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Environmental impacts from herbicide tolerant canola production in Western Canada

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ABSTRACT

The commercial production of herbicide tolerant (HT) canola began in Western Canada in 1997. With more than a decade of use, the actual farm-level environmental impact of HT canola can be evaluated. This article reports on a spring 2007 survey of nearly 600 canola farmers in the three prairie provinces of Western Canada. Producers were asked about their crop production experiences for 2005 and 2006 and expected crop planting for 2007. A reduction in the total number of chemical applications over the 3-year period was reported, resulting in a decrease of herbicide active ingredient being applied to farmland in Western Canada of nearly 1.3 million kg annually. Fewer tillage passes over the survey period were reported, improving moisture conservation, decreasing soil erosion and contributing to carbon sequestration in annual cropland. An estimated 1 million tonnes of carbon is either sequestered or no longer released under land management facilitated by HT canola production, as compared to 1995. The value of this carbon off-set is estimated to be C$5 million. Comparisons with similar studies and against non-adoption of HT canola can guide future decisions about HT canola adoption.

1. Introduction

The introduction of new technologies can raise controversy about anticipated benefits and harms. In highly polarized disputes, personal risk is often pitted against social gain, creating a fulcrum on which competing evidence about the technology is amassed. In the realm of the social and political the outcomes may be surprising, even paradoxical: France generates three-quarters of its electricity by nuclear energy, yet in February 2008, France banned the production of genetically modified (GM) corn (Agnet, 2008). The acceptance/rejection of an innovation depends on the innovations proximity to individuals as in this case, the French have clearly accepted the individually distant innovation of nuclear energy, but have just as clearly rejected the individually close innovation of GM crops. This outcome is telling in another respect. When citizens do not derive a perceived direct benefit from a technology, such as enhanced health benefits from a food product, perceived risk can outweigh the promise of indirect benefit. In the case of plants modified for herbicide tolerance, citizens in highly urbanized societies struggle to see direct benefits to them, and find arguments for producer benefits uncompelling. This paper addresses the question of whether indirect benefits of herbicide tolerant crops, such as environmental benefits, could off-set social concerns about the technology by evaluating and quantifying the beneficial environmental impacts of HT canola.

Following the limited and controlled introduction of genetically modified herbicide tolerant (GMHT) canola (*brassica napus*) in 1995 and 1996, producers in Western Canada rapidly adopted the agricultural innovation. Varieties of herbicide tolerant (HT) canola have been created using both genetic modification and mutagenesis.[1] Producers tend to be strongly focused on profit optimization, adopting only those technologies and products that improve their competitive position. The fact that virtually all of the canola seeded for the 2007 crop year in Western Canada involved herbicide tolerance suggests that there must be a substantial, sustained benefit from that innovation being realized by farmers. While producers in Western Canada have identified personal and sectoral benefits from the production of HT canola, this article identifies and quantifies a range of environmental benefits of HT canola that can be seen to be of broad social, as well as individual, benefit. The article provides a review of previous studies on the relationship between GM crops and chemical applications, outlines a survey methodology for investigating environmental impacts of HT crops, summarizes and assesses the results of a survey and provides some

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[1] Genetic modification of canola is done using the transfer of rDNA, while mutagenic varieties are developed by chemical mutation.

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Table 1
Adoption rate for HT canola varieties (million hectares). *Source*: Canola Council of Canada (2008a)

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Total canola hectares	4.9	5.3	5.5	4.8	3.8	3.6	4.6	4.8	5.1	5.2	6.3
Roundup ready	0.2	1.1	2.0	1.7	1.6	1.6	2.2	2.3	2.5	2.3	2.8
Liberty link	0.4	0.7	1.0	0.7	0.6	0.6	1.0	1.5	1.7	2.1	2.5
Clearfield	0.7	0.9	1.0	1.2	0.8	0.6	1.1	0.9	0.7	0.6	0.7
Total HT	1.3	2.7	4.0	3.6	3.0	2.8	4.3	4.7	4.9	5.0	6.0
HT (%)	26.5	51	72.7	75	79	77.8	93.5	97.9	96.1	96.2	95.2

concluding thoughts about the broader impacts of new technology on the environment.

