Residual activity of herbicides in soil

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FINAL REPORT TO
THE CANOLA COUNCIL OF CANADA

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FORWORD

This report is in two sections. The first section (pages 3 to 5) is an executive summary of important research results and is written for western Canadian producers that use Odyssey® and Pursuit® herbicide products. As such, the executive summary is a document that could be used by the Canola Council of Canada for Internet display.

The second section of this report (page 7 to 29) provides a more detailed outline of the methodology used and research results obtained. This section is written for stakeholders within the agricultural industry who would like a more technical description of the study. The detailed report includes a series of tables and graphs that summarize the data, and also discusses important findings in relation to other scientific studies.

The results of this study were presented at ten agricultural extension meetings and scientific conferences. Travel expenses related to these meetings and conferences were paid by Farenhorst through a Discovery Research Grant from the National Science and Engineering Research Council of Canada. The ten presentations were:

1. Farenhorst, A. 2002. Pesticide use: agronomic and environmental issues. Canadian Association of Agri-Retailers (CAAR) Crop Management Forum, Winnipeg, MB. Invited speaker.
2. Anderson, A. and Farenhorst, A. 2002. Impact of tillage system, landscape position and soil texture on imazethapyr residual activity in soil. Graduate student presentation to the Manitoba Institute of Agrologists Winnipeg, ON. A poster presentation.
3. Anderson, A. and Farenhorst, A. 2002. Impact of tillage system, landscape position and soil texture on imazethapyr residual activity in soil. Canadian Soil Science Society annual meeting, Banff, AB. A poster presentation with abstract.
4. Anderson, A. and Farenhorst, A. 2002. Effect of tillage and landscape position on imazethapyr persistence in soil. Proc. 45th Manitoba Society of Soil Science annual meeting, Winnipeg, MB. A poster presentation with abstract.
5. Anderson, A. and Farenhorst, A. 2002. Impact of tillage system, landscape position and soil texture on imazethapyr residual activity in soil. Graduate student presentations to the Manitoba Institute of Agrologists Winnipeg, ON. A poster presentation.
6. Farenhorst, A. 2001. Herbicide efficacy and carry-over risks. Manitoba Agronomist Conference, Winnipeg, MB. Invited speaker.
7. Farenhorst, A. 2001. Land management and pesticide issues. Farming with the Aquifer Workshop, Carberry, MB. Invited speaker.
8. Anderson, A. and Farenhorst, A. 2001. The influence of tillage practices on the residual activity of imazethapyr in soils. Canadian Soil Science Society annual meeting, Guelph, ON. An oral presentation with abstract.
9. Anderson, A. and Farenhorst, A. 2001. The influence of tillage systems and landscape position on imazethapyr persistence in soil. Proc. 44rd Manitoba Society of Soil Science annual meeting, Winnipeg, MB. A poster presentation with abstract.
10. Farenhorst, A. 1999. Herbicide fate processes in soil. A presentation to the Manitoba Canola Growers Association, Winnipeg, MB. Invited speaker.

In addition to the above presentations, a manuscript is being prepared for publication in a refereed scientific journal. The manuscript will be submitted in 2004. Discussions have also been initiated with Manitoba Agriculture and Food for the further distribution of the research results to western Canadian farmers.

The Department of Soil Science, University of Manitoba gratefully acknowledge the funding that was provided for this research by the Alberta Canola Producers Commission, the Manitoba Canola Growers, the Agri-Food Research and Development initiative, BASF, and The University of Manitoba. For additional information on this study, please contact Dr. Annemieke Farenhorst, Department of Soil Science, University of Manitoba by phone (204) 474 6858 or e-mail farenhor@ms.umanitoba.ca

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SECTION 1.

EXECUTIVE SUMMARY

The following two pages are an executive summary of the most important research results and are written for western Canadian producers that use Odyssey and Pursuit herbicide products. As such, this executive summary is a document that could be used by the Canola Council of Canada for Internet display.

This study was conducted in from 1999 to 2001 and included two growing seasons. The research project focused on herbicide residual effects of group 2 herbicide products in soil. Herbicide residual effect is here defined as the portion of herbicide residues in the soil that is available to plants by shoot or root uptake and will cause adverse effects on sensitive plants grown in that soil.

The specific objective of the research project was to compare herbicide residual effects in conventional-till versus reduced-till fields to assess the effect of the tillage system on the effectiveness of control of multiple flushes of weed emergence and growth, and on herbicide carry-over from one year to the next. Since field trials were conducted using two different herbicide products and four different soil types, secondary objectives of this research project were: (a) to compare herbicide residual effects for Odyssey versus Pursuit in soil, (b) to compare herbicide residual effects in soils with different clay, soil pH and soil organic matter contents; and (c) to compare the effect of slope position on herbicide residual effects in fine-textured soils. The results reported here are specific to Odyssey and Pursuit herbicide products.

Both Odyssey and Pursuit were applied at recommended field rates onto four different soil types, each under two different tillage systems. The four soil types were a well-drained, sandy-loam Hallboro soil; a well-drained, clay-loam Newdale soil; an imperfectly-drained, clay/clay-loam Fairland soil; and an imperfectly drained, clay-loam Varcoe soil. The two tillage systems were fields under conventional-till (heavy cultivator) and fields under reduced-till (direct seeding). The reduced-till fields were chosen on the basis that they had been under reduced-till management for at least 6 years. The conventional-till fields were selected on the basis that they were adjacent to a reduced-till field. During both growing seasons, soil moisture contents in fields were very high due to frequent rainfall events. It is important to realize that herbicide persistence and residual effects are generally less in moist soils than when soils are very dry. However, soils that are waterlogged for a long-time may show greater persistence of herbicides in soil because the lack of oxygen in these soils will reduce soil microbial communities that are otherwise capable of degrading the herbicide.

Soil was sampled throughout the growing season and also in the year following herbicide application. The herbicide residual effect of Odyssey and Pursuit in soils was assessed by comparing the growth of oat (*Avena sativa* L.) seedlings in treated-soil with that of the growth of oat seedlings in untreated soil. Based on these measurements, the following information is important to western-Canadian farmers:

Weed control efficacy due to herbicide residues in soil during the growing season:

1. For either Odyssey or Pursuit, the type of tillage system had no clear influence on the level of weed control efficacy during the growing season.
2. Both Pursuit and Odyssey products provided better long-term weed control in clay-rich soils with large amounts of soil organic matter than in coarse-textured soils with lesser clay and soil organic matter contents.
3. Pursuit provided a better long-term weed control than Odyssey in both conventional-till and reduced-till fields. The benefit of increased weed control efficacy when using Pursuit was more pronounced in soils that have lesser clay and organic matter contents.

4. In order to achieve a better long-term weed control efficacy in fields that have coarse-textured soils, it is advised to apply Pursuit rather than Odyssey. This is true for both conventional-till and reduced-till fields.
5. For fine-textured soils, Pursuit and Odyssey provided a better long-term weed control in slope positions with large amounts of soil organic matter than in slope positions with less soil organic matter.

Herbicide carry-over risks due to herbicide residues in soil in the year following herbicide applications:

1. Herbicide residues present in soil at the end of the growing season remained in soil over the winter and were still present in soil in the spring. The potential for herbicide carry-over and crop injury risks can therefore be assessed at the end of the growing season.
2. Herbicide carry-over and crop injury risks were greatest for Pursuit applications in fields that have clay-rich soils with large amounts of soil organic matter. Herbicide carry-over and crop injury risks were relatively small for Odyssey applications onto coarse-textured soils with lesser clay and soil organic matter contents.
3. For fine-textured soils, the risk of herbicide carry-over and crop injury was not influenced by slope position or soil organic matter content in these soils.
4. The risk of herbicide carry-over and crop injury was greatly reduced when soils were tilled in the spring prior to seeding.

In summary, in order to improve long-term weed control during the growing season, it is better to apply Pursuit rather than Odyssey, particularly for coarse-textured soils that have lower clay and organic matter contents. The type of tillage system has little impact on weed control efficacy during the growing season. In order to reduce herbicide carry-over from one year to the next, it is recommended that farmers use spring tillage prior to seeding, particularly for soils that have higher clay and organic matter contents. Using Odyssey rather than Pursuit could additionally reduce the risk of herbicide carry-over and crop injury.

The Department of Soil Science, University of Manitoba gratefully acknowledge the funding that was provided for this research by the Alberta Canola Producers Commission, the Manitoba Canola Growers, the Agri-Food Research and Development initiative, BASF, and The University of Manitoba. For additional information on herbicide persistence and retention in soil, please contact Dr. Annemieke Farenhorst, Department of Soil Science, University of Manitoba by phone (204) 474 6858 or e-mail farenhor@ms.umanitoba.ca

SECTION 2.

TECHNICAL REPORT

The following pages provide a detailed outline of the methodology used and research results obtained. This section is written for stakeholders within the agricultural industry who would like a more technical description of the study. This technical report has three parts:

1. Research objective and methodology in relation to that proposed to the Canola Council of Canada
2. Research results for year 1.
3. Research results for year 2.

PART I

RESEARCH OBJECTIVE AND METHODOLOGY IN RELATION TO THAT PROPOSED TO THE CONOLA COUNCIL OF CANADA

The research objective was met: The objective of this research project was to compare herbicide residual effects in conventional-till versus reduced-till soils. Specifically, the objective was to assess the effect of the tillage system on effectiveness of control of multiple flushes of weed emergence and growth, and on herbicide carry-over from one year to the next.

Herbicide residual effect is here defined as the portion of herbicide residues in the soil that is available to plants by root uptake and will cause adverse effects on sensitive plants grown in that soil.

Since field trials were conducted using two different herbicide products and four different soil types, secondary objectives of this research project were: (a) to compare herbicide residual effects for Odyssey versus Pursuit in soil, (b) to compare herbicide residual effects in soils with different clay, soil pH and soil organic matter contents, and (c) to compare the effect of slope position on herbicide residual effects in fine-textured soils.

Two herbicide products were used as proposed: The herbicide treatments consisted of Odyssey and Pursuit applications at recommended rates. Odyssey contains 35% imazethapyr and 35% imazamox formulated as a dispersible granule. Pursuit contains 240 g/L imazethapyr formulated as a liquid. Both imazethapyr and imazamox are imidazolinone herbicides that inhibit amino acid synthesis, therefore the products Odyssey and Pursuit are group two herbicides. In western Canada, both Odyssey and Pursuit are licensed for the control of annual weeds in Clearfield® canola and field peas, while Pursuit may also be used to control weeds in chickling vetch grown for seed, dry beans (pinto, pink and red varieties only), seedling alfalfa, and established alfalfa for seed production. It is recommended that Pursuit should not be applied to brown or dark brown soil zones because of severe carry-over and crop injury risks.

