Economic Performance of Crop Rotations in the Presence of Herbicide-Resistant Giant Ragweed

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ABSTRACT
Economic assessment of alternative crops and crop rotations helps farmers determine those most appropriate for their farms. The objective of this research was to evaluate the economic net return and associated financial risk for crops and crop rotations common to the midwestern United States, based on two 3-yr experiments in southern Minnesota where herbicide-resistant giant ragweed (Ambrosia trifida L.) was present. Crop rotations included corn (Zea mays L.), soybean [Glycine max L. (Merr.)], wheat (Triticum aestivum L.), and alfalfa (Medicago sativa L.). Crop rotations were continuous corn (CCC), soybean–corn–corn (SCC), corn–soybean–corn (CSC), soybean–wheat–corn (SWC), soybean–alfalfa–corn (SAC), and alfalfa–alfalfa–corn (AAC). Average crop yields during the study period were utilized along with average prices received and estimated production costs for each crop in Minnesota during this period to evaluate economic net return. Average net return of the SWC, SCC, CCC, CSC, SAC, and AAC rotations was US$11, $170, $247, $258, $368, and $919 ha–1 yr–1, respectively. The AAC rotation was stochastically dominant to all other crop rotations for risk-averse decision makers. One or 2 yr of alfalfa stochastically dominated corn, soybean, and wheat, regardless of crop rotation, largely due to more stable alfalfa prices over the study period coupled with above-average yield and lower production costs. These results confirm that rotations containing alfalfa have the potential to provide a substantial economic net return to farmers while mitigating the risk of herbicide-resistant giant ragweed (Ambrosia trifida L.) infestations.

Core Ideas
• Crop rotations containing alfalfa produced the greatest economic net return.
• Crop rotations with alfalfa stochastically dominated all other crop rotations.
• Alfalfa improves control of herbicide-resistant giant ragweed while providing substantial economic net return.


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Abbreviations: AAC, alfalfa–alfalfa–corn; CCC, continuous corn; CDF, cumulative distribution function; CSC, corn–soybean–corn; FSD, first degree stochastic dominance; SAC, soybean–alfalfa–corn; SCC, soybean–corn–corn; SSD, second degree stochastic dominance; SWC, soybean–wheat–corn.
with modes of action that are effective on herbicide-resistant giant ragweed, such as growth regulators, reducing the likelihood of herbicide-resistant giant ragweed escapes.

Although more diverse crop rotations provide weed control benefits and reduce the risk of developing herbicide-resistant weeds, the crop rotation used in a given field often is dictated by profit potential rather than ease of herbicide-resistant weed management (Beckie, 2006). Herbicide-resistant weeds increase the cost of crop production due to specialized management and therefore have the potential to alter the economic net return associated with particular crops and crop rotations (Mueller et al., 2005; Norsworthy et al., 2012).

There is a need to compare the economic net return and financial risk of crop rotations common to the midwestern United States, a region where herbicide-resistant giant ragweed is widespread (Regnier et al., 2016). The objectives were to evaluate the crop yield and the economic net return for multiple crop rotations and determine the most risk-averse crops and crop rotations using stochastic dominance analysis.

