Elevated carbon dioxide alters chemical management of Canada thistle in no-till soybean

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Differential responses of crops and weeds to anthropogenic climatic change may alter competition and crop yields. Here we examine the role of current and projected increases in carbon dioxide concentration [CO2], on soybean growth and seed yield with and without competition from Canada thistle (Cirsium arvense, a common perennial weed in soybean farming systems), over a 3-year period using no-tillage (i.e., no physical cultivation for weed removal) practices. Weed control was implemented by applying herbicide (glyphosate) as a pre-emergent treatment at the beginning of each growing season. Under a weed-free condition, round-up ready soybean demonstrated a significant response of seed yield and total above-ground biomass to elevated [CO2], but no synergistic effect of no-till over time on the response of biomass or yield to [CO2] was observed. Average above-ground weight of Canada thistle was significantly greater at elevated [CO2] for 2008 and 2009, and establishment of thistle increased as a function of [CO2] over time even with pre-emergent applications of glyphosate. Although the presence of Canada thistle reduced seed yield and biomass of soybean for both CO2 treatments from 2007 to 2009, the reduction was higher for the elevated [CO2] treatment, and a significant [CO2] × Canada thistle interaction was observed for these parameters. Overall, these are the first data to indicate that perennial weeds associated with no-tillage practices could be a greater impediment to crop yields and harder to control chemically in response to rising levels of atmospheric carbon dioxide.

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1. Introduction

No-tillage agriculture may offer a number of conservation benefits with respect to soil erosion, or water availability. In the context of rising atmospheric CO2, no-till has also been advocated as a means of slowing the increase in atmospheric CO2 by sequestering additional organic C in the soil (Lal et al., 1998). Additional C sequestration in turn, has been advocated as one strategy by which agriculture could mitigate climate change (Lal, 2004; Paustian et al., 1998).

Implementation of successful conservation or no-till practice is critically dependent on weed management. That is, because mechanical tillage is not used, or used less frequently, different weed flora can occur and costs of weed management can increase (MSU, 2009). The control of weeds in no-till is achieved primarily by the use of herbicides, often as a pre-emergent application (MSU, 2009; Nice et al., 2007).

Because herbicide applications are such an integral part of no-till operations, it is worthwhile to examine whether rising [CO2] or other aspects of climate change can alter the efficacy of chemical weed management. Previous experimental data have shown that the efficacy of glyphosate could be reduced for individual C3 weeds at elevated [CO2] under glasshouse conditions (Archambault, 2007; Ziska et al., 1999; Ziska and Teasdale, 2000). In addition, work with field grown Canada thistle (Cirsium arvense) grown in monoculture, also indicated a reduction in chemical efficacy, due in part to [CO2] induced increases in root-shoot ratio (Ziska et al., 2004). This could be particularly egregious with respect to weed control as even small segments of Canada thistle roots can regenerate into new plants (Donald, 1990). Although preliminary, these initial results have obvious implications for the efficacy of a no-till strategy as atmospheric [CO2] increases. Specifically, greater yield losses from weeds, and greater difficulty in controlling such weeds chemically, could offset any advantage of no-till systems in C sequestration and climate change mitigation.

To determine if chemical weed control associated with no-till practices was affected by increasing atmospheric CO2, Canada thistle, a perennial weed often found in no-till fields (Nice et al., 2007), was grown in conjunction with “round-up ready” soybean at ambient and ambient +300 μmol mol⁻¹ CO2 over a 3-year period using no-till cultural practices. To quantify competitive losses, soybean vegetative and reproductive characteristics were...
assessed each year as a function of both [CO₂] and Canada thistle biomass.