The results reported here are specific to Odyssey and Pursuit products.

Three research sites were selected and established as proposed: Field studies were conducted at three locations in southwestern Manitoba. The geographical locations of the three field sites are given in Figure 1 on the next page.

For each location there were two adjacent fields separated by a paved road: one reduced-till (RT) field and one conventional-till (CT) field. The largest difference between the RT versus CT fields was the type of tillage operations over the past six to ten years. The CT fields were typically tilled with a heavy cultivator and chisel plough. The RT fields were characterized by direct seeding operations. All other farm management factors such as cropping system and fertilizer applications were similar between RT and CT fields. There was no previous history of Odyssey and Pursuit use on these fields.

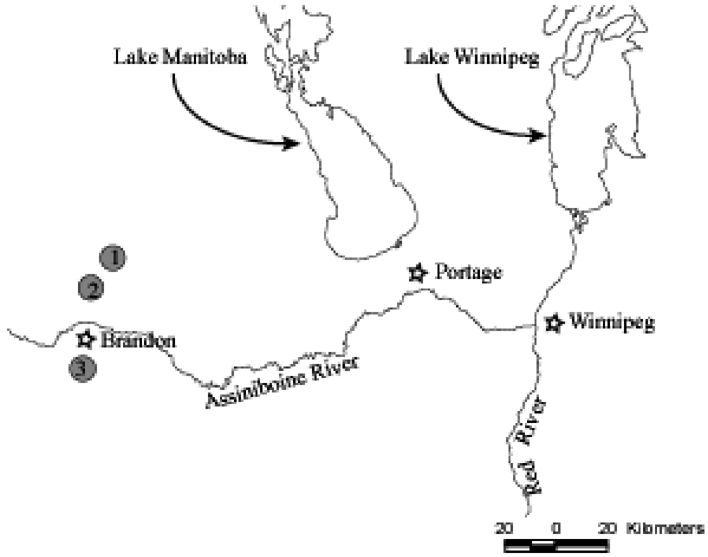

Figure 1. Geographical locations of the three field sites: 1 = Neepawa location; 2 = Brandon I location; 3 = Brandon II location. For each location, field experiments were conducted on a reduced-till field and conventional-till field.

Previous studies have quantified the effect of a *single* tillage operation on herbicide residual activity in soil (Curran et al. 1992a, Monks and Banks 1993), i.e., experiments were typically performed within a specific field where plots were either tilled or left undisturbed. Although these studies have made significant contributions to our understanding of the effects of *single* tillage operations on herbicide residual activity in soil, information was lacking on the *long-term* effects of tillage operations on herbicide residual effects in soil. For this research project, the RT fields were chosen on the basis that they had been under RT management for at least 6 years. It may take several years of RT management before soil characteristics are modified. Soil characteristics have a direct impact on the herbicide residual effects in the field. The research results are therefore directly relevant to western Canadian farmers, particularly those that are consistent with their tillage management from one year to the next.

Eight field trials were conducted instead of the proposed six field trials: It was proposed that six field trials were to be conducted from 1999 to 2000, i.e., one pair wise-comparison between RT and CT for each of the three locations in southwestern Manitoba. Instead, eight field trials were conducted from 1999 to 2002: four field trials in 1999/2000 and four field trials in 2000/2001. The 1999/2000 trials were conducted in near-level fields at both Neepawa and Brandon I locations (Figure 1). These trials were designed to compare herbicide residual effects in CT versus RT fields for both a coarse-textured and a fine-textured soil. The 2000/2001 trials were conducted in a hilly terrain at the Brandon II location (Figure 1). The trials in year two were designed to compare herbicide residual effects in CT versus RT fields for both upper slope and lower slope positions in the field.

There were eight field trials instead of six field trials for the following reasons:

a. Data obtained from repeated experiments conducted over two growing seasons is more meaningful than a single experiment conducted over one growing season.
b. It was decided to apply herbicides to the fields on the same day, ensuring a direct comparison between study sites and between fields under different tillage systems. Given that sampling procedures were labor intensive, only four field trials could be conducted in a given year.
c. Research at the Department of Soil Science (funded by the National Science Engineering Research Council of Canada) confirmed that herbicide residual effects may vary depending on slope position, at least for the herbicide 2,4-D (see Appendix A). There was therefore a need to compare herbicide residual effects in CT versus RT fields for both upper slope and lower slope positions in a field.

The field plot design was modified because the amount of land made available for the experiment was limited: It was initially proposed that the study be carried out as a randomized plot design with three herbicide treatments, i.e., Odyssey applied at a recommended field rate, Pursuit applied at a recommended field rate, and an untreated control plot. However, the field trials were conducted on commercial fields and the amount of land made available for the study was limited. Therefore, experimental plots consisted of two adjacent plots (5 x 10 m) separated lengthways by 2 m alleyways. Plots were randomly assigned one of two herbicide products, Odyssey or Pursuit. Instead of an untreated control plot, large quantities of clean soil (0-10 cm) were collected within 5 to 10 m distance of the experimental plots to provide control soils for use in bioassay experiments.
Herbicide applications were conducted as proposed but herbicides were applied to soil directly instead of to Clearfield Canola: No crops were planted, as in other studies (Monks and Banks 1993), thereby eliminating the effect of differential crop growth as a confounding factor in quantifying the effects of tillage system on herbicide residual activity in soil.

Herbicides were applied with a tractor-mounted sprayer, using a 5 m offset boom and 8001SV nozzles. The herbicide products were applied to soils at recommended field rates, which was the equivalent of 50.4 g active ingredient of imazethapyr/ha for the Pursuit plots, and 14.7 g active ingredient of imazethapyr/ha plus 14.7 g active ingredient of imazamox/ha for the Odyssey plots. The oil-based adjuvant Merge was included in the Odyssey tank mix at the rate recommended by BASF. A non-ionic surfactant Agral 90 was added to the Pursuit tank mix at the rate recommended by BASF. Prior to Pursuit and Odyssey applications, all plots were sprayed with glyphosate (Roundup) and rogued to remove weeds and ensure uniform ground coverage of Pursuit and Odyssey. Plots in the CT fields were also tilled using a light-cultivator.

Soil samples were collected as proposed with a slight modification in the timing of sampling following herbicide application: For each field trial, six soil sampling events were initially proposed, specifically at 0, 7, 14, 28, 56 and 300 days following herbicide application.

For the four field trials in year 1 (Neepawa and Brandon I locations), soil samples were collected at 4, 8, 16, 32, 64, 96 and 300 days following herbicide application, or a total of seven soil sampling events. For the four field trails in year two (Brandon II locations at both upper and lower slope positions), soil samples were collected at 12, 24, 48, 96, and 300 days, or a total of five soil sampling events.

For both the 1999/2000 and 2000/2001 trials, soil samples were not taken immediately following herbicide application due to time constrains. For year two, soil samples could not be taken until 12 days following herbicide application because severe rainstorms resulted in near-saturated soil conditions and made the field plots inaccessible.

Soil (0-10cm) was sampled using 5 cm radius PVC pipes. For each sampling day and plot, eight random soil samples taken from each plot were combined in a plastic freezer bag and frozen (-20°C) until bioassay analyses. Soil moisture content was determined gravimetrically using a subsample of soil. In order to collect the random samples, each plot was divided into 1 m^2 units at the start of the experiment and a table of random numbers was used to randomly select eight 1 m^2 units for each sampling day. Soil was never sampled twice in the same unit, i.e., once a 1 m^2 had been selected and sampled, it was excluded as a potential sampling unit on subsequent days.

Herbicide residual effects were assessed using bioassays as proposed: In consultation with Dr. Rene VanAcker (Weed scientist, University of Manitoba) and Dr. Ron Hornford (Research scientist, BASF), oats (*Avena sativa* L.) was chosen as the best indicator species to quantify residual effects of Odyssey and Pursuit in soil. Oats should not be grown until 18 months after imazethapyr application but may be grown 9 months after use of products containing only imazamox (Hager et al. 2000).

Soil samples were removed from the freezer and allowed to thaw at room temperature for 24 hours. Soil was sieved (4 mm) and added to 10 cm depth in five replicated plastic pots (10 cm diameter) at a soil bulk density equivalent to that measured for surface soils in the field. Oats seeds were pregerminated for 24 hours. Ten oat seeds were then placed at 2 cm below the soil surface and pots were watered to field capacity. Pots were incubated for 14 days in environmental growth chambers set at 25°C ± 2°C, a relative humidity of 90%, and a 12 hour day/night cycle. Pots were weighed daily and water was added to return the soil to field capacity. Care was taken to let the water infiltrate into the soil slowly, thereby minimizing the movement of herbicide residues to depth. After 14 days, the fresh weight of oat shoots grown in treated soil were measured and compared to the fresh weight of oat shoots grown in untreated soil (5 replicates). The growth weight reduction of plants in treated soil was calculated by:

$$\%GWR = 100\% - (Wt / Wu * 100\%)$$

where %GWR = the percent growth weight reduction of plants in treated soil relative to plants grown in treated soil, Wt = fresh weight of oat shoots grown in treated soil, and Wu = fresh weight of oat shoots grown in untreated soil

For each of the eight field trials, soil characteristics and herbicide sorption was determined as proposed: In addition to the field trials, soil characteristics were determined for each of the eight fields. Herbicide sorption experiments were also done as proposed. The information on soil characteristics and herbicide sorption helped to explain the results of the field trials.

For each of the eight field trials, soil characteristics were determined using air-dried, sieved (<2mm) soil. Soil organic carbon was determined by the dry combustion of 0.12g of oven-dried soil with a Leco model CHN 600 C and N determinator (Nelson and Sommers 1982). Inorganic carbon was removed prior to organic carbon measurement by digestion with 6N HCl (Thiessen et al. 1983). Soil pH values were obtained using 20ml of 0.01M $CaCl_2$ and 10g of air-dried soil (Hendershot and Lalande 1993). Soil texture was measured using the hydrometer method (Gee and Bauder 1986).