### MATERIALS AND METHODS

#### Crop Rotation Experiments

In 2012 and 2013, two replicated experiments were established at different sites near Rochester, MN (43°54'20.5" N, 92°33'55.1" W and 43°54'20.7" N, 92°33'40.3" W). The research sites had known populations of giant ragweed resistant to 5-enolpyruvylshikimate-3-phosphate synthase and acetolactate synthase inhibitor herbicides. Each experiment evaluated six crop rotations in a randomized complete block design with four replications. Plots were 10 by 15 m. Crop rotations included CCC, SCC, CSC, SWC, SAC, and AAC. These experiments, described in Goplen et al. (2017), assessed each crop rotation’s weed control benefits by monitoring giant ragweed seed bank depletion and emergence within each crop rotation. Fertilizer, P, K, and S were applied to meet crop requirements according to University of Minnesota guidelines (Kaiser et al., 2011). Adequate fertility levels of P, K, and S were maintained using monoammonium phosphate, potash, and ammonium sulfate, respectively. Ammonium nitrate was applied at planting at 191, 135, 0, and 129 kg N ha⁻¹ for corn following corn or wheat, corn following 1 yr of alfalfa, following 2 yr of alfalfa, and wheat following soybean, respectively. Corn and soybean were treated with S-metolachlor [(RS)-2-Chloro-N-(2-ethyl-6-methyl-phenyl)-N-(1-methoxypropan-2-yl)acetamide] at planting, and two post-emergence applications of glufosinate [(RS)-2-Amino-4-(hydroxy(methyl)phosphonoyl)butanoic acid]-ammonium approximately 3 and 6 wk post-planting. Seeding alfalfa was treated with a single application of 2,4-DB [4-(2,4-dichlorophenoxy)butanoic acid], dimethylamine salt 2 wk post-planting. Wheat was treated with clopyralid monoethanolamine salt [(3,6-dichloro-2-pyridinylcarboxylic acid) monoethanolamine salt], fluroxypyr [(4-Amino-3,5-dichloro-6-fluoro-2-pyridinyl)oxy]acetic acid], 1-methylheptyl ester, and MCPA isooctyl (2-ethylhexyl) ester [6-methylheptyl 2-(4-chloro-2-methylphenoxy)acetate] at approximately 2 wk post-planting. Weeds escaping herbicide control were hand weeded. Wheat was prophylactically treated with Tebuconazole [α-(1,1-dimethylethyl)-1H-1,2,4-triazole-1-ethanol] at flower initiation (Zadoks 65) to prevent infection of Fusarium head blight (Fusarium graminearum) (Simmons et al., 1995).

From 2012 to 2015, grain yield of corn, soybean, and wheat were determined by harvesting two 1.5 by 9 m areas, three 1.5 by 6 m areas, and three 1.5 by 9.1 m areas, respectively. Grain subsamples (~1 kg) were dried in a forced-air oven at 60°C until constant mass to determine moisture. Corn, soybean, and wheat yield was adjusted to 155, 130, and 135 g kg⁻¹ moisture content, respectively. To determine wheat straw yield, four samples of whole wheat plants were cut at 10 cm above the soil surface from a 0.76 by 0.91 m area within each plot prior to grain harvest. Whole samples were dried at 60°C in a forced-air oven until constant mass and threshed using a stationary thrasher to separate grain from straw to determine straw dry matter.

Alfalfa yield was measured by harvesting three 0.9 by 6.4 m areas per plot and adjusted to a dry matter basis by drying a subsample (~1 kg) at 60°C in a forced-air oven until constant mass. In the SAC rotation, where only a single year of alfalfa was grown, alfalfa was harvested three times on approximately 30-d intervals beginning in July. In the AAC rotation, alfalfa was cut twice during the seedling year on approximately 30-d intervals beginning in July, and four times during the subsequent year. Harvests occurred when alfalfa was at the early flower stage of development (Fick and Mueller, 1989). Alfalfa relative feed value was estimated using near infrared spectroscopy measurements of acid detergent fiber and neutral detergent fiber according to Jerunyna and Garcia (2004).

#### Economic Analysis

Economic net return of each crop rotation was determined by monitoring all inputs and outputs of the crop rotations during all 3 yr of the rotations. Production costs of each rotation were calculated using average costs from 2012 to 2015, in accordance with Zacharias and Grube (1984). Seed and pesticide costs were obtained from local agribusinesses and fertilizer costs were the average in Minnesota reported by USDA-National Agricultural Statistics Service (2016) during the study period. Machinery and field operation costs, which included labor and hauling costs, were obtained from Lazarus (2015) and land rental costs were set to the county average reported by Hachfeld et al. (2015). Grain drying costs for corn, soybean, and wheat were calculated based on values reported by Lazarus (2014). The giant ragweed emergence component of this study required that seed production of giant ragweed be prevented, and resulted in hand weeding of corn and soybean in most years to fully prevent giant ragweed seed production (Goplen et al., 2017). Although hand weeding was conducted, the costs associated with it were not included in this analysis.

