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# Evaluating alternative, diverse cropping systems that include canola, wheat, and red clover in Iowa

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**Evaluating alternative, diverse cropping systems that include canola, wheat, and red clover in Iowa**

by

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# TABLE OF CONTENTS

## ABSTRACT

Over the period of 2009-2013, I compared the agronomic, economic, and ecologic performance of three distinct crop rotations at the Iowa State University Agronomy and Agricultural Engineering Research Farm in Boone County. One rotation represented the contemporary norm in Iowa, while the other two rotations included “alternative” crops (canola and wheat) and a forage legume green manure interseeding (red clover). The rotations were a corn-soybean (C-Sb) system, a system common to contemporary Iowa farming operations; and two “alternative” systems: corn-spring canola-winter wheat + red clover (C-SC-WW/RC) and corn-spring wheat-winter canola + red clover (C-SW-WC/RC). All three rotations included transgenic crops, applications of liquid swine manure, synthetic fertilizers, and chemical pesticides; though, I intended for biological N fixation by the red clover green manure and crop competitiveness with weeds to be more heavily relied on in the two alternative cropping systems. The overall purpose of this research project was to provide demonstrations of and more information about alternative, diverse cropping systems for farmers in Iowa. The objectives of this dissertation research were to determine: (i) whether red clover green manure could reduce reliance on purchased N fertilizer for corn production; (ii) the best combination of spring and winter varieties of wheat and canola in terms of yield and quality; and (iii) the financial and soil erosion dynamics among the three rotation systems studied. The alternative systems were not as competitive on a production or economical basis, but they did show tremendous promise in terms of reducing the potential for soil erosion and input costs associated with agriculture, compared to the contemporary C-Sb system common across Iowa.

# CHAPTER 1. GENERAL INTRODUCTION

In Iowa, cropping systems are characterized by two primary crops—corn (*Zea mays* L.) and soybeans (*Glycine max* [L.] Merr.)—grown on 93% of all arable land in the state; approximately 55% and 38%, respectively (USDA, 2014). The typical Iowa corn-soybean rotation is detrimental to the ecological sustainability of Iowa's soils and agriculture. In this rotation 1) fields remain bare during the winter, increasing the potential for wind and water erosion of soil and leaching of nutrients out of the system; 2) the crop rotation lacks plant diversity that could enhance pest management; and 3) the crop rotation is reliant on purchased inputs in the form of synthetic fertilizers and pesticides. As recently as the mid-1970s, however, cool-season, non-corn and non-soybean crop species accounted for 30-40% of the cropland landscape in north-central and northwest Iowa (Hatfield et al., 2009). The purpose of this research project was to investigate cropping systems that would reintroduce crop species diversity on the Iowa farming landscape. This was achieved by developing extended and diversified crop rotations that include summer and winter annual species as well as perennial species. I hypothesized that cool-season oilseed crops such as canola (*Brassica napus* L.) and small grains such as wheat (*Triticum aestivum* L.) exhibiting spring and winter annual life cycles as well as perennial legumes such as red clover (*Trifolium pratense* L.) could fit into an Iowa crop rotation providing growers with alternative production options. The inclusion of species with different life cycles can also serve to improve cropping systems by increasing the amount of ground cover throughout the year (Snyder et al., 2016), protect soil and water resources by reducing soil erosion and nutrient leaching (Dinnes et al., 2002; Gaudin et al., 2013), and help disturb life cycles of problematic weed species (Liebman and Staver, 2001; Liebman and Davis, 2009). Incorporating multiple species into a crop rotation may also improve yields of other crops and improve a farmer's economic stability, while at the same time reduce the ecological footprint (Liebhardt et al., 1989; Porter et al., 2003; Liebman et al., 2008; Davis et al., 2012). The potential to reduce the amount of purchased, synthetic inputs also exists when extended and diverse crop rotations that include legumes are employed.

The addition of a perennial forage legume species such as red clover to a crop rotation, particularly when interseeded with a small grain crop like wheat or oats (*Avena sativa*, L.), can serve as a green manure providing nitrogen to subsequent crops in the rotation (Bruulsema et al., 1987; Hesterman et al., 1992; Stute and Posner, 1995; Vyn et al., 2000; Liebman et al., 2012). In a review of several studies, Gaudin et al. (2013) determined red clover green manure crops supply on average 96.7 kg N $ha^{-1}$ in nitrogen fertilizer equivalents to a subsequent corn crop. Moreover, perennial forage legumes like red clover also have the added benefit of keeping nitrogen in the soil by reducing nitrate leaching because of its growth and water demand throughout the year from early spring to late fall (Dinnes et al., 2002; Gaudin et al., 2013). Thus, less dependence on synthetic, purchased nitrogen can be achieved in systems incorporating forage legume green manures.

Canola is a cool-season oilseed crop with both winter and spring varieties (not unlike wheat or barley [*Hordeum vulgare* L.]). In North America, winter canola is typically grown in parts of the Great Plains and Northwest United States (USDA, 2017). Variety trials of winter canola, however, have been conducted, and continue to be conducted, in those regions as well as in the Midwest and Southeast United States (Stamm and Dooley, 2015). Spring canola is typically grown in North Dakota, Montana and Minnesota in the Unites States (USDA, 2017) and Saskatchewan, Alberta and Manitoba in Canada (Statistics Canada, 2017). Optimal planting dates for winter canola are six weeks prior to a killing frost (roughly, early to mid-September in

Iowa) (Martinez-Feria, 2015); spring canola is seeded as early in the spring as possible (not unlike oats or spring wheat) (Brown et al., 2008). Because of the optimal planting dates for winter canola in Iowa, winter canola best fits into a crop rotation following a spring cereal grain that is harvested in mid-summer such as wheat or oats.

Wheat (spring or winter varieties) is typically grown in the Great Plains and Pacific Northwest regions in the United States (USDA, 2017). For the period 2006-2015, approximately 26,200 acres of winter wheat were harvested in Iowa on an average annual basis (USDA, 2017). No statistics for that same time period are available for spring wheat in Iowa; the last year on record is 1964 with 4,000 acres of spring wheat that year (USDA, 2017). Even so, planting spring-seeded small grains is recommended in late March to mid-April in Iowa (Hansen, 1992). For winter wheat, the recommended seeding date in Iowa is late September or early October (Hansen, 1994; Gibson et al., 2006). As with winter canola, achieving the recommended seeding date for winter wheat in Iowa would be most likely if it followed a summer harvested crop in rotation.