2. Background

Genetically modified herbicide tolerant canola and mutagenesis canola both received federal regulatory approval in Canada in early 1995. The limited production acres for GMHT canola in 1995 and 1996 were managed through an identity preserved production system (IPPM) (Smyth and Phillips, 2001) as part of the seed multiplication process. The IPPM systems were discontinued in the winter of 1996–1997 and unhindered producer adoption began in spring 1997. The adoption rate of HT canola has been very rapid (Table 1); Roundup Ready™ and Liberty Link™ canola GMHT varieties and the Clearfield® mutagenic HT varieties rose in 6 years from 26% of total production in the first year of production to 93% in 2003.

For the 2004–2007 crop seasons, the percentage of HT canola planted has exceeded 95% of total canola production. Between 2002 and 2007, there has been a near doubling of hectares devoted to canola. The adoption of HT canola varieties is likely to be sustained. Between the 2003 and 2007 crop years, canola field trials in the prairies have been dominated by HT varieties (Table 2). Conventional canola varieties accounted for only five percent of field trials over the period. With the high level of HT canola adoption, as shown in Table 1, and the dominance of HT canola variety development as shown in Table 2, it is evident that the canola seed industry is investing significantly in HT variety development and expecting HT canola varieties to be in high demand in the future. Given this, it is important to understand the environmental effect of this sustained transformation of the canola technology.

Only one study of the impact of the new technology on the environmental effect of Western Canadian agriculture exists. The Canola Council of Canada (2001) reports that the average number of herbicide applications per acre for transgenic canola was just over two, based on a sample of 321. In contrast, the average number of applications made by conventional canola producers (sample size 315) was 1.78. These results were based on application data from the fall of 1999 and the spring of 2000. These results provide an indication of the relative change of herbicide applications associated with the adoption of transgenic crops.

No other studies examine the impact of HT canola on chemical usage, but a number of other studies considered, without coming to a consensus, chemical usage following introduction of other GM and HT crops.

Table 2
Canola variety trial data, 2003–2007. *Source*: Canola Council of Canada (2008b)

Year	Conventional	Roundup	Liberty	Clearfield	Total
2003	6	30	4	4	44
2004	2	23	4	9	38
2005	1	35	3	10	49
2006	2	34	6	8	50
2007	1	31	8	8	48
Total	12	153	25	39	229

A number of scholars estimate that GM crops have decreased the intensity and use of chemicals. Brookes and Barfoot (2005) estimate that from 1996 to 2004, the total global volume of active ingredient applied to GM crops fell by six percent, a decline attributed to the commercialization of GM crops. The authors additionally estimate a 14% reduction in the 'environmental foot print'[2] made by crop agriculture, also attributed to the adoption of GM crops. Young (2006) discusses the US introduction of glyphosate-resistant soybeans, cotton and corn, focusing on the increased use of glyphosate in crops. He documents a dramatic increase in the use of glyphosate and is concerned about the impact this might have for weed management strategies. Young does not discuss the difference in the environmental impact of glyphosate being applied versus the herbicides that it displaced, something that has been done in canola (Smyth et al., in preparation). Young's concern is that between 1997 and 2002, the variety of herbicides applied to glyphosate-resistant crops had decreased, thereby reducing the potential benefits of applying glyphosate due to increased selection pressure for glyphosate-resistant weeds. Young documents a decrease in the average number of herbicide active ingredients applied to glyphosate-resistent crops. For example, the average number of herbicide active ingredients applied to soybeans declined from 2.5 active ingredients in 1994 to 1.6 active ingredients in 2002 and in cotton the average number of herbicide active ingredients applied dropped from 3.1 active ingredients in 1997 to 2.1 active ingredients in 2001.

Benbrook (2003, 2009) argues that herbicide use increased between 1996 and 2003 by 50 million pounds and that by 2009 genetically engineered crops were responsible for an increase of 383 million pounds of herbicide applied in the US. Benbrook draws upon United States Department of Agriculture's National Agricultural Statistics Service (NASS) for his data, which does not differentiate between GM and non-GM crops and hence has to be interpolated based on secondary estimates for GM and non-GM acres. USDA–NASS data is available to 2005 and Benbrook has extrapolated for subsequent years, which show the largest increase in herbicide use. Benbrook's increase in the rate of adoption is 5% annually, which is ambitious. Adoption rates post 2005, have tapered off and to some extent, are close to approaching the upper limits of market share for this technology. Assuming a continual rate of increased adoption of 5% does not reflect the realities of the market. In addition, Benbrook assumed farmers used the recommended rate of application, which is not always an accurate reflection of production decisions.[3] Depending on a variety of factors (e.g. moisture, weed density and insect populations) producers will often apply chemical at a rate that is below the recommended rate, particularly if there is no evidence of the target they want to

[2] Brookes and Barfoot use environmental footprint as an integrated indicator capturing the "environmental impacts of individual pesticides at a single field value per hectare" (environmental impact quotient (EIQ)/ha) multiplied by the area planted to the subject type of production.

