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Extreme Grain-Based Cropping Systems: When Herbicide-Free Weed Management Meets Conservation Tillage in Northern Climates

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The challenges associated with the adoption of conservation tillage and/or low-input cropping systems, whether organic or herbicide-free, across Canada are shaped by scale, environment, and local practices. A study in eastern Canada captured the challenges of introducing low-input cropping systems in mature (20+ yr) tillage treatments in a barley/red clover/corn/soybean rotation. Each mature tillage system came with its own weed problems, but this did not affect crops such as barley and red clover, which produced similar yields across high and low input systems. However, some form of primary tillage was needed to achieve adequate weed control and yield in organic (ORG) and herbicide-free (HF) systems. The HF and ORG systems with no-till actually failed to produce a corn crop but produced soybean yields that were half or less than that for other treatments. The successful combination of conservation tillage practices and low-input systems in eastern Canada would thus appear to be crop-specific, being easier to achieve in competitive cereal crops. In western Canadian organic agriculture, tillage is practiced with low-disturbance chisel plows instead of inversion plows. However, green manure crops (summer cover crops) are often terminated with tandem discs. Both roller crimpers and mowing can successfully kill annual green manure crops such as field pea and rye, and usually result in reduced weed growth following termination. However, the lack of tillage can result in lower crop yields in wheat following green manure terminated by roller crimping compared to tillage. Challenges for no-till organic practices include perennial weed control and soil fertility. Overall, flexible crop production programs such as the former Manitoba Pesticide Free Production program and the "Agriculture raisonnée™" program in Québec are more likely to promote sustained environmental, economic, and social prosperity than rigid adherence to organic or no-till practices.
Nomenclature: Barley, *Hordeum vulgare* L.; corn, *Zea mays* L.; field pea, *Pisum sativum* L; red clover, *Trifolium pratense* L; rye, *Secale cereale* L; soybean, *Glycine max* (L.) Merr.
Key words: Blade roller, flexible crop production system, low-input cropping system, organic no-till, pesticide-free production, sustainable agriculture.

Los retos asociados a la adopción de la labranza de conservación y/o los sistemas de cultivos de bajos insumos, ya sean orgánicos o libres de herbicidas, a lo largo de Canadá, están determinados por la escala, el ambiente y las prácticas locales. Un estudio en el este de Canadá capturó los retos de introducir sistemas de cultivos de bajos insumos en sistemas maduros de labranza (20+ años) en una rotación cebada/trébol rojo/maíz/soya. Cada sistema maduro de labranza tuvo sus propios problemas de malezas, pero esto no afectó a cultivos como cebada y trébol rojo, los cuales produjeron rendimientos similares en los sistemas de altos y bajos insumos. Sin embargo, algunas formas de labranza primaria fueron necesarias para alcanzar los controles de malezas y rendimientos adecuados en sistemas orgánicos (ORG) y libres de herbicidas (HF). Los sistemas HF y ORG con cero-labranza fallaron en producir cosechas de maíz, aunque produjeron rendimientos de soya que fueron la mitad o menos que aquellos producidos en otros tratamientos. La combinación exitosa de prácticas de labranza de conservación y sistemas de bajos insumos en el este de Canadá pareciera ser específica al cultivo, siendo más fácil de alcanzar con cultivos tales como cereales competitivos. En la agricultura orgánica del oeste de Canadá, la labranza se realiza con arados de cinceles de baja perturbación en lugar de usar arados de inversión. Sin embargo, los cultivos para abono verde (cultivos de cobertura de verano) son generalmente terminados con discos en tándem. Tanto rodillos de cuchillas y aplanadoras como chapeadoras pueden matar exitosamente cultivos anuales para abono verde, tales como leguminosas y centeno, lo que usualmente resulta en un crecimiento reducido de las malezas después de la terminación del cultivo. Sin embargo, la ausencia de labranza puede resultar en bajos rendimientos en trigo después de la terminación del cultivo para abono verde usando rodillos en comparación con la labranza. Los retos en las prácticas orgánicas de cero-labranza incluyen el control de malezas perennes y la fertilidad del suelo. En general, programas flexibles de producción tales como el anterior programa de Manitoba para la Producción Libre de Plaguicidas y el programa "Agriculture raisonnée™" en Québec tienen más probabilidades de promover en forma sostenida la prosperidad ambiental, económica y social que la adhesión rígida a prácticas orgánicas o de cero-labranza.