Both winter and spring varieties of canola and wheat are harvested in mid- to late July, making them ideal candidates to precede and succeed one another in crop rotations (e.g., spring canola before winter wheat and spring wheat before winter canola). In this case, the six- to eight-week period between spring annual crop harvest and winter annual crop planting could encourage the germination and emergence of summer annual weed species and present an opportunity for control of these weeds. These emerged weeds could be eliminated by mowing and/or in the preparation of a seedbed for the subsequent winter annual crop. Either way, these weeds would not be allowed to reach maturity or seedset and thus reduce their fecundity (Liebman and Staver, 2001; Mohler, 2001; Westerman et al., 2005). Concomitantly, seeding winter canola or winter wheat in September or October should also result in adequate growth to protect soil from movement going into the winter months.

Winter annual crops (and perennial forage legumes) ultimately can serve as ideal cover crops in a crop rotation. When included in a cropping system, cover crops can reduce soil erosion (Hussain et al., 1988), increase soil organic matter (Reicosky and Forcella, 1998), and improve weed management (Buhler et al., 1998). Non-leguminous winter annual crop species, like canola and wheat, exhibit beneficial cover crop characteristics. Due to extensive rooting systems, winter cereal grasses can reduce soil erosion (Kessavalou and Walters, 1997; Kaspar et al., 2001) and nitrate leaching (Kladivko et al., 2004; Strock et al., 2004; Kaspar et al., 2012). Meisinger et al. (1991) found grass and *Brassica* species used as cover crops were especially effective at reducing nitrate leaching. Spring canola and spring wheat could also be considered (spring) cover crops in Iowa because they are seeded much earlier than—and produce vegetative soil cover much earlier than—the predominant corn and soybeans. Cover crops are viewed favorably by growers for their ability to prevent erosion and build soil organic matter, but cover crops can be viewed negatively by growers as merely another cost they must incur (Snapp et al., 2005; Singer et al., 2007). However, spring and winter annual crops that can serve as cover crops as well as cash crops could possibly be appealing to growers.

Over the period of 2009-2013, I compared the agronomic, economic, and ecologic performance of three distinct crop rotations at the Iowa State University Agronomy and Agricultural Engineering Research Farm in Boone County. One rotation represented the contemporary norm in Iowa, while the other two rotations included “alternative” crops (canola and wheat) and a forage legume green manure interseeding (red clover). The rotations were a corn-soybean (C-Sb) system, a system common to contemporary Iowa farming operations; and two “alternative” systems: corn-spring canola-winter wheat + red clover (C-SC-WW/RC) and corn-spring wheat-winter canola + red clover (C-SW-WC/RC). All three rotations included transgenic crops, applications of liquid swine manure, synthetic fertilizers, and chemical pesticides; though, I intended for biological N fixation by the red clover green manure and crop competitiveness with weeds to be more heavily relied on in the two alternative cropping systems. The overall purpose of this research project was to provide demonstrations of and more information about alternative, diverse cropping systems for farmers in Iowa. The objectives of this dissertation research were to determine: (i) whether red clover green manure could reduce reliance on purchased N fertilizer for corn production; (ii) the best combination of spring and winter varieties of wheat and canola in terms of yield and quality; and (iii) the financial and soil erosion dynamics among the three rotation systems studied. The alternative systems were not as competitive on a production or economical basis, but they did show tremendous promise in terms of reducing the potential for soil erosion and input costs associated with agriculture, compared to the contemporary C-Sb system common across Iowa.

## Dissertation organization

The concepts associated with alternative and diverse cropping systems in the U.S. Corn Belt of the Upper Midwest were explored in the three articles that comprise this dissertation. The articles portray three broad subjects that spanned the field experiment. The first article concerns the corn production year of each of the three cropping systems studied. The second article concerns the canola and wheat production years of the two alternative cropping systems studied. Finally, the third article takes a full cropping system approach in assessing the financial costs and returns associated with each of the three systems as well as an environmental assessment associated with soil erosion potential associated with the systems. Article titles and brief synopses follow below.

**Comparing corn following red clover green manure with corn following soybean (Chapter 2)**. This article focuses primarily on the corn grown in each of the three rotation systems during the period 2011-2013. Corn followed soybean (from the C-Sb system) or red clover that was frost-seeded into winter wheat (from the C-SC-WW/RC system) and into winter canola (from the C-SW-WC/RC system). Liquid swine (*Sus scrofa domesticus*) manure was injected into soybean stubble or standing red clover in the fall prior to corn; nitrogen fertilizer application was determined with in-season prescription management from soil test results. The objectives were to determine (i) red clover growth characteristics when established with either winter wheat or winter canola before being chemically terminated preceding corn in rotation and (ii) any differences in N management and corn yield response resulting corn following red clover green manures versus the more common soybean in central Iowa. Measurements included red clover biomass and C and N characteristics at the time of termination; soil N concentration at the time of corn planting, in the early summer, and post-harvest; cornstalk nitrate concentration at crop maturity; and corn grain yield.

**Cool-season cropping sequences featuring canola and wheat (Chapter 3).** This article focuses on the spring canola-winter wheat and spring wheat-winter canola phases of the two alternative cropping systems during three, two-year periods: 2010-2011, 2011-2012, and 2012-2013. These two cropping sequences were designed to determine which combination of wheat, canola and red clover (frost-seeded into the winter annual crop in spring) performed best when preceding corn in rotation. Comparisons are made between the two sequences regarding wheat and canola yields and yield quality, red clover green manure fall biomass production and C and

N characteristics, and competiveness with ambient weeds with limited, if any, chemical weed management.

**Agronomic, economic, and vegetative groundcover performance of alternative cropping systems in Iowa (Chapter 4).** This article concerns the entirety of each of the three crop rotation systems studied. Particular interest was paid to the productivity, economic performance, and potential for soil erosion resulting from the three rotation systems for the years 2011, 2012, and 2013. Economic performance was determined from costs of production (inputs and field operations) and financial returns resulting from grain and oilseed yields. The potential for erosion was determined as follows: (i) by assessing the amount of vegetative (living, green) cover provided throughout the year by each of the three rotation systems; and then (ii) using those data in a previously-established mathematical equation relating vegetative cover to soil erosion from a bare surface.

