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Derksen, D.A.

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Integrated Weed Management (IWM) and Crop Sequencing

D.A. Derksen and L. Juras

Integrated weed management (IWM) and crop sequencing are integral components of sustainable agriculture from an agronomic, economic, and environmental perspective. While crop sequencing is generally listed as a part of IWM, crop sequencing is, in fact, the vehicle that systematically implements components of IWM. Good crop sequences can reduce weed densities at the time of crop emergence thereby minimizing crop yield losses and can inhibit long-term changes in weed communities towards species that are difficult to control. Varying selection pressure is the ecological principle that accomplishes these goals. The objectives of this paper are to describe components of IWM, to describe the selection pressure exerted by crop sequences on weeds, and to provide a template that can be used to understand the interaction of IWM with crop sequencing.

IWM can be defined as the use of agronomic factors, such as cropping and tillage practices, and interventive practices, such as herbicides and biological control, in a way that reduces the reliance on any one factor. "Monocultural" weed control practices can lead to problems, such as soil erosion, weed resistance to herbicides, high input costs, and weed community changes to difficult-to-control species. Crop sequencing refers to a varied series of crops produced within a field and differs from crop rotation in that crop rotations are fixed and follow a set crop sequence. For example, a crop sequence could be a series of cereal-oilseed-cereal-pulse crops that include a wide variety of specific crops, while a crop rotation could be a spring wheat-canola-barley-pea sequence that is repeated through time.

IWM begins with **field sanitation.** Preventing weeds from entering a field by using clean seed, equipment, livestock feed, and cornposting manure to reduce viable weed seeds can avoid serious weed problems. For example, the spread of downy brome in south-western Saskatchewan occurred by importing contaminated seed from Alberta, through the use of contaminated combines used by custom harvesters, from equipment moving between fields once downy brome was established in an area, and from contaminated hay imported during dry years (Douglas et al. 1990).

Livestock **manure can** contain a significant number of weed seeds. Weed species vary in their ability to survive digestion by livestock and in their ability to survive subsequent manure cornposting (Harmon and Klien 1934). For example, field bindweed viability was greater after passage through calves and hogs than through horses and sheep, while the reverse was true for pepper grass. Blackshaw and Rode (1991) have shown that ensiling feed reduced grassy weed

*Agriculture and Agri-Food Canada, Box 1000A, RR#3, Brandon, MB R7A 5Y3.

[2]Saskatchewan Agriculture and Food, 133-3085 Albert St., Regina, SK. S4S 0B1.

seed viability to a greater extent than broadleaf weeds. While none of the grassy weeds tested survived both ensiling and digestion by livestock, Kochia, red root pigweed, lamb's quarters, wild buckwheat, round-leaved mallow, and stinkweed survived both processes. Given the expected increase in livestock production in western Canada, a better understanding of the response of weeds to livestock production and manure handling is required. Furthermore, new IWM strategies should be developed to take advantage of weed management options, such as silage production, while others need to be developed to reduce the potentially negative effects of livestock production, such as the spread of weeds with manure.

Field sanitation also includes the **removal of weeds** from areas adjacent to fields, such as ditches and fence rows, and from patches within fields by removing chaff which contains viable weed seeds or by making silage before viable seeds are produced. During wet years scentless chamomile frequently spreads outward from its habitat in sloughs and becomes very difficult to control once established in fields. Controlling weeds in field margins is particularly important in organic-production systems and in direct-seeding systems where perennial weeds, such as dandelion, can be difficult to control without tillage. Silage may become an important tool to manage herbicide resistant weeds, such as wild oat, particularly in situations where multiple resistance has occurred.

IWM strategies include a number of agronomic factors that, although not directly influenced by crop sequencing, can give a crop the advantage over weeds present within a field. The following factors enhance the weed suppressant effects of crop sequencing: the use of quality seed placed shallowly in moist soil for quick emergence, high seeding rates, crop varieties that are competitive against weeds, fertilizer placed close to the crop, optimum crop row spacings, and alternative methods of weed control.

Large crop seed has been shown to produce more competitive crop plants. Stobbe has shown that wheat plants produced from large seed are more vigourous and contribute a greater portion of the final yield than do plants from small seed (Reichenberger 1996). Further research is required to determine if the use of high quality seed can lead to greater competition against weeds and potentially to the use of lower herbicide rates or fewer herbicide applications.

