

**THE EFFECTS OF ELEVATED
CO₂ AND TEMPERATURE
ON HERBICIDE EFFICACY
AND WEED/CROP
COMPETITION**

**Final Report Prepared for the
Prairie Adaptation Research Collaborative**

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EXECUTIVE SUMMARY

The dynamics of competition between crops and weeds are affected by environmental conditions, and have been shown to change with CO₂ enrichment. Differential responses of C₃ and C₄ plants to elevated CO₂ and temperature may cause shifts in their competitive interactions. There is a need to evaluate the effects of elevated CO₂ and temperature on crop/weed competition and herbicide efficacy to develop strategies for agriculture in the face of climate change.

The objective of this study was to evaluate the effects of elevated CO₂ and temperature on the efficacy of commonly used herbicides and on crop/weed competition. Specifically, the objectives were to:

1. determine the effects of elevated CO₂ on the efficacy of herbicides in controlling wild oats, Canada thistle, redroot pigweed, green foxtail, lambsquarters, kochia and common groundsel,
2. study herbicide efficacy at ambient and elevated CO₂ levels on wild oats and green foxtail grown in competition with barley,
3. develop a CO₂ dose response curve that will be used to establish a timeline of change in herbicide efficacy by taking into account current rates of change in atmospheric CO₂,
4. study the interactive effects of elevated CO₂ and temperature on herbicide efficacy in wild oats,
5. conduct an economic analysis to provide preliminary monetary values of the effects of elevated CO₂ and temperature on weed/crop competition and herbicide efficacy.

We screened several herbicide/weed combinations and selected crops for effects of elevated CO₂ using both greenhouse-based and growth-chamber based gas exposure systems. We found that responses of weeds and crops to increasing CO₂ levels were species-specific. Herbicide efficacy can be negatively affected by elevated CO₂ and effects were dependent on the mode of action of herbicides, on weed species and on competition. While double-ambient CO₂ caused a decrease of 57% in efficacy of the herbicide Fusion applied to wild oats (C₃), no effects of elevated CO₂ were found when the herbicide was applied to green foxtail (C₄). CO₂-related

reduction in efficacy of Round-up Transorb applied to Canada thistle was reversed when weeds were grown in competition with canola. Dose response experiments showed that efficacy of certain herbicides could be adversely affected at CO₂ levels approximately 160 ppm above ambient. Based on these findings, an experiment was designed to study CO₂/temperature interactions on growth of wild oats and herbicide efficacy using either ambient levels of CO₂ or ambient + 160 ppm and daytime temperature of either 23, 26 or 29°C. Daytime temperatures above 23°C decreased growth both in control and herbicide-treated plants. Increasing daytime temperature from 23 to 29°C caused decreased efficacy in the herbicides Fusion and Liberty but not in Assert 300. Decreases in efficacy were greatest at ambient CO₂ for Fusion and greatest at ambient + 160 ppm CO₂ in Liberty. While analysis of variance did not detect a significant interaction between CO₂ and temperature, both elevated CO₂ and temperature caused decreased efficacy of the herbicide Liberty on wild oats.

The economic analysis performed using plant growth and herbicide efficacy changes suggested that potential monetary losses due to CO₂-induced decreases in herbicide efficacy can be partially or totally overcome by increases in crop yields caused by elevated CO₂. Nonetheless, the results also suggest that weed control will be crucial in realizing potential increases in economic yield of crops as atmospheric CO₂ concentrations increase. Since yields were not measured directly in this study, several assumptions were made to estimate the expected changes in yields that may occur as a result of the changes in CO₂ levels and herbicide efficacies. The changes in biomass caused by increased levels of CO₂ were translated into expected changes in yields using three different case scenarios. Case one assumed that yield increases were directly proportional to the biomass increases that occurred. Case two assumed that the increases in yields were half of the increase in biomass. Case three assumed that yields did not increase as biomass levels increased. Further studies on the effects of elevated CO₂ and temperature on crop yields and herbicide efficacy are required to diminish the uncertainties in the economic analysis. If effects of climate change on crop/weed competition and herbicide efficacy are common, they will have a significant impact on agriculture.

It was concluded that:

- 1) The efficacy of herbicides either decreased, increased or did not change when herbicides were applied to weeds grown at elevated CO₂.
- 2) Effects of elevated CO₂ on herbicide efficacy may change when weeds are grown in competition with crops.
- 3) Herbicide efficacy changes were only found to occur at 160 ppm above ambient levels of CO₂. According to the current rate of change in atmospheric concentrations of CO₂, this corresponds to approximately 50 years from present.
- 4) Elevated temperature tended to decrease herbicide efficacy and the effects of temperature and CO₂ can be additive.
- 5) The economic analysis performed using plant growth and herbicide efficacy changes suggest that potential monetary losses due to decreased herbicide efficacy can be partially or totally overcome by increases in crop yields caused by elevated CO₂. Nonetheless, the results also suggest that weed control will be crucial in realizing potential increases in economic yield of crops as atmospheric CO₂ concentrations increase.
- 6) In this study, most of the data used to produce the economic analysis were extrapolations from short-term screening experiments and several assumptions needed to be made. Further studies on the effects of elevated CO₂ and temperature on crop yields and herbicide efficacy are required to diminish the uncertainties in the economic analysis.

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1. INTRODUCTION

The concentration of CO₂ in the atmosphere is rising at a rate of 1.5-2 ppm per year, and is expected to reach 600 ppm by the middle of this century (Conway et al. 1994). Similarly, a global rise in temperature is expected to occur as a result of buildup of greenhouse gases, including CO₂ (Options Paper, Canadian Climate Program Board 1999). The lack of knowledge of the effects of agricultural pests is a major obstacle in the prediction of effects of climate change on agriculture (Prestidge and Pottinger 1990).

The dynamics of competition between weed and crop plants are affected by environmental conditions, and have been shown to change with CO₂ enrichment (Patterson and Flint 1980). Differential responses of C₃ (carbon from CO₂ initially fixed into 3-carbon compounds - e.g., barley, wild oats, redroot pigweed) and C₄ (carbon from CO₂ initially fixed into 4-carbon compound - e.g., green foxtail) plants to elevated CO₂ and temperature may cause shifts in their competitive interactions. These changes have particular significance given that most of the world's crop species are C₃ plants and that many of the major weed species are C₄ plants. While this might suggest that crops will gain competitive advantage over most weeds, other factors, such as changes in herbicide efficacy, may come into play and limit this advantage and decrease potential yield increases in crops. While many studies have examined the effects of environmental change on crop and weed interactions, relatively few have included the effects of environmental change on herbicide efficacy.