The challenges associated with the adoption of conservation tillage or low-input, grain-based cropping systems, whether organic or herbicide-free, across Canada are shaped by the nature and scale of farming operations, environment, and local practices. The provinces of Québec (QC) and Saskatchewan (SK) exemplify the range of contrasting agro-environmental conditions affecting shifts in crop production models (see Eilers et al. 2010 for details on information presented below). In 2006, the average size of farms in SK was

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at least five times that in QC (587 vs. 113 ha). The agricultural output in QC was mainly animal based (dairy, hogs, poultry and eggs, and cattle, and calves), whereas that in SK was split between canola and wheat, and cattle and calves.

The agri-environmental performance assessed for the 1981 to 2006 period suggested that risks of water contamination by nitrogen, phosphorus, coliforms, and pesticides observed in QC were greater than in SK. Conservation tillage—defined as any system leaving 30% or more crop residue on the soil surface (Eilers et al. 2010)—was practiced on 75% of cultivated land in SK (approximately 50% no-till), but only on 40% in QC (10% no-till). The certified organic acreage in 2009 was approximately 400,000 ha in SK (57% of Canadian total) compared to 41,000 ha in QC. Producers from both regions deal with short growing seasons but face somewhat different environmental conditions during the season and throughout the year. Although long-term heat unit accumulation is similar (e.g., La Pocatière QC, 1,640 growing degree days $(GDD)_{base5\ C}$; Saskatoon SK, 1,685 $GDD_{base5\ C}$), precipitation in QC can be three to four times that in SK (e.g., La Pocatière QC, 962 mm; Saskatoon SK, 348 mm).

However, in spite of these contrasts, the challenges posed by adopting conservation tillage and organic practices, singly and particularly in combination, can be similar. When surveyed in 2008, organic farmers from across Canada identified comparable research needs for cropping systems, including increased knowledge of the effects of crop rotation on biodiversity and weed management, and the use of reduced tillage/no-till in systems with cover crops (Macey 2010). In this paper, we provide a summary of results from recent research addressing these issues in each region, and describe relevant Canadian crop production program initiatives, mainly market-driven, that would support the view of a more open and flexible approach to sustainability (Welsh 2010).

Applying Herbicide-Free Weed Management to "Mature" Conservation Tillage Plots in Eastern Canada

As in the United States (Ervin et al. 2010), QC producers interested in low-input systems appear to be conducting most of their own on-farm research. Indeed, to our knowledge, limited main-stream research has addressed weed management issues in QC herbicide-free and organic grain systems (Cantin et al. 2012). However, the research conducted in other northern regions suggests that improved weed management through adjustments in crop seeding dates and rates, planting patterns, row widths, and mechanical weed control could contribute to the success of low-input grain production (Kolb et al. 2010; Mason et al. 2007; O'Donovan et al. 2012). But whether herbicide-free or organic production would be feasible under conservation tillage under the cool wet conditions of the St-Lawrence lowland ecoregion had not been formally investigated.

A study initiated in 1987 at the Centre de Développement Bioalimentaire du Québec, in La Pocatière, Québec (47°21′N, 70°02′W), compared the productivity of various crop rotations under three tillage treatments (moldboard plow, chisel plow, no-till) (Légère et al. 2011b). The experiment was conducted on a Kamouraska clay (fine, mixed, frigid Typic Humaquept; 10% sand, 30% silt, 60% clay in the surface horizon; pH = 5.9; organic matter = 4.5 g kg^{-1}; P = 94 kg ha^{-1}, Mehlich 3 extractable; K = 305 kg ha^{-1}). Starting in 2007, the tillage plots were used to determine the feasibility of applying herbicide-free weed management systems to mature conservation tillage plots. The four cropping systems included: (1) a system providing a herbicide-free (HF) growth season but allowing the use of synthetic nutrients and off-season herbicide applications; (2) a system based on agronomic practices used in organic agriculture (ORG) (nutrients supplied as dry granular poultry manure and mechanical weed control); and cropping systems using either (3) conventional crops (CONV) or (4) herbicide-tolerant, genetically modified (GM) crops with synthetic nutrients and herbicide-based weed control (Table 1). Effects on weed communities, crop yield, and on various other biological components of the agroecosystem were measured in a 4-yr barley (2007)/red clover (2008) (managed as a forage crop)/corn (2009)/soybean (2010) rotation (A. Légère and A. Vanasse, unpublished data). The crop sequence was selected with the assumption that the initial barley/red clover years would provide good weed suppression as well as nitrogen input in support of the more demanding and less competitive corn crop (Gómez et al. 2012; Liebman et al. 2012).