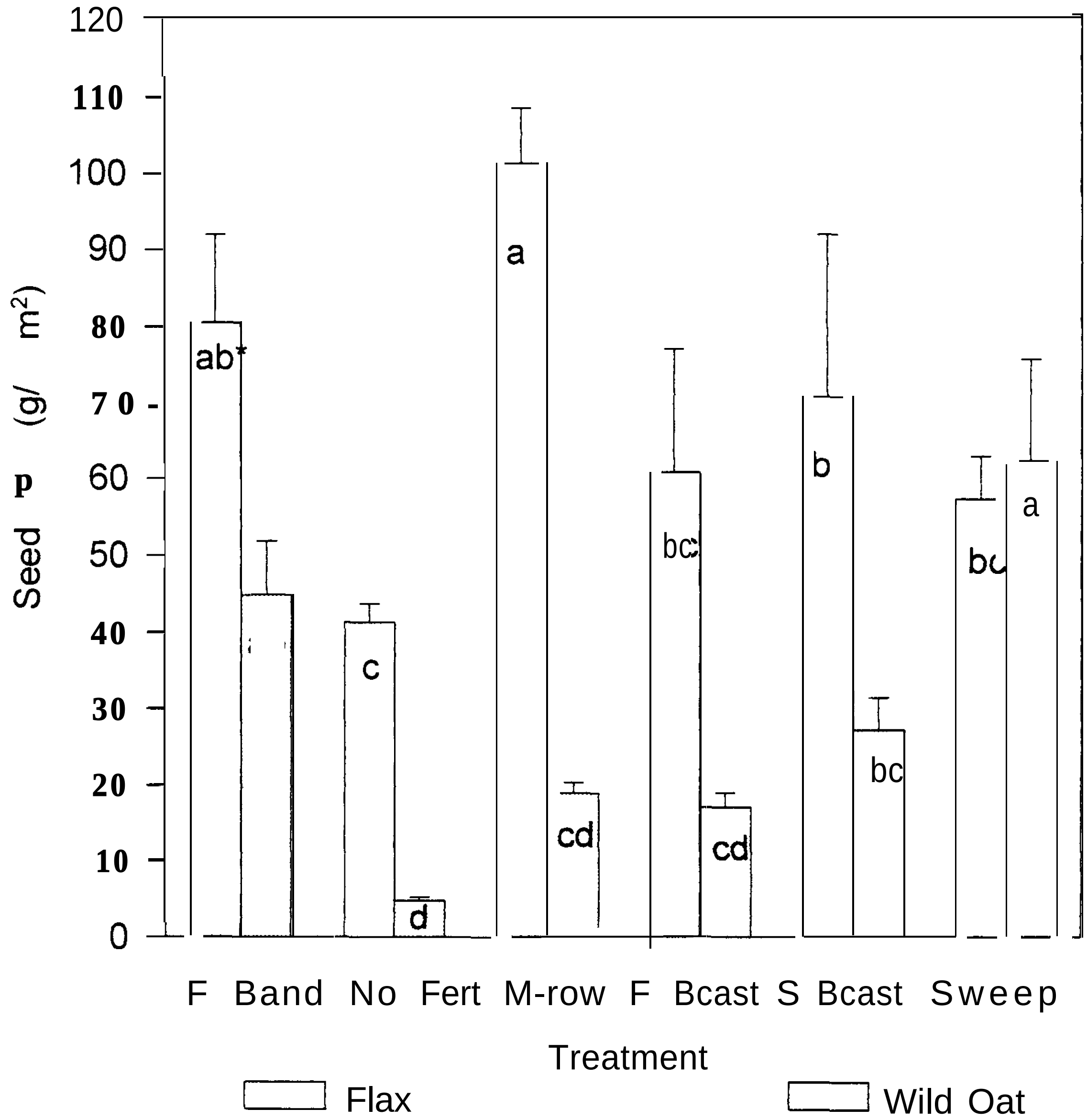
Crop loss thresholds can be used to determine if herbicide application is warranted. Crop losses due to weeds depend on the competitive ability of the crop and the density of the weeds (O.Donovan et al. 1985, Hume 1989). Thresholds have not been extensively used in western Canada; however, economic thresholds have practical potential. By determining the density of weeds prior to the application of post-emergence herbicides, it can be determined if the yield returns justify spraying. Since most herbicides provide between 90 and 99% weed control, the initial weed density can be a significant factor in obtaining crop yield advantages. For example, if initial weed densities are $1000/m^2$, 90% control leaves $100/m^2$ which may still be well above threshold values. Conversely, 90% control of $50/m^2$ leaves $5/m^2$ which may be below threshold values depending on the weed and crop. Therefore, crop sequencing and IWM practices that reduce total weed densities will optimize returns from herbicides by ensuring that the density of remaining weeds is below the level that results in an economic loss.

