Weed Management for Organic Producers

Literature Search

by
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Introduction

This literature review was requested by the Saskatchewan Organic Development Council (now the Saskatchewan Organic Directorate). The purpose of the literature review was to summarize weed control literature relevant to organic producers, as a baseline for future research efforts. It was hoped that such a document might be useful to the Saskatchewan Organic Directorate in determining research priorities, to scientific researchers assessing the organic weed control toolbox, and to organic farmers conducting their own research.

This review is presented it in a format that I hope will be both useful to researchers and farmer friendly. I have summarized research results in text form, with citations indicated as numbered endnotes. Endnotes contain full reference material for the first citation of a source. For subsequent citations of the same source, author, year, and the number of the endnote containing the full reference are listed. The summary includes introductory material on the nature of weeds, principles of weed management, and my recommendations for further research. I have also included a section indicating other sources of information.

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Weeds revisited

For many people weeds are bad, a sign of sloppy management, perhaps even an indication of weak morals. Sound weed management starts with revisiting this attitude. Weeds certainly can be problematic. They can also be useful, in themselves and in the lessons that they teach.

Benefits of weeds

In natural environments, weeds are the first species to colonize disturbed habitats. Many weeds are well adapted to survive and reproduce in conditions of very low fertility or frequent disturbance. Weeds can shade the soil surface, reducing evaporation and the harmful effects of full exposure to the sun, and reducing wind speeds at the soil surface. Weeds can be important agents of soil conservation. Weed roots can stabilize erodible soil and provide channels for the movement of water and air in the soil. Weeds may modify the habitat in ways that make a habitat more hospitable for other species.

Some weed roots penetrate so deeply that they tap nutrients unavailable to crop plants. When the weeds die, those nutrients can be mobilized to the surface layers of the soil. Weeds may indicate soil or management conditions. Redroot pigweed, for instance, is especially sensitive to low phosphorous levels. Wild mustard is also sensitive to low phosphorous levels,[1] and lamb's-quarters is associated with phosphorous deficiencies in the soil.[2] Some weeds are highly nutritious, as human food, livestock feed or for wildlife. Weeds can harbour beneficial insects, mychorrizae, birds, etc. Weeds with a shallow nectar source are particularly important as food sources for predatory wasps, hoverflies and other desirable predatory insects.[3]

Perhaps as important as their benefits to the ecosystem, weeds are a sign that nature is alive and a reminder that she is not totally compliant with our domination.

Problems with weeds

The most obvious problem with weeds is that they can reduce crop yields. Weeds use resources such as nutrients, water, sunshine and space that crops might have utilized. Some weeds may limit crop development through chemical means, either while they are alive, or as they decompose. Weeds can cause other problems as well. Some weeds are poisonous and can taint food and feed crops. Green weeds at harvest might interfere with mechanical operations. Weeds can harbour problem insects and crop diseases. Weeds in harvested crops reduce the value of the crop (dockage). Weeds in grasslands can reduce their productivity for livestock..[4] Weeds often carry social stigma that can make farmers uncomfortable on coffee row.

Weeds on organic farms

A study in Saskatchewan indicated that organic systems had more weed species and more individual weeds. Wild mustard, lamb's-quarters and Canada thistle especially were more abundant in organic systems. In that study, differences among years were greater than differences between organic and "conventional" systems.[5]

In experimental comparisons of organic and conventional systems in South Dakota, grassy weed numbers, mostly of green and yellow foxtail were substantially higher after 6 years in the organic system than they were in the conventional system. This was true for cereals, but no for soybeans. Annual broad-leaved weeds did not show consistent trends in this study.[6]

Principles of Weed Management

Weed management in organic farming systems (and in all farming systems, for that matter) has four major elements: 1) determining which weed situations are problems, 2) preventing new weed problems, 3) managing the crop environment to favour the crop over the weeds, and 4) directly treating weeds when steps 2 and 3 are not sufficient.

1. Assessing weed situations

Characteristics of weeds

Weeds are often defined as plants growing where they are not wanted. This definition reflects our adversarial attitude, and does nothing to help us understand the plants themselves. Instead we can look at weeds as components of the agricultural ecosystem. Weeds, like crops, are plants which have evolved with agriculture, and are adapted to the types of disturbances that people impose. Some plants presently regarded as weeds were initially cultivated as crops, for instance, wild oats and lamb's-quarters.[7] A study in 1980 indicated that despite enormous effort, weeds had steadily increased from 1900 to 1980.[8] This trend probably continues.

Most weeds have some characteristics in common. Weeds generally have high seed productivity. Weeds often germinate under a variety of conditions, but some portion of the population remains dormant. Weed seeds in the soil are insurance against conditions that might destroy the active population. Even though weed seeds in the soil are reduced by 95% due to germination and mortality, the seed bank can often recover in a single year.[9] Many weeds develop rapidly, are able to self-pollinate, have well developed seed dispersal mechanisms and tolerate a wide range of environmental conditions.[10]

Many sources are available to help with weed identification.[11] Knowing what weeds are common on your farm will help to determine what lessons can be learned and what management strategies might be effective against them. For example, lets consider the most abundant weed in Saskatchewan, green foxtail (commonly known as wild millet or pigeon grass). Green foxtail is an annual grass with small seeds that birds seem to love. As with most weeds, seed production can be prolific. Seeds that germinate on the soil surface, or in surface chaff, often have trouble rooting, so these species can be less abundant in zero-tillage systems. Root development, even within the soil is not extensive. Therefore, harrowing is often an effective means of control. Green foxtail is a warm season grass. It germinates more quickly and is more competitive at higher temperatures. Thus, it is more aggressive in late-seeded crops (common in organic systems), and less vigorous in cooler situations such as in zero-till, or early seeding. Mature plants vary in size from 1 inch to three or four feet.

The following is a list of the most abundant species in weed surveys across Saskatchewan:[12] wild oats, wild buckwheat, stinkweed, Canada thistle, lamb's-quarters, perennial sow-thistle, Russian thistle, wild mustard, redroot pigweed, shepherd's-purse, kochia, dandelion, quack grass. Some characteristics of these weeds is given in the following table.

Some characteristics of the most common weeds in Saskatchewan. [13,14,15,16,17]

Weed	Life history[a]	Seeds / plant	Germination	Dormancy	Maturity	Preference	Yield losses[b]	Management
Wild oats	A	250	Early	Long	Medium	Wet or low spots	10% for 10	Delayed seeding
Wild buckwheat	A	1,200	Early	Medium	Medium		22% for 30	Delayed seeding
Stinkweed	A, W	15,000	Spring / Fall	Early	Medium to long		20% for 750	Fall or spring tillage
Canada thistle	P	700	Medium	Medium	Late	Field edges	38% for 14 shoots	Fall tillage, mowing
Lamb's-quarters	A	72,000	Early	Long	Late	Organic soils	25% for 200 in barley	Delayed seeding
Perennial sow-thistle	P	10,000				Moist, fertile	No estimate	Mowing, tillage
Russian thistle	A		Early	Medium	Mid to Late	Drier sites	No estimate	Strong competition
Wild mustard	A	3,500	Early, Continual	Very long	Early to late	Cool, moist	35% for 100	
Redroot pigweed	A		Late, Warm	Long	Late	Fertile soil	No estimate	Early crop establishment
Shepherd's-purse	A, W	38,500	Spring/ fall	Medium to long	Early		No estimate	Fall or spring tillage
Kochia	A	14,600	Early	Short			No estimate	Delayed seeding
Dandelion	P					Field edges	No estimate	Tillage deeper than 2 inches
Quackgrass	P						10% per 100 shoots	Tillage, mowing spring / fall

[a] A = annual, W = winter annual, P = perennial

[b] Yield loss estimates for weed number per metre squared in wheat; for instance, 10 wild oats per metre square caused a loss of wheat yield of 10%. For perennial plants, losses are expressed per shoot rather than per plant, because it is difficult to recognize distinct plants in the field.

Characteristics of weed communities

Plant communities develop in response to their environment. Major determinants of the weed environment include factors that are beyond a farmer's control, such as climate, as well as those that are a direct result of farm management. Some factors are a combination of both, the soil temperature and moisture, for instance.

Farm practices can select for different types of weed communities. In a simple example, regular tillage selects for species and individuals that can complete their life cycles between tillage events, or that can survive tillage. When the same practices are consistently used over a long time, plants that are adapted to those practices will become abundant. A key to avoiding an abundance of a particular type of plant is to vary the farming practices so that they do not consistently favour any particular group of plants. This prevents the weed community from adjusting to the practices and building up to problem levels.

When are weeds a problem?