2. Materials and methods

Soybean and Canada thistle were grown in six square chambers 2.75 m on a side and 1.22 m tall at the outer edge. Chambers were located at the USDA experimental field site near Beltsville, Maryland, and constructed of clear acrylic plastic with sloping roofs that restricted the top opening to approximately one-third of the basal area. The roofs were designed to minimize wind penetration and [CO₂] fluctuations. Approximately 60 m³ min⁻¹ of air was blown into each chamber via perforated PVC pipe that has been placed on the ground. Half of the chambers had pure CO₂ injected continuously into blower inlets to increase the [CO₂] to 300 ± 40 μmol mol⁻¹ above that of ambient air. Air samples from the three elevated [CO₂] chambers and one ambient [CO₂] chamber were pumped into an adjacent building for [CO₂] analysis using an absolute mode infrared gas analyzer (Li 6252, Li-Cor, Inc., Lincoln, NE). Both [CO₂] and air temperatures inside and outside the chambers were recorded at 5 min intervals. During the study, daytime [CO₂] (2007-2009) averaged 387, 380 and 382 μmol mol⁻¹ (ambient); while nighttime concentrations were 502, 473 and 482 μmol mol⁻¹ (ambient) and 801, 763 and 788 μmol mol⁻¹ (elevated); respectively. An automated weather station approximately 100 m from the experimental site recorded photosynthetically active radiation and standard meteorological variables. Chambers were irrigated to prevent significant soil water deficits from developing at any time during the study.

To simulate no-till conditions, winter rye was grown as a cover crop prior to the study and in the fall of 2008. In early May of 2007, glyphosate was applied as an isopropylamine salt with standard surfactant at 2.24 kg ai ha⁻¹ (manufacturers recommended rate) as a pre-emergent treatment to all chambers to eliminate existing weed and rye populations prior to soybean planting. Following application, each chamber was divided in two, with each section randomly assigned to soybean (weed-free), or soybean plus Canada thistle. Glyphosate was not reapplied in 2007. However, glyphosate application (at the same concentration) occurred as a pre-emergent application in early May of 2008 and 2009 for weed and rye control.

Canada thistle was initially (2007) obtained from roots in a nearby fallow field, from clonal patches, sized to ∼0.5 cm in diameter and 1–2 cm in length, and planted to a depth of 5 cm within soybean rows for half of each chamber simultaneously with sowing of soybean. Following emergence, thistle was thinned to a density of two plants per meter of row. This procedure was repeated in 2008, and 2009 (i.e., [CO₂] treatments and split-plot locations did not change after 2007) following pre-emergent glyphosate application; however, if emerging shoots from previous Canada thistle populations (i.e., those not killed from the pre-emergent herbicide applications in 2008 and 2009) occurred, they were thinned to the desired density at the time of soybean planting. If additional Canada thistle was needed they were obtained from the same clonal patch used in 2007. Maintaining shoot densities was done to simulate low visual populations of Canada thistle at the start of each soybean growing season. Other weed species, if they occurred, were removed by hand. Records were kept on Canada thistle populations (above-ground biomass and replanting) to determine if they differed as a function of [CO₂] treatment and duration of the study. Any Canada thistle growing near the experimental plots was removed to prevent outside root intrusion.

For each year of the study (2007–2009), soybean ("93M20", Group III, round-up ready, indeterminate) was planted directly into the soil as shallow (<3 cm) surface cultivation. Row widths were approximately 35 cm, six rows per chamber. Rows were overseeded and then thinned to a final density of 1 plant per 10 cm of row. Initial soybean flowering was observed between 45 and 49 days after sowing (DAS) with no observable differences in phenology as a function of CO₂ concentration. Plants were considered mature when 95% of the leaves had senesced and pods were brown. Maturity had occurred by late September/early October in all years and treatments. At maturity, soybean rows for each plot (e.g., weed-free and plus thistle) were sampled for all six chambers. Plants were cut at the base, and individual pods were counted and separated by treatment. Pods were air-dried and above-ground vegetative matter was oven dried at 65 °C until a constant dry weight was obtained. For all years, pods were threshed by hand, the seed collected and weighed. A subsample of 50 seed was used to determine individual seed weight. Because soybean is usually harvested after leaf senescence, harvest index is calculated as the ratio of seed to stem and pod biomass. This parameter has been called apparent harvest index (AHI), and was determined for all treatments in the study. Above-ground dry biomass was also determined during soybean harvest for each Canada thistle plant that was within 5 cm of the soybean row that was harvested (i.e., two plants per meter of row).

Soil at initial planting was a silt-loam, with a pH 5.5, a bulk density of 1.3 g cm⁻³, and ca 2% organic matter (OM), with high availability of potassium and phosphate. At the end of the 3-year period, additional soil sampling for the weed-free plots was conducted at 15 cm intervals to a depth of 30 cm to determine long-term changes in soil characteristics, particularly C and OM as a function of [CO₂].