Revenue was calculated for each plot as the product of crop yield and average yearly price in Minnesota for each growing season from 2012 to 2015 to produce a range in revenue values for each crop rotation and crop for use in stochastic dominance analysis (Table 1). Average net return for each plot was calculated as the difference between total revenue and production costs. Average grain prices received each year for corn, soybean, and wheat in Minnesota were obtained from the USDA-National Agricultural Statistics Service (2016). Average alfalfa hay and wheat straw prices for each year were obtained from...
TABLE 1. Average prices of alfalfa, corn, soybean, wheat, and wheat straw received in Minnesota from 2012 to 2015.†

<table>
<thead>
<tr>
<th>Crop</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>CV‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>246</td>
<td>307</td>
<td>281</td>
<td>218</td>
<td>0.15</td>
</tr>
<tr>
<td>Corn</td>
<td>263</td>
<td>169</td>
<td>141</td>
<td>134</td>
<td>0.34</td>
</tr>
<tr>
<td>Soybean</td>
<td>525</td>
<td>474</td>
<td>366</td>
<td>316</td>
<td>0.23</td>
</tr>
<tr>
<td>Wheat</td>
<td>299</td>
<td>245</td>
<td>201</td>
<td>175</td>
<td>0.24</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>80</td>
<td>83</td>
<td>119</td>
<td>91</td>
<td>0.19</td>
</tr>
</tbody>
</table>

‡ CV, coefficient of variation.

RESULTS AND DISCUSSION

Production Costs

On average, the CCC rotation had the greatest average cost of production (Table 2). The second and third years of the CCC rotation were corn following corn, resulting in an average fertilizer cost that was $126 to $341 ha⁻¹ greater for the CCC rotation compared to the other rotations (Fig. 1). The CCC rotation also had the greatest average seed cost among crop rotations. The AAC rotation had the lowest average production costs compared to the other rotations, primarily due to lower overall costs for fertilizer and pesticide (Table 2, Fig. 1). Although per-hectare seed cost for alfalfa was more expensive than that for soybean and wheat, and similar to that for corn, there were no seed costs in the second year of alfalfa production since it was already established. The AAC rotation also had reduced fertilizer costs because no N fertilizer was applied to corn in this rotation beyond the 21 kg N ha⁻¹ applied as (NH₄)₂SO₄ to supply S. A literature summary by Yost et al. (2014) found that first-year corn following 2 yr of alfalfa that was direct-seeded on medium-textured soils responded to fertilizer N in only 8% of cases. In comparison, they reported that first-year corn following 1 yr of direct-seeded alfalfa on medium-textured soils, as was the case in the third year of the SAC rotation, responded to fertilizer N in 56% of cases. In this study, first-year corn following 1 yr of alfalfa and corn following soybean both received 135 kg N ha⁻¹.

Pesticide cost was substantially less for the AAC rotation compared to the other crop rotations (Fig. 1). This was largely because no pesticides were required for second-year alfalfa in the AAC rotation since no insect pests, such as potato leafhopper (Empoasca fabae) or weeds reached levels warranting treatment. The lack of hand weeding or herbicide requirements to control herbicide-resistant giant ragweed in second-year alfalfa is noteworthy, since corn and soybean plots in all rotations

Table 2. Production costs for each crop rotation by rotation-year and across rotation-years.

<table>
<thead>
<tr>
<th>Rotation-year</th>
<th>CCC</th>
<th>SCC</th>
<th>CSC</th>
<th>SWC</th>
<th>SAC</th>
<th>AAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1875</td>
<td>1341</td>
<td>1875</td>
<td>1341</td>
<td>1341</td>
<td>1446</td>
</tr>
<tr>
<td>2</td>
<td>1966</td>
<td>1875</td>
<td>1341</td>
<td>1399</td>
<td>1543</td>
<td>1195</td>
</tr>
<tr>
<td>3</td>
<td>1966</td>
<td>1966</td>
<td>1875</td>
<td>1966</td>
<td>1875</td>
<td>1643</td>
</tr>
<tr>
<td>Mean</td>
<td>1936</td>
<td>1727</td>
<td>1697</td>
<td>1569</td>
<td>1586</td>
<td>1428</td>
</tr>
</tbody>
</table>

required hand weeding in most years to control giant ragweed (populations as dense as 416 plants m⁻²) and to maintain a zero weed threshold, one of the requirements for the giant ragweed emergence component of this study (Goplen et al., 2017). Even with dense populations of giant ragweed, no hand weeding was required in wheat or alfalfa plots because herbicide-resistant giant ragweed was successfully controlled with herbicides, increased crop competition, and multiple alfalfa harvests. The cost of weed control would have been substantially greater than reported in this study if herbicide-resistant giant ragweed densities of this magnitude were not hand weeded, since the cost of hand weeding was not included in this analysis. Therefore, herbicide cost in this study for rotations that lacked wheat or alfalfa would have been greater if this study fully accounted for the increase in herbicide costs that typically occurs with the presence of herbicide-resistant weeds (Mueller et al., 2005; Norsworthy et al., 2012).