The more time that elapses between **crop emergence** and subsequent weed emergence, the less competitive are the weeds (O'Donovan et al. 1985, Blackshaw and Schaalje 1993). Although the threshold concept is a component of IWM, relative time of emergence is more important than weed densities (O'Donovan 1992, Blackshaw 1993), therefore using crop sequencing to manipulate emergence factors may be underrated as a weed management tool. Recent results at the Indian Head Experimental Farm have shown that in-crop herbicide treatment is more important than pre-seeding burn-off treatments in zero-tillage at early dates of seeding while the reverse is true at later seeding dates (Figure 1). Research is required to develop prediction models for weed and crop emergence in relation to air and soil temperature so that seeding can be timed to reduce weed impact on crop yield and potentially reduce herbicide usage.

Seeding crops at the high end of recommended **seeding rates,** or greater, has been shown to increase the competitive ability of canola, barley, safflower, navy and dry beans and peas against weeds (O'Donovan 1992, Kirkland 1993, Blackshaw and Schaalje 1991, Wall 1993, Townly-Smith and Wright 1994). Kirkland (1993) has shown that herbicides were not necessary when barley was seeded at high rates, therefore, crop seeding rates can be an effective and economical tool to manage weeds .Concerns are often expressed that the use of high crop seeding rates during dry crop years will reduce crop yield potential. At Indian Head, Lafond (1994) has recently shown that cereal yields were not significantly reduced during dry years at high seeding rates.

Selectively placing fertilizer closer to crop plants than weeds has been shown to favour crop yield over weeds . In a zero-tillage study where a uniform density of wild oats was spread over a field, no wild oat herbicides were used , and the same amount of fertilizer was applied at different timings, fertilizer placed in a mid-row band at seeding provided a higher crop yield and lower dockage than other treatments (Figure 2). Fertilizer effects may be influenced by weed density and environment. For example, when the previous research was repeated with low weed densities, little difference occurred among treatments In zero tillage, increasing rates of banded fertilizer substantially reduced green foxtail densities (O'Donovan et al. 1995). The timing and placement of fertilizer can reduce the competitiveness of weeds against crops and ultimately reduce weed densities; however, research is required under a broader range of conditions, with more weed species, and with other nutrients before general recommendations can be made.

Some **crop varieties can** be more competitive against weeds than others. For example, winter wheat cultivars that were tall in stature were more competitive than semi-dwarf cultivars against downy brome (Blackshaw 1994) and pea varieties with greater vine length were more competitive against summer annual grassy weeds (Wall 1993). Furthermore, Kirkland and Hunter have shown that Neepawa, a tall spring wheat variety, was more competitive against weeds than two varieties from the Canada Prairie Spring Wheat class (199 1). Conversely, these differences did not exist for winter and spring wheat in an experiment with quackgrass (Loeppky



*LSD p<0.05 tmt comparison by crop & weeds separately

Figure 1. Flax yield and wild oat dockage in 1993 at Indian Head, SK. F band=fall, M-row band = mid-row band, F Bcast = Fall braodcast, S Bcast = spring broadcast, Sweep = Sweep opener for seed and fertilizer common placement.

and Derksen 1994). Perhaps quackgrass, a perennial weed, captured more soil moisture than wheat, thereby, reducing the potential benefits of light competition from tall crop varieties. Research determining the relative importance of competition for light versus water in prairie conditions would be useful in directing plant breeding endeavours towards the production of crops with rapidly developing foliage, root systems, or both.