The presence of weeds in crop fields is not automatically damaging and in need of immediate control. For example, a wild oat population in a forage crop or a grain crop cut for feed will not reduce its feed value. Volunteer canola in a wheat field may be of more value than the crop if it can be separated after harvest. A few weeds in a bean or pea field may reduce wind damage and help raise the pods higher off the ground, making them easier to harvest. In a wet year, weeds in a lentil field might stress the crop into flowering, rather than producing only vegetative matter. Weeds that emerge late in the crop may be not cause crop loss in that year. If the field is fenced, they might provide suitable graze after harvest. Each situation has to be assessed within the context of the farm operation. "Sustainable weed management is thus thought- and information-intensive."[18]

Weeds are most damaging to crop yields if they have some advantage over the crop. Four factors are especially important: number, timing, vigour and chemistry. Of course, more weeds are generally more of a problem than few weeds, but weed density alone is not a satisfactory predictor of the outcome of competitions.[19] Sometimes it can even be misleading. For instance, at very high densities, green foxtail plants tend to compete strongly with each other. Even large numbers of the smallest plants probably have little competitive effect on the crop. At medium densities, plants grow larger and can severely reduce crop yields. The effect is similar to that of weeding carrots. The weed "crop" may be more vigorous when there are fewer individuals. In this instance, a moderate reduction in weed numbers may increase the weed problem.

The timing of weed-crop competition is important. Ecologists have defined a "critical period of weed competition". This is the period during which the presence of the weed reduces the yield of the crop. Weeds that are removed before the critical period, or that emerge after the critical period do not cause any yield loss. The exact timing of this period varies for different crops, for different weeds, and under different conditions such as year or location.

Weed vigour is partly a matter of timing. Weeds that emerge before the crop are generally larger and better established than the crop, and thus do more damage to crop yield than those that emerge after the crop. This gives them greater access to soil and spatial resources. Vigour also varies among species. For instance three Canada thistle plants will almost certainly cause more yield loss than three thyme-leaved spurge. Vigour will also depend on plant nutrition, disease, and herbivory.

Some weeds, for example Canada thistle, release chemicals that inhibit their neighbours. This also affects their competitive relationships.

Weeds might be considered a problem if they interfere with harvest. For instance, weeds that remain green at harvest, especially those with fibrous stems, can impede the harvesting operation. The problem depends on the crop. A low-growing weed like wild tomato can cause very little problem in a cereal crop because the plants are mostly below cutting height. In a crop like lentil, shorter cultivars of pea, or bean, severe harvest difficulties may occur. The low cut height means that wild tomatoes are harvested with the crop, and they can stain the pulse and clog the machinery.[20] Weeds like wild buckwheat, that twine through the crop can also be problematic.

Weeds are also a problem if they reduce the quality of the crop. For example, wild mustard seed cannot readily be removed from canola, and can flavour the resulting canola oil if crushed with the crop seed..

When are weeds a problem worth controlling?

The simple answer to this question is that weeds are worth controlling when the problem they cause is greater than the problem the control will cause, or greater than the cost of the control. This concept is termed the economic threshold. In practice, this is not a simple question, and the answer usually depends on the site and on the manager as much as on the weeds present. In some situations, weed control is not warranted, based on economic grounds, even where it is effective.[21] More and more, we are seeing that "complete eradication of non-crop plants is clearly not compatible with modern views of agro-ecology. ... The 'clean crop' option is slowly being replaced by an approach that understands weed control as the management of the crop's environment.[22]

Organic producers have already decided, for whatever reason, that the problem of weeds is not greater than the problem with chemical controls. Chemicals are not unique in warranting concern. All control methods have advantages and disadvantages. Environmental, economic and social factors must be weighed in deciding what control, if any, to use. Does the weed serve any environmental function? Does the control mechanism endanger off-target organisms such as nesting birds, beneficial insects, etc? Does the control mechanism contribute to soil degradation through erosion, loss of organic matter, loss of soil moisture? Can the control mechanism be altered to reduce its negative impact without losing its benefit? Will the damage caused by the weed be greater than the cost of the control? How effective will the control be? How much will control of the weed restore crop yield to its weed-free value?

2. Preventing new weed problems

Weeds enter farms and fields in a variety of ways. The first step in not having a weed problem is not to introduce weeds. Historically, a majority of our weeds were introduced from Europe and other areas of human emigration. On individual farms, weeds are introduced from neighboring farms, from suppliers, from road margin to field and from field to field. This process can be slowed, but not halted, by careful prevention and sanitation. Some seed movement is inevitable, due to birds, mammals, movement during snow melt, etc.

The first step in preventing the introduction of weeds is to sow clean seed. Weed seeds are found as contaminants in the seed from other farms,[23] or seed cleaned at grain elevators.[24] Weed seeds and vegetative parts can be transported on equipment. It is a sound practice to thoroughly clean equipment that moves between fields or beyond weed patches. This is especially important if custom work is done. A tarp over grain, soil or feed being transported will prevent contamination along roads or in yards.

Removing weeds along fence lines, shelter belts, road allowances or in other non-crop areas will prevent them from spreading to fields. Only a few weeds of field margins pose a real threat of spreading into adjacent fields.[25] Complete elimination of field margin weeds may be damaging to beneficial insects that require weeds as host species. If non-crop areas are especially weedy, they can be seeded to competitive native grasses. A delay of operations until late July will allow ground nesting birds to raise their broods.[26] Movement of Canada thistle into fields is reduced by having the field margin sown to native species, relative to having an unsown border. [27]

A chaff saver behind the combine can be used to collect weed seeds. It is especially good at collecting crop seeds that blow over and cause volunteer problems in following years, but also is effective at removing large numbers of seeds of later maturing weeds. This prevents some of the movement of weeds within a field and provides useful livestock feed. Weed seeds should be cooked, ground or pelleted before using as feed. Chickens are especially good at destroying the viability of weed seeds. Sheep, horses, swine and cattle are progressively less effective at destroying weed seed viability.[28] If green feed contains weed seeds, it can be ensiled to destroy them. Composting manures kills most weed seeds and is also a good way of utilizing waste cereal straw. [29]

3. Managing the Crop Environment

One of the most effective tools of weed management is good crop husbandry.[30] A strong and competitive crop offers less opportunity for weeds. All of the crop management techniques that contribute to good crop growth might be considered tools of weed management. To be competitive with weeds, crops must be quickly and uniformly established, vigorous, and well nourished.[31] For instance, on-row packing, rather than packing the entire field may give an advantage to the crop relative to most of the weeds.

Agronomic recommendations are often assembled from results obtained in virtually weed free experimental plots. The combination of sowing time, crop genotype, crop planting arrangement, crop density and fertilizer input that is optimal under weed free circumstances is not necessarily optimal in weedy fields. Moreover, a desirable assemblage of husbandry practices can contribute considerably to weed control at very little extra cost.[32]

Varying farm practice prevents weeds that prosper in one system from gaining too strong an advantage. Many factors can be varied to "confuse" the weeds, including extensive and varied crop rotations; alternating the timing of operations such as seeding and harvest; varying the amount and timing of tillage; and modifying the soil fertility - through green manures, livestock manures and other soil amendments, and through the use of crops that deplete nutrients to a greater or lesser extent.

Rotation

Crop rotation is the alternation of different crop types, such as spring-seeded cereals, fall-seeded cereals, oilseeds, pulses, perennial legumes and other perennial species. Rotations also include alternations between crop types, for instance between barley, and wheat or flax and canola; or between cultivars within a crop species, for instance, between Harrington and Brier barley.

A central component of almost all sustainable farming systems is the rotation of crops. Crop rotation offers the most effective, indirect method of minimizing pest, disease and weed problems and maintaining and enhancing soil structure and fertility.[33] Crop rotations can limit the build-up of weeds that are favoured in a single crop environment.[34] Crop rotations have a myriad of benefits, including increased soil microbial activity, which may increase nutrient availability, including phosphorus. When crops are rotated, yields are usually 10 to 15% higher than when they grow in monoculture.[35]

Crop rotation dictates the pattern of disturbances which ultimately lead to changes in weed species composition in agroecosystems.[36] Thus, in spring-sown crops there is selection against autumn-germinating weed species while the converse is true of autumn-sown crops.[37] There has been evidence since at least 1800's that weed incidence varies with crop rotation.[38] An extensive literature survey of over 200 references indicated that weed number, biomass and seed production are reduced in rotations and intercropping situations relative to monoculture.[39] The greater the differences between crops in a rotational sequence, the better cultural control of pests can be expected.[40] In a Saskatchewan study, the presence of winter wheat in a rotation was the factor that had the largest impact of quack grass growth. When moisture was adequate, and winter wheat established well, quack grass was suppressed.[41]

Inclusion of alfalfa or other perennial legumes in rotations may be especially helpful in managing weed problems.[42] This solution is limited, in part, by the small number of farms with livestock.[43] This problem might be overcome through creative marketing (to livestock producers or the dehy industry), in the use of alfalfa grown for seed, and of short-term plowdowns when seed prices are favorable. A further constraint results from the high moisture requirement of perennial legumes, resulting in severe drying of the soil. For this reason, introduction of perennial legumes should be done cautiously, with on-farm feasibility testing.