**Crop Yield**

Average crop yield during the study period were within 28% of the county average of 11.46, 3.49, 2.92, and 6.50 Mg ha⁻¹ yr⁻¹ for corn, soybean, wheat, and alfalfa, respectively (USDA-National Agricultural Statistics Service, 2016).

Soybean yield was 23% less than the county average during the study period (Table 3) and likely was associated with soybean sudden death syndrome (*Fusarium virguliforme* L.) confirmed during several years of this study. Soybean sudden death syndrome has the potential to reduce soybean yield up to 100%, though 5 to 15% yield loss is more common (Rupe and Hartman, 1999). Alfalfa yield in this study was greater than the county average during the study period, but varied substantially depending on whether the stand was newly seeded or previously established. Above-average alfalfa yield in this study may have been related to the direct-chopping harvest method that was used, where alfalfa was green-chopped to estimate yield. Green-chopping alfalfa has lower harvest losses compared to cutting and in-field curing and baling commonly used by farmers (Undersander et al., 2011).

Corn yield in the third rotation-year was greatest with the CSC, SWC, and SAC rotations, although corn yield in the third year with the CSC rotation did not differ from that of CCC and SCC rotations (Table 3). Greater corn yield following soybean, wheat, and alfalfa substantiates previous research that has found greater yield when corn is planted following crops other than corn, and may be due to a “non-N-rotational effect” (Crookston et al., 1991; Edwards et al., 1988; Stanger

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**Table 3. Crop yield by rotation-year for each crop rotation.†**

<table>
<thead>
<tr>
<th>Rotation-year</th>
<th>CCC</th>
<th>SCC</th>
<th>CSC</th>
<th>SWC</th>
<th>SAC</th>
<th>AAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.44</td>
<td>2.82</td>
<td>12.40</td>
<td>2.82</td>
<td>2.67</td>
<td>2.92</td>
</tr>
<tr>
<td>2</td>
<td>11.54</td>
<td>12.41</td>
<td>3.07</td>
<td>3.31§</td>
<td>8.66</td>
<td>15.38</td>
</tr>
<tr>
<td>3</td>
<td>13.09bc¶</td>
<td>13.09bc</td>
<td>13.51ab</td>
<td>13.79a</td>
<td>13.92a</td>
<td>12.61c</td>
</tr>
</tbody>
</table>

† Grain yield at 155, 130, and 135 g kg⁻¹ moisture content for corn, soybean, and wheat, respectively. Alfalfa yield reported as annual total forage dry matter yield.


§ Wheat straw yield averaged 3.83 Mg ha⁻¹.

¶ Means for corn grain yield in the third rotation-year followed by the same letter are not significantly different according to Fisher’s protected LSD test (P ≤ 0.05).
and Lauer, 2008). Corn yield in the third rotation-year was least with the AAC, SCC, and CCC rotations (Table 3). Corn yield in the AAC rotation was less than that in the third year of the CSC, SWC, and SAC rotations, possibly because no additional N fertilizer was applied. No N fertilizer was applied to corn in the AAC rotation since corn following 2 yr of alfalfa that was direct-seeded on medium-textured soils responded to fertilizer N in just 8% of cases (Yost et al., 2014).