In general, narrower-row **spacing** has been found to provide more crop competition against weeds (Kirkland 1993). In fact, narrower rows and higher seeding rates have been used to reduce herbicide rates. Since the effect of varied row spacing on weed competition can be less than that of seeding rate (Blackshaw and Schaalje 1993), high seeding rates may counteract the potentially negative effects of wide-row spacings. Past research on row spacing and weed competition has been conducted under conventional-tillage situations. Recently, Lafond (1994) has shown that spring wheat, durum, and barley yields under wide-row spacings were similar to those under narrow-row spacings in a weed free zero-tillage system. Given the current trends towards direct seeding in the Canadian prairies and the use of wide-row spacings to enhance crop residue clearance, research should be conducted on the effects of row spacing on weed competition under these new management conditions. It may be that the lack of soil disturbance coupled with crop residues between rows in direct-seeding systems counteracts the potentially negative effects of reduced weed competition due to the use of wide-row spacings.

Alternative methods of weed control are also part of IWM. Post-seeding harrowing is used in organic farming to remove shallowly rooted weeds. The use of flame devices to burn weeds prior to crop emergence is being tested in several countries. Tilling soil at night to reduce weed seed germination by removing the light, a trigger that breaks dormancy, is also being tested. Classical biological control has provided weed control of selected species in non-crop situations, and innundative biological control has potential to control weeds within annual crops (Auld and Morin 1995, Boyetchko 1996). Due to the lack of soil disturbance and the presence of crop residues which could enhance the survival of biological control agents and potentially reduce weed densities, it has been suggested that biological control may have a greater impact in zero- than conventional-tillage systems (Derksen et al. 1996). House and Brust (1989) found that weed seed predation by carabid beetles in zero tillage approached that in native plant stands. The use of smother crops has been promoted as an alternative weed management tool (Bridges 1995); however, the use of green manure crops in the Canadian prairies has not been agronomically successful due to excessive moisture usage (Townley-Smith et. al 1993). Smother crops with a harvestable yield and positive net return, such as fall rye, peas, or buckwheat may be a better alternative to “plough down” crops. Frequently, alternative methods of weed control are developed in isolation from the production system in which they will be used. Further research in alternative weed management, especially in biological control, should be conducted within the context of current trends in crop production, such as increased diversity in crop production and reduced tillage.

The previous crop, current crop, crop life cycles, and herbicide options can be directly influenced by crop sequencing. Understanding the impact of these components on weeds is an important part of developing a successful crop sequence.

The **previous crop** within a sequence can have a significant impact on weeds within subsequent crops (Dale et al. 1992). This occurs in five ways. Firstly, if a poor level of weed control was achieved, then weed problems can increase in subsequent crops. The majority of annual weeds emerge from seed produced last season (Fenner 1985). Secondly, if herbicide selection was limited within the last crop, weeds not controlled or suppressed can increase. For example, wild mustard is commonly a greater problem following canola production. Thirdly, volunteer crops can be a problem, particularly in conservation-tillage systems (Derksen et al. 1993). Fourthly, crop residues can have an impact on weed establishment. Wheat and pea residues have been found to increase the germination of wild oat compared to other crop residues (Purvis et al . 1985). Fifthly, residues from herbicides used in a previous crop can injure subsequent crops (Derksen 1995, Holm 1994),

h e r b i c i d e o p t i o n s .

cereal-

s e e d i n g d a t e

tillage.

Crop competitive ability varies. Cereals are generally more competitive than broadleaf crops with most pulses being less competitive than oilseed crops. Winter cereals can be more competitive than spring cereals when good overwintering conditions occur (Loeppky and Derksen 1994). Fall rye is more competitive than winter wheat and is less susceptible to winter injury . Canola has been found to be more competitive than flax (O'Donovan and Sharma 1983).

Varying competitive ability between competitive and non-competitive crops on an annual basis within the crop sequence may be a useful weed management strategy.

Crop life cycle can be a component of IWM. In general, annual crops select for annual weeds, biennial and winter annual crops for biennial and winter annual weeds, and perennial crops select for perennial weed species (Bridges 1995). For example, wild oats are a problem in annual crops, but rarely a problem in winter cereals (Scherdle 1982). Continuous winter cereal production can lead to increases in winter annual species (Thomas and Wise 1985). Dandelion and other perennial weeds can be problems for alfalfa producers. However, these generalizations become blurred due to interactions with other selection pressures such as herbicides, tillage, varied seeding dates, etc., on weeds; however, varying crop life cycles within a sequence of crops, changes selection pressure on weeds and can be a useful tool to reduce weed densities over time, even in the absence of herbicides (Aldrich 1984).