[3] Leeson et al. (2004), identify that 75% of canola producers apply herbicide at a rate that is lower than the recommended highest rate. The research found that 15% of producers in Saskatchewan sprayed at a rate that was below the lowest recommended rate, while 12% did not spray at all. Slightly over 60% of producers sprayed at a rate that ranged from the lowest to the mid level of recommended rates, while less than 5% were found to spray above the highest recommended rate.

control. The final factor that discounts Benbrook's assertions is that he does not take into account the increase in the number of acres being planted to the commodities he examines. For example, corn production in the US increased by over 16 million acres between 2003 and 2008 (USDA–NASS, 2008).

While the change in herbicide use is important to the environmental impacts of HT crops, it is only part of the debate as the change in tillage practices has increased carbon sequestration. The Intergovernmental Panel on Climate Change (IPCC) (2007) estimates that agriculture contributes 10–12% of anthropogenic green house gas (GHG) emissions. The World Bank (2010) estimates that 30% of world greenhouse gas emissions comes from agriculture, deforestation, land-use change and forest degradation. Among all of the choices we may make to reduce agricultural GHG emissions, crop choice and management are among the most significant.

West and Post (2002) review the analysis of 67 long-term agriculture experiments to quantify the potential soil carbon sequestration rates. In the review of the 67 experiments, they analyzed the results of 276 paired treatments and determined that changing tillage practices from conventional tillage to zero-tillage can sequester carbon at a rate of 57 g ± 14 g per meter, per year (57 ± 14 g C m^{-2} $year^{-1}$). In analyzing the annual rate of soil organic carbon (SOC), they found that most SOC change happens within the first 10–15 years of moving to zero-till. However, West and Post note that while the sequestration rate will decrease over time, it may continue for a longer period of time, possibly as long as 40–60 years.

Lal (2004) suggests that the carbon sink capacity of the world's agricultural and degraded soils is 50–66% of the world's historic carbon loss of 42–78 gigatons of carbon. Additionally, Lal et al., (2003) have argued that wide-spread adoption of conservation tillage (including zero-tillage) could sequester 24–40 metric tonnes (Mt) of carbon per year. However, Baker et al. (2007) suggest that carbon sequestration rates based on soil sampling may have biased the rates due to sampling protocols. While not arguing against the increased use of conservation tillage, the authors highlight that the soil sampling depth impacts the carbon sequestration. They suggest that shallow sample depths of less than 30 cm support carbon sequestration, while samples from depths greater than this do not support carbon sequestration.

While not engaging in this debate, we present data on carbon sequestration relating to the production of HT canola through zero-tillage and minimum tillage[4] land management practices in Western Canada.

3. Methodology

The collection of data on agricultural practices in Canada often employs a survey instrument. The present research was based on a four page, 80 question survey that was developed and distributed to agricultural producers. The time required to complete the survey was estimated to be 30–45 min. The survey was comprised of six major areas of focus: weed control; volunteer canola control; canola production history; specific weed control measures on canola fields and subsequent crops; crop and liability insurance; and general demographics. Open, closed and partially open questions were included in the survey. Space was provided to enable producers to more fully explain changes within the production system to facilitate a more complete understanding of producer choices. Where a quantification of producer attitudes was required, a simple three point scale was used, which allowed for positive, neutral and negative responses. The University of Saskatchewan's Research Ethics Board approved the survey design (BEH# 06-318).

Table 3
Distribution of usable survey responses (*N* = 571).

	Low production (%)	High production (%)	Total (%)
Alberta	14	11	25
Manitoba	NA	16	16
Saskatchewan	32	27	59
Total	46	54	100

Forty thousand surveys were distributed across the three Prairie Provinces in March and April 2007. Distribution of the survey was through Canada Post's un-addressed ad-mail service providing a cluster sampling method. This allowed for a selection of farms as defined by Canada Post within the postal code system. Participant selection was based upon geographic location in five targeted regions separated by provincial boundaries and based on historic canola production levels. High production and low production regions in each of Alberta and Saskatchewan and a high production area in Manitoba were surveyed. The target population was producers having over 40 hectares of cropland. Surveys were randomly distributed through the regions.