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# CHAPTER 2. COMPARING CORN FOLLOWING RED CLOVER GREEN MANURE WITH CORN FOLLOWING SOYBEAN

A paper for submission to Agronomy Journal

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## Abstract

Extending and diversifying a crop rotation to include cool-season crops presents farmers with the opportunity to generate biological soil nitrogen using legume green manures and reduce fertilizer use. This study, conducted in central Iowa, primarily considers the corn (*Zea mays* L.) phase of three crop rotation systems. In two systems, corn followed in rotation red clover (*Trifolium pratense* L.) green manure that was established with either winter wheat (*Triticum aestivum* L.) or winter canola (*Brassica napus* L.). In the third system, corn followed soybean (*Glycine max* [L.] Merr.) which is common in the region. Each of the three systems also received applications of swine (*Sus scrofa domesticus*) manure in the fall before corn and in-season synthetic N fertilizer as suggested by soil test recommendations. Aboveground biomass production and N content of the red clover did not differ when established with either winter wheat or winter canola. Mean aboveground biomass production and N content of red clover between the two systems ranged from 1,137–2,365 kg $ha^{-1}$ and 33–82 kg N $ha^{-1}$, respectively, across years. Manure and fertilizer N additions totaled 216 kg N $ha^{-1}$ to all systems in 2011; 182 kg N $ha^{-1}$ to the soybean system and 216 kg N $ha^{-1}$ to the canola/clover and wheat/clover systems in 2012; and 216 kg N $ha^{-1}$ to the soybean system and 182 kg N $ha^{-1}$ to the canola/clover and wheat/clover systems in 2013. Corn yields were significantly greater when following soybean compared to clover in 2011 (12.9 vs. 11.0 Mg $ha^{-1}$) and 2012 (8.4 vs. 6.3 Mg $ha^{-1}$) but similar across all systems in 2013 (7.6 Mg $ha^{-1}$). Across years, stalk $NO_3$-N concentration of corn at

physiological maturity and soil $NO_3$-N concentration at corn harvest was greater following clover than corn following soybean, but this did not correlate with greater yields. Insufficient availability of soil N was not likely the cause for lower corn yields following clover than soybean. Rather, slow chemical desiccation of red clover that resulted in delayed corn emergence in 2011 and 2012, as well as drought conditions in 2012, were the likely causes for the lower yields. This underscores the importance for proper management and suitable environmental conditions for legume green manures to be successful.

## Introduction

Legume green manures offer the potential to reduce the amount of purchased synthetic sources of N compared to less diverse contemporary rotations (Liebman et al., 2008; Davis et al., 2012). As a biological source of N, a legume green manure, such as red clover, established with a small grain can replace 87–184 kg N $ha^{-1}$ of fertilizer for the succeeding corn crop (Bruulsema and Christie, 1987; Hesterman et al., 1992; Stute and Posner, 1995; Vyn et al., 2000; Liebman et al., 2012). In contrast to synthetic fertilizers, the slow release of inorganic, plant-available N from microbial decomposition of legume green manures in synchrony with crop N uptake can also reduce the level of nitrate leakage from cropping systems (Drinkwater et al., 1998; Dinnes et al., 2002). In these types of cropping systems, successfully aligning N release from legume green manures with subsequent crop N uptake is reliant on timely management, not to mention variables that are inherently impossible to control—namely, temperature and rainfall (Steiner et al., 1999; Ruffo and Bollero, 2003).

A review of studies involving the use of red clover in cropping systems in the Corn Belt of the northern United States and southern Canada concluded that N mineralization and N capture by the subsequent crop is generally maximized under conventional tillage compared to no-till (Gaudin et al., 2013). Moreover, cool and wet conditions in the spring common in no-till soils delays N release by red clover following termination (Rice et al., 1987), although, Vyn et al. (2000) found no difference in corn yield response to clover plowed in the fall, plowed in the spring or chemically terminated in the spring. Triplett et al. (1979) and Yost et al. (2013) found that another legume green manure, alfalfa (*Medicago sativa* L.), could replace all necessary N fertilizer for corn grown under no-till management. This resulted, however, from alfalfa stands that were at least two-years old and not one established with a small grain crop the year prior to corn. Other evidence suggests that red clover contributes to reductions in N fertilizer only after building up soil organic N pools (Liebhardt et al., 1989 and Gaudin et al., 2013). This buildup, however, can take several cycles of a multi-year crop rotation during which lower yields occur before soil reserves become readily available.

With the increased adoption of no-till farming systems because of their potential to reduce soil erosion and ability to improve soil structure and aggregation (Beare et al., 1994; Six et al., 1999; Bronick and Lal, 2005; Lal et al., 2007; Montgomery, 2008), growers may be resistant to use legume green manures if tillage is required to reap most of the benefits. Additionally, multiple years of low yields or reliance on synthetic N while waiting for legume green manures to build up soil N reserves may not be appealing. As such, this study compared three crop rotation systems under minimal tillage regimes to test these concerns. Two of these systems represent extended rotations that may be suitable to the northern Corn Belt: a three-year, spring canola-winter wheat/red clover-corn rotation and a three-year spring wheat-winter canola/red clover-corn rotation. A two-year, soybean-corn rotation was included as it is typical of cash grain farming systems in the Midwest United States. This article primarily considers the corn phase of these three rotation systems. The preceding crop to corn is considered as the treatment. In the Upper Midwest, and Iowa in particular, establishing a legume green manure with winter annual small grain crops has been well documented (Blaser et al., 2006; Blaser et al., 2007). Establishing a legume green manure with canola, however, is relatively unexplored. The objectives of this study were to determine (i) whether red clover green manure growth characteristics, when established with winter canola, could be similar when established with winter wheat and (ii) if N additions to corn following clover could be reduced relative to corn following soybean while maintaining or increasing corn yields.

## Materials and Methods

### *Plot background, experimental design, and rotation systems*

The experiment was conducted during 2011-2013 at the ISU Agronomy and Agricultural Engineering Farm located in Boone County near Ames, IA (42°0’ N; 93°0’ W; 354 m above sea level). Predominant soils at the site are Clarion loam (fine-loam, mixed, superactive, mesic Typic Hapludolls) and Webster silty clay loam (fine-loamy, mixed, superactive, mesic, Typic Endoaquolls). Soil samples collected to a depth of 15 cm in the fall of 2009 indicated a mean P concentration (Bray-1) of 6 mg $kg^{-1}$, a mean K concentration (Mehlich-3 extraction) of 115 mg $kg^{-1}$, a mean organic matter concentration (combustion analysis) of 41 g $kg^{-1}$, a mean pH of 5.8, and a mean buffer pH of 6.5. Prior to the initiation of this study, the site had been managed for a number of years in a corn-soybean rotation receiving conventional fertilizers and pesticides.

The experiment was arranged in a randomized complete block design with four replications of each treatment. Treatments comprised three cropping systems: soybean followed by corn (soybean); winter wheat/red clover followed by corn (wheat/clover); winter canola/red clover followed by corn (canola/clover). Individual plot size was 9 m × 40 m.

The entire experimental site was planted with soybean in spring 2009 and the plots were established following harvest in fall 2009. The 2010 growing season acted as the establishment year for all systems. The experimental period began with the onset of the 2011 growing season.