The use of legumes in rotation began to decline when synthetic nitrogen was introduced in the 1940's.[44] Making rotations shorter (ie. by not including perennials, pastures and green manures) has reduced soil organic matter, degraded soil physical properties, and increased erosion and external inputs.[45,46] Once established, forage grasses and legumes within rotations, are very effective in suppressing growth of some annual weeds. This is a consequence of leaving soil surface undisturbed, providing dense crop canopy cover and root development, and mowing which has much more severe effect on the growth of annual weeds than on forage grasses and legumes.[47]

A Saskatchewan study indicated that weed populations were affected more by frequency of perennial forages in rotation than by any other management factor studied. With increased frequency of forage crops, there were more perennial or winter annual weeds such as dandelion, smooth brome, quack grass and narrow-leaved hawk's-beard. There were fewer annual species. Other management factors that influenced weed communities, though to a lesser extent than rotation, were the number of tillage passes and frequency of fallow. Both tillage and fallow encouraged annual weeds, but discouraged perennials and winter annuals.[48]

A good crop rotation is dependent on the site, the manager, field history and the rest of the farm operation, but a guideline for weed management is to include as much diversity as you are comfortable with. Crops rotations can vary timing (such as early seeded, late seeded, winter crops, biennials, perennials, and green manures). Crop rotations can account for differences in nutrient requirements. For instance, a three year alfalfa crop might be followed by wheat (which will use nitrogen from the breakdown of the alfalfa), a legume (that would not require a high nitrogen level and that would fix atmospheric nitrogen more effectively at low soil nitrogen levels), wheat again, and then oats (with a small nutrient requirement).[49] Rotating crops for disease and insect management can contribute to a healthy crop with less opportunity for weed growth. Crops can be rotated according to competitive ability. For instance, competitive crops such as barley or alfalfa could be grown before less competitive crops such as flax or lentil to start the less competitive crops in as clean a field as possible. Using a competitive crop, or several competitive crops following a less competitive crop can "clean up" after the weedier fields. Weed suppressing cover crops such as fall rye or sweet-clover can replace some of the summerfallow land.

Timing

In general, if weeds are uncontrolled, those that emerge before the crop have a strong competitive effect on the crop. The later that weeds emerge, the less competitive effect they have. For wild oats, the difference in competitive effect is approximately 3% yield loss per day. Mustard that emerged three days before the pea crop reduced pea weight 54%; but mustard that emerged four days after the pea crop, reduced the pea crop only 17%.[50] The amount of yield loss varies among years, crops species, crop seeding rate, time of emergence of weed relative to crop, soil and climatic factors.[51] The "critical period" in which crops are most sensitive to competition varies among crops. For wheat, this time is approximately two to four weeks after emergence.[52] Practices that either assure an early and vigorous start to the crop, or remove early weed seedlings allow crops to compete more successfully with weeds. Early seeding is particularly successful with cereals. Some pulse crops, like pea and lentil can be seeded very early. Other broad leaved crops such as bean can be more sensitive to diseases that are a greater threat when the crops are seeded into cool soil. For these crops, early seeding increases disease risk.

Late seeding is an important option that can be coupled with pre-seeding weed control (see pre-seeding tillage). This option works best for weeds that germinate early, and crops that prefer warm germination conditions and that mature quickly. Delaying seeding, of course, decreases the risk of damage from frost in the spring but increases the risk of damage from frost in the fall.

Competitive crops

Competitive ability can be viewed in two different ways: ability to tolerate competition (ie. to maintain yield in the presence of weeds) and ability to suppress weeds. Characters leading to these two might be different, but some studies indicate that tolerance and suppression may be correlated.[53] Factors that increase competitive ability seem to include rapid germination, early emergence, seedling vigour, rapid leaf expansion, large stomate number, rapid canopy development, increased plant height, early root growth, and extensive roots.[54,55,56]

Crops differ in competitive ability with weeds.[57,58] In general, barley is more competitive than spring rye. Both are more competitive than wheat or oat, and flax is less competitive. Durum wheats are less competitive than spring or winter wheat.[59] Wheat is considered more competitive than pea, and then in order of decreasing competitive ability with weeds, pea, potato, soybean, flax, and bean.[60] Most pulse crops, like lentil, are poor competitors. Canola offers poor competition to weeds in the seedling stage, but can compete well once it becomes established.[61]

Fall sown crops such as winter wheat and fall rye offer excellent early season competition, and do not require spring cultivation. These crops are especially effective at reducing winter annual and perennial weeds. Harrowing might be done in spring if seedlings do emerge in sufficient numbers. Fall sown crops also allow partial fallow after harvest, for further weed control. Greenfeed also can be used as a partial fallow replacement.[62] Weed control on partial fallows can be critical, as weeds have an opportunity to establish in the absence of crop competition.

Perennial crops such as crested wheatgrass, brome, alfalfa and sweet clover can be very competitive with annual weeds by eliminating the stimulatory effect of tillage on annual weed seeds. Perennial crops can also offer competition against perennial weeds that lasts beyond the annual crop season.[63,64] Crested wheatgrass can be more competitive than other forages.[65]

Competitive cultivars

Each crop has many different cultivars. Several major crops have variability in traits that affect competitive ability.[66] Crop breeding programs have placed relatively little emphasis on the development of superior cultivars for growth under weedy conditions,[67] yet "cultivar selection is one of the most important management decisions".[68]

A test of 250 wheat varieties in Australia showed that old standard varieties (those released between 1880 and 1950) suppressed weeds more than most of the current varieties. Strongly competitive genotypes had high early biomass accumulation, large numbers of tillers, and were tall with extensive leaf display. [69] Yield differences in weedy conditions were not found when herbicides were used. Taller cultivars had fewer weeds than shorter cultivars. Cultivars also differed in the dormancy of wheat seeds and thus, in the number of volunteer wheat plants in subsequent years.[70]

In a study of 8 wheat cultivars at Scott and Saskatoon, CDC Merlin, AC Minto and Columbus were found to be most competitive, and Genesis and Oslo least competitive with weeds. Spring spelt was the most competitive wheat in tests with "model" weeds (crop plants used to simulate weeds).[71]

Research indicates that tall, rapidly developing pea varieties such as Titan, Topper, Tipu or Victoria were more competitive than shorter types such as Radley, Danto, Patriot, Trump and AC Tamor. Leaf type might be expected to make a difference, but studies at Morden did not find an advantage to leafier varieties competing with wild mustard.[72,73] There was no effect of pea cultivar (tall, leafy Century; tall semi-leafless Tipu; short leafy Express) on grassy weed populations.[74] Semi-dwarf winter wheat varieties resulted in a 14-30% greater yield reduction from downy brome (*Bromus tectorum*) than did taller cultivars.[75] Tall and semi-dwarf wheats were equal in supporting quack grass; winter wheat suppressed quack grass.[76]

Differences among cultivars depend on the entire cropping environment, not just the presence of weeds. For instance, in years with average or below average moisture, a semileafless pea cultivar seeded at reduced rates lost more to competition with wild mustard than did a leafy cultivar, and the semileafless cultivar lost more to competition when it was seeded at low rates than when it was seeded at high rates. In a dry year, the semileafless cultivar was the better weed competitor, especially at the lower seeding rate.[77]

Seeding rate and row spacing

High seeding rates and narrow row spacings decrease the distance between crop plants, and increase the speed with which the canopy closes. This reduces the germination of weed seedlings, and gives the crop an edge in early competition. The disadvantages are that crop plants that are closely spaced will compete more with each other, will require more moisture and nutrients, will increase seed costs, and that inter-row cultivation will be less feasible.

