Rotational Effects of Cuphea on Corn, Spring Wheat, and Soybean

R. W. Gesch,* D. W. Archer, and F. Forcella

ABSTRACT

Diversifying crop rotations can give economic and environmental benefits. Cuphea (Cuphea viscosissima Jacq. × C. lanceolata W.T. Aiton) is a new oilseed crop that grows well in the Corn Belt. However, little is known about its rotational effect on corn (Zea mays L.), soybean [Glycine max (L.) Merr.], and spring wheat (Triticum aestivum L.), which are predominant crops in this region. A 4-yr study conducted in Minnesota evaluated the previous crop effects of all 2-yr rotational sequences of cuphea with corn, soybean, and wheat on crop yields and stands, soil water and N content, and production economics. Cuphea seed yield was unaffected by previous crop and yields of the other crops were unaffected by cuphea. Wheat stand was 17% greater and grain crude protein content 8% greater when following cuphea than following corn or soybean. This response was attributed to nitrate N remaining after cuphea harvest. Cuphea slightly negatively influenced soybean stands, but this was not reflected in yield. Cuphea production cost averaged $72 ha⁻¹ less than corn and $118 and $126 ha⁻¹ higher than soybean and wheat, respectively. While cuphea was not profitable at a price less than $1830 Mg⁻¹, it could provide rotational benefits, with net returns for corn and soybean following cuphea comparable to other non-monoculture sequences and higher than when grown continuously. However, the economic viability of including cuphea in rotation will be limited until the cuphea phase of the rotation can also be produced profitably. Cuphea agronomically fits in rotation with corn, soybean, or wheat, but may be best after soybean and before wheat or corn.

Cropping systems in the upper Midwest USA that primarily emphasize the production of corn, soybean, and spring wheat (Crookston et al., 1991; DeVuyst et al., 2006) are highly productive, but lack agricultural diversity (Brummer, 1998). The lack of crop species diversity that has occurred since the 1950s, particularly the prevalence of continuous cropping of corn and soybean, has resulted in increased agricultural inputs to maintain high productivity (Stanger and Lauer, 2008). This has raised both economic and environmental concerns regarding high input rates and associated soil erosion, deposition of fertilizers and pesticides into water sources, pest resistance to chemical control, and the ever-increasing production costs (Brummer, 1998).

The environmental and economic benefits of diversifying crop rotations have long been known and are well documented. Adding diverse crop species or a break crop to rotations can help suppress pathogens (Krupinsky et al., 2006; Kirkegaard et al., 2008) and result in increased nutrients (Gan et al., 2003) and more available water in the soil for the next season’s crop (Norwood, 2000; Merrill et al., 2004), thus, potentially minimizing inputs. Conversely, the previous crop can negatively influence the next crop in sequence through allelopathy (Kirkegaard et al., 2008) or by depleting water from the soil profile, leaving less water available for the following crop (Norwood, 2000). However, whether the current season’s crop in a rotation is positively or negatively impacted, or not at all, largely depends on the species sequence and particularly the previous crop (Kirkegaard et al., 1997; Merrill et al., 2004; Krupinsky et al., 2006).

Cuphea is a new oilseed crop being developed for the northern United States and is unique in that the oil produced by its seed is rich in medium-chain fatty acids similar to that of tropical plant oils (Graham, 1989). Medium-chain triglycerides are commercially used for manufacturing a myriad of products, such as detergents (Thompson, 1984), and they have excellent potential as a petroleum replacement for engine lubricants (Cermak and Isbell, 2004) and biofuel (Geller et al., 1999).

PSR23 cuphea (Knapp and Crane, 2000), which shows the greatest agronomic potential, has begun to be produced commercially in the northern Corn Belt region (Gesch et al., 2006) on a small scale for use in the cosmetic industry (Brown et al., 2007). Previously, PSR23 rotated with corn and soybean in central Illinois was shown to have a beneficial effect on corn yield, possibly due to disruption of the western corn rootworm (Dibrotica virgifera virgifera LeConte) life cycle (Behle and Isbell, 2005).

In the northern Corn Belt, corn, soybean, and spring wheat are the most prevalent crops grown (DeVuyst et al., 2006), but little is known about the rotational effects of cuphea on these crops or the economics of such production systems. Therefore, the primary objective of the present 4-yr field study was to evaluate the rotational effects of cuphea in 2-yr rotational sequences with corn, soybean, and spring wheat. Specifically, the effects of previous crop on crop yields and stands, soil water and N content, and economics of crop production were evaluated.

Abbreviations: NU, nitrogen use.