According to a mixed-model ANOVA (cropping system and tillage as fixed effects; replicates [$n = 4$] as random effect), cropping system and tillage had no effect on barley grain yield (average yield: 4,500 kg ha^{-1}). Weed biomass was generally low in most treatments; only a few plots harbored in excess of 10 kg $ha^{-1}$of weed biomass. Residual (POST weed control) weed populations were present in most plots, regardless of tillage or cropping system, and whether herbicides or harrowing had been used for weed control. Although they did not have drastic effects on barley yield, these weed populations did have the potential to produce weed seed and replenish the seed bank. In the red clover year (2009), no weed control was applied to any of the plots during the season. Still, red clover forage yields (sum of two cuts) were similar across all treatments (average yield: 5,300 kg ha^{-1}), with a narrow range of weed biomass values similar to those observed for barley.

In spite of providing good forage yields, the red clover crop did not appear to generate the expected benefits uniformly across all treatments in the following corn crop. Silage corn yields were mainly affected by cropping system: CONV and GM (15,000 kg ha^{-1}) yields were 25% greater than those in HF and ORG (11,200 kg ha^{-1}) (Figure 1A). The HF system with chisel plow tillage produced corn yields comparable to those in CONV and GM systems, whereas the HF and ORG systems with no-till failed to produce a corn crop. Tillage effects on weed biomass varied with cropping system, the tillage effect (no-till > tilled) being greater in HF than in other cropping systems (Figure 1B). Mechanical weed control operations failed to adequately control weeds in no-till HF and ORG systems. Weed biomass in the range of 1,500 to 3,000 kg ha^{-1} was associated with crop failure in these treatments.

Table 1. Summary of tillage and weed control operations according to cropping system and tillage treatments from 2007 to 2010 at La Pocatière, Québec.

	Cropping system							
	CONV[a]		GM		HF		ORG	
Year/Crop	MP & CP	NT	MP & CP	NT	MP & CP	NT	MP & CP	NT
2007 Wheat	Fall primary tillage (2006)	—	Fall primary tillage (2006)	—	Fall primary tillage (2006)	—	Fall primary tillage (2006)	
	Spring glyphosate burndown	Spring glyphosate burndown	Spring glyphosate burndown	Spring glyphosate burndown	Spring glyphosate burndown	Spring glyphosate burndown	Spring secondary tillage prior to seeding	
	Spring secondary tillage prior to seeding	—	Spring secondary tillage prior to seeding	—	Spring secondary tillage prior to seeding	—	—	
	One in-crop herbicide treatment	One in-crop herbicide treatment	One in-crop herbicide treatment	One in-crop herbicide treatment	One pass in-crop tine harrow	—	One pass in-crop tine harrow	
2008 Red clover	Fall glyphosate burndown	Fall glyphosate burndown	Fall glyphosate burndown	Fall glyphosate burndown	Fall glyphosate burndown	Fall glyphosate burndown	Fall primary tillage	
	Fall primary tillage		Fall primary tillage		Fall primary tillage			
2009 Corn	Spring secondary tillage prior to seeding	Shallow pass of cultivator prior to seeding	Spring secondary tillage prior to seeding	Shallow pass of cultivator prior to seeding	Spring secondary tillage prior to seeding	Shallow pass of cultivator prior to seeding and in-crop	Spring secondary tillage prior to seeding	Shallow pass of cultivator prior to seeding and in-crop
	Two in-crop herbicide treatments	Two in-crop herbicide treatments	Two in-crop herbicide treatments	Two in-crop herbicide treatments	One pass in-crop tine harrow (MP) or cultivator (CP)	—	One pass in-crop tine harrow (MP) or cultivator (CP)	
2010 Soybean	Spring glyphosate burndown	Spring glyphosate burndown	Spring glyphosate burndown	Spring glyphosate burndown	Spring glyphosate burndown	Spring glyphosate burndown	—	One pass in-crop tine harrow
	Spring secondary tillage prior to seeding	—	Spring secondary tillage prior to seeding	—	Spring secondary tillage prior to seeding	—	Spring secondary tillage prior to seeding	
	One in-crop herbicide treatment	One in-crop herbicide treatment	One in-crop herbicide treatment	One in-crop herbicide treatment	One pass in-crop tine harrow	One pass in-crop tine harrow	One pass in-crop tine harrow	