Crop sequencing coupled with IWM is the varied selection pressure needed to manage weeds on an annual and long-term basis. Because crop sequencing and IWM practices are difficult to separate, prescribing a sequence to manage a specific weed is seldom possible; however, if the principle of varied selection is understood, then crop sequencing and IWM can be powerful tools to suppress the negative effects of weeds on crops. The relationship between crop sequencing and IWM is best understood by examining examples of the effects of selection pressure on weeds.

The production of **winter cereal crops** in south-western Saskatchewan and southern Alberta has led to an increase in downy brome (Douglas et al. 1990). Since it is a winter annual grassy weed that could not be removed chemically from fall rye or winter wheat, downy brome increased quickly in fields were winter cereals were produced continuously. A sequence of winter cereals and fallow did not necessarily improve the situations because downy brome seed is produced early in the spring time and can be spread by delayed tillage in conservation-fallow situations. Therefore, the continuous selection pressure from winter crop production with or without fallow selected for a winter annual weed that could not be controlled by within crop herbicides. Downy brome is now managed through improved fallow techniques (them-fallow with glyphosate or early tillage) and by including summer annual crops into crop sequences, especially broadleaf crops where selective herbicides are available.

Forage crops are considered a key component to sustainable agriculture (National Research Council 1989). Forage crop production has been known to provide weed suppression in annual crops grown after forage crops are removed (Ominski et al. 1994). Manitoba farmers perceived benefits in annual crops produced for three to five years following forage production (Entz et al. 1995). Generally, forages are removed by tillage; however, concerns about subsequent soil erosion and loss of benefits from forages in rotation have been raised. Recently, Bullied and Entz (1994) have found that removing forages with herbicides compared to tillage led to increased yield in subsequent crops, presumably from increased water conservation. The varied selection pressure provided by forages in a rotation is due to their perennial nature and the resulting lack of soil disturbance. The reduction in annual weeds following forages may be due to the forage removal process of stimulating weed seed germination since dormancy may have been reduced by the lack of soil disturbance. As weed seeds spend a greater period of time in the soil, factors required to break dormancy are reduced or no longer required (Taylorson 1987). Conversely, the continuation of an undisturbed habitat when forages are removed chemically followed by zero-tillage seeding, may lead to reduced weed seed viability and seed death. Either way, the potential weed seedling numbers are reduced. Research is required to determine the mechanism of weed suppression by forages so that the practical application and implications of this mechanism can be fully realized.

Continuous triallate usage in monocultural barley production areas in Alberta has led to wild oat **resistance** (O'Donovan 1994). Unfortunately, a varied crop sequence does not ensure that resistance will be avoided or postponed. For example, many graminicides belong to the same group even though they can be used in broadleaf and/or cereal crops (Morrison and Devine 1994), therefore, rotating broadleaf and cereal crops can still lead to a monocultural herbicide usage pattern (ie: the same selection pressure). Using crop sequencing and IWM to avoid the necessity for herbicide use would reduce the likelihood of resistance.

Continuous 2,4-D usage in wheat during a 36 year period selected for lamb's quarters and stinkweed that germinated after the 2,4-D was applied (Hume 1987). Therefore, **herbicide avoidance by weeds can** result from the application of the same herbicides at the same time of year. Varied selection pressure by varying seeding dates and herbicide application dates within a given field should be used to reduce the likelihood of this occurring. Seeding the same field first every year because it is close to the machine shed should be avoided.