Copyright © 2010 by the American Society of Agronomy, 677 South Segoe Road, Madison, WI 53711. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Agronomy Journal • Volume 102, Issue 1 • 2010
This study was conducted from 2004 to 2007 on a Barnes loam soil (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) at a field site located 24 km northeast of Morris, Minnesota (45°35’ N, 95°54’ W). The experimental site was cropped with spring wheat before initiating the study.

The experimental design was a strip-plot randomized complete block replicated four times. Two-yr crop sequences were established in a matrix fashion similar to that of Krupinsky et al. (2006) to give all sequence combinations of the four crops in rotation with each other in each of four replicated blocks. The first year (2004) cuphea, corn, wheat, and soybean were sown in 9 m wide by 36 m long strips. In each successive year, the same four crops were sown perpendicular over the previous year’s crop residue. This gave a 4 × 4 matrix with 16 treatment combinations representing all combinations of the four crops in a 2-yr rotation with each other (i.e., cuphea–cuphea, corn–corn, cuphea–corn, corn–cuphea etc.). Because the study was conducted 4 yr, all 2-yr sequences were repeated in time. Individual plot size was 9 by 9 m, whereby each crop was seeded into residue of the four crops. Crop and row orientation (i.e., north to south and east to west) were randomized at the start of the experiment.

Field cultivation was used before planting of all crops. Cuphea plots were fertilized with 112–34–34–22 kg ha⁻¹ of N–P–K–S and treated with ethalfluralin 0.84 kg a.i. ha⁻¹ for weed control, which were both incorporated into soil by cultivation before planting. Wheat plots were fertilized with 78–34–34 kg ha⁻¹ of N–P–K and incorporated into soil with cultivation before planting. Corn was given starter fertilizer at a rate of 11–38 kg ha⁻¹ of N–P–K in the seedbed with seed at planting and an additional 168 kg ha⁻¹ of N was added in mid-June as ammonium nitrate in 2004 and 2005 and as anhydrous ammonia in 2006 and 2007. Starter fertilizer, 11–38 kg ha⁻¹ of N–P–K, was applied to soybean in the seedbed with seed at planting and an additional 168 kg ha⁻¹ of N was added in mid-June as ammonium nitrate in 2004 and 2005 and as anhydrous ammonia in 2006 and 2007. Starter fertilizer, 11–38 kg ha⁻¹ of N–P–K, was applied to soybean in the seedbed with seed in 2004 and 2005, but not 2006 and 2007. Levels of N–P–K in the 0- to 600-mm soil profile at the start of the study (i.e., spring 2004) are shown in Table 1. Fertilizer treatments for corn, soybean and wheat were based on standard recommendations for the experimental site and soil fertility of cuphea was based on previous studies (Gesch et al., 2006). Soil pH and organic matter were not measured in the present study. However, soil pH at the study site is generally about 7.5, ranging from 6.4 to 8.5, and organic matter in the upper 30 cm of soil ranges from 2.7 to 3.1% (unpublished data).

The following crop cultivars, which are common for the region, were used in the study: corn (Dekalb DK4446 glyphosate-resistant); wheat (Oxen); soybean (Northrup King NKS10 glyphosate-resistant); and cuphea (PSR23). In 2006 and 2007, DK 4446 corn with both glyphosate-resistant and Bt (Bacillus thuringiensis) traits was grown. Seeding dates ranged from 15 April to 30 April for wheat, 25 April to 30 April for corn, 30 April to 10 May for soybean, and 7 May to 11 May for cuphea. Corn and soybean were seeded in 76-cm spaced rows at rates of 78,000 and 430,500 seeds ha⁻¹, respectively. Cuphea was drill seeded in 61-cm spaced rows at a rate of 11.2 kg ha⁻¹ and wheat was drilled in 18-cm spaced rows at 150 kg ha⁻¹.

Weed control for corn and soybeans consisted of making two applications of N-(phosphonomethyl)glycine at 1.1 kg a.i. ha⁻¹, once in late-May to early-June and again in late-June. From 2005 to 2007, one application of [1α(S),3α(Z)]-(±)-cyano-(3-phenoxyphenyl)methyl-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate at a rate of 0.04 kg a.i. ha⁻¹ was made to soybeans in late-July to early-August to control soybean aphids (Aphis glycines Matsumura). For wheat, weed control consisted of one application of (+)-ethyl 2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]proponoate, 2,6-dibromo-4-cyanophenyl octanoate, and 4-chloro-2-methylphenoxy acidic acid at rates of 0.06, 0.23, and 0.23 kg a.i. ha⁻¹, respectively. Following wheat harvest, plots were treated in late-August with 1.1 kg a.i. ha⁻¹ of N-(phosphonomethyl)glycine to control weeds. In addition to preplant herbicide application, cuphea plots were treated once in late-June in 2004 and 2005 with 2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedicarboxylic acid at 0.11 kg a.i. ha⁻¹ to control broadleaf weeds. Cuphea has been shown to be tolerant to this rate of application (Foccella et al., 2005b). Additional weed control in cuphea plots was done by a limited amount of hand weeding.