Environmental factors such as temperature, precipitation, wind and relative humidity influence the efficacy of herbicides (Hatzios and Penner 1982; Muzik 1976). Elevated temperatures and metabolic activity tend to increase uptake, translocation and efficacy of many herbicides (Patterson et al. 1999). High concentrations of starch in leaves which commonly occurs in C₃ plants grown under CO₂ enrichment (Wong 1990) might interfere with herbicide activity (Patterson et al. 1999). Although the effects of elevated atmospheric CO₂ concentrations on weed/crop/herbicide interactions are not well known, a recent study (Ziska et al. 1999) showed that elevated CO₂ levels diminished the efficacy of the widely used herbicide glyphosate. If these effects are common and widespread, they will have a significant impact on agriculture.

There is a need to evaluate the effects of elevated CO₂ and temperature, including their interactive effects, on herbicide efficacy to develop strategies for the agricultural industry in the face of global climate change. The information provided by this study will allow us to identify and predict effects of elevated CO₂ and temperature on herbicide efficacy. From this, we will be able to prepare for these changes through development of adaptive agricultural practices for existing herbicides, especially rate and timing of application to control weeds in a high CO₂/temperature environment. If existing products cannot provide adequate control of weeds in a high CO₂/temperature environment, this work will also provide useful information for the development of new products by identifying the herbicides with modes of action that are least affected.

2. OBJECTIVES

The objective of this study was to evaluate the effects of elevated CO₂ and temperature on the efficacy of commonly used herbicides and on crop/weed competition. Specifically, the objectives were to:

1. determine the effects of elevated CO₂ on the efficacy of herbicides in controlling wild oats, Canada thistle, redroot pigweed, green foxtail, lambsquarters, kochia and common groundsel,
2. study herbicide efficacy at ambient and elevated CO₂ levels on wild oats and green foxtail grown in competition with barley,
3. develop a CO₂ dose response curve that will be used to establish a timeline of change in herbicide efficacy by taking into account current rates of change in atmospheric CO₂,
4. study the interactive effects of elevated CO₂ and temperature on herbicide efficacy in wild oats,
5. conduct an economic analysis to provide preliminary monetary values of the effects of elevated CO₂ and temperature on weed/crop competition and herbicide efficacy.

3. METHODS AND MATERIALS

3.1 Plant growth, CO₂ exposures and herbicide applications

3.1.1 Exposure system and carbon dioxide levels

The exposure systems used in this study (Figures 1 and 2) were of the flow-through type with airflow rates of approximately 1 m³/min that gave complete air exchanges in approximately 12-15 minutes. Airflow rates were determined based on pressure measurements taken in the air delivery system. Carbon dioxide concentrations were controlled by injecting pure anaerobic CO₂ from a cylinder (Praxair) into the air stream using mass flow controllers and measured using either a LI-COR 6400 photosynthesis machine or a Guardian Plus CO₂ analyzer. The exposure systems are described in detail elsewhere (Li and Archambault 2000, Archambault and Li 2001). The efficacy of several herbicides on a number of common weeds was determined at ambient (~360 ppm) and elevated (2x ambient ~720 ppm) CO₂ levels except in the dose response study described in section 3.3.

3.1.2 Plant care and growth conditions

3.1.2.1 *Screening and competition experiments*

Plants were grown in plexiglass chambers within a greenhouse (Figure 1). Light intensities at mid-canopy ranged between 300 and 825 μmols m⁻² s⁻¹. A photoperiod of 16 hours light and 8 hours dark was maintained using natural light supplemented using full-spectrum fluorescent lights and sodium halide lights. Temperatures ranged from 21 to 25°C at daytime and 13 to 20°C at nighttime and were monitored using chart recorders.

3.1.2.2 *Dose response and CO₂/temperature interaction experiments*

Plants were grown in modified growth chambers (Convion - Figure 2). Light intensities at mid-canopy ranged between 300 and 325 μmols m⁻² s⁻¹. A photoperiod of 16 hours light and 8 hours dark was maintained using fluorescent and incandescent lights. Unless otherwise stated, temperatures were 23°C in the day and 15°C at night. Temperature was monitored using chart recorders. Relative humidity levels were maintained between 40 and 60% whenever possible. Relative humidity was monitored using humidity probes (Vaisala) mounted in ports in two of the six growth chambers and logged to a Pro-logic controller.

3.1.3 Herbicide applications

When plants reached predetermined ages (stages), they were moved to an automated spray chamber for treatment at the manufacturers' recommended rates or at one-quarter the rate. The one-quarter rate applications were used to attempt to account for increased herbicide efficacy that is typical when plants are grown in controlled environments and for the lower than recommended rates that are often used by producers. The herbicides selected are commonly used on the Canadian Prairies and represent 8 chemical families with 6 herbicide groups having different modes of action.

3.2 **Screening for effects of CO₂ on herbicide efficacy**

Experiment 1

In this experiment, a preliminary trial was performed using manufacturers' recommended rates of herbicides. The efficacy of three common herbicides on the control of wild oats was studied. Wild oats were grown in 8" pots containing a standard greenhouse soil mixture at ambient and elevated CO₂ and treated with either Poast Ultra, Horizon or Assert 300. Following herbicide application, the plants were returned to the growth chambers and grown for approximately three weeks. The experimental design was:

1 species x 6 herbicide treatments (3+3 controls) x 2 CO₂ levels x 6 replicates.

A second trial was performed using both the manufacturers' recommended rates of herbicides and one-quarter rate. The efficacy of Poast Ultra, Horizon, Assert 300, Liberty, Avenge and Fusion in the control of wild oats was studied. The experimental design was:

1 species x 13 herbicide treatments (12+1 controls) x 2 CO₂ levels x 6 replicates.

Experiment 2

The efficacy of 2,4-D, Ally, Pardner and Poast Ultra in controlling wild buckwheat, redroot pigweed, kochia and green foxtail, respectively, was studied. Plants were grown as described above. The experiment was conducted in two trials.

The experimental design was:

4 species x 2 herbicide treatments (1+1 control) x 2 CO₂ levels x 6 replicates.

Experiment 3

The efficacy of Sencor, Lontrel, Lorox, Fusion, Roundup Transorb and Pursuit in the control of lambsquarters, common groundsel, wild buckwheat, green foxtail (C₄), Canada thistle (C₃) and chickweed, respectively, was studied. Plants were grown as described above. The experiment was conducted in two trials.

The experimental design was:

6 species x 3 herbicide treatments (2 rates+1 control) x 2 CO₂ levels x 4 to 6 replicates.

Assessments: Total above-ground biomass was determined after each harvest. Herbicide efficacy values were calculated as percent of control.

3.3 Dose response of herbicide efficacy – a timeline of changes in efficacy

Dose response experiments were conducted to identify the minimal CO₂ level that would affect herbicide efficacy thereby establishing a timeline for CO₂ impact on efficacy by taking into consideration the current rate of change (~1.5-2.0 ppm/year).

Wild oats were grown at 390, 410, 430, 470, 550 and 710 ppm to establish a dose response relationship of CO₂ in the presence and absence of herbicide. This experiment also served to determine a dose response relationship for CO₂ on wild oats and to establish a critical CO₂ level at which growth and perhaps competitiveness will increase.