Weather data from within 4 km of the experimental site were compiled from the Iowa Environmental Mesonet for 2011, 2012, 2013, and the period 1951-2013. Accumulation of decomposition days (DCD) was used to compare the climatic conditions for red clover residue decomposition after red clover termination for each year. The DCD values were calculated using the model of Steiner et al. (1999) and verified by Ruffo and Bollero (2003) and Quemada (2005) for legume green manure decomposition. This model considers temperature and moisture as the two limiting factors to plant residue decomposition. The DCD value for a given day ranges between 0 and 1, with a value of 1 indicating optimum conditions for residue decomposition. The lesser of the temperature and moisture coefficients represents the DCD value for a given day. After Steiner et al. (1999), the temperature coefficient for a given day was calculated as follows:

$$TC = \frac{2 \times (Tmean)^2 \times (Topt)^2 - (Tmean)^4}{(Topt)^4}$$

[1]

where Tmean is the mean daily air temperature and Topt is considered the optimum air temperature for residue decomposition (32ºC). The minimum value for Tmean is set to 0ºC. The moisture coefficient assumes 4 mm of precipitation in a day as sufficient to fully wet surface residues for optimal residue decomposition (Steiner et al. 1999). The moisture coefficient for a given day is set to 1 if daily precipitation is ≥4 mm. If daily precipitation is <4 mm, the moisture coefficient is determined by dividing the daily precipitation amount by 4 added to half of the previous day's moisture coefficient. The moisture coefficient is reduced by a factor of 0.5 in the absence of precipitation each day after the last detectable precipitation.

*Crop management*

Soybeans, wheat/clover, and canola/clover were grown in the 2010, 2011, and 2012 growing seasons. Glyphosate-tolerant soybeans (cv. DuPont Pioneer 92Y60) were planted in 76-cm rows with a no-till planter in mid-May, managed with conventional herbicides, and harvested in late September or early October using commercial harvesting equipment. Winter wheat (cv. Expedition) and winter canola (cv. Sitro) were seeded using a drill with a 19-cm row spacing following tandem disk tillage in early October and early September, respectively, previous to the growing season. Fertilizer N, P, and K was surface broadcast each fall prior to tillage and wheat and canola seeding at a rate of 24 kg N, 91 kg P, and 91 kg K $ha^{-1}$ as urea, triple super phosphate, and potash, respectively. An additional 34 kg N $ha^{-1}$ as urea was surface broadcast to both wheat and canola during early March. Red clover (cv. Mammoth) was seeded by surface broadcasting at a rate of 20 kg $ha^{-1}$ when the fertilizer N was applied to wheat and canola in March. Wheat and canola were harvested in early to mid-July using commercial harvesting equipment. The wheat straw was raked and baled soon after harvest. Red clover was occasionally mowed to suppress weeds following harvest of wheat and canola. In establishing the experiment during fall 2009 following the harvest of soybeans that were planted to the entire site, cropping patterns similar to those described above were used with one exception. Spring canola (cv. Pioneer 45H73), interseeded with red clover, was seeded on 1 Apr. 2010 in place of winter canola in the canola/clover sequence that year, as the soybeans were harvested too late in fall 2009 to permit the seeding of winter canola. Soybean and red clover seeds were inoculated with appropriate *Bradyrhizobium* and *Rhizobium* treatments before planting.

Synthetic fertilizers, applied at rates based on soil tests, as well as liquid swine manure were applied prior to planting corn (Table 1). Liquid swine manure was injection applied in November 2010, 2011, and 2012 at a target rate of 114 kg N $ha^{-1}$ into soybean stubble and standing red clover. With injection application, we assumed 98% of the N and 100% of the P and K in the manure to be available for the crop year immediately following application (Sawyer and Mallarino, 2008). Calculated application rates of N, P, and K in liquid swine manure were based on analyses conducted by MVTL Laboratories, Inc. (Nevada, IA). The manure applied in November 2011 ahead of the 2012 crop year was acquired from two different sources and as such resulted in approximately half of the amount of P being applied to blocks 1 and 2 versus blocks 3 and 4 (Table 1). Post-emergence side-dress N applications to corn in all systems were determined using the Late Spring Soil Nitrate Test (LSNT) (Blackmer et al., 1997). Manure and fertilizer N additions totaled 216 kg N $ha^{-1}$ to all systems in 2011; 182 kg N $ha^{-1}$ to all systems in 2012; and 216 kg N $ha^{-1}$ to the soybean system and 182 kg N $ha^{-1}$ to the canola/clover and wheat/clover systems in 2013 (Table 1). Seven to 17 d prior to planting corn in the wheat/clover and canola/clover systems, red clover was chemically terminated with 2,4-D amine (0.28 kg a.i. $ha^{-1}$) and glyphosate as isopropylamine salt (0.91 kg a.i. $ha^{-1}$).

Glyphosate-tolerant corn (cv. Channel 209-76r) was planted in 76-cm wide rows at a seeding rate of 80,500 seeds $ha^{-1}$ on 10 May 2011, 11 May 2012, and 24 May 2013. Zero tillage (no-till) was used in the soybean system except for a tandem disk in spring 2013 to incorporate surface broadcast P fertilizer prior to planting corn. In 2012 and 2013, corn in the wheat/clover and canola/clover systems was planted into 76-cm wide rows after strip tillage created 15-cm wide tilled strips in each planter row. Strip tillage was performed in order to better achieve proper seed placement in chemically terminated red clover residue.

Weed control for corn consisted of a pre-emergence application of dimethenamid-P (1.06 kg a.i. $ha^{-1}$) and glyphosate as isopropylamine salt (0.91 kg a.i. $ha^{-1}$) as a tank mix just after planting. When necessary, glyphosate as isopropylamine salt (1.15 kg a.i. $ha^{-1}$) was applied postemergence to control weeds.

*Crop and soil sampling*

Aboveground biomass of red clover in the wheat/clover and canola/clover systems was determined in the spring just prior to chemical termination and subsequent corn planting. Shoot material was clipped at ground level from three randomly located 0.25-$m^2$ quadrats in plots on 2 May 2011, 23 April 2012, and 6 May 2013. Upon clipping of red clover, replicate samples were combined, dried at 60ºC for at least 4 d, and weighed. Carbon and nitrogen concentration of red clover biomass was determined by the Iowa State University Soil and Plant Analysis Laboratory.

To determine fall stalk $NO_3$-N concentration, 20 cm sections of cornstalk sections were collected shortly after corn had reached physiological maturity but prior to grain harvest on 7 Oct. 2011, 15 Oct. 2012, and 29 Sept. 2013 from 15 randomly selected plants within each corn plot (Blackmer and Mallarino, 1996). The samples were dried and ground and stalk $NO_3$-N concentration was determined by the Iowa State University Plant and Soil Analysis Laboratory.

Grain yields of corn were determined from the central four rows (121 $m^2$) of each plot using a combine equipped with a grain tank on a load cell. Yields were adjusted to a moisture level of 155 g $kg^{-1}$.