After corn harvest in the fall, from mid- to late-October, all plots were tilled. Wheat, soybean, and cuphea plots were chisel plowed, while corn plots were moldboard plowed.

### Soil Sampling for Nitrogen and Moisture Content

In the spring before sowing and in the fall after harvesting, soil cores (20-mm diameter) were taken in two randomly chosen areas from all plots and separated into 0- to 300-mm and 300- to 600-mm depths; the two cores from each plot were combined by depth. In 2004, nitrate and ammonium N were determined for spring and fall soil samples using standard soil testing procedures (Mulvaney, 1996). From 2005 to 2007, nitrate and ammonium N were determined only for fall soil samples. Soil moisture was determined gravimetrically (kg water kg⁻¹ soil) for spring soil samples and a subset of samples in fall after drying to constant weight at 105°C. Additional samples were taken using a 51-mm diameter probe on 7 Oct. 2007 after harvesting and used to determine bulk density (Mg m⁻³). Soil water content was converted from gravimetric to volumetric basis using soil bulk density measurements.

Total seasonal nitrogen use (NU) for each crop was determined by:

\[
NU = (N_S + N_A) - N_F \quad [1]
\]

where \(N_S\) is the amount (kg ha⁻¹) of N (NO₃⁻–N + NH₄⁻–N) in the top 600 mm of soil at the beginning of the growing season, \(N_A\) is the amount of N fertilizer added, and \(N_F\) is the residual soil N present after harvest. Total NU in the top 600 mm of soil was not partitioned between plant uptake and that lost through leaching, volatilization, and denitrification. Fall soil N content from the previous year was used for \(N_S\) and we assumed little or no

---

**Table 1. Initial levels of N–P–K in the 0- to 600-mm soil profile before planting in the spring of 2004 at the beginning of the study. Values are means ± SE. There were no significant differences between treatments at the P < 0.05 level.**

<table>
<thead>
<tr>
<th>Crop sown</th>
<th>NO₃⁻–N</th>
<th>NH₄⁻–N</th>
<th>P</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>151 ± 9</td>
<td>87 ± 7</td>
<td>55 ± 7</td>
<td>1318 ± 93</td>
</tr>
<tr>
<td>W</td>
<td>149 ± 11</td>
<td>90 ± 7</td>
<td>63 ± 7</td>
<td>1280 ± 75</td>
</tr>
<tr>
<td>S</td>
<td>129 ± 8</td>
<td>73 ± 5</td>
<td>57 ± 5</td>
<td>1279 ± 76</td>
</tr>
<tr>
<td>Cu</td>
<td>145 ± 8</td>
<td>89 ± 8</td>
<td>57 ± 7</td>
<td>1292 ± 96</td>
</tr>
</tbody>
</table>
Harvesting and Plant Stands

All four crops were harvested using a plot combine with appropriate head for the crop. For cuphea, a soybean header was used. Crop harvest dates were: wheat, 27 July to 12 August; cuphea, 31 August to 27 September; soybean, 12 September to 8 October; and corn, 1 October to 19 October. Yield samples were taken from a 1.5 by 6.0 m strip from the center of each plot, except for corn, which was taken from a 3.0 by 6.0 m strip. After combining, cuphea seed was dried in a forced-air oven at 43°C for 48 h and screen-cleaned before determining yield. Drying and cleaning was unnecessary for the other crops. Seed yields were adjusted to a moisture content of 155, 130, 135, and 110 g kg⁻¹ for corn, soybean, wheat, and cuphea, respectively.

A subset of harvested seed was taken for each crop from each plot to determine total C and N and seed oil. Total N and C were determined with a Leco CN-2000 combustion analyzer (Leco Corporation, St. Joseph, MI) and N was multiplied by 6.25 to convert to crude protein. Cuphea seed oil content was determined by pulsed NMR (Bruker Minispec pcl20, Bruker, The Woodlands, TX). Before analysis, the instrument was calibrated with pure oil extracted from PSR23 cuphea.

Plant stands were measured just before grain harvest on all plots. Wheat stands were not measured in 2004 and 2005. Corn plant stands were measured from 6 m of the two center harvest rows. Soybean stands were taken on 1 m of two harvest rows, while cuphea and wheat stands were measured on 1 m of one of the harvest rows. Air temperature and precipitation were measured at an automated weather station located approximately 50 m from the study site.