Net Return

Net return was calculated using average input costs (Table 2) during the study period, average crop yield (Table 3), and average crop prices received in Minnesota from 2012 to 2015 (Table 1). The CCC rotation was the only rotation which averaged a net positive return in each rotation-year (Table 4). Negative net return occurred in rotation-years with soybean, wheat, and first-year alfalfa in the AAC rotation. The greatest average net return for a given rotation-year occurred with second-year alfalfa in the AAC rotation. The large average net return of second-year alfalfa partially contributed to the AAC rotation having the greatest average net return during the study period. Additionally, the University of Minnesota fertilizer guidelines credit a N fertilizer replacement value of 168 kg N ha⁻¹ to corn following the first-year alfalfa in the AAC rotation. The greatest average net return occurred in rotation-years with soybean, wheat, and alfalfa partially contributed to the AAC rotation having the greatest average net return during the study period. Additionally, the University of Minnesota fertilizer guidelines credit a N fertilizer replacement value of 168 kg N ha⁻¹ to corn following 2 yr of alfalfa, which reduced N fertilizer costs and contributed to greater net return for corn in the AAC rotation compared to corn in other rotations (Kaiser et al., 2011). There was more variation in net return among years for the AAC rotation compared to the other rotations, largely due to the negative net return in first-year alfalfa in this rotation. When net return was averaged across the first and second years of alfalfa in the AAC rotation, as is typically done to evaluate net return from alfalfa, net return was $1765 ha⁻¹ yr⁻¹, which was substantially greater than any single-year net return in the other rotations.

To evaluate the full distribution of net returns possible for each crop rotation, both FSD and SDS analyses were performed to determine the stochastically dominant rotations. The CSC, SAC, and AAC rotations were among the dominant rotations based on FSD, as the CSC and SAC rotations dominated the SWC rotation and the AAC rotation dominated the SCC, SWC, and SAC rotations (Table 5). This demonstrated that the AAC rotation was the most dominant by FSD and aligns with the AAC rotation having the greatest average net return ($919 ha⁻¹ yr⁻¹). The SWC rotation was dominated by the CSC, SAC, and AAC rotations by FSD due to the lower CDF of net returns at all levels of net return, in agreement with the lower average net return for the SWC rotation ($11 ha⁻¹ yr⁻¹) compared to the other rotations ($170–$919 ha⁻¹ yr⁻¹) (Fig. 2; Table 4).

Using SSD, crop rotations were identified that would be most attractive to decision makers who prefer greater to lesser net return and are risk averse. The CCC, CSC, SAC, and AAC rotations were the stochastically dominant rotations based on SSD (Table 5). The AAC rotation dominated all other rotations based on SSD, having greater net returns with less variability, representative of lower financial risk. The AAC rotation had greater net return at lower values of cumulative probability and never produced a negative net return; at greater values of cumulative probability net returns did not differ among the AAC, CSC, and CCC rotations (Fig. 2). Although the CCC and CSC rotations did occasionally produce greater net return than the AAC rotation, the AAC rotation had less variability; area under the CDF for the AAC rotation was less than that for the CSC and CCC rotations at all levels of net return, demonstrating that the AAC rotation dominated the CSC and CCC rotations by SSD. First- and second-degree stochastic dominance for the AAC rotation likely was associated with

Table 4. Net return for each crop rotation by rotation-year and across rotation-years.

<table>
<thead>
<tr>
<th>Rotation- year</th>
<th>CCC</th>
<th>SCC</th>
<th>CSC</th>
<th>SWC</th>
<th>SAC</th>
<th>AAC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>US$ ha⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>323.32</td>
<td>-153.80</td>
<td>315.44</td>
<td>-157.56</td>
<td>-217.14</td>
<td>-678.39</td>
</tr>
<tr>
<td>2</td>
<td>72.99</td>
<td>317.63</td>
<td>-52.69</td>
<td>-279.89</td>
<td>736.14</td>
<td>2851.44</td>
</tr>
<tr>
<td>3</td>
<td>345.41</td>
<td>346.32</td>
<td>511.95</td>
<td>469.79</td>
<td>584.03</td>
<td>584.70</td>
</tr>
<tr>
<td>Mean</td>
<td>247.24a‡</td>
<td>170.05b</td>
<td>258.23a</td>
<td>10.78c</td>
<td>367.68b</td>
<td>919.25e</td>
</tr>
<tr>
<td>SE§</td>
<td>17.19</td>
<td>63.23</td>
<td>66.74</td>
<td>47.86</td>
<td>67.86</td>
<td>158.53</td>
</tr>
</tbody>
</table>


§ Means for corn grain yield in the third rotation-year followed by the same letter are not significantly different according to Fisher’s protected LSD test (P ≤ 0.05).

Table 5. Results of first and second degree stochastic dominance analysis of net return for crop rotations.