The experimental design was:

1 species x 6 CO₂ levels x 4 herbicide treatments (3+1 control) x 5 replicates.

Assessments: As in section 3.2.

3.4 Effects of elevated CO₂ on herbicide efficacy in weed/crop competitive interactions

The efficacy of herbicides on weeds grown in competitive interactions with barley or canola at ambient and elevated CO₂ levels was studied. Barley and wild oats, barley and green foxtail, canola and wild oats and Roundup ready canola and Canada thistle were grown at a 4:1 crop to weed ratio in 8" pots containing a standard greenhouse soil mixture. The wild oats/barley were treated with Assert 300, green foxtail/barley with Achieve, wild oats/canola with Fusion and Canada thistle/canola with Roundup Transorb. The plants were treated with herbicides as described above and grown for 50 to 60 days following herbicide application.

The experimental design for each crop/weed combination was:

3 herbicide treatments (2 rates+controls) x 2 CO₂ levels x 5 replicates.

Assessments: Crop and weed plants were harvested separately and total above-ground biomass of each was determined. Efficacy and crop to weed ratios were calculated.

3.5 Interactive effects of elevated CO₂ and day temperature on herbicide efficacy

Based on the results of the experiment described above, ambient + 160 ppm CO₂ was selected as the lowest concentration to have a significant effect on herbicide efficacy and was therefore used in this experiment. The effects of elevated CO₂ and temperature on growth of wild oats and herbicide efficacy were studied. Plants were prepared as described above and treated with either Fusion, Assert 300 or Liberty at the three leaf stage. Temperature regimes were either 23/18, 26/18 or 29/18°C day/night. Plants were grown for an additional 3 weeks after herbicide treatment. The experimental design was:

1 weed species x 4 herbicide treatments (3+1 control) x 3 temperature regimes x 2 CO₂ levels x 5 replicates.

Assessments: As in section 3.2.

3.6 Data analysis

Where appropriate, treatment effects were computed using ANOVAs and differences between treatments were determined using Duncan's Multiple Range tests. Dose response curves of the effects of elevated CO₂ on growth of wild oats and on the efficacy of selected herbicides were produced to obtain a timeline for changes in efficacy by taking into account the rate of change in ambient CO₂ concentrations. An economic analysis was conducted to estimate the change in revenues per acre for barley and canola that would result from increased CO₂ levels. The analyses were conducted using plant growth changes, herbicide efficacy changes and information on the effects of weeds on crop production in western Canada (example: Swanton *et al.* 1993).

4. RESULTS

4.1 Effects of elevated CO₂ and temperature on crop and weed growth

Above-ground biomass of crops and weeds not treated with herbicides was used to determine responsiveness of different species to elevated CO₂. When several weed species were grown in

the absence of interspecific competition, all species responded by increasing above-ground biomass (Table 1). Responses ranged from increases of 122.9 to 255.6% in Canada thistle and green foxtail, respectively, but the magnitude of response varied between trials. Barley grown in competition with green foxtail and wild oats showed CO₂-induced increases in biomass of 121.3 and 124.4%, respectively (Table 2). While biomass of green foxtail grown with barley increased with increased CO₂, biomass in wild oats diminished. Canola grown with Canada thistle and wild oats increased biomass by 130.2 and 136.7%, respectively, with elevated CO₂ (Table 2). While Canada thistle showed little response to CO₂ when grown with canola, wild oats grown with canola increased biomass by 152.7%. Barley appeared to compete better against wild oats at elevated CO₂ than did canola (Table 2).

The interactive effects of elevated CO₂ and temperature on growth of wild oats were studied. Above-ground biomass decreased as daytime temperature increased from 23 to 26 and 29°C at both ambient and elevated CO₂ (Figure 4). In general, above-ground biomass remained greater in plants grown at elevated CO₂ than in those grown at ambient CO₂ (Figure 4).

4.2 Screening for effects of CO₂ on herbicide efficacy

The effects of elevated CO₂ on efficacy of a number of herbicides applied at either the manufacturers' recommended rates or at quarter rates were determined (Table 3). While most herbicides were unaffected by elevated CO₂, decreased efficacy was occasionally observed especially when herbicides were applied at quarter rates. When wild oats were treated with Liberty at full and quarter rates, elevated CO₂ caused decreases in efficacy of 26.1 and 28.4%, respectively (Table 3). Significant CO₂-related decreases in efficacy were also found when Avenge and Fusion were applied to wild oats at quarter rates (Table 3). Conversely, no effects of CO₂ were found when Fusion was applied to green foxtail. Carbon dioxide-related decreases were also observed when Roundup Transorb was applied to Canada thistle, when Pursuit was applied to chickweed and when Lontrel was applied to common groundsel, all at quarter rates. Increases in efficacy were observed when wild oats were treated with Assert 300 and when wild buckwheat was treated with 2,4-D, both at full rates (Table 3).

4.3 Dose response of herbicide efficacy – a timeline of changes in efficacy

Based on results of the screening experiments described above, CO₂ dose-response experiments were conducted on selected weed/herbicide combinations to determine a timeline for changes in efficacy based on the current rate of change in atmospheric CO₂ levels (1.5 – 2.0 ppm/year). Assert 300 and Liberty, both at full rates, and Fusion at quarter rate were selected as treatments for this experiment and were applied to wild oats grown at approximately 390, 410, 430, 470, 550 and 710 ppm CO₂. Above-ground biomass increased by approximately 148% in control plants grown at 710 ppm relative to ambient levels (Figure 3). Carbon-dioxide related increases in above-ground biomass were also observed in plants treated with Fusion and Liberty but not those treated with Assert 300 (Figure 3). While herbicide efficacy calculated as a proportion of above-ground biomass of non-treated plants grown at equivalent CO₂ levels decreased with increasing CO₂ levels in plants treated with Liberty, no CO₂ effects on efficacy were found in plants treated with Fusion or Assert 300 (Figure 3). Reductions in efficacy of the herbicide Liberty were significant at 160 ppm above ambient. Results obtained for Fusion and Assert 300 were in conflict with those obtained in screening experiments.

4.4 Effects of elevated CO₂ on herbicide efficacy in weed/crop competitive interactions

Effects of elevated CO₂ on herbicide efficacy in weeds grown in competition with crops were also examined (Table 4). When Canada thistle was grown in competition with Roundup ready canola, the efficacy of Roundup Transorb was greater than that observed in screening experiments at both full and quarter rates and the CO₂-related decrease in efficacy observed in the screening experiments was abolished (Table 4). This was also the case when wild oats were grown in competition with barley and treated with Fusion. No CO₂-related changes in efficacy were observed when green foxtail was grown in competition with barley and treated with Achieve (Table 4).