Economic Analysis

Annual enterprise budgets were constructed for each treatment using the cost and returns estimator (CARE) (USDA-NRCS, 1995), based on the operations and inputs used in the field study each year. Crop and input prices were held fixed to isolate production-related effects from market effects. Machinery costs were from University of Minnesota Extension Service (Lazarus, 2008). A wage rate of $12.00 h⁻¹ and a diesel fuel price of $0.79 L⁻¹ from University of Minnesota Extension Service (Lazarus, 2008).

With the inclusion of land charges, net return estimates represent returns attributed to management activities.

Statistical Analysis

The experimental data were analyzed by ANOVA using the Mixed Procedure of SAS (SAS for Windows 9.1, SAS Inst., Cary, NC). Data were analyzed separately by year and across years to determine effects over the experimental period. In analyzing effects across years, the treatment (i.e., crop or previous crop in sequence) was a fixed effect and year and block were random effects. Treatment mean comparisons were made by year and across years when the F test was ≤ 0.05 using least significant differences (LSD) at the P = 0.05 level.

RESULTS AND DISCUSSION

Climate

The 120-yr average total precipitation during the growing season (i.e., May–September) near the study site is 404 mm (Table 2). In 2004 (the establishment year of the study) and 2005, total growing season precipitation was 113 and 101 mm, respectively, above the 120-yr average, while 2006 and 2007 were 159 and 62 mm, respectively, below the 120-yr average (Table 2). The 2006 growing season was exceptionally dry. Cumulative precipitation from June through August, a critical period for growth and seed development of the crops studied, was 70% below that of the 120-yr average for the same period.

Average growing season temperature progressively increased between 2004 and 2007 (Table 2). In 2004, average growing season temperature was 1°C below the 120-yr average and in 2005 place of hand-weeding costs to better reflect expenses that would be incurred by a producer growing cuphea over a larger area.

Herbicide prices were from North Dakota State University Extension Service (Zollinger, 2008). Fertilizer and seed prices were based on 2007 price levels (USDA-NASS, 2008). For corn, wheat, and soybean, the crop price was the average of 2004–2008 Minnesota marketing year average prices (USDA-NASS, 2009). Since cuphea is a new crop, prices and seed costs have not been established. Based on initial targeting of cuphea to specialty oil markets, we assumed seed would be provided to producers as part of a production contract and we used a contract price of $1100 Mg⁻¹ for any cuphea produced. This price reflects payments that were made to producers by a commercial contractor in initial farm trials. Crop drying and hauling costs were based on Iowa State University Extension custom rates (Edwards et al., 2009). A land charge of $210 ha⁻¹ was included based on the 2007 average crop-land rental rate for Stevens County, Minnesota (Hachfeld et al., 2008). With the inclusion of land charges, net return estimates represent returns attributed to management activities.

Table 2. Monthly accumulated precipitation and mean air temperature for the 2004–2007 growing seasons.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>158</td>
<td>76</td>
<td>47</td>
<td>75</td>
<td>75.3</td>
<td>11.9</td>
<td>12.4</td>
<td>15.1</td>
<td>16.5</td>
<td>13.5</td>
</tr>
<tr>
<td>June</td>
<td>83</td>
<td>155</td>
<td>28</td>
<td>84</td>
<td>101.0</td>
<td>17.6</td>
<td>21.0</td>
<td>20.2</td>
<td>20.8</td>
<td>18.9</td>
</tr>
<tr>
<td>July</td>
<td>117</td>
<td>82</td>
<td>27</td>
<td>10</td>
<td>93.2</td>
<td>20.6</td>
<td>22.0</td>
<td>23.8</td>
<td>22.6</td>
<td>21.6</td>
</tr>
<tr>
<td>August</td>
<td>48</td>
<td>74</td>
<td>27</td>
<td>58</td>
<td>76.0</td>
<td>17.2</td>
<td>19.6</td>
<td>20.9</td>
<td>19.8</td>
<td>20.4</td>
</tr>
<tr>
<td>September</td>
<td>111</td>
<td>118</td>
<td>116</td>
<td>115</td>
<td>58.7</td>
<td>17.5</td>
<td>17.1</td>
<td>14.0</td>
<td>16.5</td>
<td>15.1</td>
</tr>
<tr>
<td>Total</td>
<td>517</td>
<td>505</td>
<td>245</td>
<td>342</td>
<td>403.2</td>
<td>16.9</td>
<td>18.4</td>
<td>18.8</td>
<td>19.2</td>
<td>17.9</td>
</tr>
</tbody>
</table>

† Based on the 120-yr average monthly temperature and accumulated rainfall for the Morris, MN location. Data were collected and compiled from the University of Minnesota West Central Research and Outreach Center, approximately 24 km from the study site.
through 2007 it was above average by 0.5 to 1.3°C. The early part of the growing season in 2006 and 2007 was abnormally warm. The average of the mean monthly air temperature between May and July for 2006 and 2007 was 1.7 and 2.0°C, respectively, higher than that of the 120-yr average for the same period.