The herbicide sorption capacity of the eight soils was assessed using batch-equilibrium procedures with analytical-grade imazethapyr (99% purity; SUPELCO; Bellefonte, PA). Imazamox was not studied because this herbicide was not available commercially as analytical grade. Herbicide solutions were prepared in 0.01 M $CaCl_2$ and initial imazethapyr concentrations were 1, 2, 4, 8, and 16 mg/L. Exactly 10 mL of each herbicide solution was added to 5 g of sieved (< 2mm), air-dried soil (triplicates) in 50 ml Teflon centrifuge tubes. Tubes were then placed in a rotary shaker for 24 hrs to reach equilibrium at room temperature and in the dark. Following equilibrium, the soil slurries were centrifuged at 10,000 RPM for 10 minutes and the supernatant was subsampled (10 mL) in duplicates to quantify the concentration of imazethapyr remaining in the equilibrium solution by gas chromatography – nitrogen phosphorus detection (HP6890 GC-NPD). Prior to GC-NPD analyses, imazethapyr residues in equilibrium solutions were extracted with methylene chloride (5 mL). Methylene chloride was then evaporated to dryness with nitrogen gas and imazethapyr residues were redisolved in methanol (1 ml) and 100 μl phenyltrimethylammonium hydroxide (a derivitizing agent) was added. GC-NDP configurations were: column: 30m x 0.32 mm; carrier gas: helium set at 69 mL/min; detector gases: hydrogen set at 60 mL/min and air set at 60 mL/min; oven temperature: initially 55 ºC, held for 1 min., then increased to 285 ºC at 25ºC /min for a final 2.8 min hold; and total running time: 13 min.

The amount of imazethapyr sorbed onto soil was determined by the difference between the initial and equilibrium imazethapyr concentrations. The Freundlich distribution coefficient, K_f [$\mu g^{1-1/n}$ g^{-1} $mL^{1/n}$], was quantified by nonlinear regression using the empirical Freundlich equation in the log transformation form:

$$\text{Log } C_s = \log K_f + {}^{1/n} \log C_e$$

where C_s = the amount of imazethapyr in soil at equilibrium [$\mu g\ g^{-1}$], C_e = the amount of imazethapyr in solution at equilibrium [$\mu g\ mL^{-1}$] and 1/n = dimensionless Freundlich constant.

Greater Freundlich values represent greater herbicide sorption by soil.

PART II

RESEARCH RESULTS IN YEAR 1

Soil characteristics and herbicide sorption: Soils were in the black soil zone. The coarse-textured soil was from the Hallboro soil series and classified as a well-drained Orthic Black Chernozem. The fine-textured soil was from the Fairland soil series and classified as a imperfectly-drained Orthic Black Chernozem.

Clay content varied from 10% in the Hallboro sandy-loam under RT to 41% in the Fairland clay under RT (Table 1). Soil organic carbon content increased with increasing clay content, as expected. There was no consistent trend in the impact of tillage operations on soil organic carbon content.

Soil pH ranged from 5.9 in the Fairland clay-loam under CT to 7.0 in the Hallboro sandy-loam under RT. The lesser soil pH in the clay loam soil under CT may have contributed to a greater sorption of herbicides, relative to the other soils (Table 1). As soil pH decreases, there is an increasing potential for imazethapyr sorption by soil (Loux et al. 1989).

TABLE 1. Selected soil properties and Freundlich sorption coefficients (Kf) for imazethapyr in the four agricultural fields.

	Fairland soil series		Hallboro soil series	
	CT	RT	CT	RT
Soil texture	Clay loam	Clay	Sandy loam	Sandy loam
Clay content (%)	27	41	14	10
Soil organic C (%)	3.05	3.27	1.13	0.68
Soil pH	5.9	6.5	6.4	7.0
Soil bulk density in field (g cm^{-3})	1.07*	1.01*	1.26*	1.29*
Moisture content at field capacity (%)	30	30	20	20
Kf ($\mu^{1-1/n}$ $g^{-1}mL^{1/n}$), a measure of herbicide sorption by soil	1.06	0.74	0.63	0.86

* for the bioassay experiments, the soil bulk density were adjusted to 1.04 and 1.27 Kg/m^3, for the Fairland and Hallboro soil series, respectively. These bulk densities corresponded to the bulk density measured for surface soils in the field. There was no difference in bulk densities between tillage systems.

Soil moisture conditions during the growing season: Soil moisture content may influence Odyseey and Pursuit persistence and residual activity in soil. For both Fairland and Hallboro soils, soil moisture content was near or above field capacity for most days during the growing season (Figures 1 and 2). The soil moisture content at field capacity was determined to be 30% for the fine-textured Fairland soils and 20% for the coarse-textured Hallboro soils (Table 1)

The near-saturated soil conditions in the fields resulted from frequent rainfall events before and after herbicide application. For the fine-textured Fairland soils, soil moisture content was generally greater in RT than CT, as expected. The soil moisture content in the coarser-textured Hallboro soil showed no consistent trend in the effect of tillage system on soil moisture content (Figure 2).

Given that sufficient soil moisture was available to microorganisms in the soil, herbicide biodegradation was an important herbicide dissipation process in both Hallboro and Fairland soils. The optimum soil water content for imadazolinone biodegradation is 75% of field capacity (Flint and Witt 1997, Vischette 2002). Given the frequent rainfall events and near-saturated soil conditions, it is possible that herbicide leaching was also an important pathway of imadazolinone dissipation from the 0-10 cm surface soil layer (Jourdan et al. 1998), particularly in the coarse-textured Hallboro soils. Herbicide sorption by soil was small for both Hallboro and Fairland soils (Table 1), indicating that imazethapyr is potentially mobile. The four agricultural fields were near-leveled and herbicide movement by surface runoff was not imminent. Imadozolinone losses due to volatization and photodegradation processes have been shown to be minimal (Goetz et al. 1990; Curran et al. 1992b).

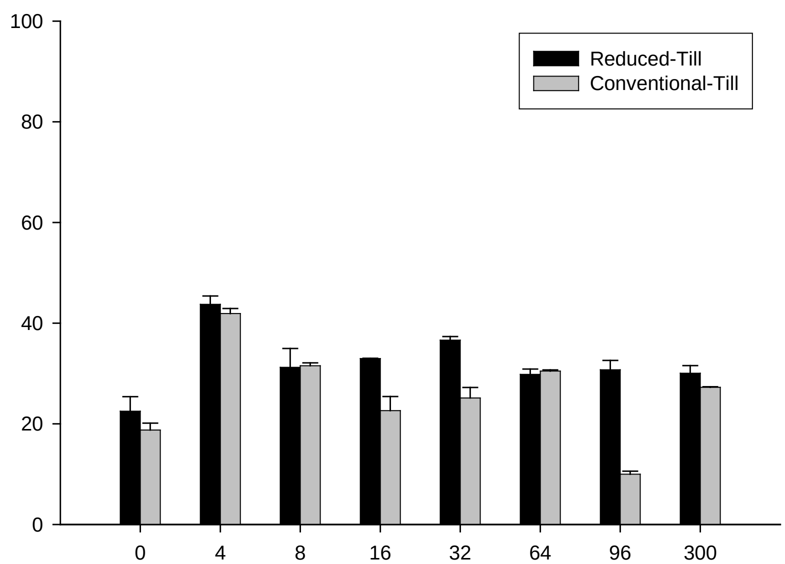

Figure 1. Soil moisture content in Fairland soils under reduced-till (RT) and conventional-till (CT).

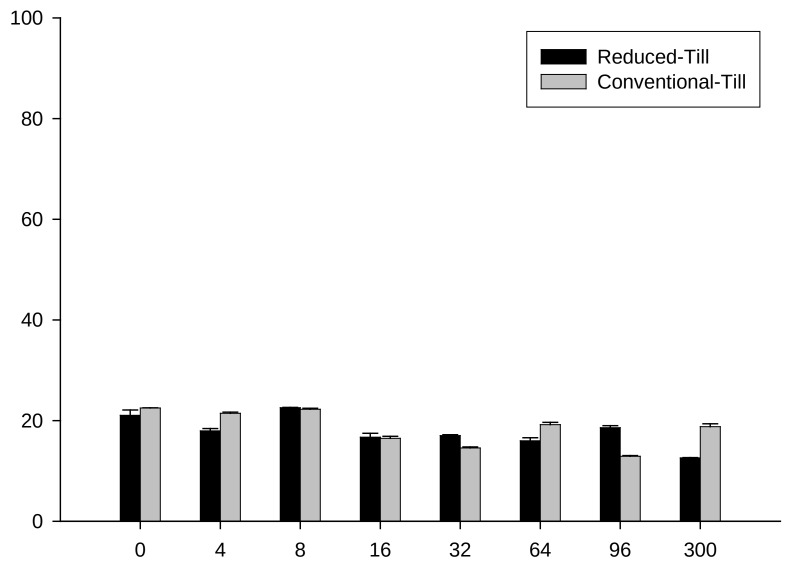

Figure 2. Soil moisture content in Hallboro soils under reduced-till (RT) and conventional-till (CT).

Herbicide residual activity during the growing season: The data were grouped by either herbicide product, soil type or tillage system.

Effect of herbicide product - When data were grouped by herbicide product (Figures 3 to 7 on page 16), soils with Pursuit showed generally more herbicide residual activity than soils with Odyssey (Figure 3). This suggested that Pursuit will provide better long-term weed control than Odyssey in soil. This was expected because the herbicide dose applied was less for Odyssey than Pursuit.

The difference in herbicide residual activity between Pursuit and Odyssey treated soils was more pronounced for the coarse-textured Hallboro soils (Figure 4) than for the fine-textured Fairland soils (Figure 5). This suggested that Pursuit will provide better long-term weed control than Odyssey in soil and that the benefit of increased weed control efficacy is more pronounced in soils that have lesser clay and organic matter contents.

The difference in herbicide residual activity between Pursuit and Odyssey treated soils was greater in the in the CT fields (Figure 6) that in the RT fields (Figure 7). This suggested that Pursuit will provide better long-term weed control than Odyssey in soil and that the benefit of increased weed control efficacy is more pronounced in CT field than RT fields.

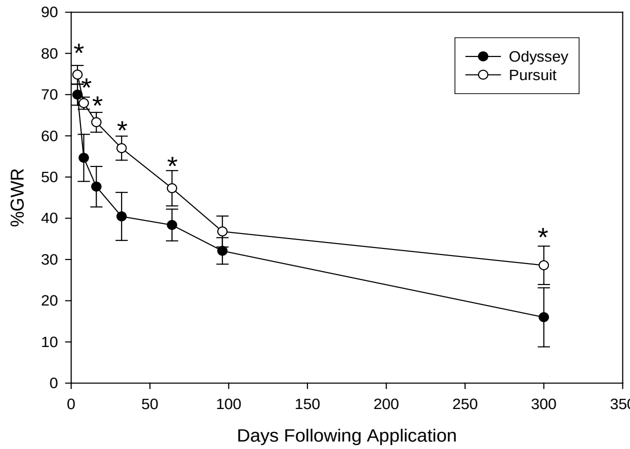

Figure 3. Response of oat seedlings to Odyssey or Pursuit when considering all of the data.