<table>
<thead>
<tr>
<th>Crop rotation†</th>
<th>First degree</th>
<th>Second degree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dominates</td>
<td>Indifferent</td>
</tr>
<tr>
<td>1-CCC</td>
<td>–</td>
<td>2.3,4.5,6</td>
</tr>
<tr>
<td>2-SCC</td>
<td>–</td>
<td>1.3,4.5</td>
</tr>
<tr>
<td>3-CSC</td>
<td>4</td>
<td>1.2,5.6</td>
</tr>
<tr>
<td>4-SWC</td>
<td>–</td>
<td>1.2</td>
</tr>
<tr>
<td>5-SAC</td>
<td>4</td>
<td>1.2,3</td>
</tr>
<tr>
<td>6-AAC</td>
<td>2.4,5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

less variable prices for alfalfa during 2012 to 2015 compared to corn, soybean, and wheat (Table 1). Above-average and high-quality alfalfa yield, combined with relatively stable alfalfa prices during the study period, resulted in the AAC rotation dominating all other crop rotations by SSD. Adequate and high-quality alfalfa yield in the SAC also contributed to the SAC rotation dominating all other rotations except the AAC rotation by SSD. Although a single year of alfalfa in crop rotations is uncommon, results from this study show that it can provide substantial net return if high yield and high-quality alfalfa can be achieved. Adding an additional year of alfalfa to the SAC and AAC rotations likely would increase net return, as high alfalfa yield can generally be sustained for up to 3 yr without additional establishment expenses (Undersander and Barnett, 2008). Previous research has shown that rotations of corn and soybean tend to dominate continuous corn and rotations with wheat or alfalfa by FSD and SSD (Zacharias and Grube, 1984; Stanger et al., 2008); however, the stochastically dominant crop rotations will vary depending on specific scenarios (DeVuyst and Halvorson, 2004). Overall, more diverse crop rotations generally reduce risk through more stable and greater yield and price diversification, where low prices for one crop can be offset by greater prices for another crop in a given year (Helmers et al., 2001; Meyer-Aurich et al., 2006).

Since farmers often adjust the crop planted based on changing market and weather conditions, stochastic dominance analysis was performed for individual crops planted regardless of preceding crop or crop rotation. Net return for corn production was highly variable in this study, ranging from less than $300 ha$^{-1}$ yr$^{-1}$ to more than $2000$ ha$^{-1}$ yr$^{-1}$ (Fig. 3). Large variation in net return for corn production was largely due to variation in corn price (Table 1), as well as variation in input costs among rotations. Due to the large variation in net return for corn, corn dominated soybean and wheat by FSD and SSD but not 1 or 2 yr of alfalfa (Table 6). Even with wheat straw harvested to supplement income from grain, corn, soybean, and 1 and 2 yr of alfalfa dominated wheat by FSD and SSD since wheat rarely produced a positive net return. Two years of alfalfa dominated soybean and wheat by FSD, and dominated all crops by SSD since the area under the CDF was less than that for other crops at all levels of net return (Fig. 3, Table 6). One year of alfalfa dominated soybean and wheat by FSD, and dominated all crops except 2 yr of alfalfa by SSD. Stochastic dominance of 1 and 2 yr of alfalfa over all other crops was related to relatively stable alfalfa price and above-average yield, which provided greater net return with less variability. The economic net return and stochastic dominance of alfalfa, however, will vary based on the ability to harvest and market quality alfalfa. Soybean only dominated wheat by FSD and SSD, likely because soybean yield averaged 23% less than the county average during this study.

Herbicide-Resistant Giant Ragweed Implications

Results from this study indicate that crop rotations that include alfalfa are among the most attractive for financially risk-averse decision makers, confirming that alfalfa is a suitable crop to plant when herbicide-resistant giant ragweed is present. In these same experiments, the AAC rotation was the best rotation for controlling herbicide-resistant giant ragweed, as it had similar levels of seed bank depletion with less total emergence of giant ragweed compared to the other rotations (Goplen et al., 2017). With reduced emergence of giant ragweed in the AAC rotation, there was less reliance on herbicides since alfalfa harvests controlled herbicide-resistant giant ragweed in alfalfa and the herbicides used in wheat were effective at controlling giant ragweed. Weeding escaped giant ragweed by hand in corn and soybean can...
substantially increase production costs. Hand weeding glyphosate \(\text{N-(phosphonomethyl)glycine}\)-resistant palmer amaranth (\textit{Amaranthus palmeri} L.) in Georgia cotton cost $27 ha\(^{-1}\) (Sosnoskie and Culpepper, 2014). If the cost of hand weeding giant ragweed is similar to that for hand weeding palmer amaranth, planting wheat or alfalfa would become much more economical than found in this study since hand weeding was not required for these crops. If giant ragweed is allowed to compete with corn and soybean, corn yield can be reduced by up to 90% with 1.4 giant ragweed plants m\(^{-2}\) (Harrison et al., 2001) and soybean yield can be reduced by 45 to 77% with 1.0 giant ragweed plant m\(^{-2}\) (Webster et al., 1994).