### Soil Moisture and Nitrogen

The amount of soil water available to a crop in the spring at planting in the subhumid northwestern Corn Belt depends on water used by the previous crop and infiltration of snow melt. The previous crop in a rotation can impact the amount of water available in the soil profile for the proceeding crop (Merrill et al., 2004; Krupinsky et al., 2006), and influences crop yields (Norwood, 2000). In the present study, differences in spring soil water content in the 0- to 600-mm profile were not large between treatments, but the previous crop did have a significant effect ($P < 0.05$) (Fig. 1A).

Averaged across years, when cuphea was the previous crop, less water was available for the subsequent spring crop than when corn was the previous crop, but cuphea left more available than soybean and was similar to that of wheat (Fig. 1A). On average, water available in the 0- to 600-mm profile at planting was 6% lower following soybean as compared with following corn, while cuphea was 3% lower than corn when it was the previous crop. He attributed this response to sunflower and soybeans' greater water use in the 1.8-m soil profile than corn and sorghum.

The pattern of fall soil water content in the upper 600-mm soil profile after harvest (Fig. 1B), which reflects seasonal crop water usage, was somewhat similar to that of the spring moisture content (Fig. 1A). However, soil water depletion by cuphea was not significantly different from soybean. Crop species and length of growing season are important factors affecting soil water depletion (Merrill et al., 2004). Cuphea's root system is not as extensive or deep as soybean, but both are C$_3$ crops with similar heights, leaf area, and growing season lengths (Gesch et al., 2002).

Crop total NU was different among the species studied, but was not influenced by the previous crop in sequence. Cuphea used less N than corn and tended to use less than wheat in 2004 and 2006, although both crops had similar NU in 2005 and 2007 (Fig. 2). Nitrogen use averaged across years was greatest for corn, intermediate for cuphea and wheat, and soybean, because it is a legume, was least (Fig. 2).

Cuphea production led to more residual NO$_3$–N and NH$_4$–N remaining in the 0- to 600-mm soil profile after harvest than corn, wheat, and soybean (Fig. 3). This indicates that more soil N would be available to the following crop, particularly early in the growing season. Under cuphea production, Berti et al. (2008b) observed that residual soil NO$_3$–N after harvest increased linearly with N fertility from 44 to 200 kg ha$^{-1}$ at the 0- to 300-mm and 300- to 600-mm depths, but saw no accumulation below 600 mm. In our study, the large amount of residual N remaining after cuphea (Fig. 3) was primarily due to its inherently shallow root system and relatively low NU (Fig. 2), but might also be related to a high rate of mineralization of plant tissue (Johnson et al., 2007).

Cuphea grown in a Barnes loam soil typically contains >80% of its root length density in the upper 300 mm of the soil profile (Sharratt and Gesch, 2004) and after a crop has absorbed sufficient nitrate for growth, nitrate can then accumulate in the soil and leach to lower depths in the profile (Black, 1992). Flax

---

**Figure 1.** Volumetric water content in the 0- to 600-mm soil profile in the spring (A) as affected by previous crop and fall (B) as affected by the current season's crop. Values are treatment means. Within years and averaged across years, bars followed by a different letter are significantly different at the $P \leq 0.05$ level. In all figures, C = corn, W = spring wheat, Cu = cuphea, and S = soybean.

**Figure 2.** Seasonal total soil N use for the current season's crop. Values are means for the given crop. Within years and averaged across years, bars followed by a different letter are significantly different at the $P \leq 0.05$ level.

**Figure 3.** Nitrogen Use (kg ha$^{-1}$) for Crop.
(Linum usitatissimum L.), which also has a shallow root system has been shown to leave more residual N in the soil than either canola or mustard (Kirkegaard et al., 1997). The unusually high level of residual nitrate left by cuphea in 2006 (Fig. 3) was a consequence of low productivity due to drought and high temperatures (Table 2). Lower productivity environments would be expected to result in even greater residual N accumulation close to where fertilizer was applied (Berti et al., 2008b).

Furthermore, greater residual soil nitrate following cuphea might be related to the N mineralization from decomposition of plant residue. Cuphea vegetative tissues have a lower C to N ratio than those of corn and soybean (Johnson et al., 2007) and thus, may decompose more rapidly in the field. The low C to N ratio in vegetative material of cuphea may reflect its ability to uptake adequate levels of N, but not translate this into seed yield (Berti et al., 2008b). This may have resulted in a greater amount of mineralized N from its residue than from residues of the other crops studied.