High seedling rates are especially helpful on weedy land. On weed-free land, recommended rates are equally good to high seedling rates.[78,79] High seedling rates allow for some damage from post-seeding tillage, and for better competition with weeds. An increase of 25% above normal is often recommended. High seeding rates may cause some problem in a dry year. On the other hand, high seeding rates may be advantageous in a dry year if seedlings more effectively cover the soil and reduce evaporation from the soil surface. If there is enough moisture, high seeding rates will speed maturity (2 to 3 days), and result in shorter plants with fewer tillers. Yield losses may be reduced. In one Saskatchewan study, increased seeding rate of peas reduced weed numbers; high populations of pea competed well with weeds.[80] In another study, at Scott, Saskatchewan, barley yielded the most at narrow row spacing and increased seeding density. Weed biomass was reduced by both narrower row spacings and increased seeding density.[81]

Green feed and silage crops can be seeded at higher rates to increase crop competition and feed quality. Increased seeding rates should also be used if either post-seeding or post-emergence tillage is planned. This will help compensate for any damage caused by in-crop tillage. Under certain environmental conditions, higher seeding rates may increase disease incidence or may result in higher lodging losses.

Narrow row spacing allows crops to more completely fill the available space, leaving less for the weeds. An alternative that does not involve machinery modification, but accomplishes much the same effect, is cross-seeding.

Allelopathy

Allelopathy in plants is the production of compounds that inhibit the growth of other plants. It may be direct, by living plants, or indirect through the products of plant decomposition. Allelopathy may be mediated by micro-organisms.[82] Both crops and weeds have been found to be allelopathic. Allelopathic crops include barley, oat, wheat, rye, canola, black mustard, other mustard spp., buckwheat, red clover, white clover, sweet-clover, hairy vetch, creeping red fescue, tall fescue, and perennial ryegrass.[83,84,85,86] The allelopathy of these plants can be used in a number of ways. The allelopathic crops, in rotation, may help in weed suppression in subsequent crops. As with all other techniques, caution needs to be employed. Allelopathic crops may suppress subsequent crop growth. Allelopathic crops can also be used as cover crops or green manures.

Cover crops, green manures and mulches

Cover crops may be sown to protect soil from erosion, for snow trapping or to increase soil organic matter. When the cover crop fixes nitrogen or otherwise improves soil properties, it is often referred to as a green manure. Both cover crops and green manures can have weed suppressing qualities. They may shade the ground, reducing temperature fluctuation and the weed seed germination that depends on it.[87] They may compete with weeds, and thus reduce their vigour, or they may have allelopathic properties. Any tillage to kill the cover crop will also suppress weeds.

Cover crops can be sown into existing crops. If so, the timing should correspond to the time when weeds no longer cause yield losses (the end of the critical period).[88] Cover crops may also be sown after harvest, or in place of a fallow. Successfully established cover crops can develop sufficiently dense canopies in the fall to interfere with growth of perennial and winter annual weeds. Most tests of cover crops involve fall or winter cereals sown in the late summer and killed by herbicides the following spring. [89] Weed densities have been reduced significantly over those where no residues were present. These tests have been conducted over a range of soils and cropping systems.[90] One organic alternative is to mow or plow the cover crop in the spring. Fall seeded and spring tilled winter hardy rape substantially reduced lamb's-quarters and pigweed growth in a subsequent potato crop, and may have suppressed nematodes and diseases as well.[91] Another alternative is to use species that are not winter hardy. Tests with sorghum and oats showed weed suppression, but not as large an effect as when a winter hardy crop was killed chemically in the spring.[92] Winter-killed cover crops form a mulch in the spring that further suppresses weed establishment and growth.[93] Mulches may suppress weeds, though they are generally inadequate to control perennial weeds.[94] The suppression of crops is generally less than that of weeds, in part because crops generally have larger seeds. Water use by the mulch crop is often offset by greater snow-trapping.

Allelopathic mulches have potential problems as well as advantages. They may deplete moisture, and immobilize nutrients, especially nitrogen. The latter problem can be partially avoided by including rapidly decomposing legume in the mix.[95] The allelopathic effect may inhibit germination of small-seeded crops.[96] Cover crops may be more effective when tillage is eliminated, as the residues are thus more concentrated at the soil surface.[97]

Weed suppressing mulches need not be crop residues. Small areas of perennial weeds can be mulched with substances like manure. For effective control, a substantial amount of manure is required - three feet or more deep, at least four feet beyond the patch. Alternatives includer tar paper or black polyethylene, and mulched wood. These mulches need to be maintained for at least one year for good weed suppression.[98]

Intercropping

Intercropping involves growing two crops at a time. It often has weed suppression benefits, especially relative to the least competitive crop grown alone. Benefits may come from increased competition or from allelopathy. Competition of the intercrop on the weed may be increased because of increased crop density, increased shading,[99] or because two different crops access nutrients differently. A disadvantage of intercropping is that plant density of both crops needs to be carefully adjusted. Higher total densities may be problematic in years of low moisture. In the case of underseeded crops, the underseed density and timing are compromises between competing with the weeds, but not competing overly with the crop.

Intercrops may not always offer the best yields or weed suppression. A barley-pea intercrop yielded more crop weight than pea alone, but less than barley alone. The intercrop suppressed weeds (mostly wild mustard, lamb's-quarters and redroot pigweed) better than the pea crop, but not as well as the barley crop.[100]

Probably the most common intercrop in Saskatchewan is a cereal underseeded to a legume. Some producers seed clover after wheat is up, at about the four-leaf stage. The clover can be seeded while harrowing to cover seed and kill weeds.[101] Clover underseeded in cereals suppressed growth of quack grass.[102] Clover in winter wheat reduced weed biomass, but in dry years also reduced yields of wheat.[103]

Other intercropping options are possible. Flax/lentil intercrops have been successful in North Dakota, but results in Saskatchewan have not been conclusive. The Saskatchewan Pulse Board would not recommend the practice.[104] Pea can be intercropped with either cereals such as barley or oilseeds such as canola and mustard.[105] Studies indicate that intercropping field peas with barley can provide high levels of protein production while increasing competitive pressure on weeds.[106]

Soil fertility

Crops and weeds have the same basic nutrient requirements. They can differ in their ability to access nutrients because of differences in their root structures or mycorrhizal associations. They also can differ in their ability to tolerate nutrient imbalances, or in their efficiency at converting nutrients into growth. In general, because strong and vigorous crops are the best agents of weed suppression, good soil fertility is an element of weed management. In one study where herbicides were not used, researchers found that soil amendments (cattle manure and potato compost and alternating years of legume green manure) substantially reduced the weed biomass, possibly by improving crop competitiveness.[107]

In some instances, the balance between crop and weed may be negatively affected by increased nutrient level. Nutrient levels are generally recommended on the assumption that herbicides will be used, and that weeds are not an important consideration. Lower nutrient availability means less available for weed growth as well as for crop growth.

One author claimed, after reviewing numerous research reports on the effect of fertilization on weeds, "weeds are capable of absorbing nutrients faster and in relatively bigger amounts than crop plants and thus profit more from fertilization. In the presence of a high weed population density, fertilizer application may stimulate weed growth so greatly that the crop plants will be overgrown and suppressed."[108]

The effect of nitrogen status depends on both the weed and the crop. Wild oat-wheat competition experiments showed that wild oats were better able to compete with wheat at higher nitrogen levels. Wild oat seed production increased with nitrogen, while wheat yield decreased. Wheat yield increased with added nitrogen only if wild oats plants were less than 2% of the total plant counts.[109] In another study, total weed density (several species) was highest at lowest nitrogen level in cereal crops.[110] In fields where nitrogen is depleted, weed populations that are responsive to nitrogen can be most effectively controlled with crop competition.[111]

Phosphate fertilizers applied at seeding have been shown to increase crop competitiveness.[112] Barn manure, or other high phosphate sources may have similar effects. If possible, there is an advantage in placing nutrients where they are more readily accessed by the crop than by the weeds. Although crop competitiveness may improve with improved nutrient status, some weeds are more effective at utilizing excess resources than are crops.[113] Higher nutrient levels stimulate the competitive ability of wild oats, green foxtail and barnyard grass.[114] Other weeds might be limited by nutrient levels that are adequate for crop growth. Redroot pigweed, for instance, is especially sensitive to low phosphorous levels, and will not grow well if phosphorous is depleted.[115] Wild mustard is also sensitive to low phosphorous levels,[116] but lamb's-quarters may be more abundant in soils with phosphorous deficiencies.[117]

Studies done in all major soil zones in Saskatchewan indicated that wheat greatly benefitted from additional nitrogen and phosphorous if it had a competitive advantage over the weeds, but weeds greatly benefitted from the additional nutrients if they had the initial advantage.[118] Crop-weed competition for nutrients, and crop-weed competition for other factors at different nutrient levels, are both complex interactions that depend on many factors - crop species, weed species, moisture, timing of nutrient release, spatial arrangement of the nutrients, nutrient ratios, etc.