4.5 Interactive effects of elevated CO₂ and day temperature on herbicide efficacy

Based on the results of the experiment described above, ambient + 160 ppm CO₂ was selected as the lowest concentration to have a significant effect on herbicide efficacy and was therefore used in this experiment. The effects of elevated CO₂ and temperature on growth of wild oats and efficacy of Fusion, Liberty and Assert 300 in controlling wild oats were studied. Analysis of variance showed significant effects of herbicide, CO₂ level, temperature and interactions of

herbicide and CO₂ level and herbicide and temperature on above-ground biomass (Table 5). Duncan's multiple range tests showed that, as expected, herbicides decreased biomass (Table 6). They also showed that increased CO₂ caused increased biomass whereas increasing daytime temperature caused decreased biomass. Analysis of variance also showed significant effects of herbicide, temperature and interaction between herbicide and CO₂ on herbicide efficacy (Table 5). Duncan's Multiple range tests showed that, overall, the efficacy of Assert 300 was greater than that of Fusion and Liberty, that CO₂ level did not affect efficacy and that increased temperature caused a decrease in efficacy (Table 6). The lack of interaction between CO₂ and temperature suggests that the CO₂ effect is independent of temperature. Efficacy of Fusion and Liberty decreased with increasing temperature while that of Assert 300 remained unaffected (Figure 5). Temperature-dependent decreases in efficacy were greatest at ambient CO₂ for Fusion (62%) and greatest at ambient + 160 ppm CO₂ in Liberty (24%). While analysis of variance did not detect a significant interaction between CO₂ and temperature, both elevated CO₂ and temperature caused decreased efficacy of the herbicide Liberty on wild oats.

4.6 Economic analysis

An economic analysis was conducted to estimate the change in revenues per acre for barley and canola that would result from increased CO₂ levels. Since yields were not measured directly in this study, several assumptions were made to estimate the expected changes in yields that may occur as a result of the changes in CO₂ levels and herbicide efficacies. The changes in biomass caused by increased levels of CO₂ (Table 2) were translated into expected changes in yields using three different case scenarios. Case One assumed that yield increases were directly proportional to the biomass increases that occurred. Case Two assumed that the increases in yields were half of the increase in biomass. Case Three assumed that yields did not increase as biomass levels increased.

The initial biomass increases were obtained from Table 2 where the percentage change in barley and canola biomass were measured when grown with selected weed species. From these data the respective yield changes were calculated. Once initial changes in yields caused by increased CO₂ levels were counted, changes in herbicide efficacies were examined. Data regarding the changes in herbicide efficacy caused by doubling CO₂ levels are reported in Table 3.

The ten-year average yield of barley in Alberta is 58.3 bushels/acre and of canola is 24.4 bushels per acre¹. It has been estimated that weeds in Alberta have reduced yields of barley by 8% and canola by 10%². This means that, in the absence of weeds, average yields in Alberta would have been 62.96 bushels per acre for barley and 26.8 bushels per acre for canola.

The effect that increasing CO₂ levels had on the yields and efficacies of various herbicides varied significantly (Table 7). For the majority of herbicides, herbicide efficacy levels improved under double CO₂ conditions resulting in further yield increases above the yield increases caused by higher biomass levels in both barley and canola. Under normal CO₂ conditions, when using herbicides, barley yields increased on average by 4.1 bushels/ acre. Under double CO₂, when combining the two effects of improved herbicide efficacy and higher yields, barley yields varied depending on the case scenario; Case One yields increased on average by 5.2 bushels/acre, Case Two yields increased on average by 4.7 bushels/acre, and Case Three yields increased on average by 4.2 bushels/acre.

Similarly, in canola, under normal conditions, the average increase in yield when using herbicides was 2.1 bushels/acre. When canola is grown in double CO₂ conditions yields varied depending on the case scenario used. In Case One, canola yields were estimated to increase on average by 2.8 bushels/acre, while in Cases Two and Three canola yields were estimated to increase on average by 2.45 and 2.05 bushels/acre, respectively.

To provide an overall valuation of the effects of increasing CO₂ levels on crop yields the ten-year average prices in Alberta for barley (\$2.21 per bushel) and canola (\$7.22 per bushel)³ were multiplied by increases in yields (Tables 8 and 9). Under normal CO₂ levels, when using herbicides, the average increase in value for barley was \$9.18 per acre. Under double CO₂, the average increase in value of barley varied depending on the case scenario; in Case One the average increase in value was \$11.41 per acre, in Case Two the average increase in value was \$10.32 per acre, and in Case Three the average increase in value per acre was \$9.23. However,

¹ Barley and Canola Acreage and Production of Alberta Census Divisions 1989-1998. Alberta Agriculture, Food and Rural Development.

² Wild Oats. 1995. Alberta Agriculture, Food and Rural Development.

³ Field Crop Statistics for Alberta: Average Farm Value of Principal Crops. 2000. Alberta Agriculture, Food and Rural Development

the value of the crop decreased in the double CO₂ scenario when using the herbicide Liberty, owing to its much lower efficacy.

For canola, the average increase in monetary value, under normal conditions, when using herbicides was \$15.14 per acre (Table 9). Under double CO₂ conditions the changes in monetary values for canola are the following: in Case One the increase in value per acre was \$20.37, in Case Two the increase in value per acre was \$17.68, and in Case Three the increase in value per acre was \$14.99. Similarly, the value of the crop decreased for the herbicide Liberty in the double CO₂ scenario. It also decreased in the case of Fusion applied to wild oats and Roundup Transorb applied to Canada thistle assuming a 0:1 yield to biomass increase of canola.

5. DISCUSSION

5.1 Responses of plant growth

Carbon dioxide levels in the atmosphere are increasing and are expected to double within the next century (Trabalka et al. 1985). The potential effects of increasing CO₂ in the atmosphere on temperature has been the subject of much debate and estimates range from increases of 0.25°C or less to greater than 4.2°C (Schlesinger and Mitchell 1985; Idso 1980; Kimball and Idso 1983). Both increases in CO₂ levels and temperature are expected to have effects on plant growth. In the present study, elevated CO₂ caused increased plant growth and elevated temperature caused decreased growth in wild oats. Differences in responses of plants to these changes are also expected to cause differences in plant interactions as well as function and structure of ecosystems, both natural and managed (Bazzaz 1990; Patterson and Flint 1990). Carbon dioxide-induced changes in crop to weed ratios were found in the present study (data not shown).

Weed scientists have emphasized the importance of studying the effects of environmental stresses and changes as they influence crop and weed interactions (Aldrich 1984; Bauer et al. 1991; Patterson 1995). The dynamics of competition between weed and crop plants are affected by environmental conditions, and have been shown to change with CO₂ enrichment (Patterson and Flint 1980) and temperature (Nogushi and Nakymme 1978; Cordes and Bauman 1984). A specific concern is the differential response to elevated CO₂ and temperature by C₃ and C₄

plants, with C₃ plants showing a greater increase in growth under high CO₂ (Imai and Murata 1977) and C₄ plants showing better growth with increase in temperature. It is expected that there will be a subsequent shift in the competitive interaction between C₃ (e.g., barley, wild oats, redroot pigweed) and C₄ (e.g., green foxtail) plants. Examples of this are found in the literature. For example, Ziska (2000) found CO₂-induced increased loss in soybean yield in plants grown with lambsquarters (C₃) whereas soybean yield loss diminished in plants grown with pigweed (C₄).