Data were analyzed using a two-way ANOVA, split-plot design (Statview Inc, SAS Institute, Cary, NC). There were three replicate chambers of both [CO₂] levels, for each of 3 years, with each chamber a split-plot (thistle/weed-free, or plus Canada thistle). CO₂ concentration, +/− thistle, and year were fixed effects. A one-way ANOVA was used to determine [CO₂] effects on soil C, nitrogen and OM. Effects of thistle, growth [CO₂], year, and their interactions were tested, using a probability level of 5%. If significant effects were found, means were compared using Fisher’s LSD.

3. Results

With no-till and 100% weed control, soybean seed yield and AHI increased across years (Table 1). Elevated [CO₂] resulted in significant increases in both total above-ground biomass and seed yield when averaged for all 3 years of the study. There was year to year variation as to whether a significant increase was observed for either parameter (Fig. 1), but no significant year x [CO₂] interaction for any parameter at harvest (Table 1). Overall, a more consistent increase was observed for total biomass (∼32%), than for seed yield (18–42% stimulation) with elevated [CO₂] during the study. Increases in seed yield at elevated [CO₂] were associated with increases in pod number (per m⁻²) and not with seed size or seeds per pod (Table 1).

Under no-till, a slight, but significant increase in % soil C was observed at the end of a 3-year period, but only for the top layer of soil (Table 2). Carbon dioxide treatment per se resulted in a significant increase in % C and OM, but only at 15 cm. No increase, either over time, or as a function of [CO₂], was observed at 30 cm (Table 2).

There was no effect of [CO₂] on above-ground biomass of Canada thistle at the end of the first year the weed was introduced (2007, Fig. 2). Significant effects of [CO₂] were noted, however, in both 2008 and 2009, with approximately double the amount of Canada thistle biomass observed at the higher CO₂ concentration (Fig. 2).

Comparisons of Canada thistle, [CO₂] and year for soybean parameters at final harvest indicated significant effects of thistle on seed yield, total biomass and pod number, but no effect on seed weight or seeds per pod (Table 3). Inclusion of Canada thistle in the
Table 1
Averages and level of statistical significance for the two-way ANOVA for year and [CO2], ambient and ambient + 300 µmol mol⁻¹ (elevated) for harvest characteristics of round-up ready soybean grown with no weeds.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Averages</th>
<th>Level of significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2007</td>
<td>2008</td>
</tr>
<tr>
<td>Seed yield</td>
<td>g m⁻²</td>
<td>326</td>
<td>404</td>
</tr>
<tr>
<td>Total biomass</td>
<td>g m⁻²</td>
<td>856</td>
<td>758</td>
</tr>
<tr>
<td>50 seed wt.</td>
<td>g</td>
<td>5.31</td>
<td>7.05</td>
</tr>
<tr>
<td>Pod number</td>
<td># m⁻²</td>
<td>1098</td>
<td>1306</td>
</tr>
<tr>
<td>Seeds/pod</td>
<td></td>
<td>1.86</td>
<td>2.39</td>
</tr>
<tr>
<td>AHI²</td>
<td></td>
<td>0.40</td>
<td>0.53</td>
</tr>
</tbody>
</table>

P < 0.05 is in bold.

*a AHI is apparent harvest index, the ratio of seed yield to total above-ground biomass at maturity.

Fig. 1. Changes in above-ground biomass and seed yield of genetically modified soybean (round-up ready) at ambient and elevated (ambient + 250 µmol mol⁻¹) CO₂ with no-tillage in a weed-free condition. Glyphosate was applied as a pre-emergent treatment for all years of the study. *Indicates a significant difference as a function of [CO₂] for a given year. Summary statistics for all 3 years are given in Table 1. Additional details can be found in Section 2.

ANOVA resulted in no significant effect of [CO₂] on seed yield or total biomass of soybean, although pod number was still significant (Table 3). For 2008, an additional application of glyphosate (besides the pre-emergent application) was necessary in early August to control weed populations for both [CO₂] treatments. Significant interactions were observed for [CO₂] × Canada thistle for significant reductions in seed yield, total biomass and pod number of soybean (Table 3). This is consistent with the overall response of soybean

Table 2
Percent carbon, nitrogen and organic matter at three depths, 5, 15 and 30 cm after 3 years of soybean production as a function of ambient or elevated (ambient + 300 µmol mol⁻¹) carbon dioxide. Uppercase letter indicates a significant increase in % C or % N relative to the tilled soil in 2007, and asterisk indicates a significant difference related to CO₂ treatment after 3 years of no-till. % N and C in 2007 were 0.206 and 2.12, respectively.