The concentration of soil $NO_3$-N was determined to a depth of 30 cm. Soil samples were collected within 6 d of corn planting (at-plant sample) in April or May; 20 to 30 d after planting when corn was 15 to 30 cm high (LSNT sample); and after corn harvest in October or November (post-harvest sample). A minimum of four cores was taken and composited from each plot.

*Data analysis*

Crop and soil data were analyzed with mixed-effect models using the Fit Model procedure in JMP Pro 10.0 statistical software (SAS Institute, Cary, NC, 2012). Analysis of variance was conducted with year, crop system, and their interaction considered as fixed factors while block was considered as a random factor. Mean separations among year × crop system combinations were conducted using two orthogonal contrasts by year: (i) the soybean system vs. the average of the wheat/clover and canola/clover systems and (ii) the wheat/clover system vs. the canola/clover system. A repeated measures approach was used to examine the effects of sampling date, crop system, and their interaction on soil $NO_3$-N concentrations in each year. Relationships between soil $NO_3$-N, red clover characteristics, corn stalk $NO_3$-N concentrations, and corn grain yield were examined using correlation analyses. The relationship between red clover biomass and N content of the biomass was further analyzed using a linear regression. Unless otherwise indicated, values were considered significant at $P \leq 0.05$.

## Results

*Climate*

Climatic conditions during the 2011-2013 corn growing seasons and how they compared to long-term (1951-2013) trends are shown in Figure 1 (Iowa Environmental Mesonet, 2013). In 2011, temperature and precipitation did not deviate from the long-term trends for much of the growing season. However, beginning in mid-August (DOY 230), predominantly dry conditions prevailed into the fall that year. The 2012 growing season was marked by above-normal temperatures and below-normal precipitation beginning in May (DOY 130). In 2013, the spring (DOY 90-160) was predominantly cooler and wetter than normally observed. The cooler temperatures prevailed into mid-August (DOY 235) after which above-normal temperatures were observed. Predominantly dry conditions prevailed for much of the summer growing season in 2013, beginning in June (DOY 160).

Precipitation occurred throughout the spring (DOY 90-150) at normal levels in 2011 and above-normal levels in 2012 and 2013 (Fig. 1), indicating that soil moisture conditions were likely not limiting decomposition and N mineralization potential of red clover residue. The number of DCD accumulated, which takes into account both temperature and moisture conditions, during the period between corn planting and the LSNT date (approx. 35 d) was least in 2012 (6.2), intermediate in 2011 (10.9), and greatest in 2013 (14.5).

*Red clover green manure in the wheat/clover and canola/clover treatments*

In the wheat/clover and canola/clover treatments, red clover was grown as a green manure before corn. Red clover was frost-seeded into both treatments at the time of winter wheat and winter canola green-up in the year prior to the corn phase. Red clover aboveground biomass, N concentration, N content, C concentration, C content, and C:N ratio were mostly not affected by winter wheat or winter canola but were affected by year (Table 2). Across all years and in both treatments, red clover aboveground biomass production and N content was similar to those recorded in experiments in Michigan (Tiffin and Hesterman, 1998) and Ontario (Vyn et al., 2000) where clover was established with winter wheat but was less than that recorded in an experiment in Iowa (Liebman et al., 2012) where clover was established with oats (*Avena sativa* L.). In the present study, red clover produced the most aboveground biomass ($P < 0.0001$), had the greatest N content ($P < 0.0001$), and had the greatest C content ($P < 0.0001$) in 2012 compared to 2011 and 2013 (Table 2). This reflects the above-normal temperatures in spring 2012 (DOY 90-160) (Fig. 1) which caused the clover to green up earlier than in other years and resulted in a greater accumulation of heat units (results not shown) and subsequent biomass production by the clover prior to chemical termination and corn planting. Indeed, red clover N content was strongly correlated with aboveground biomass in all years (2011: $r$ = 0.8786, $P$ = 0.0041; 2012: $r$ = 0.9834, $P$ < 0.0001; 2013: $r$ = 0.7553, $P$ = 0.0302) (Table 2). Because of these strong correlations, regression analysis was used to further explore the relationship across systems and across years. Regression analysis showed a strong linear response of red clover N content to aboveground biomass (Fig. 2).

Red clover C:N ratio did not differ between the two treatments or among years (Table 2) and fell within the range considered suitable for net N mineralization by microbial decomposition under adequate soil environmental conditions (Bruulsema and Christie, 1987). Across all years and both treatments, red clover C:N ratio was negatively correlated with N concentration ($r$ = -0.7810, $P$ < 0.0001) and N content ($r$ = -0.4770, $P$ = 0.0184) but was not correlated with C concentration ($r$ = 0.2423, $P$ = 0.2539) or C content ($r$ = -0.3175, $P$ = 0.1305) (Table 2).

*Soil N dynamics in corn*

Repeated measures analysis determined that the effect of sampling date on soil $NO_3$-N concentration differed for each preceding crop treatment each year (Table 3). It is important to note that all treatments received the same amount of manure N in each year while the amount of fertilizer N applied after the LSNT sampling date differed by year (Table 1). In 2011, each treatment received the same amount of fertilizer N (102 kg N $ha^{-1}$); in 2012 the red clover green manure systems received more fertilizer N than the soybean system (102 vs. 68 kg N $ha^{-1}$); and in 2013 the red clover green manure systems received less fertilizer N than the soybean system (68 vs. 102 kg N $ha^{-1}$) (Table 1). In 2011, soil $NO_3$-N concentration did not differ across the sampling dates for any of the treatments (Table 3). In 2012 and 2013, soil $NO_3$-N concentration following soybean tended to be greatest at the LSNT date, whereas concentrations in the wheat/clover and canola/clover treatments tended to increase through the season (Table 3). These patterns observed in the wheat/clover and canola/clover treatments in 2012 and 2013 reflect those of previous studies that noted greater soil $NO_3$-N concentrations late in the season compared to early in the season as a result of legume green manures in no-till corn systems (Huntington et al., 1985; Groffman et al., 1987).

Soil $NO_3$-N concentrations for the at-planting sampling date were affected by both year and preceding crop; concentrations for the LSNT and post-harvest dates were affected by the interaction between year and preceding crop (Table 3). Greatest soil $NO_3$-N concentrations at the time of corn planting occurred in 2011, and across years, concentrations were similar after soybean and wheat/clover and least after canola/clover (Table 3).

There was no difference in soil $NO_3$-N concentration in LSNT samples among preceding crop treatments in 2011; the soybean treatment had the greatest concentration in 2012; and the red clover green manure treatments had the greatest concentration in 2013 (Table 3). Moreover, greatest soil $NO_3$-N soil concentrations in the LSNT samples for corn following wheat/clover and canola/clover occurred in 2013. For the post-harvest sampling date, soil $NO_3$-N concentrations were similar among treatments in 2011 and greatest when corn followed wheat/clover and canola/clover in 2012 and 2013 (Table 3).