An additional option for improving control of herbicide-resistant giant ragweed is delayed planting. On average, 90% of giant ragweed in these experiments emerged before 4 June (Goplen et al., 2017). A single pass with a field cultivator just prior to corn and soybean planting on 4 June has the potential to provide 90% control of giant ragweed (Goplen et al., 2017). Delayed planting also allows preemergence herbicides to extend residual activity later into the growing season. Due to an abnormally wet spring, corn and soybean planting in 2013 was delayed until 12 June, which allowed for most giant ragweed to be controlled prior to planting, enabling the postemergence herbicides to be more effective and eliminating the need for hand weeding. Although delayed planting can improve control of giant ragweed in corn and soybean, delaying planting until late May can reduce corn and soybean grain yield by 15 and 10%, respectively (Van Roekel and Coulter, 2011; De Bruin and Pedersen, 2008). If herbicide-resistant giant ragweed is not adequately controlled in corn or soybean, the AAC rotation in this study would be more attractive to risk-averse decision makers.

**CONCLUSIONS**

Results from this study indicate that the AAC rotation would be preferred by financially risk-averse decision makers, especially when herbicide-resistant giant ragweed is present as hand weeding was not required to prevent giant ragweed seed production in alfalfa. This analysis assumed that there is an accessible and established alfalfa market but results likely will differ based on market access and current market prices. Prices for alfalfa during this study were more stable compared to those for corn, soybean, and wheat. Changes in net return for the AAC rotation based on market access would likely be related to additional costs required to transport alfalfa to an established market, and will vary by farm. If alfalfa is not a feasible crop for a producer, then the CSC and CCC rotations would be the next most preferable rotations after the AAC rotation, both of which are suitable for herbicide-resistant giant ragweed management. When weed seed production is eliminated, 96% of the giant ragweed seed bank was depleted in 2 yr of alfalfa was calculated as the average of both years.

**Table 6. Results of first and second degree stochastic dominance analysis of net return for individual crops, regardless of crop rotation or rotation-year. Net return of 2 yr of alfalfa was calculated as the average of both years.**

<table>
<thead>
<tr>
<th>Crop†</th>
<th>First order</th>
<th>Second order</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dominates</td>
<td>Indifferent</td>
</tr>
<tr>
<td>Corn</td>
<td>S,W</td>
<td>A1,A2</td>
</tr>
<tr>
<td>Soybean</td>
<td>W</td>
<td>–</td>
</tr>
<tr>
<td>Wheat</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Annual alfalfa</td>
<td>S,W</td>
<td>C,A2</td>
</tr>
</tbody>
</table>

† A1, Annual alfalfa; A2, 2 yr of alfalfa; C, corn; S, soybean; W, wheat.

![Cumulative distribution function of net return by individual crop, regardless of crop rotation or rotation-year. Net return of 2 yr of alfalfa was calculated as the average of both years.](image)
with all crop rotations in the experiments utilized in this study. Since herbicides with greater efficacy on herbicide-resistant giant ragweed are available for corn compared to soybean, such as growth regulator and pigment inhibitor herbicides, there is potential for the giant ragweed seed bank to be substantially depleted in the 2 yr of corn before planting soybean in the SCC rotation. Therefore, if weed seed production can be prevented for 2 yr during a SCC rotation, the giant ragweed population likely would be depleted enough so that control of giant ragweed in soybean would be more manageable. This research provides valuable knowledge on the economic performance of crop and crop rotation options for fields in the midwestern United States with herbicide-resistant giant ragweed. In particular, results from this study demonstrate that alfalfa is a valuable crop in terms of economic net return and management of herbicide-resistant weeds.

REFERENCES


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