5.2 Herbicide efficacy

Herbicide efficacy was found to either increase, decrease or remain the same when plants were grown at elevated CO₂ and efficacy changes were species-specific. Differences in growth response and effects of CO₂ on herbicide efficacy between wild oats (C₃) and green foxtail (C₄) serve to illustrate the complexity of the issue. The results suggest that assumptions as to CO₂-induced effects on herbicide efficacy cannot be made. Effects of competition on CO₂-induced changes in herbicide efficacy further complicate the issue.

Increased efficacy of herbicides on weeds grown in competition may have resulted from the length of the experiment where the competitive advantage of herbicide resistant crops increased over time. The herbicide/competition combination appeared to abolish the detrimental effects of elevated CO₂ on herbicide efficacy.

Studies on effects of environmental conditions on herbicide efficacy on quack grass have shown that increased light, temperature and humidity immediately following application increased herbicide efficacy but that prolonged exposure of plants to increased temperature and light decreased efficacy (Coupland 1986). In this study, increased daytime temperature also caused decreased herbicide efficacy but no interactions were found between CO₂ level and temperature (Table 5). The results of the present study indicate that both CO₂ level and temperature can affect herbicide efficacy and that in most cases elevated CO₂ and temperature, when they did have an effect, caused decreased efficacy. It seems likely that interactive effects of these two parameters would occur under certain conditions, perhaps in other weed species or on other herbicides.

5.3 Economic analysis

Changes in plant growth, yield and herbicide efficacy as influenced by changes in atmospheric CO₂ levels and temperature have the potential to affect productivity and profitability of agriculture. While increased weed growth and decreased herbicide efficacies would lead to losses in crop yields, growth and productivity of crops can also be modified by environmental factors. Predictions of productivity of agricultural systems under future environmental conditions require an understanding of the interplay between these factors.

In this study, an economic analysis was conducted to estimate the change in revenues per acre for barley and canola that would result from increased CO₂ levels. The analysis was conducted using plant growth changes, herbicide efficacy changes and information on the effects of weeds on crop production in western Canada (example: Swanton *et al.* 1993). The results of this analysis show the possibility that increased CO₂ levels may cause increased crop yields despite increases in weed growth and changes in herbicide efficacy. For example, the economic analysis predicts an increase of \$3.55 per acre in the value of barley at elevated CO₂ when the herbicide Assert 300 is used to control wild oats (Table 8). Severe decreases in herbicide efficacy may, however, deny the realization of increased yields and profits in a high CO₂ future. For example, the economic analysis predicts a decrease of \$2.21 per acre in the value of barley at elevated CO₂ when the herbicide Liberty is used to control wild oats (Table 8). These results suggest that economic gain can be achieved through an understanding of the effects of elevated CO₂ on plant growth and herbicide efficacy, through the selection of herbicides that are either unaffected or for which effects are promoted and through preparatory actions and adaptation of agricultural practices.

6. CONCLUSIONS

- 1) The efficacy of herbicides either decreased, increased or did not change when herbicides were applied to weeds grown at elevated CO₂.
- 2) Effects of elevated CO₂ on herbicide efficacy may change when weeds are grown in competition with crops.

- 3) Herbicide efficacy changes were only found to occur at 160 ppm above ambient levels of CO₂. According to the current rate of change in atmospheric concentrations of CO₂, this corresponds to approximately 50 years from present.
- 4) Elevated temperature tended to decrease herbicide efficacy and the effects of temperature and CO₂ can be additive.
- 5) The economic analysis performed using plant growth and herbicide efficacy changes suggest that potential monetary losses due to decreased herbicide efficacy can be partially or totally overcome by increases in crop yields caused by elevated CO₂. Nonetheless, the results also suggest that weed control will be crucial in realizing potential increases in economic yield of crops as atmospheric CO₂ concentrations increase.
- 6) In this study, most of the data used to produce the economic analysis were extrapolations from short-term screening experiments and several assumptions needed to be made. Further studies on the effects of elevated CO₂ and temperature on crop yields and herbicide efficacy are required to diminish the uncertainties in the economic analysis.

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Figure 1. A 4-chamber, greenhouse-based CO₂ exposure system was constructed at the Alberta Research Council, Vegreville, Alberta to conduct studies on the effects of elevated CO₂ on crops and weeds.



Figure 2. Six-chamber exposure system at ARC, Vegreville. Conviron growth chambers were previously modified for ethylene experiments and were retrofitted for use as a CO₂ exposure system.

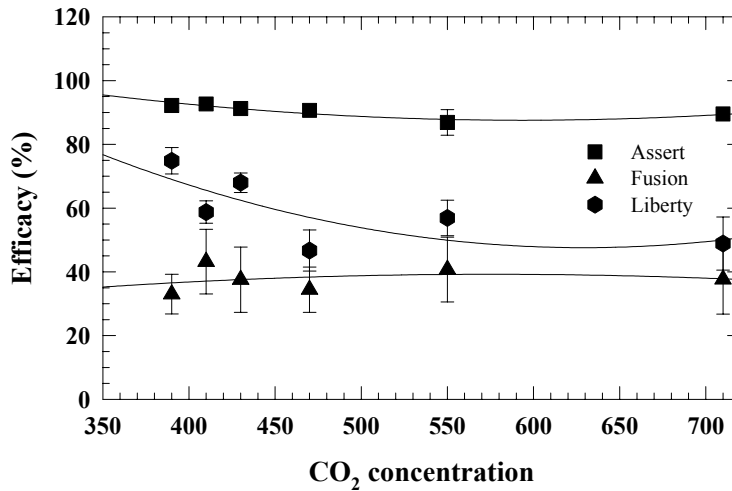
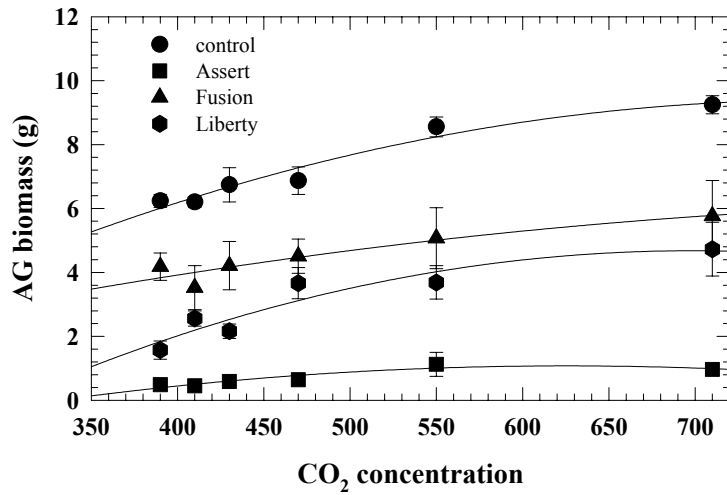


Figure 3. Effects of increasing CO₂ levels on above-ground biomass (top) and herbicide efficacy (bottom) in wild oats. Herbicides were applied at the three-leaf stage. Plants were grown for three weeks following herbicide application. N = 5.