In 2007, the amount of NO3–N following harvest was not different among crops (Fig. 3). However, total soil N (NO3 + NH4–N) was considerably greater following cuphea than the other three crops, which was primarily due to a higher level of NH4 (Fig. 3). We are not sure why there was a greater proportion of NH4– to NO3–N following cuphea harvest in 2007, but it might be related to differences in when soil was sampled. The proportion of NH4– to NO3–N was also relatively high for cuphea in 2005. In both 2005 and 2007, soil was sampled about 3 wk earlier than in 2004 and 2006.

Analysis was also conducted to determine if differences in residual NO3–N persisted through the subsequent crop. Results showed that differences in soil NO3–N persisted through the subsequent corn and cuphea crops, but not for soybean and wheat. For both corn and cuphea, residual NO3–N was greatest when the previous crop was cuphea (Fig. 4). This suggests that corn and cuphea did not fully utilize the additional N resulting from the previous cuphea crop. Conversely, the results further suggest that wheat and soybean, which were not affected by the previous crop, did use the residual N left by cuphea the previous fall.

**Crop Yields**

Cuphea seed yield was not affected by the previous crop in this study (Fig. 5). Seed yield of cuphea averaged across sequence treatments was greater in 2004 (564 kg ha–1) and 2005 (538 kg ha–1), when precipitation was above normal, than in 2006 (222 kg ha–1) and 2007 (471 kg ha–1) when precipitation was below normal. The exceptionally low yield in 2006 was primarily due to lack of precipitation (Fig. 5 and Table 2). Cuphea (PSR23) is susceptible to drought stress largely due to a shallow root system and relatively low water use efficiency (Sharratt and Gesch, 2004; Gesch et al., 2009). Earlier than normal harvest of cuphea in 2006 (harvested 31 August) also contributed to low yields. Typically, cuphea seed yields in west central Minnesota are greatest when harvested in mid-September to early-October (Gesch et al., 2005). The early harvest in 2006 was necessitated by severe drought suffered by plants that led to accelerated development and increased seed shattering. Seed shattering remains a problem in cuphea and can result in variable yields (Forcella et al., 2005a; Gesch et al., 2005).

During the experiment, both corn and soybean showed a consistent yield decline when grown in monoculture (Fig. 5).
soybean yields following cuphea were not significantly different from yields when these crops were grown in non-monoculture sequences. In 2005, soybean yield was lower when following cuphea than when the previous crop was corn or wheat, but this effect did not persist in subsequent years (Fig. 5).

Average wheat yields were not significantly different following cuphea than when grown in any other sequence. It is notable that average wheat grain yield across cropping sequences was greatest in 2006 followed by 2007. To a large extent, this was likely due to the above average early growing season temperatures combined with low precipitation (Table 2), which created ideal conditions for early season plant growth and suppression of pathogens during those years.

**Plant Response**

Cuphea plant population density varied both among crop sequences and years, although differences were not significant (Fig. 6). Cuphea requires a shallow seeding depth and good soil-to-seed contact for optimum emergence. Germination and emergence can dramatically decline when planted deeper than 13 mm (Berti et al., 2008a), which was the seeding depth in the present study. However, seeding depth likely varied due to changes in terrain and soil surface residue and was probably the primary cause of variations in cuphea stands. Cuphea plant population density did not appear to affect seed yield (Fig. 5). For instance, average plant stand in 2004 was 61 plants m$^{-2}$ and that in 2005 was 34 plants m$^{-2}$, yet the mean yield across treatments was nearly identical in both years. This can be attributed to the indeterminate growth habit and high branching ability of cuphea (Gesch et al., 2002).

When grown as the previous crop, cuphea had a negative effect on soybean stand in one out of 3 yr (Fig. 6). When averaged across years, the effect was slight ($F$ test = 0.08) on soybean stand and positive ($F$ test < 0.05) on wheat stand (Fig. 6). In 2004 and 2005 soybean stands across all crop sequences were considerably lower than in 2006 and 2007. Early emergence plant counts were also taken (data not shown) and were similar to final stand counts. Starter fertilizer (11 and 38 kg ha$^{-1}$ of N and P as ammonium phosphate) was applied to soybean at planting in 2004 and 2005. Early season growth and grain yield of soybean grown in the northern Great Plains have been reported to benefit from starter N (Osborne and Riedell, 2006). However, little information exists on the effect of starter N on seed germination and emergence of soybean, although corn germination is known to be inhibited by urea when banded soon after planting (Ouyang et al., 1998). We surmised that the N in the starter fertilizer, perhaps in combination with cold, wet soils at planting, hampered germination and emergence of soybean (based on field observation in an adjacent soybean study) and therefore, discontinued its use after 2005.
We are not sure why cuphea led to a small negative trend in soybean plant population density. Besides mere chance, another possible reason could be an allelopathic influence of cuphea residue. Graham (1988) reported that soybean germination was inhibited in fields previously planted with Cuphea wrightii and suggested that allelopathy may have been a factor, but no details of the study were given. Although Cuphea wrightii is in the same genus, it is not closely related to PSR23 cuphea. Another possible explanation for the low soybean stands was that the high levels of \( N \) left in the soil following cuphea (Fig. 3) may have affected germination and emergence similarly to that of starter \( N \) in 2004 and 2005.