[a] Abbreviations: CONV, using conventional crop varieties; GM, using genetically-modified, herbicide-tolerant crops; HF, herbicide-free during the crop growth period; ORG, organic; MP: moldboard plow tillage; CP, chisel plow tillage; NT, no-till.

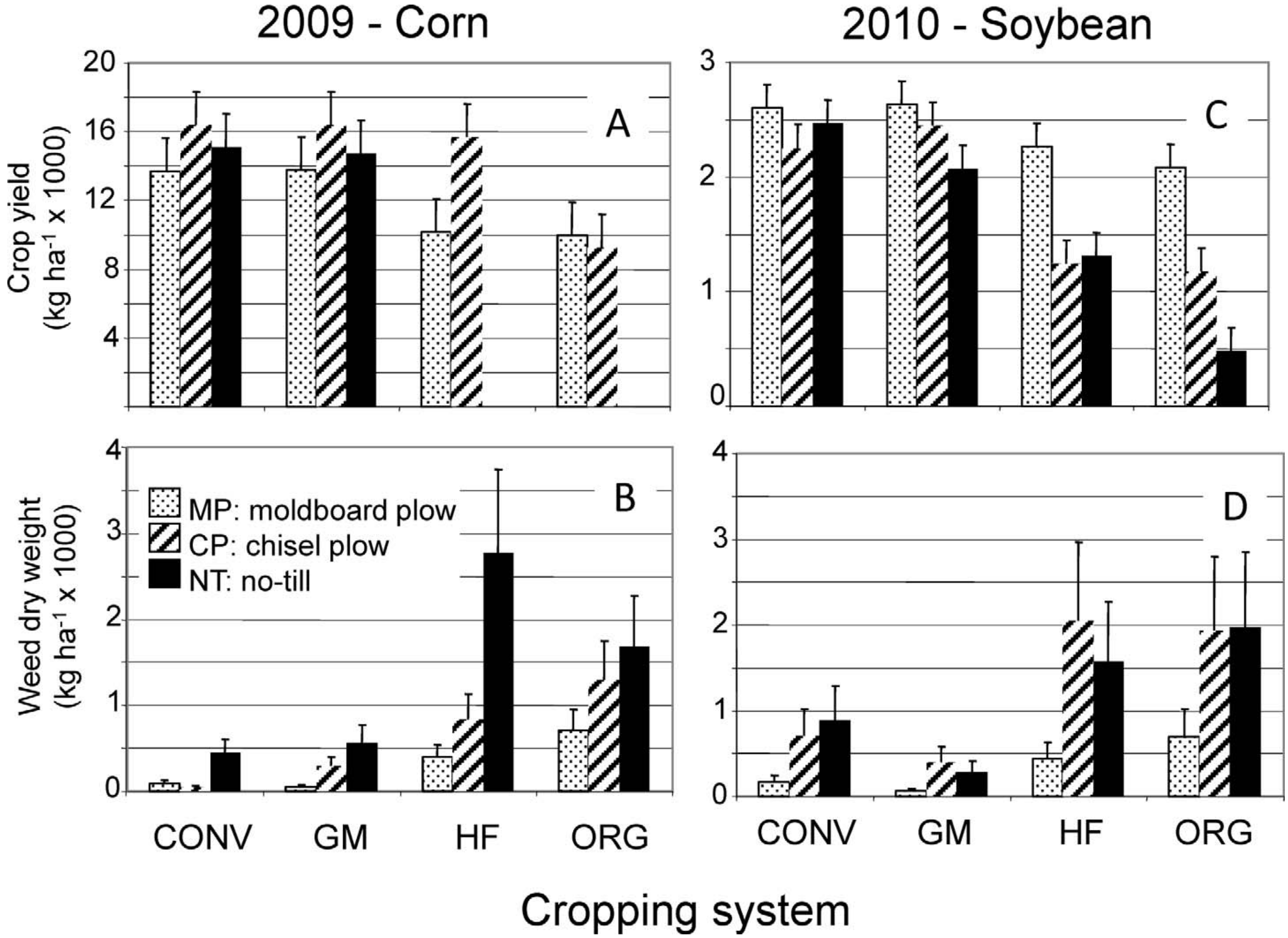

Figure 1. Mean (with SE error bars) values for crop yield (A, C) and mid-season weed biomass (POST weed control) (B, D) according to cropping system (CONV, using conventional crop varieties; GM, using genetically-modified, herbicide-tolerant crops; HF, herbicide-free during the crop growth period; ORG, organic) and tillage (MP, moldboard plow; CP, chisel plow; NT, no-till) for crops grown in 2009 and 2010 at La Pocatière, Québec.

Tillage had no effect on soybean yield in CONV and GM systems. The HF and ORG systems with moldboard plow tillage produced soybean yields (2,200 kg ha^{-1}) comparable to those in CONV and GM systems (2,400 kg ha^{-1}) (Figure 1C). In contrast with corn, the HF and ORG systems with no-till actually produced a soybean crop but yields were half or less (1,100 kg ha^{-1}) than for those with moldboard plow and for yields from all other CONV and GM treatments, regardless of tillage. Weed biomass in HF and ORG systems with chisel plow and no-till was greater than in other treatments, with biomass values averaging close to 2,000 kg ha^{-1} (Figure 1D).

Overall, the feasibility of applying low input cropping systems to mature conservation tillage plots varied with crop. The success of conservation tillage in organic farming depends on high standards of management, including diversified crop rotations, and an integrated weed management (IWM) approach (Carr et al. 2012a; Peigné et al. 2007). Clearly, this challenge is compounded when dealing with mature conservation tillage plots. In our case, each 20-yr-old tillage plot came with its own weed problems, actual and potential (Légère et al. 2005). Seedbanks assessed in 2006, the year prior to the start of this study, were approximately 50 to 80% greater in no-till than in chisel or moldboard plow tillage treatments (Légère et al. 2011a). This "established" weed situation had little effect on competitive crops such as barley and red clover, even in HF or ORG no-till systems. For both corn and soybean, some form of primary tillage (moldboard or chisel plow) was needed to achieve adequate weed control and yield in ORG and HF systems.