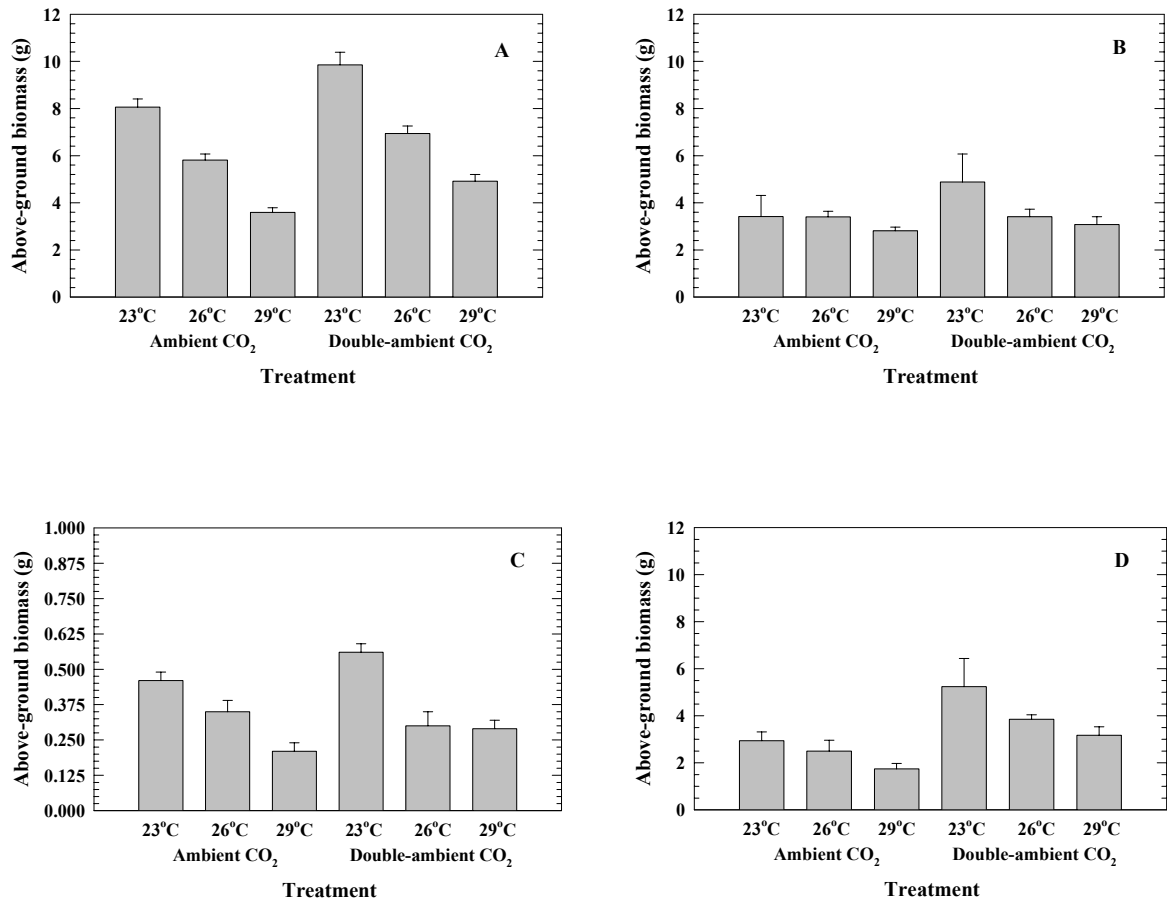


Figure 4. Above-ground biomass of wild oat plants grown at different daytime temperatures either at ambient or ambient + 160 ppm CO₂. No herbicide applied (A), Fusion (B), Assert 300 (C) and Liberty (D). N = 5.

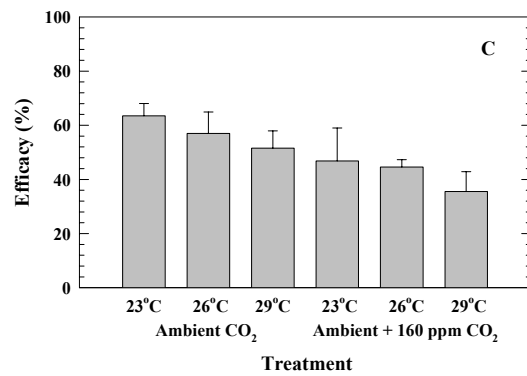
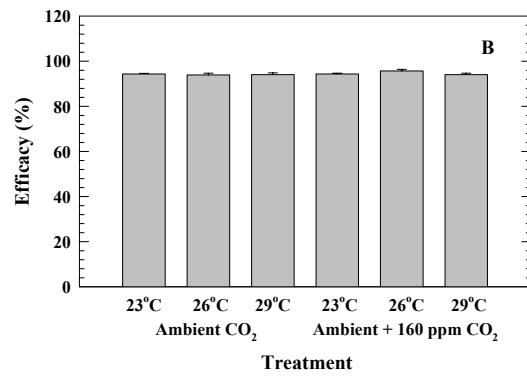
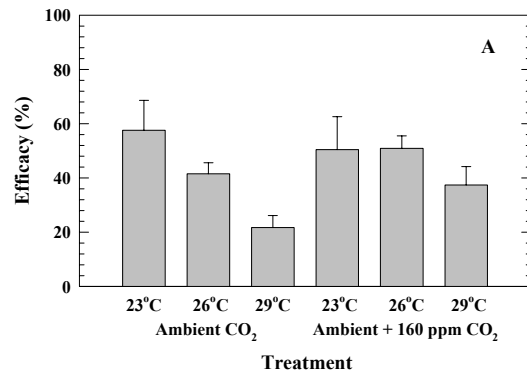


Figure 5. Herbicide efficacy of Fusion (A), Assert 300 (B) and Liberty (C) applied to wild oats grown at different temperatures at either ambient or ambient + 160 ppm CO₂. N= 5.

Table 1. Above-ground biomass (g) and percent change in biomass of weed species grown at ambient and double-ambient CO₂ levels. Plants were grown for 4 weeks. Plants grown in two separate trials are indicated using a '1' (trial 1) and a '2' (trial 2). N = 5.