The positive effect of cuphea on wheat plant population density (Fig. 6) was most likely due to the residual \( \text{NO}_3^-\) left behind by cuphea the previous fall. The beneficial effect of residual soil \( N \) following legume and nonlegume crops grown before wheat and other cereals is well documented (Kirkegaard et al., 2008). Alternatively, weed control tactics used for cuphea, which were effective in controlling several weeds species including redroot pigweed (Amaranthus retroflexus), might also have contributed to greater wheat stands. Redroot pigweed is a common weed at the study site, and it is known to have a strong allelopathic effect on germination of durum wheat (Triticum turgidum) (Qasem, 1995).

Wheat grain crude protein content was positively influenced when cuphea was grown as the previous crop (Table 3). Wheat grain protein was 8% higher when following cuphea as compared with the average protein content following corn, wheat, and soybean (Table 3). The improved crude protein content was most likely due to improved early season growth resulting from residual \( \text{NO}_3^-\) left by cuphea the previous fall that translated to greater seed protein at grain fill. In the absence of soil-borne diseases, Kirkegaard et al. (1997) cited \( N \) availability following cuphea (Fig. 3) may have affected germination and growth of durum wheat (Triticum turgidum) (Qasem, 1995).

Table 3. Trend in crude protein and total carbon content of wheat and soybean grain as influenced by the previous crop in rotation. Values are means from 2005 to 2007. Values within columns followed by the same letter are not significantly different at the \( P \leq 0.05 \) level.

<table>
<thead>
<tr>
<th>Previous crop</th>
<th>Wheat</th>
<th>Soybean</th>
<th>Corn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crude protein</td>
<td>Total C</td>
<td>Crude protein</td>
</tr>
<tr>
<td>C</td>
<td>160 b</td>
<td>431 a</td>
<td>385 bc</td>
</tr>
<tr>
<td>W</td>
<td>162 b</td>
<td>432 a</td>
<td>380 c</td>
</tr>
<tr>
<td>S</td>
<td>161 b</td>
<td>431 a</td>
<td>396 a</td>
</tr>
<tr>
<td>Cu</td>
<td>174 a</td>
<td>440 a</td>
<td>388 b</td>
</tr>
<tr>
<td>2004 Avg†</td>
<td>164 ± 1.4</td>
<td>429 ± 1.4</td>
<td>395 ± 0.4</td>
</tr>
</tbody>
</table>

† No significant differences were detected between rotation treatments; 2004 was the establishment year with spring wheat as the previous crop.

Production Economics

Generally, production costs for cuphea were lower than corn, but greater than that of soybean and wheat (Fig. 7). Averaged across treatments and years the cost of producing cuphea was $752 ha\(^{-1}\), while that for corn, soybean, and wheat was $924, $634, and $626 ha\(^{-1}\), respectively (Fig. 7). Average cost of production was lower when the previous crop was either cuphea or soybean due to differences in costs of field operations following harvest of these crops compared with corn and wheat. Fields were moldboard plowed in the fall after corn harvest, while fields were chisel plowed after all other crops. Wheat fields were sprayed after harvest (twice in 2007) but before fall tillage to control weeds, reducing weed seed production and potential future weed pressure.

Some year-to-year variation in production costs occurred due to adjustments in management practices and as a result of varying weather conditions. The lower cost of cuphea production in 2006 was primarily due to lower seed drying and fertilizer costs. Because of cuphea’s indeterminate growth (Gesch et al., 2002), its seed at harvest tended to be quite wet (about 45 to 55%). Similarly, the high cost of corn production in 2005 was primarily due to high seed drying costs, with seed moisture content at harvest ranging from 24 to 25% that year. Soybean production costs were also higher in 2005, but this was primarily due to the use of starter fertilizer, which was omitted in subsequent years.

Net returns for cuphea were negative in all years regardless of previous crop (Fig. 8), indicating that a price of $1100 Mg\(^{-1}\) would not be sufficient for cuphea to be profitable given the low yields (Fig. 5) and relatively high production costs incurred in this study (Fig. 7). With the 2005 to 2007 average yields observed in Table 4. Cuphea seed oil content as affected by previous crop. Values within columns followed by the same letter are not significantly different at the \( P \leq 0.05 \) level.