Still, we believe that the balance of successes vs. failures was determined by certain factors that could be improved upon, even in corn and soybean. Our weed control options were limited by the rather small pool of mechanical and other alternative weed control tools available to us. Crop sequence could likely be optimized to enhance weed control in less competitive crops such as corn (Anderson 2011; Carr et al. 2012a). Also, weather events, such as the very cool spring in 2009, delayed planting and narrowed the time frame in which it was possible to apply weed control measures in an already short growing season. But overall, it would seem that under the limiting conditions of more northern agroecosystems, competitive short-season crops should be favored over long-season crops in herbicide-free or organic conservation tillage systems.

Organic No-Tillage Research in Western Canada

There has been considerable interest recently in the development of an organic no-till cropping system in many regions of North America, including the Canadian prairies. This interest has been mainly research-driven and has resulted in recent conference symposia (including this one) as well as a special edition of one journal (Carr et al. 2012b). Much of the initial research into organic no-till systems has focused on using a roller crimper to terminate cover crops (Ashford and Reeves 2003). In cereals, there is usually little regrowth if the cover crop has begun flowering before the rolling operation. This system has shown potential in organic soybean grown following a rolled fall rye cover crop. In this system, a fall rye cover crop sown the previous fall is rolled after flowering in the spring (Davis 2010). Shortly after this, soybeans are seeded into the rolled rye mulch. In northeastern United States, cover crop mulches producing greater than 8 Mg ha^{-1} of dry biomass can suppress weed biomass by 75% or more (Teasdale and Mohler 2000).