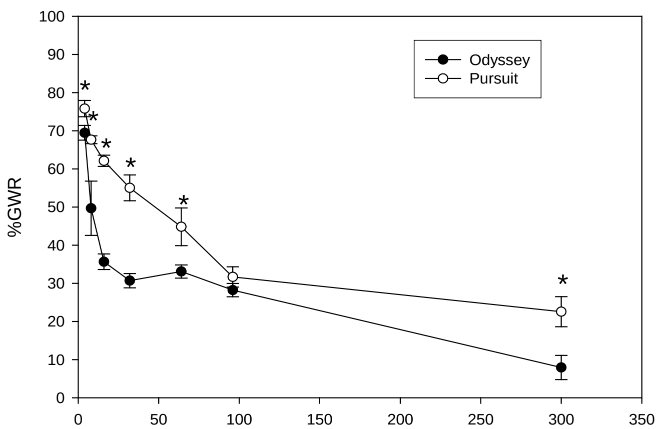

Figure 4. Response of oat seedlings to Odyssey or Pursuit when considering only Hallboro soil.

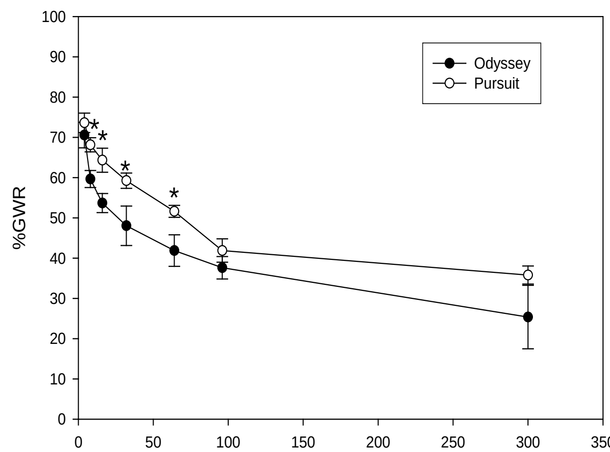

Figure 5. Response of oat seedlings to Odyssey or Pursuit when considering only Fairdale soil

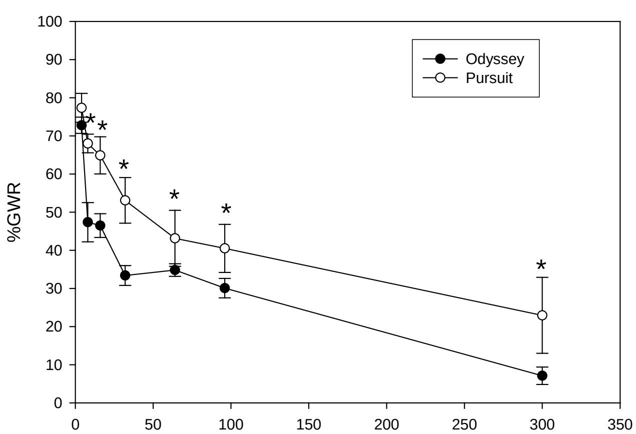

Figure 6. Response of oat seedlings to Odyssey or Pursuit when considering only conventional-till.

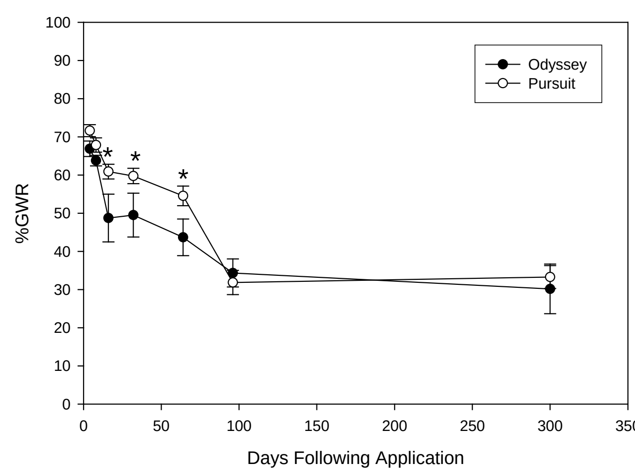

Figure 7. Response of oat seedlings to Odyssey or Pursuit when considering only reduced-till.

*** Difference is significant at the 5% level.**

Effect of soil type: When data were grouped by soil type (Figures 8 to 12 on page 18), the herbicide residual activity during the growing season was greater in the fine-textured Fairland soils than in the coarse-textured Hallboro soils (Figure 8). The greater amount of soil organic matter and clay content in the fine-textured Fairland would have increased the retention of herbicides by soil over time, thereby reducing herbicide degradation rates and increasing the persistence of herbicide residual activity in soil. Since the Hallboro soil has a sandy loam texture, it is also possible that there was a greater movement of herbicide residues from the 0-10 cm surface layer to deeper depths, relative to the more clay-rich Fairland soils. In essence, these results suggest that both Pursuit and Odyssey products provide the best long-term weed control in clay-rich soils with more soil organic matter.

The difference in herbicide residual activity between the fine-textured Fairland soils and the coarse-textured Hallboro soils was larger for Odyssey (Figure 9) than for Pursuit (Figure 10). Odyssey contains the herbicide imazamox in addition to imazethapyr. Imazethapyr is the only herbicide in Pursuit. It is possible that imazamox was less persistent or more mobile in soil than imazethapyr, thereby explaining the fact that the difference in residual herbicide activity between the fine-textured Fairland soils and the coarse-textured Hallboro soils was larger for Odyssey than for Pursuit. In summary, these results suggest that in order to achieve a long-term weed control efficacy in fields that have coarse-textured soils, it is better to apply Pursuit than Odyssey.

The difference in herbicide residual activity between the fine-textured Fairland soils and the coarse-textured Hallboro soils were very similar for CT (Figure 11) and RT (Figure 12) fields. This suggests that regardless of the tillage system Pursuit and Odyssey applications to fields with fine-textured soils will result in a greater long-term weed control efficacy than Pursuit and Odyssey applications to fields with coarse-textured soils.

Effect of tillage system: When data were grouped by tillage system (Figure 13 to 17 on page 19), RT fields generally demonstrated a greater persistence in herbicide residual activity than CT fields (Figure 13).

The type of herbicide product applied influenced the extent to which the herbicide residual activity in CT fields was different from that in ZT fields. For Odyssey, RT fields demonstrated a significantly greater herbicide residual activity than CT fields from 4 to 8 days and from 32 to 64 days after Odyssey applications, while there were no differences in herbicide residual activity between CT and ZT fields at day 16 and 96 after Odyssey applications (Figure 14). For Pursuit, RT fields demonstrated a greater herbicide residual activity than CT fields at from 32 to 64 days following Pursuit applications, but CT fields had a greater herbicide residual activity than RT fields at days 4 and 96 following Pursuit applications (Figure 15). For Pursuit, there were no differences in herbicide residual activity between RT and CT fields on the other sampling days (days 8 and 16 following herbicide application). In summary, these results suggest that when Odyssey is applied, long-term weed control efficacy is generally greater in RT than CT fields. When Pursuit is applied, the impact of tillage system on long-term weed control efficacy is not consistent to a particular type of tillage system.

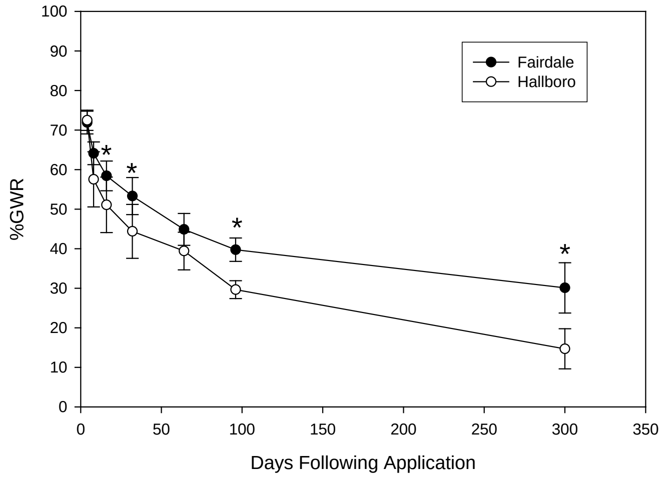

Figure 8. Response of oat seedlings to herbicides in Fairdale or Hallboro soils when considering all of the data.

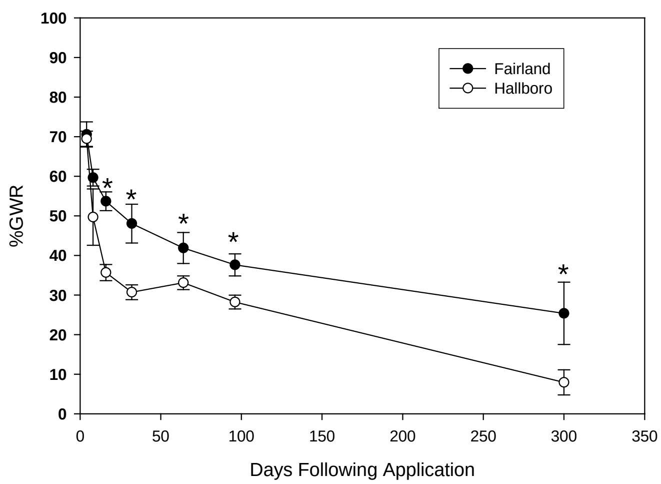

Figure 9. Response of oat seedlings to herbicides in Fairdale or Hallboro soils when considering only Odyssey.

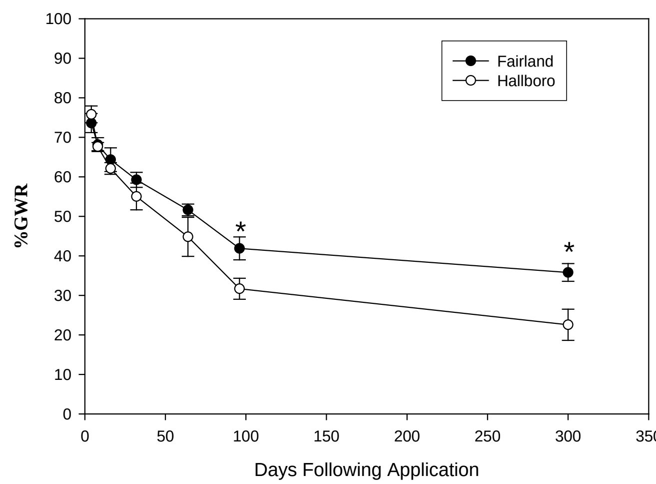

Figure 10. Response of oat seedlings to herbicides in Fairdale or Hallboro soils when considering only

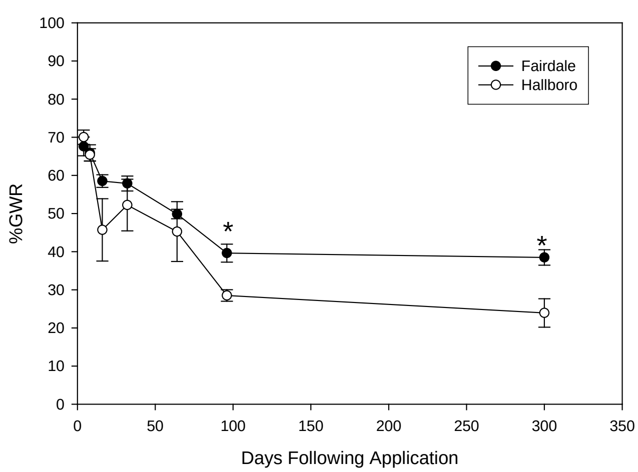

Figure 11. Response of oat seedlings to herbicides in Fairdale or Hallboro soils when considering only reduced-till.