<table>
<thead>
<tr>
<th>Previous crop†</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oil content</td>
<td>g kg(^{-1})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>316 a</td>
<td>296 b</td>
<td>301 a</td>
<td>304 b</td>
</tr>
<tr>
<td>W</td>
<td>320 a</td>
<td>321 a</td>
<td>309 a</td>
<td>317 a</td>
</tr>
<tr>
<td>S</td>
<td>315 a</td>
<td>314 a</td>
<td>305 a</td>
<td>311 ab</td>
</tr>
<tr>
<td>Cu</td>
<td>314 a</td>
<td>310 ab</td>
<td>309 a</td>
<td>311 ab</td>
</tr>
<tr>
<td>Yearly Avg</td>
<td>316</td>
<td>310</td>
<td>306</td>
<td></td>
</tr>
</tbody>
</table>

† No significant differences were detected between treatments in 2004. Average seed oil content in 2004 was 331 ± 1.8 g kg\(^{-1}\).
this study, a price of $1830 Mg⁻¹ would be necessary for cuphea income to cover production costs. Greater labor intensity of cuphea management compared with the other three crops, and relatively high seed drying, fertilizer, and herbicide costs were primary factors resulting in high production costs. Cuphea, when grown as the previous crop, did have a positive influence on overall net returns for corn and soybean (Fig. 8) relative to growing these crops continuously, increasing corn net returns $274 ha⁻¹ relative to a continuous corn sequence and increasing soybean net returns $95 ha⁻¹ relative to continuous soybean. However, the influence was not significantly greater than for any other rotational crop, and would not be sufficient to offset losses incurred in the cuphea production year. Cuphea did have a negative effect on soybean net return in 2005 (Fig. 8), primarily due to its effect on soybean yield (Fig. 5). However, cuphea had a positive effect on wheat net return in 2007 due to a combination of positive yield effect and lower wheat production costs following cuphea than following corn or wheat (Fig. 7).

Net returns for cuphea could be greatly increased through reducing N fertilizer input. Both this study and a previous one (Berti et al., 2008b) have clearly shown that yield and economic returns of PSR23 cuphea do not warrant the extensive use of N fertilizer. Also, S is probably not necessary (Gesch, unpublished data, 2008). Additionally, returns could be increased by harvesting seed at lower moisture content, which can be accomplished by swathing the crop (Forcella et al., 2007), and by developing cheaper weed-control options. Ultimately, however, improved cultivars with higher yielding potential will be needed to make cuphea an economically viable crop that will compete for medium-chain oil markets currently supplied by coconut and palm kernel oils. Presently, cuphea is being marketed to the cosmetic industry (Berti et al., 2008b) where its oil is highly valued.

**CONCLUSIONS**

Our results show that cuphea will fit well agronomically into rotations with the primary Midwestern crops corn, soybean, and spring wheat. Cuphea’s water use requirement appears to be similar to that of spring wheat, and because of relatively low NU it may not require much N fertilizer for its production. Although cuphea may have a slight negative effect on soybean plant emergence, average soybean yields were not affected. Conversely, wheat emergence and stand development and grain protein content responded positively when following cuphea in rotation. This was primarily due to residual mineralized N remaining in the soil following cuphea production. Cuphea may have appeal as an additional crop in northern Corn Belt cropping systems from the standpoint of its low N requirement and positive effect on wheat.

![Fig. 7. Crop production costs as affected by previous crop in rotation. Values are treatment means. For averages across years, bars followed by a different letter are significantly different at the P ≤ 0.05 level.](image1)

![Fig. 8. Crop net returns as affected by previous crop in rotation. Values are treatment means. Within years and averaged across years, bars followed by a different letter are significantly different at the P ≤ 0.05 level](image2)
In our study, production cost of cuphea was less than corn, but greater than soybean and wheat. However, cuphea is truly a new crop, and evidence from this and other studies (Forcella et al., 2007; Berti et al., 2008b) indicate that production costs can be substantially reduced with improved harvest, weed control, and fertilizer management. Presently, the break-even price for profitable production of cuphea is too high to warrant producing cuphea to compete with large-scale markets for medium-chain fatty acids such as the soap and detergent industry. Largey, this is due to PSR23’s low seed-yield potential. For the mean time, niche markets that produce high-valued products, such as the cosmetic industry, would be needed to support profitable cuphea production on a small scale until improved cultivars are developed. Based on our findings, if cuphea is grown, it is recommended that it be rotated after soybean or before wheat or corn.

ACKNOWLEDGMENTS
The authors wish to thank Mr. Jim Eklund and Joe Boots for expert field assistance. We also would like to acknowledge funding by Procter and Gamble for cuphea research.

REFERENCES