Livestock manures can be used to improve soil nutrient levels. Manure should be composted to kill most weed seeds. Soil tests should be used to determine appropriate amounts to add.

4. Directly treating weeds

Much of weed management consists of avoiding weed problems and facilitating crop growth rather than attacking weeds directly. However, direct weed control is sometimes necessary even with prudent agronomic practice and a thoughtful, tolerant attitude. Every weed control technique has benefits and detriments. Non-chemical methods are not automatically environmentally friendly.[119] An appropriate compromise between these will be site, and producer specific. Alterations can sometime be made in a technique to reduce the detriments without greatly reducing the benefits. In developing effective and efficient weed management strategies, growers need to be aware of the advantages, disadvantages and limitations of all the tools available to them.

Mechanical Weed Control

Tillage is is often seen as the organic alternative to chemical weed control. Tillage can be very effective at reducing weed populations, but it does far more than kill weeds. It should not be enthusiastically embraced without considering the possible difficulties it entails. Tillage tends to dry out and warm up the soil. Tillage can loosen and pulverize the soil. It may cause soil degradation and loss of soil fertility through erosion and leaching.[120] Tillage speeds the decomposition of organic matter. Excess cultivation increases nitrogen volatilization to the atmosphere and the potential for nitrate leaching. It can affect the survival of beneficial invertebrates and soil microfauna and microflora.[121,122] Tillage reduces the populations of weed-seed eating carabid beetles and field crickets.[123] In terms of weed control, deep tillage is a mixed blessing. It may bring up dormant seeds buried in the soil, and bury other seeds "for later".[124] Tillage places weed seeds in better contact with the soil, facilitating germination. Tillage exposes soil and weed seeds to the light. For some species this triggers germination. When cultivation was performed at night or if the implement was covered, weed populations were reduced by up to 50%.[125,126] Perennial weeds can be spread on tillage equipment. Tillage favors some species over others, and thus is one of the management tools that can be used to alter weed communities.[127]

Hand weeding

Hand weeding or hoeing may be useful in areas where new weeds are introduced to a field, in order to keep those weeds from spreading throughout the fields. Hand rouging is routine on pedigreed seed farms, and may be practical on a large scale if the weed numbers are small. Hand weeding of shelterbelts and other border areas may also be beneficial.

Out of crop tillage

<u>Fall tillage</u> is used to destroy winter annual and biennial weeds that may be more difficult to control in the spring. Some summer annual weeds may be encouraged to germinate by fall tillage and then winter-killed. However, tillage also buries weed seeds that may then become dormant,

acting as a reserve for later years. Fall tillage should be shallow (less than 4 inches) to avoid burying weed seeds.[128]

Fall tillage can also be effective against perennial weeds. Plants can be killed by exposing the roots, if freezing temperatures follow shortly after tillage.[129] Fall tillage reduces stubble and trash cover, and thus reduces snow trapping. It also accelerates soil erosion. Use of tillage equipment such as the Noble or Victory blades that leave the stubble standing will alleviate some of the risk of fall tillage. These types of equipment are less effective in cool wet conditions. Leaving strips may also help trap snow. Tillage of weedy patches rather than entire fields may also reduce risk.

Spring tillage can be used for weed control as well as to prepare the seedbed. Shallow (less than three inches) pre-seeding tillage in early spring can aerate and warm the soil, thus stimulating seedling germination. Where residues are heavy, a disc-type implement may work best. Rod-weeders or cultivators are more appropriate if residues are light.[130] Packers following the harrows can firm the soil and further encourage weed seed germination. The first operation should be the deepest, with each successive one shallower. The following operations should destroy weed growth while conserving as much soil moisture as possible.[131] Seeding may be delayed about 10 days after the final tillage. This practice can be especially successful at reducing the weed seedbank of winter annual and early emerging species, such as stinkweed,[132] knotweed, Russian pigweed, Russian thistle, lamb's-quarters, wild mustard,[133] wild oats, and wild buckwheat. Weed control can be very successful with delayed seeding, but crop yields may be reduced by the practice either because of increased losses due to delayed harvest, or from reduced moisture in tilled soils.[134,135,136] Where moisture is sufficient, multiple tillage events can be used. If so, early maturing crops should be considered to reduce the risk of frost due to late seeding. Care should be taken not to deplete soil moisture to the extent that it reduces stand emergence or vigour.

Fallow can be used as a weed control method. Repeated cultivation can be detrimental to the soil, increasing salinization, erosion and the depletion of organic mater and nitrogen from the soil. Tillage equipment may spread plant parts throughout the field. These effects can be lessened in many ways: fallow may be used for a partial season, for instance, after plowdown of an underseeded crop , or mowing of green feed; implements that retain residues or stubble can be used; speeds can be modified to reduce erosion; uncultivated strips may be left between cultivated areas; where weeds occur only in patches, cultivation may be done in only in these areas; if weed emergence on erodible knolls is limited, these can be left untilled to conserve residues and limit erosion.

Fallow can be used to reduce the weed seedbank by allowing weeds to germinate, then killing them before they set seed. This will be especially effective with weeds that have short dormancy periods, such as kochia, goat's beard, hare's ear mustard, Indian mustard, Russian thistle, cow cockle, green foxtail, downy brome, wild buckwheat or foxtail barley.[137] Some reduction is possible for weeds with longer dormancy, but some seeds will survive. Three to six tillage operations may be required for effective annual weed control during the fallow year.[138] An early start is recommended for summer fallow tillage, perhaps by mid-May.[139] Tillage operations should be as shallow as possible to avoid bringing new weed seeds to the soil surface. The initial operation should always be the deepest with subsequent ones progressively shallower. Tillage is most effective when the soil surface is dry and air temperature is high. Tilling small seedlings when the soil surface is moist will usually produce poor results, as many of the seedlings are transplanted rather than being killed.[140]

Fallow may also be used to control perennials such as Canada thistle and perennial sow-thistle.[141] Tillage may be best left until the weeds begin to bloom. Food reserves are at a low at this time, and thus the tillage is most effective[142]. Once tillage begins it should continue each time the plant reaches a height of about 3 inches, until freeze up. This approach will starve the root system and prevent it from forming any food reserves. The plants will enter winter in a very weakened state and many of them will not survive.[143] This late season tillage for perennial control may be used after an early maturing crop, in a partial fallow situation.[144] Appropriate crops include sweet clover, early barley, fall rye, or oat cut for feed.

Quackgrass problems should be handled in a somewhat different manner. Tillage to control this weed depends on physically damaging the root system. In dry years a cultivator with narrow spikes will be effective, as this will drag roots and rhizomes to the surface where they will dry out and die. In wet years or areas, the first tillage operation should be with a disc implement that cuts the rhizomes into small pieces. Each of these smaller sections of rhizome will try to establish a new plant, which in turn has to be destroyed by subsequent tillage. New plant growth should not be allowed to grow taller than three inches before being tilled.[145] Tillage should be no deeper than required to do an effective job. Shallow tillage will concentrate the rhizomes on or near the soil surface, resulting in a more uniform emergence and better control from future tillage operations.[146]

Alternating intensive tillage and cropping has been used to reduce severe perennial weed problems.[147]

In crop tillage

Harrowing after seeding but before the crop emerges can be useful if weeds emerge before the crop. A rod weeder, cable weeder or flexible harrow may be used. Success is improved if the tillage is less than two inches deep, if soil is dry, the crop sprouts are less than 3/4 of an inch (usually within three or four days of seeding), and if crop is seeded heavily and deeply. Large amounts of trash, compacted soil and unfavorable weather make this option less practical in some years.