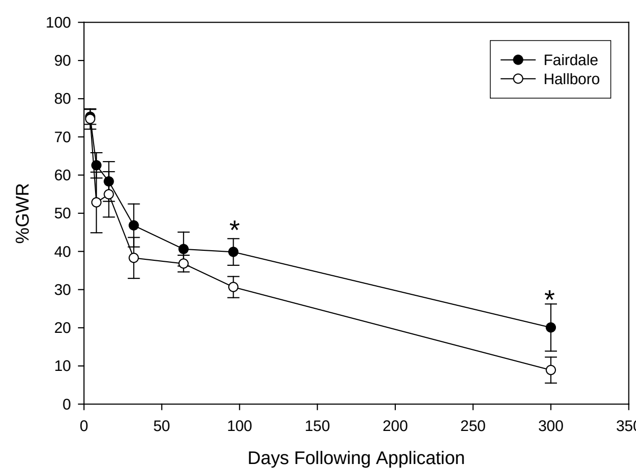

Figure 12. Response of oat seedlings to herbicides in Fairdale or Hallboro soils when considering only conventional-till.

*** Difference is significant at the 5% level.**

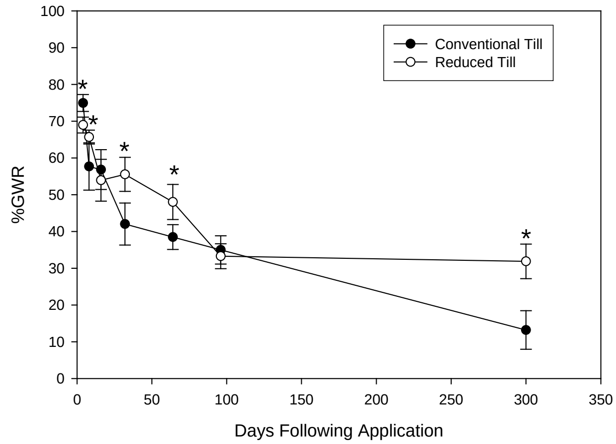

Figure 13. Response of oat seedlings to herbicides in conventional-till and reduced-till when considering both Odyssey and Pursuit.

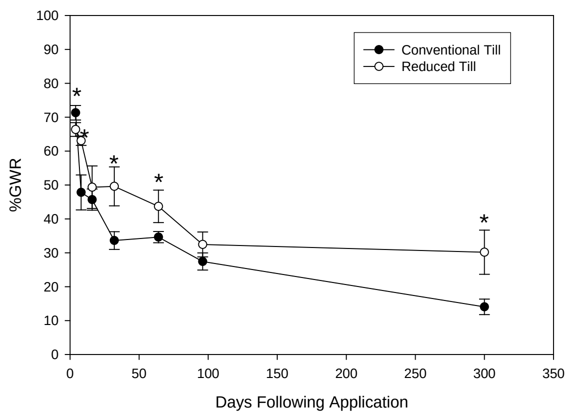

Figure 14. Response of oat seedlings to herbicides in conventional-till or reduced-till when considering only Odyssey

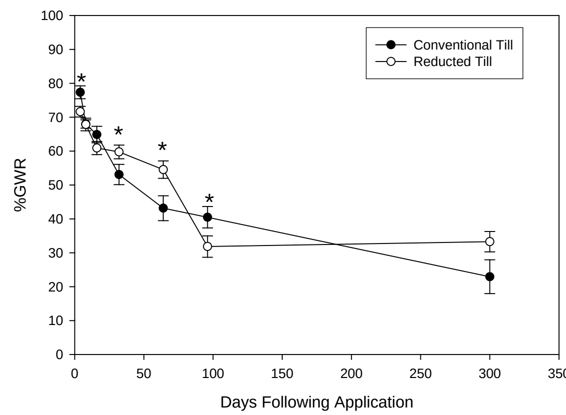

Figure 15. . Response of oat seedlings to herbicides in conventional-till or reduced-till when considering only Pursuit.

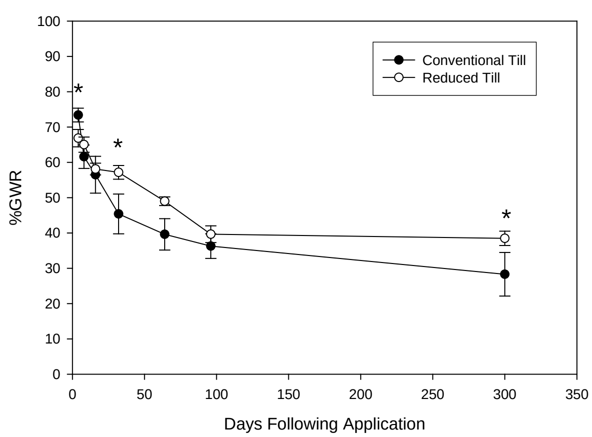

Figure 16. Response of oat seedlings to herbicides in conventional-till or reduced-till when considering only Fairdale soils.

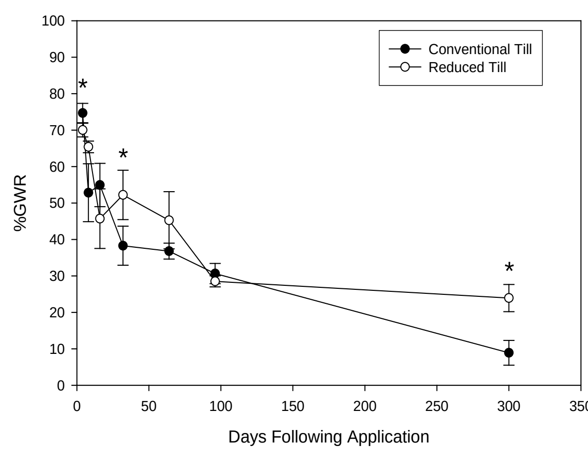

Figure 17. Response of oat seedlings to herbicides in conventional-till or reduced-till when considering only Hallboro soils.

***Difference is significant at the 5% level.**

The extent to which the herbicide residual activity in CT fields was different from that in ZT fields was consistent for Fairdale (Figure 16) and Hallboro (Figure 17) soils. For both Fairdale and Hallboro soils, CT fields demonstrated a somewhat greater herbicide residual activity in soil than RT fields at 4 days following application. However, RT fields showed much greater herbicide residual activity in soil than CT fields at 32 following herbicide applications. The type of tillage system had no effect on herbicide residual activity at the other sampling days (8, 16, 64 and 96 days after herbicide application). These results suggested that during the middle of the growing season RT fields have a better long-term weed control efficacy than CT fields, but CT fields have a slightly greater weed control efficacy early in the growing season. The results also indicate that the effect of tillage system on weed control efficacy is consistent regardless of the type of soil.

Herbicide carry-over into the next growing season: The data were grouped by either herbicide product, soil type or tillage system.

Effect of herbicide product - When data were grouped by herbicide product (Figures 3 to 7 on 16), Pursuit applications onto soils resulted in a significantly greater risk of herbicide carry-over and crop injury than Odyssey applications (Figure 3). The greater risk of herbicide carry-over and crop injury with Pursuit versus Odyssey applications was particularly significant in the coarse-textured Hallboro soils (Figure 4), and the effect of the type of herbicide product applied was much less pronounced in the fine-textured Fairland soils (Figure 5). These result indicate that Pursuit applications onto coarse-textured soils increase the risk of herbicide carry-over and crop injury relative to Odyssey applications, but that Pursuit and Odyssey applications onto fine-textured soils result in similar risks of herbicide carry-over and crop injury.

Pursuit applications in CT fields resulted in a significantly greater risk of herbicide carry-over and crop injury than Odyssey applications onto the same fields (Figure 6). In contrast, either Pursuit or Odyssey applications to RT soils showed a similar risk in herbicide carry-over and crop injury (Figure 7). In summary, these results suggest that herbicide carry-over and crop injury risks in RT fields is not influenced by the type of herbicide product applied, but in CT fields the risks of herbicide carry-over and crop injury is greater for Pursuit than for Odyssey applications.

Effect of soil type: When data were grouped by soil type (Figures 8 to 12 on page 18), there was a greater risk of herbicide carry-over from one year to the next in the fine-textured Fairland soils than in the coarse-textured Hallboro soils (Figure 8). This again suggested that the greater amount of soil organic matter and clay content in the fine-textured Fairland would have increased herbicide sorption over time, thereby reducing herbicide degradation rates and increasing the persistence of herbicide residual activity in soil.

The herbicide carry-over risk in both the fine-textured Fairland soils and the coarse-textured Hallboro soils was more severe for Pursuit than for Odyssey (compare %GWR for both Fairland and Hallboro soils in figures 9 and 10). The least risk of herbicide carry-over occurred in the coarse-textured Hallboro soils onto which Odyssey was applied (Figure 9). The greatest risks of herbicide carry-over occurred in the fine-textured Fairland soils onto which Pursuit was applied (Figure 10). In summary, these results suggest that herbicide carry-over and crop injury is greatest for Pursuit applications in fields that have clay-rich soils with large amounts of soil organic matter. These results also suggest that herbicide carry-over and crop injury risks are relatively small for Odyssey applications onto coarse-textured soils with lesser clay and soil organic matter contents.

For both CT (Figure 11) and RT (Figure 12) fields, the risk of herbicide carry-over from one year to the next was greater for the fine-textured Fairdale soils than the coarse-textured Hallboro soils. The difference in the risk of herbicide carry-over between soil types was smaller in ZT than CT soils. These results suggested again that there is a greater risk of herbicide carry-over from one year to the next in the fine-textured soils than in coarse-textured Hallboro soils, particularly in RT fields.