Weed Species	Ambient CO ₂		Double-ambient CO ₂		Percent Change
	Mean	S.E.	Mean	S.E.	
green foxtail - 1	4.78	0.82	12.22	0.98	255.6
green foxtail - 2	2.70	0.30	3.40	0.40	125.9
kochia	4.55	0.33	7.10	0.48	156.0
redroot pigweed	4.52	0.07	6.22	0.54	137.6
wild buckwheat - 1	2.48	0.17	3.62	0.13	146.0
wild buckwheat - 2	2.57	0.24	3.44	0.18	133.9
common groundsel	1.95	0.21	2.43	0.16	124.6
wild oats - 1	2.10	0.13	3.27	0.36	155.7
wild oats - 2	3.10	0.20	5.70	0.40	183.9
Canada thistle	3.50	0.40	4.30	0.40	122.9
chickweed	1.20	0.10	2.01	0.20	167.5

Table 2. Above-ground biomass (g) and percent change in biomass of crop and weed species grown in competition at ambient and double-ambient CO₂ levels. Plants were grown at a 4:1 crop:weed ratio for 60 to 70 days. N = 5.

Crop Species	Ambient CO ₂		Double-ambient CO ₂		% Change	Weed Species	Ambient CO ₂		Double-ambient CO ₂		% Change
	Mean	S.E.	Mean	S.E.			Mean	S.E.	Mean	S.E.	
barley	13.01	0.27	15.78	0.73	121.3	green foxtail	0.52	0.11	0.59	0.12	113.46
barley	24.20	1.59	30.11	1.73	124.4	wild oats	9.72	1.19	7.04	2.00	72.43
canola	39.80	2.00	51.80	7.00	130.2	Canada thistle	6.53	3.27	6.74	3.67	103.22
canola	31.10	1.70	42.50	7.10	136.7	wild oats	6.68	1.90	10.20	2.86	152.69

Table 3. Herbicide efficacy and efficacy changes at ambient (low) and double-ambient (high) CO₂ levels. Herbicides were applied at recommended stages at either the manufacturers' recommended rate or quarter rate. Plants were grown for three weeks following application of herbicide. Values are means \pm S.E. N = 4 to 6.

Weed Species	Herbicide	Full Rate			Quarter Rate		
		Low CO ₂	High CO ₂	% Change	Low CO ₂	High CO ₂	% Change
wild oats	Assert 300	78.4 (9.4)	90.7 (0.7)	15.7	54.3 (8.7)	55.8 (5.8)	2.8
wild oats	Horizon	87.7 (6.6)	95.2 (0.3)	8.6	56.8 (9.0)	64.3 (9.4)	13.2
wild oats	Poast Ultra	94.0 (0.9)	95.1 (1.3)	1.2	93.9 (0.4)	94.9 (0.6)	1.1
wild oats	Liberty	82.5 (3.1)	61.0 (12.6)	-26.1**	46.9 (8.3)	33.6 (4.2)	-28.4
wild oats	Avenge	88.8 (1.5)	90.3 (0.9)	1.7	74.6 (3.0)	57.6 (1.4)	-22.8**
wild oats	Fusion	91.5 (0.5)	90.0 (0.5)	-1.6	79.3 (7.0)	34.2 (13.0)	-56.9**
green foxtail	Poast Ultra	92.4 (0.7)	96.8 (0.5)	4.8	N.A.	N.A.	N.A.
green foxtail	Fusion	97.6 (0.5)	97.5 (0.4)	-0.1	97.2 (0.5)	97.8 (0.4)	0.8
Canada thistle	Roundup Transorb	78.6 (2.8)	73.2 (2.3)	-6.9	78.0 (2.6)	65.4 (3.1)	-16.4**
chickweed	Pursuit	98.5 (0.4)	98.4 (0.8)	-0.1	86.5 (2.3)	69.6 (2.5)	-19.5**
wild buckwheat	2,4-D	39.0 (4.1)	49.5 (4.8)	26.9	N.A.	N.A.	N.A.
wild buckwheat	Lorox	44.6 (10.1)	37.9 (8.8)	-15.0	20.4 (7.8)	21.9 (5.7)	7.4
red root pigweed	Ally	96.7 (0.6)	92.3 (0.7)	-4.6	N.A.	N.A.	N.A.
kochia	Pardner	98.5 (0.4)	98.4 (0.2)	-0.1	N.A.	N.A.	N.A.
lambsquarters	Sencor	99.0 (0.1)	97.9 (0.2)	-1.1	28.2 (10.0)	29.8 (1.3)	5.7
common groundsel	Lontrel	92.7 (0.7)	84.1 (1.0)	-8.9**	81.9 (2.5)	71.3 (3.4)	-12.9**

Table 4. Herbicide efficacy and efficacy changes at ambient (low) and double-ambient (high) CO₂ levels. Herbicides were applied at recommended stages at either the manufacturers' recommended rate or quarter rate. Plants in dose response experiments were grown for 3 weeks following herbicide application whereas plants in competition experiments were grown for 50 to 60 days. Values are means ± S.E. N = 4 to 6.

Weed Species	Herbicide	Experiment Type	Full Rate			Quarter Rate		
			Low CO ₂	High CO ₂	% Change	Low CO ₂	High CO ₂	% Change
wild oats	Assert 300	dose response	92.2 (0.3)	89.5 (1.4)	-2.9	N.A.	N.A.	N.A.
wild oats	Liberty	dose response	74.8 (4.1)	48.9 (8.3)	-34.6	N.A.	N.A.	N.A.
wild oats	Fusion	dose response	N.A.	N.A.	N.A.	32.9 (6.2)	37.6 (10.9)	14.3
wild oats	Assert 300	competition - barley	79.6 (4.4)	77.5 (9.8)	-2.6	43.3 (18.5)	30.9 (16.8)	-28.6
green foxtail	Achieve	competition - barley	92.9 (1.6)	92.9 (1.0)	0.0	92.7 (1.2)	89.9 (0.8)	3.0
Canada thistle	Roundup Transorb	competition - canola	97.3 (0.6)	98.4 (0.3)	1.1	97.2 (0.4)	97.9 (0.2)	0.7
wild oats	Fusion	competition - canola	98.9 (0.1)	97.8 (1.5)	-1.1	98.7 (0.1)	96.5 (2.7)	-2.2

Table 5. Results of analysis of variance procedure for biomass and herbicide efficacy in wild oats grown at ambient and ambient + 160 ppm CO₂ at either 23°C, 26°C or 29°C. Herbicides were Fusion, Liberty and Assert 300. Asterisks denote significant effects at P ≥ 0.05.