Summer fallow has been a part of prairie agriculture almost since crop production began; however, it was recognized as early as 1925 that alternatives needed to be found to reduce soil erosion and degradation (Champlin 1925). Fallowing has been practised to release soil nutrients, store soil moisture, and control weeds. With recent advances in agricultural technology, fallowing may no longer be necessary except in semi-arid regions of the prairies (Derksen et al. 1994). Fallow practices can reduce weed densities in subsequent crops (Blackshaw et al. 1994, Derksen et al. 1993, Hume 1982); however, it may only be useful for controlling weeds with short seed dormancies (Froud-Williams 1988). Even where weed densities have been reduced due to the use of fallow, the benefits of receiving an income from annually harvesting a crop can be greater than those accrued from fallow (Derksen et al. 1994, Lafond et al. 1994). Furthermore, fallow can select for certain species. Foxtail barley and dandelion have been strongly associated with chemical fallow used in zero-tillage systems (Hume et al. 1991, Derksen et al. 1993) and wild buckwheat and wild tomato have been associated with conventional- and minimum-tillage fallow, respectively (Derksen et al. 1993). Therefore, fallow is a selection pressure on weeds and, given the potential for soil erosion and degradation, it should be used for weed management only as a last resort.

Past data has indicated that **reduced-tillage systems** select for perennial weeds (Froud-

Williams 1988). Given that herbicide options have increased for the suppression of perennial weeds, recent data has shown that perennial weeds are not necessarily associated with zero-tillage to a greater extent than with conventional tillage (Derksen et al. 1995. Legere et al. 1993). Experimental data and field surveys have shown that crop sequencing has a greater impact on weed communities than tillage systems (Frick and Thomas, Dale et al. 1992, Derksen et al. 1994). Therefore, crop sequencing is an integral component of IWM in conservation-tillage systems.

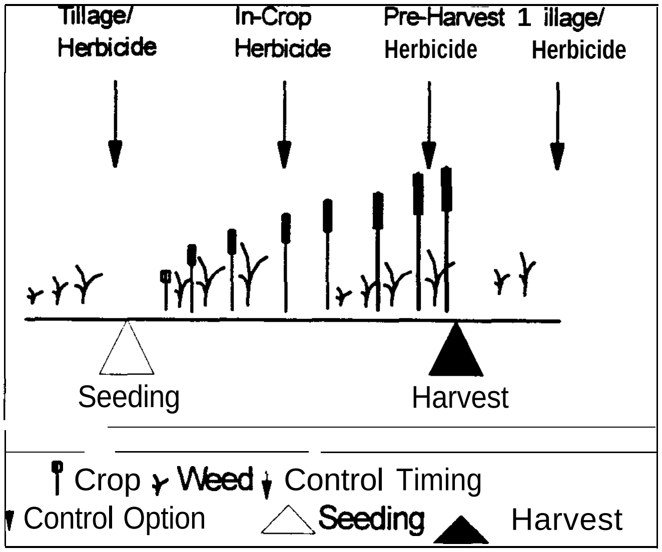


Figure 1. Template to illustrate options for weed management during one season.

The following **template** has been proposed to understand the interactions of IWM and crop sequencing (Derksen 1995). The use of tillage and herbicides for weed control in annual prairie crops occurs at four times during the growing season: before seeding, within crop, pre-harvest, and post-harvest (Figure 3). Using all four options may not be necessary if crop sequencing is planned with weed management in mind (Figure 4). For example, if weeds are controlled the previous fall, then weed control through tillage or pre-seeding herbicide treatments may not be necessary. Conversely, if seeding is delayed, then the majority of weed control may occur with pre-seeding tillage or herbicide usage. In the early seeding situation, greater emphasis will have to be placed on in-crop herbicide usage because weeds will emerge with or shortly after the crop. In the delayed seeding scenario, in-crop herbicide usage may not be required, especially in zero tillage where weed emergence with the crop has not been stimulated by tillage. Visualizing the interactions of crop seeding date, herbicide usage, and crop competitive ability by using a weed management template will provide an indication of potential weed problems.