Effect of tillage system: When data were grouped by tillage system (Figure 13 to 17 on page 19), the risk of herbicide carry-over and crop injury was much greater in RT fields than in CT fields (Figure 13). These results were consistent regardless of the type of herbicide product applied (Figures 14 and 15) and regardless of the soil type (Figures 16 and 17). The CT fields were tilled in the spring, prior to soil sampling at 300 days following herbicide application. It is therefore clear that tillage operations dilute the amount of herbicide residues in soil by mixing these herbicide residues into the plough layer. In summary, the risk of herbicide carry-over and crop injury is greatly reduced when soils are tilled in the spring prior to seeding.

PART II

RESEARCH RESULTS IN YEAR 2

Soil characteristics and herbicide sorption: Soils were in the black soil zone. Both upper slope positions and the lower slope positions were characterized by clay-loam soils (Table 2). Soils in the upper slope position were classified as well-drained Orthic Black Chernozems from the Newdale soil series. Lower slope positions were classified as imperfectly-drained Gleyed Rego Black Chernozemic soils from the Varcoe soil series.

Clay content in soils was similar regardless of slope position or tillage system. Soil pH was also similar regardless of slope position or tillage system and ranged from 7.4 in the Varcoe soil under RT to 7.7 in the Varcoe soil under CT.

Soils under RT showed a greater difference in soil organic matter content between upper and lower slope positions than soils under CT. There was no consistent trend in the impact of slope position on soil organic carbon content. Soils under RT showed lesser soil organic matter content in upper slope position than lower slope positions. Soils under CT showed greater soil organic matter content in upper slope positions than lower slope positions.

The soil in the upper slope position under zero-till contained lesser soil organic matter than other soils. This soil also had lesser herbicide sorption than other soils. Other studies have shown that imadazolinone sorption decreased with decreasing soil organic matter contents (Senesi et al. 1997).

TABLE 2. Selected soil properties and Freundlich sorption coefficients (Kf) for imazethapyr in the four agricultural fields.

	Newdale soil series (upper slope positions)		Varcoe soil series (lower slope positions)	
	CT	RT	CT	RT
Soil texture	Clay loam	Clay loam	Clay loam	Clay loam
Clay content (%)	27	27	27	29
Soil organic C (%)	3.62	2.87	3.19	4.23
Soil pH	7.7	7.5	7.6	7.4
Soil bulk density in field (g cm^{-3})	0.84*	0.86*	0.85*	0.79*
Moisture content at field capacity (%)	50	48	50	51
Kf ($\mu^{1-1/n}$ $g^{-1}mL^{1/n}$), a measure of herbicide sorption by soil	1.66	0.77	2.13	1.61

* for the bioassay experiments, the soil bulk density were adjusted to 0.85 Kg/m^3 for all soils. These bulk densities corresponded to the bulk density measured for surface soils in the field. There was no difference in bulk densities between tillage systems and between slope position.

Soil moisture conditions during the growing season: Soil moisture content may influence Odyseey and Pursuit persistence and residual activity in soil. For both Newdale and Varcoe soils, soil moisture content was near or above field capacity for most days during the growing season (Figures 18 and 19). These saturated soil conditions resulted from frequent rainfall events before and after herbicide application.

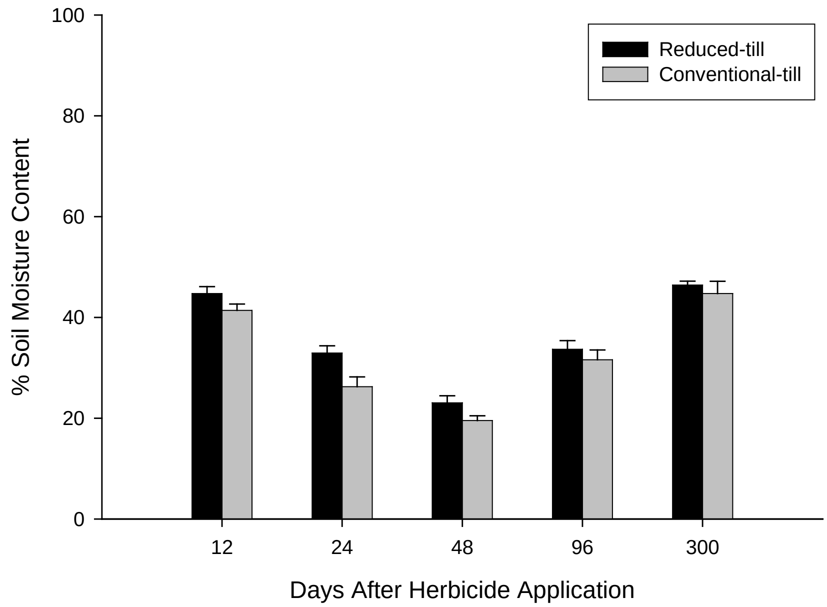

Figure 18. Soil moisture content in Newdale soils under reduced-till (RT) and conventional-till (CT).

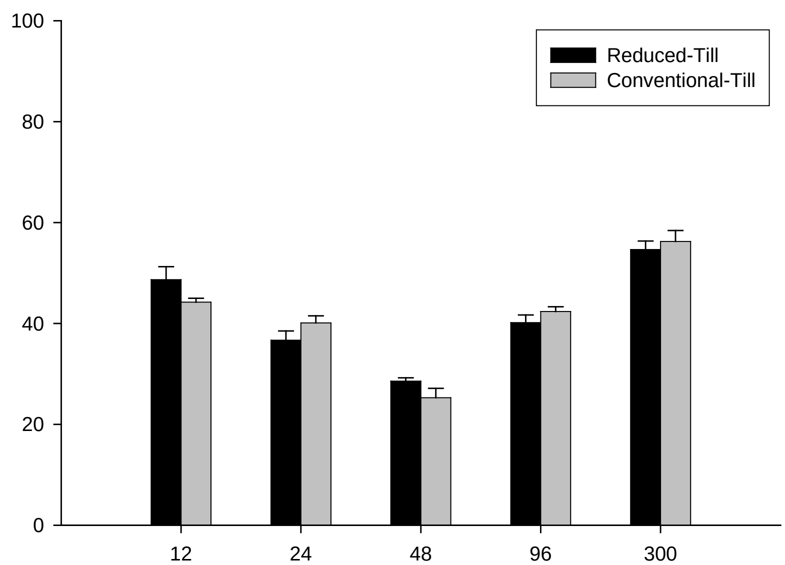

Figure 19. Soil moisture content in Vacoe soils under reduced-till (RT) and conventional-till (CT).

Herbicide residual activity during the growing season: The data were grouped by either herbicide product, soil type or tillage system.

Effect of herbicide product - When data were grouped by herbicide product (Figures 20 to 24 on 25), the difference in herbicide residual activity between Odyssey and Pursuit products was relatively small (Figure 20). However, Pursuit demonstrated a significantly greater herbicide residual activity than Odyssey between 12 and 24 days following herbicide application (Figure 20). These results indicate that for clay-rich soils with large amounts of soil organic matter, the product Pursuit shows a better weed control efficacy than the product Odyssey, but only early in the growing season.

The difference in herbicide residual activity between Pursuit and Odyssey treated soils was more pronounced for lower slope positions (Varcoe soils: Figure 21) than upper slope positions (Newdale soils: Figure 22). It was also clear that Pursuit demonstrated a significantly greater herbicide residual activity than Odyssey early in the growing season, but the difference in herbicide residual activity in Pursuit versus Odyssey treated soils diminished thereafter (Figures 21 and 22). These results indicate that for clay-rich soils with large amounts of soil organic matter and early in the growing season, the product Pursuit shows a better weed control efficacy than the product Odyssey, particularly in lower slope positions of fields.

For CT fields, Pursuit has a significantly greater herbicide residual activity than Odyssey from 12 to 24 days following Pursuit applications, but the type of herbicide product had no significant effect on the level of herbicide activity in soil at 48 and 64 days following herbicide application (Figure 23). For the RT fields, Pursuit had a greater herbicide residual activity than Odyssey at 12 days after herbicide applications, but there were no significant differences in herbicide residual effects between herbicide products on subsequent sampling days (Figure 24). These results suggested that for clay-rich soils with large amounts of soil organic matter under either CT or RT management, the product Pursuit shows a better weed control efficacy than the product Odyssey, but only early in the growing season.

Effect of soil type: When data were grouped by soil type (Figures 25 to 29 on page 26), there was no overall effect of slope position on herbicide residual activity in soil (Figure 25). When the data was further split by soil type (Figures 26 and 27), these results were consistent except that the Newdale soil (upper slope position) showed a greater herbicide residual activity than the Varoce soil (lower slope position) at 12 days following Pursuit applications (Figure 27).

When the effect of soil type was evaluated for CT fields only, the herbicide residual activity was greater for the Newdale soils (upper slope position) than the Varcoe soils (lower slope position) from 48 to 96 days after herbicide application (Figure 28). In contrast, for the RT fields, the herbicide residual activity was greater for the Varcoe soils (lower slope position) than the Newdale soils (upper slope position) from 24 to 96 days after herbicide application (Figure 29). In essence, these results indicate that herbicide bioactivity over the growing season was less persistent for the upper slope positions in RT fields and lower slope positions in CT fields than for lower slope positions in RT fields and upper slope positions in CT fields. More importantly,

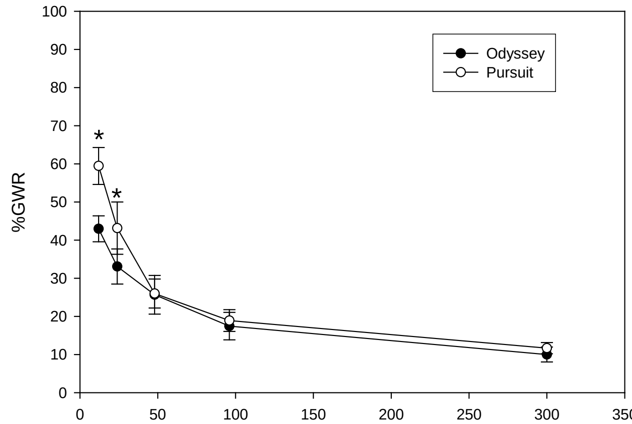

Figure 20. Response of oat seedlings to Odyssey or Pursuit when considering all data.