Tillage with a drag or flex harrow after the crop emerges can also be effective. Weeds such as Russian thistle, tumble mustard, wild buckwheat and stinkweed were controlled in a Swift Current study by harrowing either before cereal crop emergence, or when the crop was four inches high.[148] Species such as green foxtail, lamb's-quarters and redroot pigweed which usually emerge from shallow depths can be controlled well.[149] Seedlings that emerge from greater depths will not be as effectively controlled. At Scott, Saskatchewan, both the number of harrowing passes (one to four) and the amount of spring moisture determined the effectiveness of harrowing at controlling wild oats, and the amount of damage to wheat.[150]

A rotary harrow has been used successfully for both pre-emergent and post-emergent weed control. A rotary harrow can be used with an excess of trash, where a tine harrow would clog. Pre-seeding harrowing needs an aggressive angle, but post-emergent harrowing should disturb plants as little as possible. Harrowing may not kill all the weeds, but can damage them, to allow the crop a competitive advantage. Extra caution is needed if conditions are very dry.[151]

A rotary hoe cultivator can travel at relatively high speeds, and can be used with large seeded crops before crop emergence or until the crop is a couple inches tall. The whirling curved tines throw small weeds out of the upper layers of soil where they dry out and die. A rotary hoe is particularly effective on germinated but not yet emerged weed seedlings. Some damage may occur to emerged crop, but can compensate with slight increase in sowing rate.[152]

Recommended stages for post-emergent tillage are as follows:[153] wheat - from the two to four leaf stage; barley - from the two to four leaf stage (before tillering); oat - post-emergent harrowing is not recommended; sunflower - up to the six leaf stage; fababean - when the crop is between two to six inches tall; lentil and field pea - in the seedling stage (no more than four inches tall). Harrowing is best on a hot sunny day, when the foliage is dry.[154] Damage can be reduced in harrowing peas if finger weeders or flexible harrows are used.[155] A British study indicated that late spring harrowing of winter wheat "appears promising", as risk of crop damage are small.[156]

For all crops, some losses are expected. If harrowing is planned, it is best to seed heavily to compensate for these losses. Cereals are generally harrowed with the rows, while large seeded broad-leaved crops are often harrowed across the rows. Small-seeded broad-leaved crops such as canola are not well suited to harrowing. Harrowing flax is not recommended, though some producers have been successful at double harrowing at about the four to five inch stage.[157]

<u>Interrow cultivation</u> can be used on row crops for weed control. Potatoes, sunflowers and silage corn are row crops that are grown in Saskatchewan and can be cultivated between the rows. Other crops such as wheat, oats and barley, that are traditionally grown in solid-seeded stands can also be grown in wider rows.[158] Wide row seeding can be done with an ordinary seed drill by blocking some of the runs. Often two or three runs are left open, and five runs are blocked off in each set of seven or eight spouts. Cultivation may be performed by special straddle row cultivator, or by an ordinary cultivator with some shovels removed. Shields may be placed on the cultivator to avoid throwing soil on the crop row. Early harrowing may be used cross-wise to control weeds in-row. Two to three cultivations may be used. Obviously, the shovel pattern and seed drill pattern need to be coordinated. Barley and oats were found to respond more favourably to this type of tillage than wheat.[159]

Other creative options are possible. Dwayne Woolhouse, an Assiniboia farmer, has mounted 9 whirling cutters (similar to "weed whackers") on 25 feet of his swather. He uses this cut thistles and other weeds that are above than his shorter crops such as lentil.

Thermal control

Flaming

Flaming and infared radiation have been used for the control of weeds. Methods involve the use of propane, butane or gas burners to generate a direct flame, or to heat either a ceramic or metal burner. Some thermal methods involve microwaves.[160] Seedlings (but not perennials or mature annuals)[161] are killed by temperatures of 90 to 100 C.[162] Plants show only slight colour changes after treatment but die within 48 hours. Grasses have a slightly higher temperature tolerance than broad-leaved weeds, allowing weeding to be somewhat selective.[163] These methods require care in adjusting flame and speed, and are more suited to wide row spacing where crops can be protected more easily. In a comparative study, both methods required about 60 kilograms of propane per ha to give effective control of cotyledon to four leaf weeds.[164] These techniques appear to use no more energy than cultivation with tyned implements (under Australian conditions).[165] Flaming is used in higher value organic row crops and/or crops with slow germination that leads to weed seeds emerging prior to the crop.[166] It could be used pre-emergence for weed control in cereals, although costs might be prohibitive,[167] and energy use is intensive.

Weedy fallow

Fallow land may be left uncultivated, and burned in the spring prior to seeding. Trials at Scott found this type of fallow to be equally effective to conventional tilled fallow.[168] Snow trap by the dead weeds may have made up for moisture use in the fallow year. A relatively hot fire may have eliminated weed seeds at the soil surface. A disadvantage is that fire reduces surface organic matter. Using this practice over extended periods led to serious invasions by perennial sow-thistle and Canada thistle.

Burning

Stubble burning is used to remove surface trash without tillage, and to destroy weed seeds.[169,170] This technique is more effective if there is abundant straw. Weed seeds lying on the soil can be effectively killed, though those in soil are not. Stubble burning may be especially effective in areas where straw accumulates, such as swaths, or around depressions.[171,172] Burning of stubble in the fall reduces cover, and thus increases erosion risk. Burning of stubble in the spring is less effective at weed control. Burning can also be used to remove weeds from areas such as roadside ditches.[173]

Mowing

Mowing can be an effective part of weed control where tillage is undesirable, or in conjunction with perennial forages. Mowing may be used to prevent seed set, if it is done early enough. To be effective, mowing should be done before flowering, as many weeds can set seed very quickly after flowering, using the reserves left in the portion of cut stem that remains attached to the flowers.[174,175] Many weeds, such as wild oats or Russian thistle, can be used in green feed if cut before seed set. Mowing can be useful in giving an advantage to perennial forages over weeds. For the control of perennial weeds, mowing might be delayed until the onset of flowering of the weed. At this time, food reserves are at a low point. The weed will respond by sending up new stems, further depleting its reserves. Mowing at about three week intervals can severely weaken or even kill the weeds.[176]

Mowing can also interfere with beneficial creatures. Bird nestling mortality can be reduced if mowing is delayed until mid to late July.[177]

Biological Weed Control

Biocontrol of weeds is the use of living organisms to destroy weeds, or to inhibit them enough to reduce their competitive ability with crops. Biocontrol includes the use of livestock, introduction of classical biocontrol agents, and the increase and use of helpful organisms (innundative biocontrol).

Livestock

Biocontrol on mixed farms may include the use of livestock for grazing weeds, or to consume mown weeds, chaff, and screenings. Goats are browsers, and are therefore especially good for the control of woody plants, such as aspen or rose. Sheep can be an effective biocontrol for leafy spurge. Once they acquire a taste for it, sheep can consume large quantities of spurge, which provides them with a nutritious forage.[178] Sheep are especially good for weed control, as they graze close to the ground, and will readily eat thistles.[179] Goats also eat thistles.[180] Sheep can be used in growing legumes to graze out grassy weeds.[181] Geese have been used in garden plots to control grassy weeds.[182] Weeder geese can be used (at 5 to 6 geese per hectare) after crops grow too large to be eaten by birds. Hogs can be used for control of perennial weeds between cropping seasons, in fenced fields at a rate of 24 animals per hectare. Cattle and sheep can be used for early grazing to prevent weed growth. Weed regrowth faces strong competition from legumes and grasses in pasture.[183] If livestock are used to graze mature weeds, or to dispose of screenings or chaff, many but not all weed seeds will be destroyed by digestion.[184]

Classical biocontrol

Classical biocontrol recognizes that many weeds were introduced to new areas without their natural predators. If the predators are specific to the weeds, and unlikely to attack other species, the predators can be introduced to the new area to control the weeds. This method has had good long-term success in some instances, particularly in rangeland. It is less common in cropped land.

Nodding thistle is attacked by a weevil, *Rhinocyllus conicus* introduced to Saskatchewan in 1968.[185] Weevils may be gathered by collecting about 500 infected nodding thistle seed heads in mid-August, and placing them in new stands. Several years are required for the weevil population to become established as to be effective at controlling the thistle.

Leafy spurge can be controlled by black dot spurge beetle *Aphthona nigriscutis,* and to a lesser degree by the copper spurge beetle *Aphthona flava*. Larvae feed on spurge roots. The black dot spurge beetle is more effective on high, dry and exposed sites, on coarse soils. In Alberta, redistribution of beetles is about 65% successful. Redistribution is accomplished by collection and release of adult beetles.[186]

Toadflax seed predators *Brachypterolus pulicarius* and *Gymnaetron antirrhini* can be spread by placing infected toadflax stems among flower stems at the new site.[187] Additional agents being tested for toadflax control include the stem boring weevil *Mecinus janthinus,* the root boring moth *Eteobalea serratella* and the root galling weevil *Gymnetron linariae.*

The tortoise beetle *Cassida azurea* has been released in Alberta for bladder campion control.

Innundative biocontrol

Innundative biocontrol involves applying an organism that is already present at a low level, but at higher levels could be more effective at suppressing the weed. Most of these are fungal diseases that are "brewed" or fermented in large numbers and applied like a herbicide to the weed plants.

BioMal is a myco-herbicide that contains viable spores of a fungus, *Colletrotichum gloeosporoides* f. sp. *malvae*, that infects round-leaved mallow. Tests indicate that it can have a significant effect on the weed population. It currently is not available on the market.