<table>
<thead>
<tr>
<th>Depth</th>
<th>% nitrogen</th>
<th>% carbon</th>
<th>% organic matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 cm</td>
<td>0.187</td>
<td>0.194</td>
<td>2.54    a</td>
</tr>
<tr>
<td>15 cm</td>
<td>0.122</td>
<td>0.135</td>
<td>1.47    *</td>
</tr>
<tr>
<td>30 cm</td>
<td>0.066</td>
<td>0.070</td>
<td>0.67    1</td>
</tr>
</tbody>
</table>

Fig. 2. Change in above-ground dry weight of Canada thistle (Cirsium arvense) as a function of [CO₂] for 3 years of a field trial under no-till conditions. *Indicates significant differences as a function of [CO₂] treatment.

Table 3
Averages and level of statistical significance for the three-way ANOVA for year and [CO₂] for harvest characteristics of round-up ready soybean grown under no-till conditions at the specifications given in Table 1 but with and without the presence of Canadian thistle populations (two per linear meter of row, +CT, −CT). No year × [CO₂] × CT interactions were observed for any parameter.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Averages</th>
<th>Level of significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2007</td>
<td>2008</td>
</tr>
<tr>
<td>Seed yield</td>
<td>g m⁻²</td>
<td>284</td>
<td>331</td>
</tr>
<tr>
<td>Total biomass</td>
<td>g m⁻²</td>
<td>772</td>
<td>618</td>
</tr>
<tr>
<td>50 seed wt.</td>
<td>g</td>
<td>5.22</td>
<td>7.08</td>
</tr>
<tr>
<td>Pod number</td>
<td># m⁻²</td>
<td>1063</td>
<td>1115</td>
</tr>
<tr>
<td>Seeds/pod</td>
<td></td>
<td>2.01</td>
<td>2.33</td>
</tr>
<tr>
<td>Thistle biomass</td>
<td>g m⁻²</td>
<td>66.3</td>
<td>72.0</td>
</tr>
<tr>
<td>AHI²</td>
<td></td>
<td>0.38</td>
<td>0.54</td>
</tr>
</tbody>
</table>

P < 0.05 is in bold.

*a AHI is apparent harvest index, the ratio of seed yield to total above-ground biomass at maturity.
to Canada thistle, with greater reductions observed in both above-ground biomass and seed yield of soybean over time at elevated \([\text{CO}_2]\) (Fig. 3).

At the beginning of the experiment, all Canada thistle was introduced as cuttings. If glyphosate applications were effective, then no populations of Canada thistle should have become established (i.e., new shoot growth from live roots would not have occurred), and re-introduction of cuttings would have to occur each year of the experiment. With few exceptions, this was true of the ambient \([\text{CO}_2]\) treatment (Fig. 4). However, for the elevated \([\text{CO}_2]\) treatment, the number of cuttings that had to be reestablished diminished significantly over time, to approximately 30% by the end of the experiment (Fig. 4) indicating greater establishment of Canada thistle as a function of \([\text{CO}_2]\).

4. Discussion

Although no-till practices can provide conservation benefits for water and soil, adoption of such practices is not universal, in part because of concerns regarding initial yield reductions and economic risk (Archer and Reicosky, 2009). For the current study, initial yields of soybean were low, but did increase over time, as has been observed previously for no-till soybean on moderate to well-drained soils (e.g., DeFelice et al., 2006). Although other studies (e.g., Ainsworth et al., 2002) have shown that soybean can respond to rising atmospheric \([\text{CO}_2]\) per se, no data have been available on whether such a response is amenable by no-till practices. The data here, for a weed-free condition, do not indicate any \([\text{CO}_2]\) × year interaction for soybean yield or biomass with no-till.