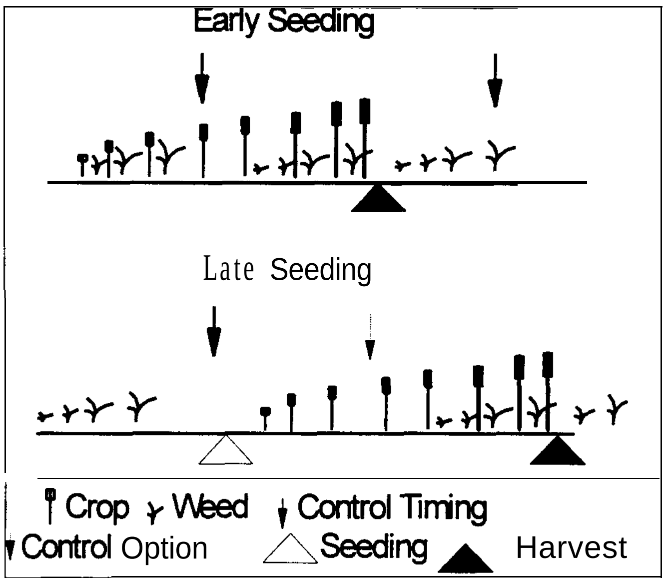


Figure 2. Illustration of reduced herbicide options using different dates of seeding.

A **multi-year template can** be used to analyse the effect of crop sequencing and IWM on weed communities. For example, a four year lentil-wheat-canola-wheat sequence where only pre-seeding and in-crop treatments are applied, will select for weeds such as Canada thistle, dandelion, or winter annual weeds, that germinate under a growing and maturing crop (Figure 5). Dandelion and Canada thistle are difficult to control with herbicides the next season and established Canada thistle is difficult to control with tillage. A more balanced approach is to spread selection pressure out through the growing season (Figure 6). In this example, pre-harvest herbicides are applied one year in four and post-harvest herbicides or tillage are used every year to reduce the build up of perennial and winter annual weeds.

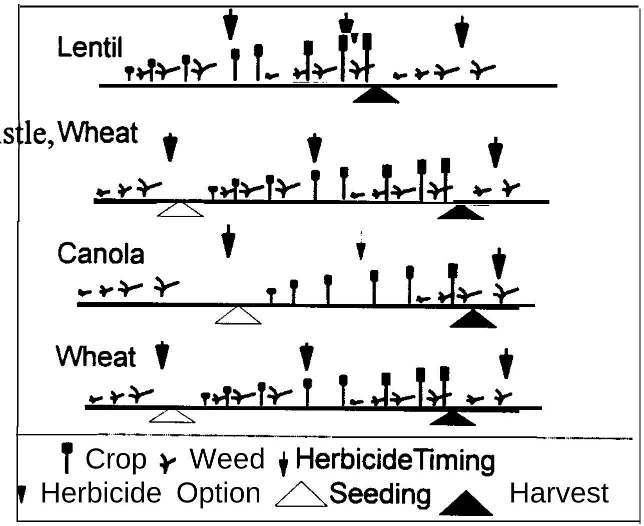


Figure 3. Illustration of varied selection pressure through the growing season in a four year crop sequence.

A new **study was** established at Indian Head, SK to determine the effects of using varied selection pressure as a means of reducing herbicide usage. The study has six crop rotations in each of zero- and conventional-tillage systems that follow a cereal-oilseed-cereal-lentil sequence. All phases of the rotations were present each year with four replications. Crop seeding rates, fertilization, and herbicide applications were done according to recommended practice. Herbicides used were the same in each tillage system. The results presented were taken from the first four rotations. In the low-input rotations grassy weed herbicide usage was reduced by 50% (no treatment in wheat) and broadleaf weed control was reduced in terms of rates used or weed spectrum controlled. Delayed seeding by 10- 14 days was practised for the low-input wheat crops. Given that pulse crops occurred every other year in the second low-input rotation, fertilizer rates were 50% of those used in the high input rotations and seeding dates followed an early/late pattern every other year.

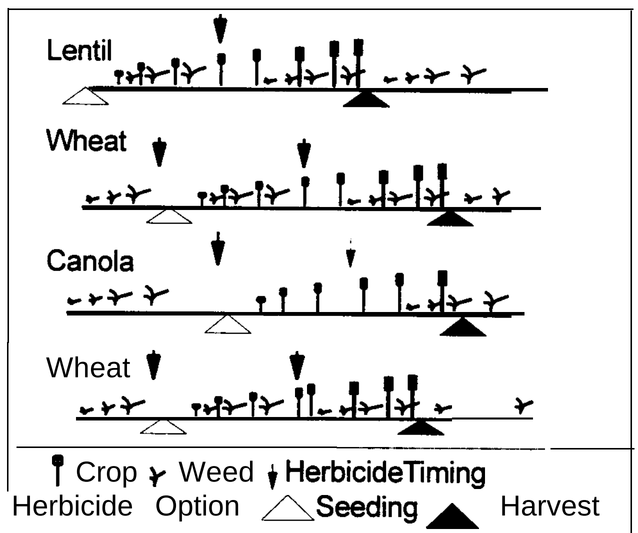


Figure 4. Illustration of a four year crop sequence with selection pressure focused on spring germinating species.