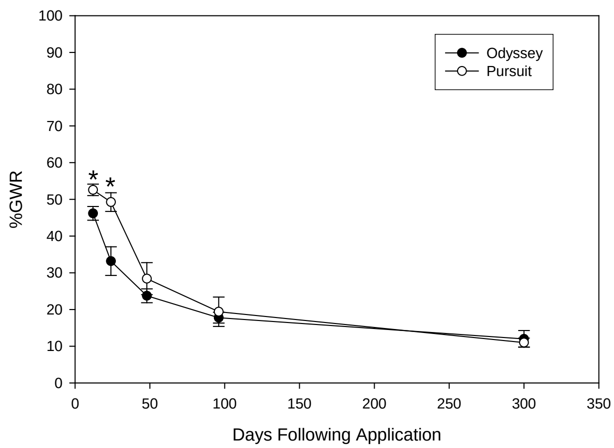

Figure 21. Response of oat seedlings to Odyssey or Pursuit when considering only Varcoe soil.

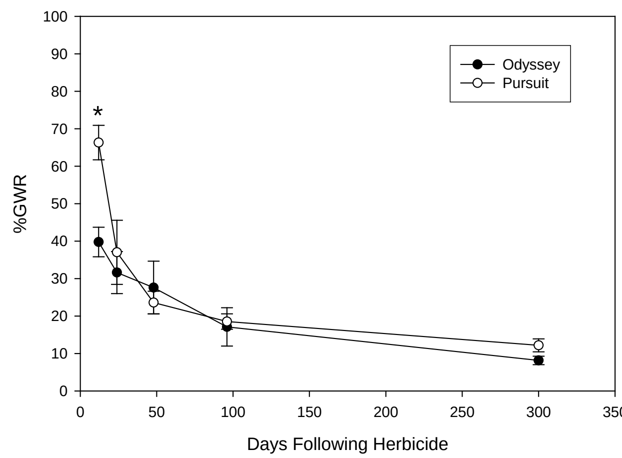

Figure 22. Response of oat seedlings to Odyssey or Pursuit when considering only Newdale soil.

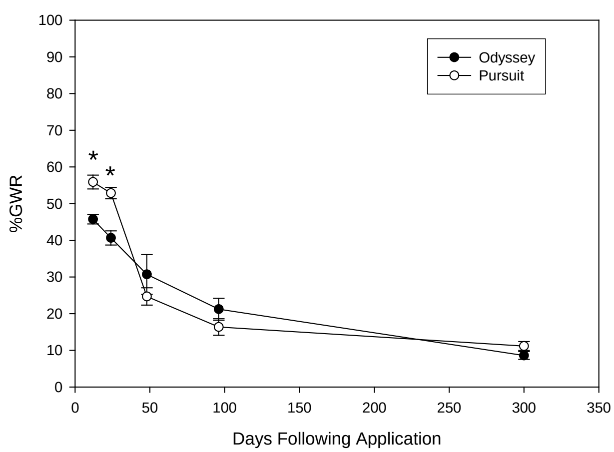

Figure 23. Response of oat seedlings to Odyssey or Pursuit when considering only conventional-till.

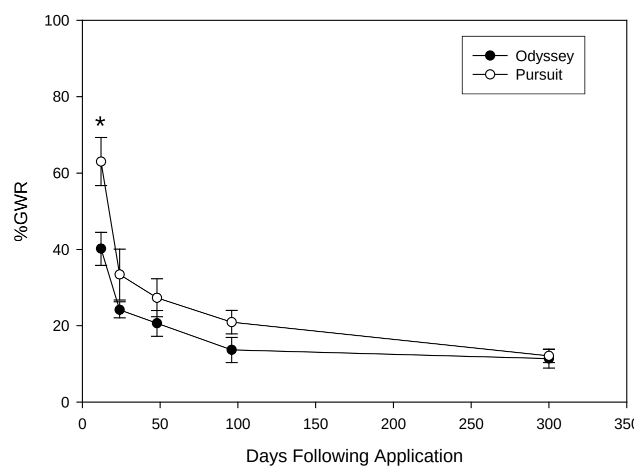

Figure 24. Response of oat seedlings to Odyssey or Pursuit when considering only reduced-till.

*** Significantly different at the 5% level.**

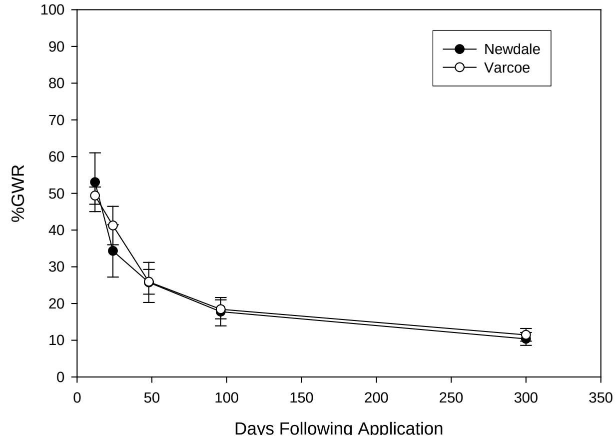

Figure 25. Response of oat seedlings to herbicides in Newdale or Varcoe soils when considering all data.

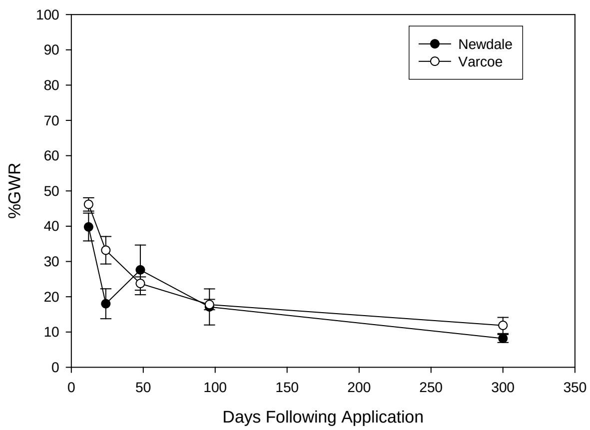

Figure 26. Response of oat seedlings to herbicides in Newdale or Varcoe soils when considering only Odyssey.

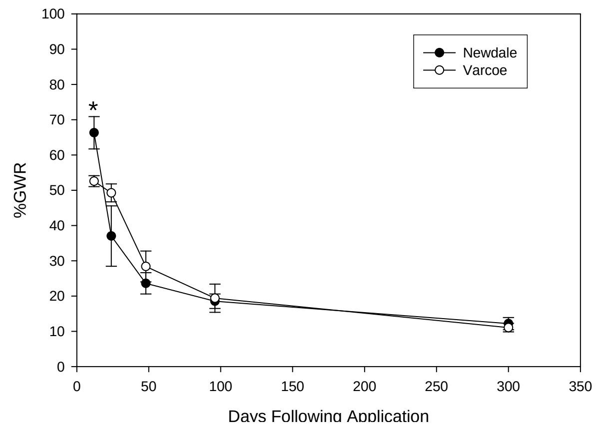

Figure 27. Response of oat seedlings to herbicides in Newdale or Varcoe soils when considering only Pursuit

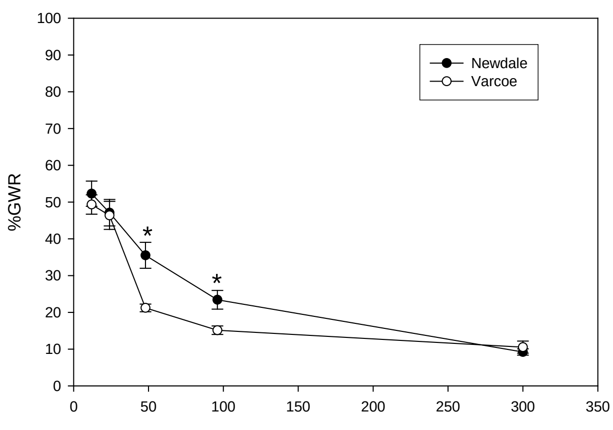

Figure 28. Response of oat seedlings to herbicides in Newdale or Varcoe soils when considering only conventional tillage.

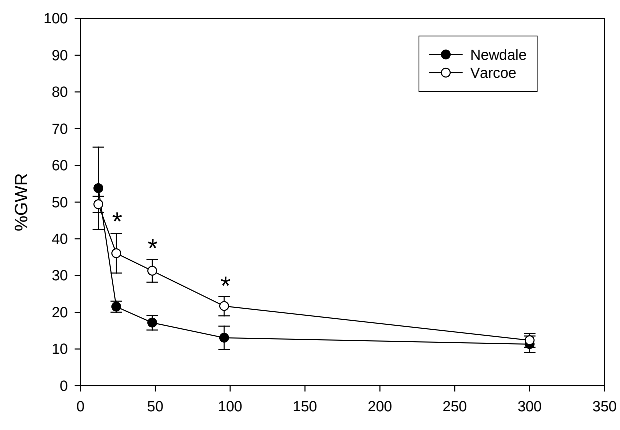

Figure 29. Response of oat seedlings to herbicides in Newdale or Varcoe soils when considering only reduced tillage

*** Significantly different at the 5% level.**

soil organic carbon content was smaller for both upper slope positions in RT fields (2.87%) and lower slope positions in CT fields (3.19%) than for both lower slope positions in RT fields (4.23%) and upper slope positions in CT fields (3.62%). As such, there was a relation between herbicide residual activity and the amount of organic carbon in soil. Specifically, soils with greater soil organic matter content have greater herbicide residual activities compared to soils with lesser soil organic matter content. Other studies have also found that imazethapyr persistence increases with increasing soil organic content (Loux and Reese, 1993). In summary, both Pursuit and Odyssey products provide the best long-term weed control in soils with large amounts of soil organic matter.

Effect of tillage system: When data were grouped by tillage system (Figure 30 to 34 on page 28), the type of tillage system had no influence on the extent of herbicide residual activity in the soil, except at 24 days following herbicide application when CT fields demonstrated a greater persistence in herbicide residual activity than RT fields (Figure 30).

For Odyssey, CT fields demonstrated a significantly greater herbicide residual activity than RT fields from 24 to 48 days after Odyssey applications, while there were no differences in herbicide residual activity between CT and ZT fields at the other sampling days (Figure 31). For Pursuit, CT fields demonstrated a greater herbicide residual activity than RT fields only at 48 days following Pursuit applications (Figure 32). From 48 to 96 days after Pursuit applications, the herbicide residual activity was slightly greater in RT fields than CT fields (Figure 32), but the differences between in herbicide residual activity between the two tillage systems were not statistically significant. In summary, these results suggest that when Odyssey is applied, long-term weed control efficacy is generally greater in CT than RT fields. This result is in contrast with the result obtained for Odyssey in the 1999/2000 field trials. When Pursuit is applied, the impact of tillage system on long-term weed control efficacy is not consistent to a particular type of tillage system. This result is similar to that obtained for Pursuit in the 1999/2000 field trials.