To increase the response rate a lottery prize was employed. The lottery consisted of two draws, among eligible survey respondents, for consumer electronic goods valued at $250 each. In total 685 surveys were received with 571 meeting the population criteria. Outliers within the database were identified and removed utilizing the box plot method as developed by Tukey (1977) and outlined by NIST/SEMATECH (2006). Extreme outliers, or upper outliers, were identified based on the amount of hectares treated by the herbicide. Table 3 outlines the distribution of usable responses across the three Prairie Provinces and between areas of low and high canola production.[5] Canada is a large nation with numerous eco-regions, but most canola is grown in three main regions. A small amount of canola is produced in the Boreal Shield West eco-region, located in the very eastern part of Manitoba. While the number of respondents relative to the number of surveys distributed indicates a low response rate (1.71%) it is important to note that the Canada Post's un-addressed ad-mail service delivers surveys to all mail addresses within the identified region. There is no way to know how many households received surveys that were not farmers or did not produce canola. Therefore, the actual response rate is unknown and is most certainly greater than what can be calculated here. The important point is that demographically, our respondents are very representative of the national agriculture census data.

The demographics of the sample population are similar to the source population as reported in the Statistics Canada 2006 Farm Census (Table 4) (Statistics Canada, 2006). The average age of farmers is 52 in Saskatchewan and Alberta, and 51 in Manitoba. Our survey population has a substantially higher level of post-secondary education, where the census data identifies the percentage of producers with a university degree in Manitoba at 8%, Saskatchewan at 8% and Alberta at 9%.[6] Average farm size of the sample population was greater than that of census data, where the average Alberta farm size was 427 hectares, Saskatchewan 589 hectares and Manitoba 405 hectares.

[4] For the purposes of this paper, zero-tillage refers to direct seeding that does not disturb the soil. Minimum-tillage refers to the use of harrows following direct seeding, which is done to reduce the ridges in fields.

[5] High and low production zones were based upon historical canola production data for the three prairie provinces.

[6] The number of respondents with a university degree is substantially higher in Saskatchewan than is reflected in the census data. A variety of factors contribute to this. The farm size is larger than average and producers are slightly younger than the average, which tend to be correlated with higher levels of education. Moreover, the affiliation of this research with the University of Saskatchewan may have triggered a greater response from graduates than from others.

Table 4
Producer demographics. *Source*: Survey and Statistics Canada 2006 Farm Census

		Alberta	Saskatchewan	Manitoba	Total/average
Number of respondents to survey		144	335	92	571
Average age	Sample	45–54	45–54	45–54	45–54
	Census	*52*	*52*	*51*	52
University degree	Sample (%)	14	21	7	14
	Census (%)	*9*	*8*	*8*	8
Average farm size (hectares)	Sample	669	705	549	670
	Census	*427*	*589*	*405*	473
Average canola hectares		205	193	162	190
Average experience with canola		19.3	20.6	20.8	20.3
First year with GMHT canola		1999	1999	1998	1999

Table 5
Volume of herbicide applied in 1995. *Source*: Brimner et al. (2005) and Smyth et al. (in preparation)

Herbicides	Percentage of total hectares	Number of hectares	Grams of active ingredient per hectare	Amount of active ingredient applied (kg)
Ethalfluralin	32	1,660,830	1100	1,826,913
Trifluralin	31	1,608,929	800	1,287,143
Clopyralid	15	830,415	151	125,393
Sethoxydim	15	778,514	144	112,106
Ethametsulfuron	15	778,514	15	11,678
Total	109%	5,657,720	NA	3,363,233

Table 6
Volume of herbicide applied in 2006. *Source*: Smyth et al. (in preparation)

Herbicides	Percentage of total hectares	Number of hectares	Grams of active ingredient per hectare	Amount of active ingredient applied (kg)
Glyphosate	48	2,505,814	697	1,746,552
Glufosinate	12	626,453	477	298,818
Imazmox	4	208,818	15	3132
Imazethapyr	4	208,818	15	3132
2,4-D	2	104,409	414	43,225
Total	70%	3,654,312	NA	2,091,727

The survey respondents had relatively large operations (670 hectares), with, on average, over one-quarter of their operation dedicated to canola (Table 4). The average respondent has farmed for 30 years and belongs to the 45–54 age group. These producers reported growing canola for an average 20 years and adopting GMHT canola first in 1999; on average they reported that they removed conventional canola varieties from their crop rotations by 2000.