Parameter	Source	Degrees of Freedom	SS	MS	F Value
biomass	herbicide	3	571.3	190.4	183.33 *
	CO ₂	1	26.0	26.0	25.05 *
	temperature	2	76.4	38.2	36.76 *
	herbicide*CO ₂	3	12.9	4.3	4.15 *
	CO ₂ *temperature	2	3.6	1.8	1.72
	herbicide*temperature	6	55.6	9.3	8.92 *
efficacy	herbicide	2	46465.4	23232.7	120.53 *
	CO ₂	1	176.3	176.3	0.91
	temperature	2	2290.9	1145.5	5.94 *
	herbicide*CO ₂	2	1788.2	894.1	4.64 *
	CO ₂ *temperature	2	295.9	148.0	0.77
	herbicide*temperature	4	1521.0	380.3	1.97

Table 6. Results of Duncan's multiple range tests for biomass and herbicide efficacy in wild oats. Herbicides: 1 = control, 2 = Fusion, 3 = Liberty and 4 = Assert 300. CO₂: 1 = ambient and 2 = ambient + 160 ppm. Temperature: 1 = 23°C, 2 = 26°C and 3 = 29°C.

Parameter	Source	Duncan Grouping by Source			
		1	2	3	4
biomass	herbicide	A	B	B	C
	CO ₂	B	A		
	temperature	A	B	C	
efficacy	herbicide		B	B	A
	CO ₂	A	A		
	temperature	A	A	B	

Table 7. Effects of doubling of CO₂ on yields of barley and canola with changes in herbicide efficacy and three yield change case scenarios. Case One: Assumes that the increase in yields is directly proportional to the increase in biomass (1:1). Case Two: Assumes that the increase in yields is 50% of the increase in biomass (0.5:1). Case Three: Assumes that yields do not increase as biomass increases (0:1).

BARLEY			Change In Yields		Change In Yields		Change In Yields	
Wild Oats	Efficacy %		Case One		Case Two		Case Three	
Herbicides	Ambient CO₂	Double CO₂	Ambient CO₂	Double CO₂	Ambient CO₂	Double CO₂	Ambient CO₂	Double CO₂
Assert 300	78.40	90.70	3.66	5.26	3.66	4.75	3.66	4.23
Horizon	87.70	95.20	4.09	5.52	4.09	4.98	4.09	4.44
Poast Ultra	94.00	95.10	4.38	5.52	4.38	4.98	4.38	4.44
Liberty	82.50	61.00	3.85	3.54	3.85	3.19	3.85	2.85
Avenge	88.80	90.30	4.14	5.24	4.14	4.73	4.14	4.21
Fusion	91.50	90.00	4.27	5.22	4.27	4.71	4.27	4.20
Green Foxtail	Efficacy %		Case One		Case Two		Case Three	
Herbicides	Ambient CO₂	Double CO₂	Ambient CO₂	Double CO₂	Ambient CO₂	Double CO₂	Ambient CO₂	Double CO₂
Poast Ultra	92.40	96.80	4.31	5.48	4.31	5.00	4.31	4.51
Fusion	97.60	97.50	4.55	5.52	4.55	5.03	4.55	4.55

CANOLA			Change In Yields		Change In Yields		Change In Yields	
Wild Oats	Efficacy %		Case One		Case Two		Case Three	
Herbicides	Ambient CO₂	High CO₂	Ambient CO₂	High CO₂	Ambient CO₂	High CO₂	Ambient CO₂	High CO₂
Assert 300	78.40	90.70	1.91	3.03	1.91	2.62	1.91	2.21
Horizon	87.70	95.20	2.14	3.18	2.14	2.75	2.14	2.32
Poast Ultra	94.00	95.10	2.29	3.17	2.29	2.75	2.29	2.32
Liberty	82.50	61.00	2.01	2.03	2.01	1.76	2.01	1.49
Avenge	88.80	90.30	2.17	3.01	2.17	2.61	2.17	2.20
Fusion	91.50	90.00	2.23	3.00	2.23	2.60	2.23	2.20
Canada Thistle	Efficacy %		Case One		Case Two		Case Three	
Herbicide	Ambient CO₂	High CO₂	Ambient CO₂	High CO₂	Ambient CO₂	High CO₂	Ambient CO₂	High CO₂
Roundup	78.60	73.20	1.92	2.33	1.92	2.06	1.92	1.79
Transorb								

Table 8. Monetary analysis of the effects of doubling CO₂ in barley production. Ten year average price \$2.21/bushel. Case One: Assumes that the increase in yields is directly proportional to the increase in biomass (1:1). Case Two: Assumes that the increase in yields is 50% of the increase in biomass (0.5:1). Case Three: Assumes that yields do not increase as biomass increases (0:1).

Wild Oats	Change in \$ Value/Acre		Change in \$ Value/Acre		Change in \$ Value/Acre	
	Case One		Case Two		Case Three	
Herbicides	Ambient CO ₂	Double CO ₂	Ambient CO ₂	Double CO ₂	Ambient CO ₂	Double CO ₂
Assert 300	8.08	11.63	8.08	10.49	8.08	9.35
Horizon	9.04	12.21	9.04	11.01	9.04	9.81
Poast Ultra	9.69	12.19	9.69	11.00	9.69	9.80
Liberty	8.50	7.82	8.50	7.05	8.50	6.29
Avenge	9.15	11.58	9.15	10.44	9.15	9.31
Fusion	9.43	11.54	9.43	10.41	9.43	9.28

Green Foxtail	Change in \$ Value/Acre		Change in \$ Value/Acre		Change in \$ Value/Acre	
	Case One		Case Two		Case Three	
Herbicides	Ambient CO ₂	Double CO ₂	Ambient CO ₂	Double CO ₂	Ambient CO ₂	Double CO ₂
Poast Ultra	9.52	12.10	9.52	11.04	9.52	9.98
Fusion	10.06	12.19	10.06	11.12	10.06	10.05

Table 9. Monetary analysis of the effects of doubling CO₂ in canola production. Ten year average price \$7.22/bushel. Case One: Assumes that the increase in yields is directly proportional to the increase in biomass (1:1). Case Two: Assumes that the increase in yields is 50% of the increase in biomass (0.5:1). Case Three: Assumes that yields do not increase as biomass increases (0:1).

Wild Oats	Change in \$ Value/Acre		Change in \$ Value/Acre		Change in \$ Value/Acre	
	Case One		Case Two		Case Three	
Herbicides	Ambient CO ₂	Double CO ₂	Ambient CO ₂	Double CO ₂	Ambient CO ₂	Double CO ₂
Assert 300	13.81	21.84	13.81	18.91	13.81	15.98
Horizon	15.45	22.93	15.45	19.85	15.45	16.77
Poast Ultra	16.56	22.90	16.56	19.83	16.56	16.75
Liberty	14.53	14.69	14.53	12.72	14.53	10.75
Avenge	15.64	21.75	15.64	18.83	15.64	15.91
Fusion	16.12	21.67	16.12	18.76	16.12	15.86

Canada Thistle	Change in \$ Value/Acre		Change in \$ Value/Acre		Change in \$ Value/Acre	
	Case One		Case Two		Case Three	
Herbicide	Ambient CO ₂	Double CO ₂	Ambient CO ₂	Double CO ₂	Ambient CO ₂	Double CO ₂
Roundup	13.85	16.79	13.85	14.84	13.85	12.90
Transorb						