Four years of data have shown that weed densities did not increase in the low-input rotations when assessments were made at the time of in-crop spraying, in late July, or the weed seedbank (Tables l-3). In the low-input herbicide and fertilizer rotation, weed densities were lower than in the high-input rotations. The success of this rotation was likely due to the early/late pattern of seeding, because the major difference between the low-input rotations was in seeding dates and not herbicides used. Crop yields and net-returns were also similar or greater in the low input rotations (data not presented). This example indicates that IWM strategies coupled with crop sequencing can be used successfully to manage weeds, even when herbicide usage is reduced.

Table 1. Average weed density ($\#/m^2 \pm$ SE) of all species present prior to in-crop herbicide annlication 1992-l 995.

Rotation		Zero tillage	Conventional tillage
R1	Wheat-Canola-Wheat-Lentil	2 19 ± 39.4	351 ± 41.2
R2	Wheat-Canola-Wheat-Lentil	12 1 ± 26.4	186.5 ± 44.0
R3	Wheat-Canola-Wheat-Lentil	190 ± 3 5.8	238 ± 33.6
R4	Wheat-Pea-Wheat-Lentil	115 ± 24.5	215 ± 47.3
		Contrasts (p value)	
Zero versus Conventional tillage*			co.03
Interaction Tillage system + rotation*			ns
R1+R2 vs R3+R4			ns
R1 vs R2			<0.08
R3 vs R4			<0.0001

*F value
20 quadrats were counted per plot per year, each value in the table is a mean of 1280 numbers.

Table 2. Average weed density (#/m^2 ± SE) of all species present in July of 1992-1995.

Rotation		Zero tillage	Conventional tillage
R1	Wheat-Canola-Wheat-Lentil	133±11.8	168 ± 18.2
R2	Wheat-Canola-Wheat-Lentil	102 ± 10.9	88 ± 8.7
R3	Wheat-Canola-Wheat-Lentil	115 ± 11.9	120 ± 13.1
R4	Wheat-Pea-Wheat-Lentil	84 ± 9.7	74 ± 6.6

Contrasts (p value)	
Zero versus Conventional tillage *	ns
Interaction Tillage system + rotation*	ns
R1+R2 vs R3+R4	co.003
R1 vs R2	<0.001
R3 vs R4	<0.0001

*F value
20 quadrats were counted per plot per year, each value in the table is a mean of 1280 numbers.

Table 3. Average weed density (#/m^2 ± SE) of all species present in the seed bank (fall 1994).

Rotation		Zero tillage	Conventional tillage
R1	Wheat-Canola-Wheat-Lentil	4508 ± 424	4467 ± 430
R2	Wheat-Canola-Wheat-Lentil	4597 ± 387	3965 ± 251
R3	Wheat-Canola-Wheat-Lentil	4710 ± 391	4778 ± 499
R4	Wheat-Pea-Wheat-Lentil	3053 ± 338	2951 ± 302

Contrasts (p value)	
Zero versus Conventional tillage *	ns
Interaction Tillage system + rotation*	<0.0001
R1+R2 vs R3+R4	co.003
R1 vs R2	<0.0001
R3 vs R4	<0.0001

*F value
20 soil cores were taken per plot with each value in the table being a mean of 320 numbers.

In conclusion, crop sequencing can be used to enhance IWM strategies in order to vary selection pressure on weed communities thereby reducing crop losses due to weeds, reducing weed densities, and inhibiting negative changes in weed communities. Varying selection pressure can be accomplished by choosing crops with different competitive abilities, choosing crops with different life cycles, varying seeding dates within a field, varying herbicide timing, and choosing crops within which alternative methods of weed control can be used. Coupling varied selection pressure on a long-term or multi-year basis with other IWM practices that prevent weed spread, and that enhance the competitive ability of crops against weeds will enhance the sustainability of agriculture by reducing reliance on any one weed management tool.

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