For the 2005 and 2006 crop years, farmers reported that 48% of their land was allocated to Roundup Ready™ varieties, 37% used Liberty Link™ and 10% used Clearfield®. These adoption rates are consistent with the adoption rates provided by the canola industry, which identifies Roundup Ready™ market share at 44%, Liberty Link™ at 40% and Clearfield® at 11% (Anderson, 2008).[7]

4. Results and analysis

Producers were asked how their herbicide application practices had changed following the adoption of HT canola and they indicated that they were making an average of one less application per year. These findings correspond to the broad observations over a range of crops and landscapes of Gianessi et al. (2002) and Brookes and Barfoot (2005). Table 5 reports the volume of herbicide active ingredient applied in 1995, the 3.36 million kg serves as a benchmark for following comparisons. The percentage of hectares that had herbicide applied in 1995 is greater than the actual number of hectares that were sown to canola due to the tank-mixing of herbicides. There were 5.19 million hectares of canola production in 1995.

The volume of active ingredient applied to canola following the commercialization of HT canola has declined (Table 6). Smyth et al. (in preparation) provide the number of hectares that had herbicides applied to them and the application rates. This table reveals that only 70% of canola hectares received herbicide applications.[8] Cultivation as a form of weed control will account for some of the variance in herbicide application.

While applying herbicide to 70% of canola production might seem low, it is not outside of what is normal in crop production. It is not uncommon for producers that use tillage as part of their land management practices to get excellent weed control at the time of seeding. In years with excellent soil moisture and abundant heat, canola germination is rapid, creating a canopy on the field that dramatically limits the number of weeds that emerge following seeding. Therefore, in some years, producers do not need to apply a post-emergence herbicide application to control weeds. In the spring of 2006, moisture conditions were listed as excellent for most of the prairies and the temperature was above average (Canadian Wheat Board, 2006).

Since Table 5 over-reports and Table 6 under-reports the actual hectares of canola production, Table 7 contrasts the actual hectares of canola production with the amount of active ingredient. Table 7 provides a contrast using the same application percentages for the production between 2005 and 2007. Table 1 provides the canola hectares for the production years of 2005, 2006 and 2007. While an application percentage of 70% in 2006 might be lower than average, even if this increased by an addition 10% or 20% for 2007, the amount of active ingredient being applied would still be lower than the amount applied in 1995. The amount of land in canola production has increased by 21% between 1995 and 2007, yet even if the percentage of land that herbicides are applied to rises to 90%, the amount of active ingredient that is applied is still lower than what was applied in 1995. Table 7 demonstrates that while the production of canola has risen following the intro-

[7] Personal communication with Program Manager, Canola Council of Canada.

[8] As noted by Leeson et al. (2004), in 2003 12% of canola producers did not spray. This figure ranges as high as 17% for barley growers in that year. Some producers only use tillage as their means to control weeds.

Table 7
Comparison of canola hectares and active ingredient application.

	1995	2005	2006	2007
Hectares of canola production	5,190,093	5,099,039	5,220,445	6,272,627
Amount of herbicide active ingredient (kg)	3,363,233	2,046,142	2,091,727	2,517,081

duction of HT canola, the amount of herbicide active ingredient is lower than what was applied previously.

One of the significant environmental impacts revealed through the survey was the correlation between the adoption of HT canola and the increase in producer use of minimum tillage or zero-tillage practices. Use of tillage has markedly decreased from 1999 when 89% of western Canadian canola was produced under management that used tillage operations as the leading form of weed control (Canola Council of Canada, 2001). The survey revealed that in 2006, 65% of the canola grown on the Prairies is managed using zero-tillage or minimum tillage method (Table 8). While in the last two decades changes in such factors as farm size and farm equipment have contributed to a general movement across the prairies away from the conventional practice of summerfallow, it is evident from this survey that producers that have made this transition to reduced tillage have found a benefit in using HT canola. Young (2006) states that the introduction of glyphosate-resistant soybean and cotton is likely a contributing factor in recent increases in no-tillage production of these crops in the US. The reason is that producers are getting very high levels of weed control in fields seeded with HT canola, to the level that there is no longer a need to pre-work fields before seeding in the following crop year. Traditionally, producers have tilled their fields prior to seeding as a form of early weed control. The use of HT canola would appear to have eliminated this practice as producers now apply herbicides to 'burn-off' weeds prior to seeding.