The system of rolled fall rye followed by an annual grain crop system will not work on the Canadian prairies, because the growing season is too short following flowering of fall rye in the spring. Even in North Dakota, which receives more heat units than the Canadian prairies, it was not possible for the short-season crops buckwheat and dry bean to be grown to maturity following termination of fall-sown cover crops (Carr et al. 2012a). Furthermore, the semiarid climate of the Canadian prairies make it unlikely that cover crops could ever produce 8 Mg ha^{-1} of dry biomass, and even if they did, there would be little soil moisture remaining to grow a cash crop. Because of these climatic limitations, research into organic no-till on the Canadian Prairies has focused mainly on using roller crimpers to eliminate the tillage associated with terminating green manure cover crops.

Green manure cover crops have been advocated as summer fallow replacement on the Canadian prairies (Townley-Smith 1993). Typically, an annual or biennial legume crop is grown as green manure so that atmospheric nitrogen can be fixed. The crops are usually terminated by tillage during crop flowering to prevent viable seed production and to allow for rainfall to partially recharge the soil. Because soil water is generally limiting in much of the prairies, earlier green manure termination usually results in greater yields for the following crop because of less water use by the green manure crop (Biederbeck and Bouman. 1994).

In western Canada, Vaisman et al. (2011) first investigated the agronomic implications of replacing tillage with roller crimping to terminate a pea/oat (*Pisum sativum* L./*Avena sativa* L.) green manure crop. They used either tillage or roller crimping at four distinct timings between terminating the green manure crop and preparing the land for seeding the following year. In 2 of 3 site-yr, replacing tillage operations with roller crimping reduced wheat yield the following year. The authors speculated that this occurred because of reduced soil nitrogen mineralization. However, the no-till treatment resulted in fewer weeds in the following wheat crop compared to tilled treatments. Shirtliffe and Johnson (2012) compared pea green manure crop termination by roller crimping, mowing, or tillage on green manure and weed regrowth, as well as weed and crop responses in the following wheat crop. Weed regrowth following termination was reduced by approximately four fold with roller crimping and mowing compared to the tillage treatment at the earliest termination timing, presumably because of the lack of tillage to initiate new weed growth. Wheat yield and weed biomass following the green manure crops were unaffected by method of termination. Likewise, weed biomass was not affected the year following wheat.

Perhaps the lack of any long-term effects in Shirtliffe and Johnson's study (2012) is not surprising, because there was no attempt to establish a continuous, no-till organic system, and only tillage associated with green manure termination was replaced with no-till methods. In contrast, Carr et al. (2012a) found that, in North Dakota, weed growth about 75 d after rolling was greater than that after tillage with a tandem disk in 2 of 3 yr, but similar across treatments in the other year. Carr et al. (2012a) also evaluated a low-disturbance blade plow (also known as a "Noble Blade") that can undercut plants, yet results in almost no surface soil disturbance. In 1 of 3 yr, weed biomass after termination with the blade plow was lower than with rolling, but did not differ between treatments in the other 2 yr.

The surface crop residue of reduced tillage organic, or even no-till organic might have implications for the machinery used for POST weed control by organic farmers. The problem is that many implements used for in-crop weeding in solid-seeded grain crops are ineffective because they become plugged with the large amounts of surface crop residue that are present in a no-till cropping system (Leblanc and Cloutier 2011). However, Shirtliffe and Johnson (2012) identified that a minimum tillage rotary hoe can operate in the residue of a conventional no-till system. Furthermore, multiple passes by a rotary hoe did not appreciably reduce the amount of surface crop residue. The rotary hoe does have limitations as a mechanical weed control implement because it only effectively controls small-seeded, shallow-germinating weeds, from the "white-thread" (germinated but not fully emerged) to the cotyledon stage.

Implementing an IWM system that combines multiple control methods can further help reduce annual weed problems on organic farms and should be a component of no-till crop production in both conventional (Anderson 2008) and organic cropping systems (Nord et al. 2011). Integrating multiple-control tactics, including increased seeding rates, competitive crop cultivars, and in-crop harrowing has been successful in reducing weed biomass by greater than 70% in western Canada under organic conditions (Benaragama 2011). The inability of organic no-till cropping systems to control creeping perennial weeds is probably the greatest weakness of such systems (Carr et al. 2012a; Mirsky et al. 2012). In particular, Canada thistle [*Cirsium arvense* (L.)