*Cornstalk nitrate concentration*

Cornstalk $NO_3$-N concentration at physiological maturity differed among years and preceding crop treatments but the year × crop system interaction was not significant (Table 4). With respect to reaching corn yield potential, corn stalk $NO_3$-N concentration is considered deficient at < 250 mg $NO_3$-N $kg^{-1}$, marginal at 250-700 mg $NO_3$-N $kg^{-1}$, optimal at 700-2000 mg

$NO_3$-N $kg^{-1}$, and excessive at > 2000 mg $NO_3$-N $kg^{-1}$ (Blackmer and Mallarino, 1996). In each year, stalk $NO_3$-N concentration was least for corn following soybean while concentrations were similar for corn following either wheat/clover or canola/clover (Table 4). Across preceding crop treatments, greatest stalk $NO_3$-N concentrations were observed in 2011 with concentrations from each treatment in the optimal category. In 2012, stalk concentrations for corn following wheat/clover and canola/clover were in the marginal category while stalk concentration after soybean was considered low. Low levels were observed from each of the treatments in 2013. Stalk nitrate concentrations were negatively correlated with LSNT soil $NO_3$-N concentrations in 2011 ($r$ = -0.57, $P$ = 0.0516) and 2012 ($r$ = -0.88, $P$ = 0.0002) with no significant correlations detected in 2013.

*Corn yields*

Corn yields were influenced by year, preceding crop, and the year × preceding crop interaction (Table 4). Greatest corn yields were observed in 2011 as periods of prolonged heat and drought conditions during the 2012 and 2013 growing seasons (Fig. 1) reduced corn yields those years below the 10-year Boone County average of 10.96 Mg $ha^{-1}$ (NASS, 2014). Corn yields following wheat/clover and canola/clover were similar in each year. Corn yields were negatively correlated with stalk $NO_3$-N concentrations in 2011 ($r$ = -0.86, $P$ = 0.0003) and 2012 ($r$ = -0.72, $P$ = 0.0080). Corn yields were positively correlated with LSNT soil $NO_3$-N concentrations ($r$ = 0.69, $P$ = 0.0130) but negatively correlated with post-harvest soil $NO_3$-N concentrations ($r$ = -0.59, $P$ = 0.0431) in 2012. No significant correlations with yield were detected in 2013.

## Discussion

The results of this study show that red clover green manure can be established with winter canola just as successfully as with winter wheat. Year was the strongest factor in determining red clover performance as biomass and C and N characteristics of red clover were equivalent when established with either winter canola or winter wheat (Table 2). Moreover, one can expect N inputs from the clover to increase linearly with biomass regardless of these two systems (Fig. 2). Results also show that legume green manures can replace synthetic forms of N fertilizer while maintaining corn yields, provided the occurrence of proper crop management and adequate climatic conditions as was demonstrated in 2013 when yields were similar across treatments despite the red clover green manure treatments receiving 34 kg N $ha^{-1}$ less fertilizer N than the soybean treatment. The drought conditions during the 2012 and 2013 growing seasons had pronounced effects on soil and plant N characteristics measured as well as corn yields. Drought conditions predominated following the side dressing of N fertilizer in 2012 (DOY 170) and 2013 (DOY 184) (Fig. 1) and likely prevented uptake of soil N by the corn late in the season. A substantial amount of plant-available soil N remained unused by the corn in those years, particularly in the wheat/clover and canola/clover systems. This was especially true in 2013 when the greatest soil $NO_3$-N concentrations were observed for the post-harvest sample (Table 3). As evidenced by the soil and stalk $NO_3$-N concentrations and corn yields observed, alignment between soil N availability and corn N uptake was never sufficiently achieved in the wheat/clover and canola/clover systems. The reason for this misalignment, however, differed among the years of this study.

In 2011, corn yields following wheat/clover and canola/clover treatments were equivalent but were both lower than yields when corn followed soybean (Table 4) despite corn in all treatments receiving equal amounts of side-dressed N fertilizer (Table 1) and experiencing similar soil $NO_3$-N dynamics through the growing season (Table 3). Stalk $NO_3$-N concentrations at maturity for corn after wheat/clover and canola/clover, however, exceeded those after soybean in that year (Table 4). Furthermore, stalk concentrations from all treatments fell within the optimum range for reaching corn yield potential (Blackmer and Mallarino, 1996). This suggests that N availability may not have been limiting and was not necessarily the cause for lower corn yields following wheat/clover and canola/clover compared to corn that followed soybean. Stalk $NO_3$-N concentrations were negatively correlated with LSNT soil $NO_3$-N concentrations ($r$ = -0.57, $P$ = 0.0516) and corn yields were negatively correlated with stalk $NO_3$-N concentrations ($r$ = -0.86, $P$ = 0.0003). Thus, it is likely that a substantial amount of N from the red clover became plant-available too late in the growing season for corn uptake in the wheat/clover and canola/clover treatments.

In 2012, corn yields were once again greater following soybean than when following wheat/clover and canola/clover (Table 4). In this year, however, the corn after wheat/clover and canola/clover received more synthetic N fertilizer as a side-dress application (102 vs. 68 kg N $ha^{-1}$; Table 1). This was recommended by Blackmer et al. (1997) owing to lower soil $NO_3$-N concentrations at the LSNT date following wheat/clover and canola/clover than corn after soybean (Table 3). Stalk $NO_3$-N concentrations at corn maturity were less than in 2011, but concentrations were once again greater after wheat/clover and canola/clover than those following soybean (Table 4). Just as in 2011, stalk $NO_3$-N concentrations were negatively correlated with LSNT soil $NO_3$-N concentrations ($r$ = -0.87, $P$ = 0.0002) and corn yields were negatively correlated with stalk $NO_3$-N concentrations ($r$ = -0.72, $P$ = 0.0080). Unlike in 2011, post-harvest soil $NO_3$-N concentrations were greater following wheat/clover and canola/clover than when following soybean (Table 3) and corn yields were negatively correlated with post-harvest soil

$NO_3$-N concentrations ($r$ = -0.59, $P$ = 0.0431) in 2012. With more N in the soil late in the season and more N in the stalk when the corn followed wheat/clover and canola/clover, this suggests N availability to the corn may not have been the limiting factor when it came to reduced yields in 2012 so much as the timing of its availability. Indeed, LSNT soil $NO_3$-N concentrations earlier in the year were greatest when following soybeans (Table 3) and corn yields were positively correlated with LSNT soil $NO_3$-N concentrations ($r$ = 0.69, $P$ = 0.0130). Thus, more N available to the corn earlier in the season in 2012 was the likely reason that corn yields were greater following soybean than the red clover green manures.