In addition to conservation benefits, the role of no-till farming for sequestering soil \(\text{C}\) has been suggested as a possible strategy for mitigating \(\text{CO}_2\), an anthropogenic greenhouse gas. Indeed, the potential for U.S. cropland to sequester \(\text{C}\) and mitigate the greenhouse effect has been projected to be considerable (Lal et al., 1998). Whether the ability of agriculture soils matches its potential to sequester \(\text{C}\) is still an open question, however, since recent assessments have suggested that no-till may sequester \(\text{C}\) in the upper layers of some soils but may not store more than traditional plowing does over the entire soil profile (Blanco-Canqui and Lal, 2008).

Fig. 3. Percent change in above-ground biomass and seed yield for genetically modified soybean at ambient and elevated carbon dioxide (ambient + 300 \(\mu\text{mol mol}^{-1}\)) when grown with Canadian thistle, relative to the weed-free condition. Summary statistics for all 3 years are given in Table 3. *Indicates significant differences as a function of \([\text{CO}_2]\) treatment.

For the current study, no-till did result in additional \(\text{C}\) storage in the upper profile, with an additional increase observed for the elevated \([\text{CO}_2]\) treatment, presumably due to a greater enhancement of root:shoot ratio as has been observed previously for Canada thistle at elevated \([\text{CO}_2]\) (Ziska et al., 2004); however, estimates below 30 cm were not made.

Because mechanical tilling is used to control weeds, any benefits of no-tillage, whether for conservation or for potential \(\text{C}\) sequestration, is dependent on proper weed management (Buholer, 1995; Owen, 1998). Management strategies may include scouting a no-till field for novel weeds, e.g., continuous no-till may result in a shift to more perennial weeds (Gibson et al., 2005); particularly important is the use of herbicides for weed control, usually, but not limited, to pre-emergent applications to ensure a weed-free condition prior to planting (MSU, 2009).

The use of no-till practices has been complemented by the development and commercialization of glyphosate tolerant crops since the crop is protected from any detrimental effects. One such crop is soybean, with a current estimate that approximately 90% of the current U.S. crop is glyphosate tolerant (i.e., “round-up ready”) (Economic Research Service, 2009).

For this study, Canada thistle, a perennial weed often found in no-till situations (Gibson et al., 2005), responded more to elevated \([\text{CO}_2]\) than round-up ready soybean. The establishment of Canada thistle increased as a function of \([\text{CO}_2]\) (i.e., fewer replantings of cuttings), even with applications of glyphosate. These results are consistent with previous experiments regarding the response of Canada thistle to elevated \([\text{CO}_2]\) and the reduced efficacy of this species to glyphosate in monoculture (Ziska et al., 2004). As a result, thistle reduced soybean yield more at elevated than ambient \([\text{CO}_2]\).

In addition, the degree (percent) impact for above-ground biomass and seed yield of soybean increased with time at the elevated relative to the ambient \([\text{CO}_2]\) condition. In effect, any increase in soybean yield as a function of \([\text{CO}_2]\) was negated by the enhanced establishment of Canada thistle. If, in fact, weeds and especially perennial weeds, respond more to rising \([\text{CO}_2]\) than the crop, any potential increase in soybean yield in a no-till environment could require enhanced weed management.

What will be the nature of such management strategies? New agronomic practices could adapt to any increase in \([\text{CO}_2]\) (or changing climate) by increasing the frequency of application or the concentration of the active ingredient in the herbicide. However,
such an adaptation strategy could involve additional economic (or environmental) costs and any potential benefits from no-tillage could be offset by an increased expense for herbicides. Such costs may be in addition to others that reflect the over-utilization of herbicides, particularly glyphosate, the subsequent increase in glyphosate resistant weeds (Owen and Zelaya, 2005), and the presence of herbicides in surface and groundwater (Barbash et al., 2001).

Alternatively, the use of cover crops and/or mulches that maintain adequate weed control in conjunction with minimum tillage practices have been shown to provide conservation benefits while reducing herbicide use (e.g., Teasdale, 1996); and could provide one means to adapt to any CO2 induced reduction in herbicide efficacy.

Overall, it should be recognized that rising [CO2] and climatic change will evoke differential responses in crops and weeds, and that the nature of these responses will have implications for potential crop yields and weed management (Archambault, 2007). While a more complete assessment of weed-crop competition and weed management is needed, any mitigation strategy (e.g., C sequestration) that relies on the increased use of herbicides should consider the possibility that such a strategy is also likely to be impacted by [CO2] and/or climatic change.

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References