When asked about tillage practices, many producers report moving to minimum or zero-tillage operations, with over half of the respondents indicating that they do not use tillage as a weed control method any longer. Those farmers using Clearfield technology are more likely to be using zero-tillage and, correspondingly, are less dependent on conventional cultivation, while those using the Roundup Ready technology are slightly less likely to use zero-tillage (Table 8).

As indicated in Table 8, nearly two-thirds of producers utilize either zero-tillage or minimum tillage as their preferred form of land management. Harrowing is classified as a method of minimum tillage. Despite the increasingly wide-spread adoption of minimum or zero-tillage practices across Western Canada, one of the barriers to adoption of these reduced tillage management practices has been fewer options for effective weed control. Therefore, the effective weed control provided by the HT technology has contributed to the increased utilization of minimum or zero-tillage operations. It is possible to state with statistical confidence that there is a correlation between the adoption of HT canola and the increased movement to conservation tillage (Ammann, 2005; Brookes and Barfoot, 2005; Dill et al., 2008; Fawcett and Towery, 2002; Fernandez-Cornejo et al., 2010).

Table 8
Tillage operations and HT canola systems (2006).

Tillage method	Clearfield	Liberty link	Roundup ready	Average/total
Zero-till	60.0%	53.3%	50.3%	54.5%
Harrow	12.5%	11.9%	9.8%	11.4%
Cultivation	22.5%	20.0%	24.2%	22.2%
Cultivation and harrow	5.0%	14.8%	15.7%	11.8%
Margin of error	15.5%	8.4%	7.9%	5.4%
Number of respondents	40	135	153	328

Producers report that they are able to gain superior levels of weed control by utilizing HT canola in their cropping rotations, which allows them to direct seed the second year crop into the canola stubble. The survey revealed two major productivity benefits to be gained from this practice. First, maintaining stubble on the soil increases snow capture and thereby increases spring soil moisture levels while greater levels of soil organic material contributes to moisture conservation in the soil, enabling canola seed to germinate in a soil bed that has a higher level of moisture than conventionally-tilled fields. This is extremely important in arid areas of the Prairies. Eighty-three percent of respondents indicated that they have greater soil moisture with this land management method. Second, the reduction in intensive tillage of land and the move to minimum and zero-tillage allows producers to seed HT canola with a minimum of soil disturbance, thereby reducing the soil's exposure to wind. When asked about experiences with soil erosion following the adoption of HT canola, 86% of producers in our survey reported that they have reduced soil erosion. Soil erosion is problematic for many areas of Western Canada, especially in the lighter soil zones that typically receive less precipitation. When asked about the land that they routinely seed canola into, 41% of producers indicated that they are seeding HT canola into land that they identified as erodable. Producers further identified that soil humus is improving on their erodable land. Controlling weeds on erodable land previously meant that producers had to utilize some form of tillage weed control. Producers can use zero-till equipment to seed canola and use the same equipment the following year to seed a cereal or pulse crop. One-third of respondents indicated that they now have improved soil structure following the adoption of minimum or zero-tillage.

An additional environmental benefit facilitated by the adoption of HT canola and the move to minimum and zero-tillage is greater carbon sequestration. The transition to these methods of land management results in increased stocks of carbon (carbon sinks) maintained in soils being used to produce annual crops (West and Post, 2002). The reduced soil disturbance associated with reduced tillage decreases the rate of decomposition of crop residues and thereby maintains more of that carbon in and on the soil rather than releasing the carbon into the atmosphere and contributing to atmospheric greenhouse gas stocks (Lal, 2005). Furthermore, the practice of continuous cropping, as compared to management systems that include regular fallow periods, may increase the amount of carbon that is sequestered by annual cropping.