In both 2011 and 2012, the corn that followed wheat/clover and canola/clover was slower to emerge than the corn that followed soybean, though this was not explicitly measured in this study. In previous research involving no-till soils and spring chemical clover termination, Vyn et al. (2000) observed slow corn emergence patterns and reduced yields in one site-year when red clover was slower to desiccate compared to other site-years. Other researchers have also found slowed development and reduced yields of corn due to grass and legume cover crops. Teasdale and Mohler (1993) and Johnson et al. (1998) suggest this could be due to reduced soil temperatures by the cover crop at the time of corn planting. More recently, Acharya et al. (2017) documented an increase in root diseases of corn resulting from a winter rye (*Secale cereale* L.) cover crop terminated near the time of corn planting. In the present study, the red clover in the wheat/clover and canola/clover treatments was slow to desiccate prior to planting corn in 2011 and 2012 due to precipitation events and cool temperatures immediately following the application of herbicides that likely diminished the chemicals' activity on the clover. Along with delaying corn emergence, this also likely delayed the release of N from the clover residue resulting in asynchronous available N with corn N demand in the wheat/clover and canola/clover treatments those years. Furthermore, at-plant soil $NO_3$-N concentration was less following red clover green manure than it was following soybeans in each year (Table 3) and soil nitrogen deficiencies at the time of corn planting caused by cover crops have also been cited as possible reasons for reduced corn yields (Karlen and Doran, 1991; Tollenaar et al., 1993). Finally, Mitchell and Tell (1977) and Tollenaar et al. (1993) also cite reduced corn growth owing to the amount of cover crop biomass produced prior to termination and corn planting. Of the three years in the present study, 2011 and 2012 saw the most red clover biomass (Table 2) which in turn may have interfered with corn emergence and development those years.

In 2013, it is likely that more mineralization of N from red clover decomposition occurred earlier in the growing season than in 2011 or 2012 as a result of more successful chemical termination and subsequent desiccation of red clover in 2013. Conditions were conducive for herbicide activity at the time of chemical termination of the red clover in 2013 and corn yields did not differ among the sequences that year (Table 4). Moreover, the greatest accumulation of DCD between corn planting and the LSNT sample date occurred in 2013 (14.5) compared to 2011 (10.9) and 2012 (6.2). Ruffo and Bollero (2003) found that a hairy vetch (*Vicia villosa* Roth) legume green manure chemically terminated and left on the soil surface in the spring released approximately 67% of its aboveground N after the accumulation of 10 DCD in central Illinois. The hairy vetch in their study had produced approximately the same amount of aboveground biomass and N content prior to termination and corn planting as the red clover in the present study. The greatest accumulation of DCD in 2013 in the present study signaled the best climatic conditions for red clover N release between the time of termination and the LSNT sample among the three years. Furthermore, aboveground biomass of red clover was least in 2013 (Table 2). Steiner et al. (1999) found that the decomposition rate of legume green manures was inversely related to the amount of aboveground biomass at the time of termination. Thus, among the three years of the present study, the least amount of red clover aboveground biomass in the wheat/clover and canola/clover sequences coupled with the greatest accumulation of DCD in the spring of 2013 presented the best opportunity for N release from the clover by the time of the LSNT date. In fact, soil $NO_3$-N concentrations at the LSNT date for corn following wheat/clover and canola/clover were greatest in 2013 compared to 2011 and 2012 (Table 3). These soil $NO_3$-N concentrations for corn following wheat/clover and canola/clover at the LSNT date in 2013 resembled those in previous experiments where red clover preceded corn in rotation under no-tillage in Ontario (Vyn et al., 2000) and spring tillage in Iowa (Liebman et al., 2012). Stalk analysis at corn physiological maturity indicated low concentration levels of $NO_3$-N across all treatments in 2013; in fact, these were the lowest concentrations observed in any of the years (Table 4). Low stalk $NO_3$-N concentrations are generally the result of insufficient plant-available soil N (Blackmer and Mallarino, 1996). Post-harvest soil $NO_3$-N concentrations, however, were greatest for the corn after wheat/clover and canola/clover in 2013 (Table 3). They were also greater than those at the LSNT date for those treatments that year (Table 3). This suggests ample availability of soil N for the corn that followed wheat/clover and canola/clover albeit perhaps too late in the season to completely utilize the available N.

The greater amount of residual soil $NO_3$-N at the end of the 2013 growing season following corn preceded by wheat/clover and canola/clover suggests that the corn in those treatments may have had the potential to produce greater yields than corn that followed soybean if precipitation patterns had been closer to the long-term average that year (Fig. 1). Previous research in Iowa by Liebman et al. (2012) determined the N fertilizer replacement value of spring-tilled red clover green manure to corn ranged from 87 to 134 kg N ha$^{-1}$ in years where soil moisture conditions were adequate for the decomposition of the green manure. Less mineralization of N from legume residues is considered to occur with low- or no-tillage (as was used in the present study) compared to when residues are incorporated into the soil via tillage (Wilson and Hargrove, 1986; Rice et al., 1987; Varco et al., 1993; Dou et al., 1995). Yost et al. (2013), however, suggested that for corn grown under no-tillage that followed alfalfa in rotation, the LSNT might not adequately account for potential future available soil N. They further suggested that recommended side-dress N fertilizer rates could be lowered for corn under no-tillage following two to seven years of alfalfa. Because corn yields in this study were similar across all treatments in 2013 (Table 4), the red clover in the wheat/clover and canola/clover treatments likely accounted for the additional side-dressed 34 kg N $ha^{-1}$ of fertilizer N that corn following soybean received that year (Table 1). Substantial mineralization of plant-available N from the clover in the present study likely occurred early in the season in 2013, but dry conditions that predominated beginning in June (DOY 160) and continued through the remainder of the growing season (Fig. 1) prevented complete uptake of that N by the corn that followed the red clover green manures.