Scop.] is troublesome on organic farms in SK, ranking as the seventh most common weed in terms of relative abundance (Shirtliffe and Knight 2003). The tillage regime required to kill Canada thistle is especially onerous, with multiple tillage passes per season required to fragment the roots and deplete stored carbohydrates (Håkansson 2003). We have personally observed organic research land as well as commercial organic farms that have become completely overrun with Canada thistle to the extent that annual crop production is impossible without excessive yield losses.

Challenges to organic crop production on the prairies extend beyond weed control issues to soil nutrients. Soil phosphorus levels on western Canadian organic farms are very low (Entz et al. 2001; Knight et al. 2010). Organic crop production on the prairies is export-based with little livestock production; therefore little manure is used on the land. In Saskatchewan, only 10 of 60 surveyed organic fields had any manure application in the previous 5 yr (Knight et al. 2010). This problem is further exacerbated by the regulations that effectively preclude the usage of nonorganically produced manures on organic farmland in Canada. Because of weeds and phosphorus deficiency, long-term yields in well-managed organic research plots usually are about 70% of conventional yields on a single-year basis (Brandt et al. 2010). However, this single-year figure does not account for the complete lack of grain yield that occurs in years when green manure cover crops are grown.

An alternative to organic no-till production might be needed, given the production issues associated with extensive, export-based organic crop production in western Canada. Studies comparing food produced under organic and conventional systems have failed to identify consistent differences in levels of macronutrients, although fruit and vegetables grown organically are often higher in minerals and vitamins (Lairon 2011. The main qualitative difference between organic and conventional food is the detection of pesticides. In a recent review, Winter (2012) found that in all cases, pesticide residues were detected much less frequently in organic compared to unlabeled foods. Many consumers choose to eat organic food to reduce their exposure to pesticides (Winter 2012). Perhaps what is needed for western Canada is a no-till cropping system that allows for effective perennial weed control and adequate crop phosphorus supply, yet that will be able to supply consumers with food that is low in pesticide residues.

Flexible Crop Production Programs for a Sustainable Agriculture

The research results presented above from contrasting regions of Canada suggest that conservation tillage might be somewhat compatible with herbicide-free or organic cropping systems, but would be generally more difficult to achieve in certain crops, particularly in the "extreme" no-till/organic combination. The difficulty lies in trying to grow crops in an unpredictable environment according to rigid rules, either related to strict adherence to a no-till practice or dictated by certification bodies for organic cropping systems. The resulting problems and frustrations are apparently driving a substantial number of farmers across Europe to revert from organic to conventional farming techniques (Sahm et al. 2012). It would appear that flexible crop production programs would be more likely to successfully address environmental, economic and social issues related to sustainable agriculture (Ervin et al. 2010; Liebig et al. 2007).

Such a flexible crop production program was developed in Manitoba through a participatory process involving farmers and scientists, with the goal of facilitating pesticide use reduction (Nazarko et al. 2004). This "Pesticide Free Production" (PFP) program prohibited in-crop use of pesticides and seed treatments but allowed synthetic fertilizers and nonresidual pesticide use prior to crop emergence. Unlike the rigid rules of organic agriculture, PFP was intended to be a flexible program that farmers could opt out of during any one season without future implications. PFP encouraged farmers to adhere to threshold-based pest management and only use pesticides when necessary to produce crops in an economically viable way, while at the same time reducing the pesticide load on the environment and the risk for developing pesticide-resistant biotypes.