Using the response rate to this survey as a reflection of the percentage of producers in each eco-region, it is possible to use the percentage of producers that are using reduced tillage practices to determine the number of tonnes of carbon that are sequestered annually, relative to land that is managed using conventional tillage. The economic value of that sequestration can then be calculated. Results of the survey, reported in Table 9, suggest that reduced tillage related to canola cultivation in Western Canada sequesters just over 35,000 tonnes of carbon annually. When this volume is valued using a carbon price of \$5.00/tonnes of carbon ((\$1.36/tonnes of CO_2 equivalent), the financial benefit is \$175,000. While the price of carbon is highly volatile (with values ranging from highs of \$27.00/tonnes to lows of \$0/tonnes) as markets for carbon exchange are in the very early stages and subject to shocks, the authors believe that \$5.00/tonnes of carbon is a conservative value with long-term price predictions from the Chicago Climate Exchange and the European Climate Exchange being significantly higher.

Table 9
Value and amount of carbon sequestered using minimum tillage ($C). *Source*: Co-efficients come from McConkey et al. (2006)

Eco-region	Min-till hectares	Carbon sequestration co-efficient (tonnes/hectare/year)	Carbon sequestered (tonnes/year)	Value of carbon sequestered ($/year)
Boreal Shield West	3557	0.04	142	$710
Boreal Plains	112,757	0.04	4510	$22,550
Subhumid Prairies	289,927	0.07	20,295	$101,475
Semiarid Prairies	252,385	0.04	10,095	$50,475
Total	658,626	NA	35,042	$175,210

Table 10
Value and amount of carbon sequestered using zero-tillage ($C). *Source*: Co-efficients come from McConkey et al. (2006)

Eco-region	Zero-till hectares	Carbon sequestration co-efficient (tonnes/hectare/year)	Carbon sequestered (tonnes/year)	Value of carbon sequestered ($/year)
Boreal Shield West	18,223	0.16	2916	$14,580
Boreal Plains	577,744	0.14	80,884	$404,420
Subhumid Prairies	1,485,531	0.15	222,830	$1,114,150
Semiarid Prairies	1,293,175	0.10	129,318	$646,590
Total	3,374,673	NA	435,948	$2,179,740

The number of producers that are presently utilizing zero-tillage practices is considerably greater than in 1999, and therefore the volume and value of the carbon being sequestered is also larger (Table 10). Over 3.3 million hectares were produced using zero-tillage in 2006, which annually sequesters 436,000 tonnes of carbon, relative to conventionally-tilled land. Again assuming a market value of carbon $5.00/tonnes, the annual value of this is approximately $2.18 million. When the value of carbon sequestered by minimum and zero-tillage practices are combined, the annual value of increased carbon sequestration, compared to conventional tillage management, is $2.35 million, while the volume of carbon being sequestered increases by approximately 470,000 tonnes/year.

A further environmental impact that can be linked to the adoption of HT canola is the value of carbon no longer released due to the conventional tillage of fields planted to canola. Routine cultivation of land releases carbon into the atmosphere each time the land is tilled. Since these fields are now being managed using reduced tillage, or zero-tillage, the soil carbon stock is no longer decreased through emissions when the field is seeded, or released at a lower level, with reduced tillage. Table 11 provides a value for this soil carbon that will not be released due to the change in tillage management. The combined value of Tables 9–11 is C$4960,100, while the total volume of carbon sequestered and not released is 992,020 tonnes.

Without a benchmark, it is difficult to appreciate the relative value of the carbon sequestration illustrated in Tables 9 and 10. Because the number of hectares of land under zero and minimum tillage has increase substantially over the past decade, it is misleading to compare the above figures to data from a decade ago. To provide a comparable benchmark that is meaningful, we have determined the volume and value of carbon sequestration as if HT canola had not been commercialized. It is assumed that the rate of tillage would not have changed. Canola Council of Canada data suggests only 11% of producers practiced zero or minimum tillage in 1999. While the CCC data does not differentiate between zero and minimum tillage, the data calculated in Table 12 assumes either all producers using conservation tillage used minimum tillage (MT) or all used zero-till (ZT). The volume of carbon sequestered ranges from 36,711 to 89,134 and the value of this ranges from $183,555 to $445,670.

When the ranges from Table 12 are compared with the combined values of Tables 9 and 10, it becomes possible to comprehend the environmental impact of HT canola. Compared to the scenario without HT canola, producers are presently sequestering between 381,000 and 434,000 additional tonnes of carbon annually. The additional value of this carbon sequestration ranges between $1.91 M and $2.17 M.