A bacteria, *Pseudomonas syringae* pv *tagetis,* is under commercial development for the control of Canada thistle.[188]

Encouraging beneficial biota

Another alternative for biocontrol is to increase the beneficial creatures by maintaining habitat for them. This might include reducing tillage, maintaining shelterbelts and wooded refuges, sloughs, or borders, and leaving unbroken native land. The blind use of refuge habitats is risky, because it is difficult to determine, at first, if the organisms that are harbored in this way are beneficial or harmful. However, careful observation should help in making that decision.

Biological agents in the soil can also affect the competitive relationships among crops and weeds. Some biological agents are available to improve crop growth, such as the rhizobial inoculants used with legumes, or the fungal organism of Provide. Arbuscular mycorrhizae (AM) can benefit plants by facilitating the uptake of nutrients and improving growth and yield.[189] These mycorrhizae benefit some species such as cereals and legumes over species that do not associate with them,[190] such as wild mustard, lamb's-quarters, wild buckwheat, tame mustard, canola and quinoa.

Some farm practices may alter the ability of microbials to contribute to crop growth. The use of pesticides and fertilizers, for instance, reduces the effect of AM in conventional systems, but AM may be relatively important in organic systems. The ability to benefit from AM may have been bred out of some varieties. Future breeding that considers this factor might offer greater competitive ability. In the mean time, mycorrhizae might be encouraged through the reduction of long-term fallowing; reduction of mustard and canola crops, or underseeding these crop to legumes such as clover; and the increase of legume crops.

Other soil organisms can be directly detrimental to weeds. Seed-borne bacteria may be effective at reducing dormant weed seed populations. Rhizobacteria might have potential for the reducing the vigour of grass weeds in cereal crops. Application of microbial agents to control weeds is not economically viable at the moment, but they may prove to be useful in the future. Reduction of tillage might foster the growth of these bacteria, which actively grow on crop residues, and which are favoured by the cooler, moister environment which the residues generate.[191]

Helpful insects can be encouraged by providing habitat, such as shelterbelts and uncultivated areas. Some Carabidae insects have shown a preference to species of foxtail.[192]

Conclusions

A great variety of resources are available to the organic producer for weed management. Because organic weed management is more system than symptom based, it is complex, and unique to each farm ecosystem and each farm manager.

Recommendations for further research

Determining appropriate technologies depends as strongly on on-farm testing by producers as it does on expert recommendations. Nevertheless, research support can be very useful. The following suggestions for further research are gleaned from the literature, from discussions with researchers and farmers, and from my own personal biases.

Attitude

In my opinion, the primary problem with herbicides is that they have been so effective that they colour our perceptions about weeds. We consider weeds not as the inevitable result of fertile soil, but as the enemy. Herbicides are the tools of arrogance that have allowed us to thoughtlessly attack everything that we didn't plan for. In doing this, we have deepened the rift between ourselves and natural processes.

System level research

If we are to move our focus from weed control to the management of disturbances in farm ecosystems, we will need to change our attitudes, and gather more information on how systems functions as wholes. "Refocusing away from a predominately single tool (herbicides) toward more integrated, long-term weed management approaches will require greater understanding of biological systems than we currently possess."[193] One of our research goals should be this greater understanding. More must be learned about nutrient cycling through agricultural ecosystems, biological control, allelopathic crop combinations, diverse crop mixtures and rotations, breeding crops that resist pests, and the relative benefits of various cover crops.[194]

Livestock

Long term rotations that include a perennial phase offer distinct benefits in terms of soil quality and weed management. Currently, the only way to get alfalfa or another perennial legume back into the production system on most farms would be to include livestock as part of the production system.[195,196] Livestock also re-claim what might otherwise be seen as useless, such as weeds in stubble, screenings, chaff, patches mown for weed control, etc. These benefits are unlikely to arise from a limited number of highly concentrated livestock operations. Options that generate the "livestock advantage" without livestock might also be pursued. For instance, dehy and seed alfalfa, partnerships with livestock producers, etc.

On-farm testing

Although allelopathic interactions, companion planting, cover cropping, etc. are important techniques, much of the information is anecdotal and based on local knowledge. There is plenty of scope for co-operative on-farm research to improve these techniuques and explain their effectiveness.[197] Producer driven research, that partners researchers and producers might be most effective. Surveys of "top" organic producers would be useful to document effective weed management practices.

Breeding

Crop breeding programs have placed relatively little emphasis on the development of superior varieties for growth under weedy conditions. However, breeding crops for their ability to suppress or tolerate weeds would be a useful research direction with rapidly accessible benefits for farmers.[198],[199] Development of cover crops that provide acceptable weed management, do not require herbicide to kill or suppress their growth and are do not deplete available water would be useful.[200] The breeding of a winter-hardy cover crop that dies out naturally before the start of the critical period of weed interference of the main crop would further enhance this method of weed control.[201] Development of crops with allelopathic potential might also be useful.[202]

Techniques

Our understanding of equipment and techniques for in-crop tillage is fairly rudimentary. Further investigation might include the use of rotary harrows, rotary hoes, ground driven rolling cultivators or lilliston cultivators, steerage hoes, sweeps, knives, midmounted tools for control of depth, flexible polypropylene brush weeders and tyne harrows.[203]

Biological control is another area of research with the potential to be useful to the organic community.[204] A greater understanding is needed of the role of soil organisms in nutrient uptake and in mediating competition between crops and weeds.

Support

The emerging organic industry has failed to receive the kind of research and extension support that was given to the no-till movement, for instance. This is understandable for a number of reasons: biological interactions are more complex than chemical treatments; a greater knowledge base is required to manage multiple interacting factors; interactions may be site specific, or history specific; organic systems, by definition, do not encourage partnerships with input suppliers. There are still huge benefits for all players, building bridges between organic producers, researchers and appropriate segments of industry.

Resources

Research programs:

Organic Production Research, Weed Control. Agri-Food Innovation Fund Special Crop Spoke Program. Eric Johnson and Ken Kirkland. Scott and Melfort Research Farms, Agriculture and Agri-Food Canada.

Six different projects on weed control in organically grown cereals, oilseeds and pulses look at seeding rates, cross seeding, seeding depth, timing of pre-seeding tillage, post-emergent harrowing, interrow tillage, and intercropping.

Alternative Cropping Study. Stewart Brandt. Scott Research Farm. Agriculture and Agri-Food Canada.

A long-term study comparing organic, high and reduced input systems, and for each of these comparing rotations that include perennial forages and annuals, continuous cropping with diverse annual crops, or fallow cropping with a low diversity of crops.

Integrated Management of Crop Pests. Agri-Food Innovation Fund. Gordon Thomas. Agriculture and Agri-Food Canada, University of Saskatchewan, and Saskatchewan Wheat Pool, Watrous.

A comparison of pest management systems that include a range of tillage and chemical treatments, including one system with no herbicide.

Crop Production Systems for Dryland Farming. Jill Clapperton. Lethbridge Research Station. Agriculture and Agri-Food Canada.

A comparison of crop production systems, including organic, and rotations that range from a single crop, to an intercrop of rye grass, sweet clover and fenugreek. Livestock grazing is included in the study.

Farming system study. South Dakota State University.

A comparison of organic, conventional and reduced-till farming systems from 1984-1993.

Organizations:

Alternative Energy Resources Organization (AERO), 44 North Last Chance Gulch, Helena, Montana, USA 59601.

AERO is a non-profit membership organization dedicated to the development of sustainable agriculture, energy technologies based on renewable resources and conversation, and vital rural communities.

Canadian Organic Growers Inc., (COG), Box 6408, Station J, Ottawa, ON. K2A 3Y6.

COG is a Canada-wide, non-profit, voluntary association devoted to all aspects of sustainable agriculture. It provides a quarterly magazine to members.

Ecological Agriculture Projects, (EAP), P.O. Box 191, MacDonald College, 21-111 Lakeshore Road, Ste-Anne de Bellevue, PQ H9X lC0.

The EAP has a large collection of information on ecological farming. It publishes numerous papers and offers courses on ecological farming. Write for a publications list.

REAP - Canada (Resource Efficient Agrigultural Production), Box 125, Glenaldale House, Ste-Anne-du-Bellevue, PQ H9X 3V9.

Northern Plains Sustainable Agricultural Society, (NPSAS), RR#1, Box 73, Windsor, ND, USA 58424.

NPSAS is a non-profit educational organization. It published a handbook on sustainable agriculture in 1988. NPSAS members work with the Carrington Research Station on research projects and hold field days in the summer.

Organic Crop Improvement Association. Inc. (OCIA), Box 299, Cornwall, PEI COA lH0.