In Manitoba, PFP was evaluated at the farm scale (2000 and 2001) (Nazarko et al. 2003) and in a small-plot PFP experiment initiated in 2000 by the University of Manitoba (Schoofs et al. 2005). In certifiable fields at the farm scale (71 farms, 120 fields), PFP resulted in 8 to 10% lower yields than the conventional average, with manageable weed densities in spite of the reduction in herbicide use (Nazarko et al. 2003). Both on-farm and experimental data highlighted the importance of crop selection for the success of PFP (Gulden et al. 2011; Nazarko et al. 2003; Schoofs et al. 2005). The small-plot PFP experiment initiated in 2000 focused on in-crop herbicide omissions and contained both a 4-yr annual grain crop rotation (flax/oats/canola/wheat) and an annual grain/perennial forage rotation (flax/oats/alfalfa/alfalfa). Within each rotation, three levels of in-crop weed management were examined: low, medium, and high. In high weed management treatments, in-crop herbicides were used in all annual field crops; in medium weed management treatments, in-crop herbicides were omitted systematically from the oat crop; and in low weed management treatments, in-crop herbicides were omitted from both the oat and the flax crops. The study was managed using no-till practices.

A regression analysis of weed biomass and crop yield was conducted for the flax and oat crops across the three rotations using averaged data collected from the first 4 yr of the study (Schoofs et al. 2005). The relationship between weed biomass and crop yield was only significant in the flax crop (annual grain rotation $R^2 = 0.39$, $P < 0.074$; annual grain/perennial forage rotation $R^2 = 0.82$, $P < 0.001$), but was not significant for the oat crop in either rotation. The relationship between flax yield and weed biomass reflects the poor competitive ability of flax. In the competitive oat crop, weed biomass (79 to 788 kg ha^{-1}) was of little consequence to oat yield. After 10 yr of implementing the treatments, weed seed banks had increased in treatments where herbicides were omitted, but this did not translate into yield losses in competitive crops (e.g., oats) or in crops where highly effective herbicide programs were available (e.g., canola and wheat) (Gulden et al. 2011). Economic benefits were more likely attained if herbicide omissions occurred in competitive crops where the yield benefits from in-crop herbicide use did not outweigh the cost of herbicide application (Gulden 2012).

The studies in Manitoba and Québec have outlined initial steps toward successful reduction of in-crop herbicide use in reduced-tillage cropping systems. These begin by reducing in-crop herbicide applications in the most competitive crops in the rotation. The success of in-crop herbicide omissions, of course, depends on maximizing IWM efforts. A suite of cultural weed management techniques used by all farmers can be fine-tuned to maximize the crop's ability to compete with weeds, and the addition of effective in-crop mechanical weed management (such as harrowing on occasion), can be used to further improve weed management when necessary (Johnson et al. 2011). Under western Canadian conditions, diversified crop rotations, increased planting densities, planting of competitive cultivars, and appropriate fertilizer placement are techniques that, when used continuously and in combination, dramatically reduce weed population densities, biomass, and seed return (e.g., Blackshaw et al. 2004; Harker et al. 2010). These techniques can also effectively shift the requirement for in-crop herbicides from obligate to facultative. The over-reliance on herbicides for weed management has recently been facilitated by the increasing number of herbicide-resistant crops (Harker et al. 2012; Mortensen et al. 2012). This has resulted in the proliferation of herbicide-resistant weeds whose management could jeopardize soil conservation and cropping system sustainability (CAST 2012).

A major challenge hindering the adoption of more flexible PFP-like systems by farmers will be to overcome the "clean field" aesthetics that have become synonymous with "successful" industrial agriculture. Clean field aesthetics, slightly lower yields despite improved economic return, lack of a marketing/branding premium and official recognition, and perceived risks associated with higher weed populations contributed to the abandonment of PFP in Manitoba not long after its inception.

To be successful, programs such as the PFP require support and recognition, and need to be embraced by the whole production/supply chain, from the farmer to the consumer. Including the latter is crucial, because they are the ones who, in the end, are driving decisions by affecting the market. One very successful Québec bakery has embraced this concept by making their commitment to sustainable agriculture a part of their direct marketing effort (Première Moisson 2012). This bakery has fully engaged in the traceability of the ingredients used in their baking products to ensure that the grains have been produced according to sustainable practices (Agriculture raisonnée™: Sustainable Agriculture). Farmers involved in this partnership are committed to using sustainable practices (e.g., crop rotation, few to no pesticides, reduced use of fertilizers) that are validated and graded to confirm compliance. In this context, adoption of sustainable practices is clearly favored by the fact that they are valued both by business and customers. Low-input crop production programs that will allow farmers to tailor and choose the practices most adapted to their circumstances could be the key to long-term sustainability in both regions of Canada and beyond.

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