale*
Dayflower, Benghal – *Commelina benghalensis*
Deadnettle – *Lamium* spp.
Dock, broadleaf – *Rumex obtusifolius*
Dodder – *Cuscuta* spp.
Fescue, tall – *Festuca arundinacea*
Foxtails – *Setaria* spp.
Foxtail, giant – *Setaria faberi*
Galinsoga – *Galinsoga* spp.
Garlic Mustard - *Alliaria petiolata*
Goosegrass – *Eleusine indica*
Greenbrier – *Smilax* sp.
Horsenettle – *Solanum carolinense*
Jointvetch, northern – *Aeschynomene indica*
Johnsongrass – *Sorghum halapense*
Klamath weed (= St. Johnswort) – *Hypericum perforatum*
Knapweed, spotted – *Centaurea biebersteinii*
(= *C. maculosa*)
Kudzu – *Pueraria lobata*
Lambsquarters, common – *Chenopodium album*
Lettuce, prickly – *Lactuca serriola*
Loosestrife, purple – *Lythrum salicaria*
Milkweeds – *Asclepias* spp.
Morning glories – *Ipomoea* spp.
Mustards, wild – *Brassica* spp. and *Sinapis arvensis*
Nutsedge, purple – *Cyperus rotundus*
Nutsedge, yellow – *Cyperus esculentus*
Pigweeds – *Amaranthus* spp.
Poison-ivy – *Toxicodendron radicans*
Pokeweed, common – *Phytolacca Americana*
Puncturevine – *Tribulus terrestris*
Purslane, common – *Portulaca oleracea*
Quackgrass – *Elymus repens* (= *Elytrigia repens*)
Ragweed, common – *Ambrosia artemisiifolia*
Ragwort, tansy – *Jacobaea vulgaris*
Shepherd’s-purse – *Capsella bursa-pastoris*
Sedge, deep-rooted – *Cyperus entrerianus*
Senna, coffee – *Senna occidentalis*
Sicklepod – *Senna obtusifolia* (= *Cassia obtusifolia*)
Smartweeds – *Polygonum* spp.
Stranglervine (= Milkweedvine) – *Morrenia odorata*
Sowthistle, annual – (*Sonchus oleraceus* and *S. asper*)
Thistle, Canada – *Cirsium arvense*
Thistle, musk – *Carduus nutans*
Tree of Heaven – *Ailanthus altissima*
Thistle, plumeless – *Carduus acanthoides*
Velvetleaf – *Abutilon theophrasti*

Weeds, continued

Waterhyacinth – *Echhornia crassipes*
Witchweed – *Striga asiatica*

Crops

Artichoke, Jerusalem – *Helianthus tuberosus*
Asian greens – *Brassica* spp.
Barley – *Hordeum vulgare*
Bean, bell – *Vicia faba*
Bean, common – *Phaseolus vulgaris*
Beet – *Beta vulgaris*
Broccoli – *Brassica oleracea*, botrytis group
Buckwheat – *Fagopyrum esculentum*
Cabbage – *Brassica oleracea*, capitata group
Carrot – *Daucus carota*
Clovers – *Trifolium* spp.
Clover, berseem – *Trifolium alexandrinum*
Clover, crimson – *Trifolium incarnatum*
Clover, red – *Trifolium pratense*
Corn (sweet and field) – *Zea mays*
Cotton – *Gossypium* spp.
Cowpea – *Vigna unguiculata*
Eggplant – *Solanum melongena*
Fescue – *Festuca* spp.
Garlic – *Allium sativum*
Leek – *Allium porrum*
Lettuce – *Lactuca sativa*
Melon – *Cucumis melo*
Millet, foxtail – *Setaria italica*
Millet, Japanese – *Echinochloa crus-galli* ssp. *frumentacea*
Millet, pearl – *Pennisetum glaucum*
Millet, proso – *Panicum miliaceum*
Oats – *Avena sativa*
Onion – *Allium cepa*
Orchardgrass – *Dactylus glomerata*
Parsley – *Petroselinum crispum*
Parsnip – *Pastinaca sativa*
Peas, vegetable, field, and Austrian – *Pisum sativum*
Pepper – *Capsicum* spp.
Potato, Irish – *Solanum tuberosum*
Potato, sweet – *Ipomoea batatas*
Radish, salad, forage, fodder, daikon – *Raphanus sativus*
Rice – *Oryza sativa*
Ryegrass – *Lolium* spp.
Rye, winter – *Secale cereale*
Sorghum – *Sorghum bicolor*
Sorghum-sudangrass – *Sorghum bicolor X sudanense*
Soybean – *Glycine max*
Spinach – *Spinacia oleracea*
Strawberry – *Fragaria* spp.
Sunflower – *Helianthus annuus*
Squash, winter and summer – *Cucurbita* spp.
Timothy – *Phleum pratense*
Tomato – *Lycopersicon esculentum*
Turnip – *Brassica rapa*
Vetch, common – *Vicia sativa*
Vetch, hairy – *Vicia villosa*
Wheat – *Triticum aestivum*