OCIA is an international association of organic farmers, processors and merchants. There are chapters in nine provinces (eight chapters in Saskatchewan) and chapters in other North, Central and South American, European and Asian countries. OCIA is involved in professional updating of farmers and colleagues and provides independent third party certification for organic foods.

Organic Food Producers Association of North America (OFPANA), P.O. Box 664, Lehigh Valley, PA, USA 18001.

OFPANA is a continent-wide "umbrella" trade association representing the major organic food processors, private companies, distributors, organic farm organizations and consultants. In 1985, OFPANA drafted-a document which provided guidelines for the organic food industry and has encouraged common certification standards.

Organic Producers Association of Manitoba Co-op Ltd., (OPAM), Box 929 Virden MB, ROM 2C0

OPAM has organized a third party certification arrangement, participates in meetings concerning standards and legislation and provides information.

Books:

Aero's Guide to Sustainable Agriculture in Northern Rockies and Plains. 1989. N. Matheson (ed). Alternative Energy Resource Organization. Montana, USA.[205]

Agro-Alternatives. G. Smith and W. Groenen. Saskatchewan Research Council.

A valuable guide for those interested in organic and low input production systems.[206]

Agroecology The Scientific Basis of Alternative Agriculture. Miguel A. Altieri with contributions by Richard B. Norgaard, Susanna B. Hecht, John G. Farrell, and Matt Liebman. Westview Press, Boulder Co. 1987.

Includes sections on theory, system design, and technologies, as well as practical sections on polyculture, cover cropping, crop rotation, reduced tillage, agroforestry, and ecological weed, insect and disease management. The examples are global, and many may not specifically apply to our climate. This book provides a strong ecological perspective.

Alternative Agriculture. 1989. National Research Council, National Academy Press, Washington D.C.

Cereal-Legume Cropping Systems: Nine Farm Case Studies in the Dryland Northern Plains, Canadian Prairies and Intermountain Northwest. 1991. Matheson, Nancy, et al. Alternative Energy Resources Organization: Helena, Montana, USA.

Case studies provide information about how to incorporate legumes into rotations. Includes two Saskatchewan farms.[207]

Cultural Farming Research Summary. A review of research and recommendations. 1978. E.G. Reekie. Unpublished. Funded by Saskatchewan Department of Agriculture.

Earthcare: Ecological Agriculture in Saskatchewan. 1980. Hanley, Paul, (Ed.) Earthcare Group, Regina.

An excellent source of information gathered with the prairie producer in mind. An update, with slight reorganization and sections on newer crops would be valuable.

Effects of a Transition to Ecological-Organic Agriculture in Manitoba. 1985.
Robinson, Paul. Unpublished Masters Thesis, University of Manitoba, Winnipeg MB.

Ecology and Integrated Farming systems. John Wiley and Sons Ltd. Bristol UK.

Field Scouting Guide. Anonymous. [no year indicated] Canada-Manitoba Agreement on Agricultural Sustainability.

Colour pictures and descriptions of the biology, crop losses and control (leans to herbicides) of 18 weeds. Also includes similar descriptions of common diseases and insects.

Guide to Crop Protection in Alberta: Non-Chemical Control. 1989. Media' Print Branch, Alberta Agriculture, 7000-113 Street, Edmonton, AB T6H 5T6.

*Practical advise on many aspects of weed control, including detailed descriptions of 32 weed species***.** *Also includes sections on insect and disease management.*

Organic Agricultural Directory. 1989. Les Editions Humus/Canadian Organic Growers, Inc. COG, Box 6408, Station J, Ottawa, ON K2A 3Y6.
A complete directory of Canadian associations, traders, producer organizations, consultants, etc.

Organic Farming. Nicolas Lampkin. Farming Press. Ipswich, UK. 1990 .
A wide ranging book with detailed information of soil, plant nutrition, livestock, weed management, disease control, fodder, horticulture, marketing, processing and economics. Examples primarily from the UK, and may not specifically apply.

Organic Farming in Canada. 1984. Hill, Stuart. Ecological Agricultural Projects, MacDonald College, McGill University.

Organic Field Crop Handbook. 1992. Macey, Anne (Ed.) Canadian Organic Growers, Ottawa ON.
Contains sections on crops and crop rotations.[208]

Practical Crop Protection. Weeds Insects Diseases. Alberta Agriculture. 1994 Food and Rural Development Publishing Branch.
An update to the Guide to Crop Protection in Alberta*. Though not advocating organic agriculture, it contains much practical advise that could be used by organic producers.*

Switching to a Sustainable System. 1988. Kirschenmann, Frederick The Northern Plains Sustainable Agricultural Society, Windsor, North Dakota.

Sustainable Agricultural Systems. Edited by C. A. Edwards, R. Lal, Pl. Madden, R. H. Miller and G. House. Soil and Water Conservation Society. Ankeny, Iowa. 1990.

The Intelligent Farm - The biological theory of ionization principles as applied to farming. 1979. A. F. Beddoe, Bioagriculture Associates.
Discusses how to balance fertility, productivity and health. Interesting quotes. Section on weed control.[209]

The Organic Handbook 5 - Weeds. How to control and love them. 1991. J. Readman, Henry Doubleday Research Association / Search Press.
Simple but sound ecological principles, lovely photographs and comments on herbal uses, remedies and other benefits of weeds. Examples are British.
The Soul of Soil. 3rd edition. 1995. G. Gershuny and J. Smillie. agAccess. Davis, California
A good primer of soil principles. Simple and concise.[210]

Weeds and Why They Grow. 1994. J.L. McCaman. Self-published. Sand Lake, Michigan.

An ecclectic scrapbook of philosophy, information, speculation and some rather questionable suggestions. Should be viewed with a discriminant eye, but offers some food for thought.

Weed Ecology. Implications for Management. 2nd edition. 1997. S. Radosevich, J. Holt, C. Ghersa. John Wiley & Sons Inc. Toronto.

An intensive look at weed ecology, with more information than the casual reader is likely to want, but an excellent textbook for the "serious" student. ***.*** *Examples are primarily from the U.K. (historical) or southern U.S. About 20% of the book deals with herbicides.*

Periodicals*:*

Acres, USA, A Voice for Eco-Agriculture Box-9547, Kansas City, MI, USA 64133.

A national newspaper on eco-agricultural issues and topics in the U.S.

American Journal of Alternative Agriculture. Institute for Alternative Agriculture, 9200 Edmonston Road, Suite 117, Greenbelt, MD, USA 20770.

A scientific journal on alternative agriculture.

Cognition. Canadian Organic Growers, Box 6408, Station J, Ottawa, ON K2A 3Y6. .

Synergy. Box 97, Drinkwater, SK SOH 1G0 (Phone: 306-693-3266).

A magazine for organic farming, urban gardening and consumer information.

The New Farm. Rodale Press, 222 Main St., Emmaus, PA, USA 18098.

A popular magazine on ecological agriculture. The Rodale Institute also operates research farms and has other published materials.

Factsheets:

Foster, Kerry. 1996. FARMFACTS. Organic Crop Production. Sustainable Production Branch, Saskatchewan Agriculture and Food.

An informative and well written series of articles on a range of production issues for organic producers in Saskatchewan, including weed management.

Integrated Weed Management - Making it work on your farm. D. Kelner. FactSheet. Manitoba Agriculture

An excellent, yet simple review.

Websites:

Http://www.ocia.org

The website for the Organic Crop Improvement Association.

Http://www.gks.com/cog/index.htm

The website for Canadian Organic Growers. Includes information on pesticides.

Http://www.aginfonet.sk.ca/agricarta/main.html

A Saskatchewan Agriculture and Food site. Includes information on weeds and weed control (mostly with chemicals). Under "farm management" includes information on organic farming.

Http://www.agrenv.mcgill.ca:80/Extension/EAP/index.htm

Includes extensive literature about organic food, organic farming, organic weed control, weed identification

Http://www.homestead.org/agrinet.htm

A list of agricultural links, including several on organic farming.

Http://res.agr.ca/lond/pmrc/society.html

Very informative site on agricultural research, including Weed Science Society of America.

Http://www.agnic.org/cc/

Alternatives for organic farmers, including insect, weed and soil management.

Http://www.agretex.com/

Information for organic farms on pest control, plant nutrition and soil.

Http://www.agric.gov.ab.ca

Useful section on weed control, though not specifically organic.

Http://www.nal.usda.gov/afsic/search.htm

Listing of information relevant to organic farming, but not especially weed oriented.

Http://www.netlife.fi/meky/links0.html

International movements for organic agriculture. Of limited local relevance

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