The extent to which the herbicide residual activity in CT fields was different from that in ZT fields was inconsistent for Newdale (Figure 33) and Varcoe (Figure 34) soils. For the Newdale soil (upper slope positions), CT fields had a much greater herbicide residual activity than RT fields from 24 to 96 days following herbicide application. The Newdale soil (upper slope position) in the RT field had a small soil organic matter content (Table 2) and herbicide residual activity decreased rapidly in this soil between 12 and 24 days following herbicide application. For the Varcoe soil, herbicide residual activity was larger in CT than RT fields up to 48 days following herbicide applications, but the herbicide residual activity was larger in RT than CT fields for the second part of the growing season. In summary, the results for the Newdale soil indicate that soil organic matter content has a strong effect on the level of weed control efficacy in soil. The results for the Varcoe soils are in agreement with the results for the soils in 1999/2000 field trials: early in the growing season, CT fields have a slightly greater weed control than RT, but over time RT fields have a better long-term weed control efficacy than CT fields.

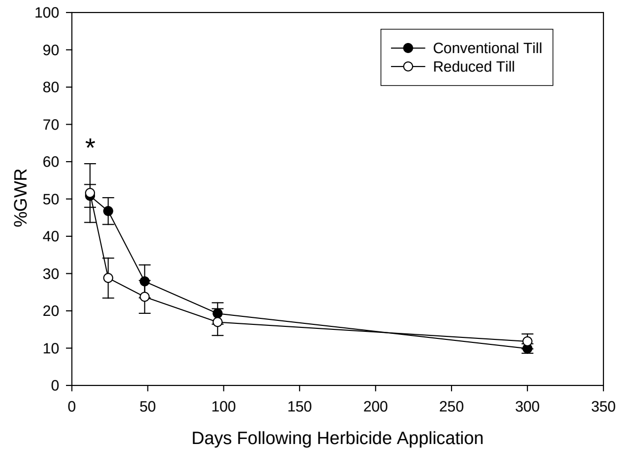

Figure 30. Response of oat seedlings toherbicides conventional-till or reduced-till when considering all data.

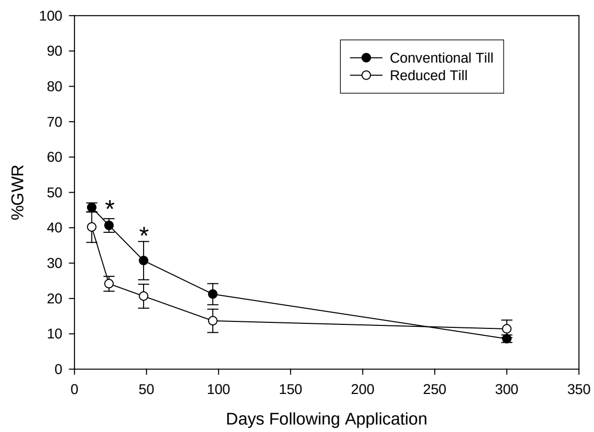

Figure 31. Response of oat seedlings to herbicides in conventional-till or reduced-till when considering only Odyssey.

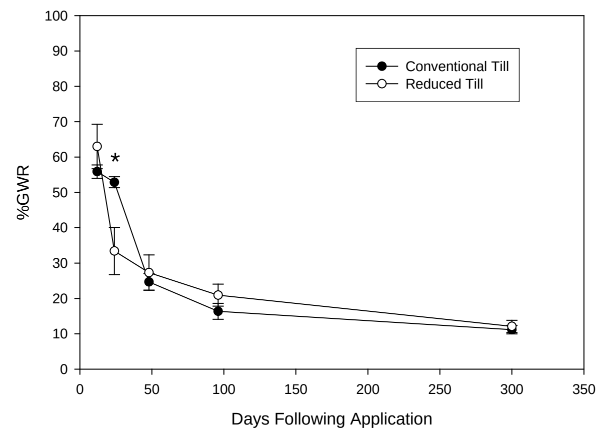

Figure 32. Response of oat seedlings to herbicides in conventional-till or reduced-till when considering only Pursuit

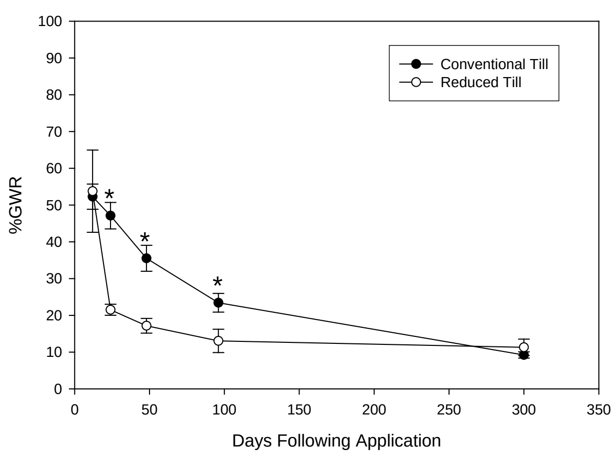

Figure 33. Response of oat seedlings to herbicides in conventional-till or reduced-till when considering only Newdale soil.

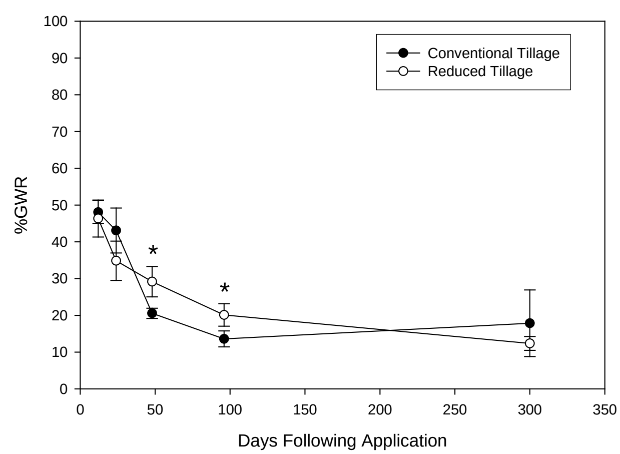

Figure 34. Response of oat seedlings to herbicides in conventional-till or reduced-till when considering only Varcoe soil.

*** Significantly different at the 5% level.**

Herbicide carry-over into the next growing season: The data were grouped by either herbicide product, soil type or tillage system.

Effect of herbicide product - When data were grouped by herbicide product (Figures 20 to 24 on 25), type of herbicide product had no effect on the risk of herbicide carry-over and crop injury (Figure 20). This result was consistent regardless of slope position (Figures 21 and 22) or tillage system (Figures 23 and 24). These results are in agreement with the result of the 1999/2000 field trials which also showed that that Pursuit and Odyssey applications onto fine-textured soils result in similar risks of herbicide carry-over and crop injury.

Effect of soil type: When data were grouped by slope position (Figures 25 to 29 on page 26), there was a similar risk of herbicide carry-over in Newdale (upper slope position) and Varcoe (lower slope position) soils (Figure 25), regardless whether Odyssey (Figure 26) or Pursuit (Figure 27) was applied. For both CT (Figure 28) and RT (Figure 29) fields, Newdale (upper slope position) and Varcoe (lower slope position) soils showed similar herbicide carry-over risks. In summary, for fine-textured soils, upper slope and lower slope positions in both CT and RT fields have very similar risks of herbicide carry-over and crop injury.

Effect of tillage system: When data were grouped by tillage system (Figure 30 to 34 on page 28), the risk of herbicide carry-over and crop injury was similar for CT and RT fields (Figure 30). This result was consistent regardless of herbicide product (Figures 31 and 32) or slope position (Figures 33 and 34). The CT fields were not tilled prior to soil sampling at 300 days following herbicide application. These results suggest risks of herbicide carry-over and crop injury is similar for CT and RT fields if no tillage operations are done in the spring. This result is in agreement with the results of the field trials in 1999/2000 where tillage operations prior to soil sampling at 300 days following herbicide application diluted the amount of herbicide residues in CT fields by mixing herbicide residues into the plough layer. In summary, the risk of herbicide carry-over and crop injury will only be reduced when soils are tilled in the spring prior to seeding.

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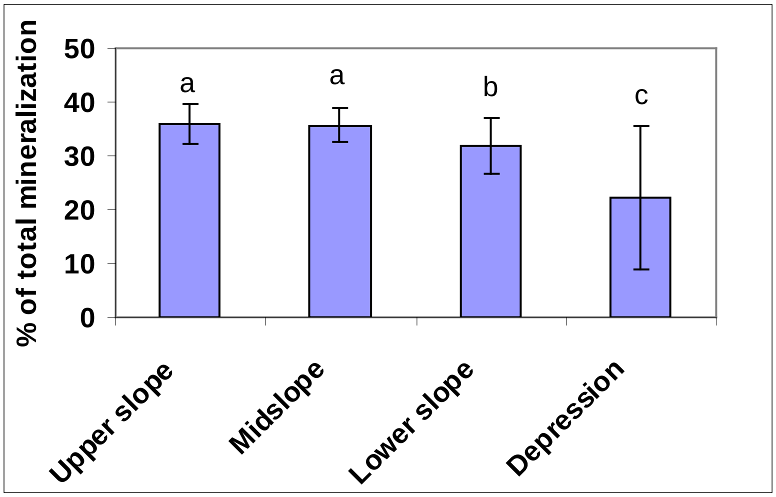
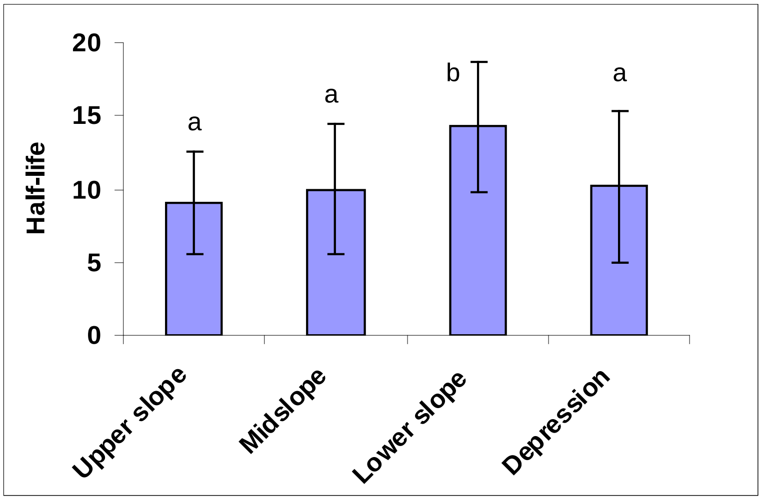
APPENDIX A

PERSISTENCE OF 2,4-D AS INFLUENCED BY SLOPE POSITION



Effect of landscape position on total mineralization of 2,4-D in soil at 130 days following herbicide application.



Effect of landscape position on 2,4-D half-lives in soil.