It is important to note that all of the environmental benefits discussed above can not be solely attributed to the commercial adoption of HT canola. Since 2000, there have been advances in conservation tillage equipment, changes in spraying and harvesting technologies and changes in the socio-economic characteristics of prairie agriculture (i.e. increase in the average size of farms). The relationship between the increased move towards conversation

Table 11
Value and amount of carbon no longer released through tillage ($C). *Source*: Co-efficients come from McConkey et al. (2006)

Eco-region	Zero and minimum tillage hectares	Carbon sequestration co-efficient (tonnes/hectares/year)	Carbon sequestered (tonnes/hectare)	Value of carbon sequestered
Boreal Shield West	21,780	0.16	3485	$17,425
Boreal Plains	690,501	0.14	96,670	$483,350
Subhumid Prairies	1,775,459	0.15	266,319	$1,331,595
Semiarid Prairies	1,545,560	0.10	154,556	$772,780
Total	4,033,300	NA	521,030	$2,605,150

Table 12
Value and amount of carbon sequestered using pre-GM land management. *Source*: Co-efficients come from McConkey et al. (2006)

Eco-region	MT or ZT acres	Mt co-eff	ZT co-eff	MT t/ac	ZT t/ac	$MT	$ZT
Boreal Shield West	3726	0.04	0.16	149	596	$745	$2980
Boreal Plains	118,126	0.04	0.14	4725	16,538	$23,625	$82,690
Subhumid Prairies	303,733	0.07	0.15	21,261	45,560	$106,305	$227,800
Semiarid Prairies	264,404	0.04	0.10	10,576	26,440	$52,880	$132,200
Total	689,989	NA	NA	36,711	89,134	$183,555	$445,670

tillage and HT canola has happened simultaneously, but can not be said to be co-dependant upon each other. It is possible to argue that many of the changes arrived from conservation tillage would have occurred to some degree in the absence of HT canola. However, the presence of these HT varieties appears to have contributed to the rate and extent of adoption of reduced tillage management.

5. Conclusions

Three observations can be made in light of the results of our survey of HT canola producers in Western Canada. First, prairie producers overwhelmingly prefer HT canola to all other canola varieties. Conventional, non-HT varieties exist and are still approved for commercial production. Yet if HT canola was not delivering agronomic and economic benefits to producers, the prairie canola industry would not be witnessing virtual full adoption of HT canola.

Second, environmental impacts have been, and are being, widely observed by prairie canola producers. While the prairie agriculture movement away from summerfallow to zero-tillage can not entirely be credited to HT canola, it is certainly a factor. Control of weeds was one of the barriers in a substantial movement to zero-tillage, but the commercialization and adoption of HT canola has introduce a new weed control option that has facilitated this change. Producers are now able to direct seed HT canola, use the respective herbicide and gain a clear advantage in weed control. Producers that have not or can not adopt HT canola are forced to rely on tillage as their leading method of weed control and thus foregoing the soil conservation benefits of this new technology.

Third, the value of carbon sequestration is substantial, especially when contrasted against the earlier period before HT canola was introduced. Had HT canola not been developed and commercialized in Canada, the difference in terms of carbon sequestering between canola farming practices prior to HT canola and now is estimated to be nearly one million tonnes of carbon annually. In this way HT has contributed to the sequestration of carbon, and if farms in Canada were placed on a total energy budget including greenhouse gas emissions, farmers using HT canola would be better off than those using conventional varieties.

It should be noted that the environmental benefits reported above are higher than those of other studies (Brookes and Barfoot, 2005; National Research Council, 2010; Demont et al., 2004; Demont et al., 2008; Wesseler et al., 2007). The authors believe that the reason for this is twofold. First, the carbon sequestration co-efficients that we use for this research will be specifically related to the eco-regions for the Prairie region of Western Canada. Indeed the co-efficients vary across the eco-regions that are included in our study and so the co-efficients used in studies in the USA and Europe will have different carbon sequestration co-efficients that may be providing lower environmental benefits. Second, canola is well suited to zero-tillage land management, as compared to the results of Demont et al. (2004) that examine sugar beets. The land management system required to produce sugar beets is considerably more environmentally invasive.

It remains the case that citizens and consumers are likely to be unmoved by reports of producer benefits. In Canada, approximately two percent of the population farms, leaving the vast majority of people in urban and semi-urban contexts and unaware of primary agricultural production. With increasing awareness of the environmental impact of agriculture, impact that knows no boundaries, the indirect benefits of HT canola production cited here may lead to more wide-spread countenancing of crop biotechnology in Canada and elsewhere.

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