The results of this study showed that a red clover green manure can be successfully established with winter canola. Similar amounts of biomass, C and N were produced by red clover seeded with winter wheat or winter canola, suggesting either crop as a viable establishment strategy for red clover green manure. The results also reemphasize the importance of synchronicity between soil available N and corn N uptake for optimal corn yields. Replacing synthetic N applied to corn with N from green manures can be achieved provided environmental conditions for chemical desiccation and microbial decomposition of red clover residue occur. Incomplete termination of red clover green manure due to cool temperatures and rainfall that interfered with chemical desiccation resulted in lower corn yields than when corn followed soybean in rotation as was observed in this study in 2011 and 2012. The likely causes for these lower yields were the slowly desiccating red clover delaying corn emergence and the N from the decomposing red clover residue becoming available too late in the growing season for the corn to benefit from it. In 2013, corn yields across treatments were equivalent. Soil $NO_3$-N concentrations at the late-spring date that year were greater when corn followed wheat/clover and canola/clover and corn in these treatments received less fertilizer N as a side-dress application than corn that followed soybean. This corresponded with more favorable environmental conditions for red clover termination compared to the two previous years and, as such, in 2013 corn across all the treatments emerged at a similar rate. As a result of successful termination, red clover N became plant-available as the corn began a period of more rapid uptake from the soil replacing the need for synthetic N. Also in 2013, corn following wheat/clover and canola/clover appeared in plots that were in wheat/clover and canola/clover during the establishment year of 2010. A full cycle of the extended rotations (spring canola-winter wheat/red clover-corn and spring wheat-winter canola/red clover-corn) had thus been completed in 2013. This confirms the findings of Liebhardt et al. (1989), Liebman et al. (2008) and Davis et al. (2012) in that multiple cycles of an extended crop rotation featuring a legume green manure are necessary before N fertilizer can be reduced and corn yields maintained. Future research involving legume green manures in minimal tillage situations should explore means to increase soil N availability earlier in the growing season and within the first year of legume green manure inclusion in a cropping system.

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Table 1. Fertilizer and swine manure additions for corn grown in 2011-2013.

| System | 2011 | 2012 | 2013 |
|---|---|---|---|
| Soybean | 114 kg N $ha^{-1}$ + 34 kg P $ha^{-1}$ + 83 kg K $ha^{-1}$ as liquid swine manure before planting; 102 kg N $ha^{-1}$ as UAN†, side-dressed | Blocks 1 and 2: 114 kg N $ha^{-1}$ + 32 kg P $ha^{-1}$ + 78 kg K $ha^{-1}$ as liquid swine manure before planting; 68 kg N $ha^{-1}$ as UAN, side-dressed; Blocks 3 and 4: 114 kg N $ha^{-1}$ + 77 kg P $ha^{-1}$ + 83 kg K $ha^{-1}$ as liquid swine manure before planting; 68 kg N $ha^{-1}$ as UAN, side-dressed | 114 kg N $ha^{-1}$ + 36 kg P $ha^{-1}$ + 66 kg K $ha^{-1}$ as liquid swine manure and 26 kg N $ha^{-1}$ and 114 kg P $ha^{-1}$ as MAP‡ before planting; 102 kg N $ha^{-1}$ as UAN, side-dressed |
| Wheat/clover | 114 kg N $ha^{-1}$ + 34 kg P $ha^{-1}$ + 83 kg K $ha^{-1}$ as liquid swine manure before planting; 102 kg N $ha^{-1}$ as UAN, side-dressed | Blocks 1 and 2: 114 kg N $ha^{-1}$ + 32 kg P $ha^{-1}$ + 78 kg K $ha^{-1}$ as liquid swine manure before planting; 102 kg N $ha^{-1}$ as UAN, side-dressed; Blocks 3 and 4: 114 kg N $ha^{-1}$ + 77 kg P $ha^{-1}$ + 83 kg K $ha^{-1}$ as liquid swine manure before planting; 102 kg N $ha^{-1}$ as UAN, side-dressed | 114 kg N $ha^{-1}$ + 36 kg P $ha^{-1}$ + 66 kg K as liquid swine manure before planting; kg N $ha^{-1}$ as UAN, side-dressed |
| Canola/clover | 114 kg N $ha^{-1}$ + 34 kg P $ha^{-1}$ + 83 kg K $ha^{-1}$ as liquid swine manure before planting; 102 kg N $ha^{-1}$ as UAN, side-dressed | Blocks 1 and 2: 114 kg N $ha^{-1}$ + 32 kg P $ha^{-1}$ + 78 kg K $ha^{-1}$ as liquid swine manure before planting; 102 kg N $ha^{-1}$ as UAN, side-dressed; Blocks 3 and 4: 114 kg N $ha^{-1}$ + 77 kg P $ha^{-1}$ + 83 kg K $ha^{-1}$ as liquid swine manure before planting; 102 kg N $ha^{-1}$ as UAN, side-dressed | 114 kg N $ha^{-1}$ + 36 kg P $ha^{-1}$ + 66 kg K $ha^{-1}$ as liquid swine manure before planting; 68 kg N $ha^{-1}$ as UAN, side-dressed |

† UAN: urea ammonium nitrate.

‡ MAP: monoammonium phosphate.

Table 2. Aboveground biomass, biomass N and C concentrations, total N and C contents, and C:N for red clover in the spring just prior to chemical termination and corn planting. Biomass samples were collected on 2 May 2011, 23 April 2012, and 6 May 2013.

| Year<br>Previous crop | Biomass | N concentration | N content† | C concentration | C content† | C:N ratio |
|---|---|---|---|---|---|---|
| 2011 | kg ha$^{-1}$ | g N kg$^{-1}$ | kg N ha$^{-1}$ | g C kg$^{-1}$ | kg C ha$^{-1}$ | |
| Soybean | - | - | - | - | - | - |
| Wheat/clover | 1330 | 32.3 | 43 | 421.3 | 560 | 13.1 |
| Canola/clover | 1544 | 30.8 | 47 | 418.0 | 645 | 13.8 |
| 2012 | | | | | | |
| Soybean | - | - | - | - | - | - |
| Wheat/clover | 2080 | 34.6 | 72 | 404.7 | 841 | 11.7 |
| Canola/clover | 2650 | 35.7 | 92 | 410.0 | 1049 | 11.5 |
| 2013 | | | | | | |
| Soybean | - | - | - | - | - | - |
| Wheat/clover | 1153 | 30.4 | 35 | 364.8 | 422 | 12.0 |
| Canola/clover | 1120 | 28.0 | 31 | 370.2 | 415 | 13.5 |
| SE | 130 | 1.1 | 5 | 6.7 | 52 | 0.6 |
| Significance | | | | *P* value | | |
| Year (Y) | <0.0001 | 0.0003 | <0.0001 | <0.0001 | <0.0001 | 0.0385 |
| Previous crop (C) | 0.0552 | 0.3323 | 0.1214 | 0.6545 | 0.0417 | 0.2306 |
| Y × C | 0.1751 | 0.2956 | 0.0794 | 0.7609 | 0.1534 | 0.4225 |

† Content is calculated as the product of biomass and corresponding concentration.

Table 3. Soil $NO_3$-N concentration in the surface 30 cm at corn planting, in late-spring prior to any side-dressed N (LSNT), and post-harvest in 2011-2013.

| Year<br>Previous crop | At-plant† | LSNT‡ | Post-harvest§ |
|---|---|---|---|
| 2011 | ------------------------- mg NO3-N kg$^{-1}$ ------------------------- | | |
| Soybean | 11.75 aA¶ | 9.50 aA | 9.88 aA |
| Wheat/clover | 10.63 abA | 8.25 aA | 8.83 aA |
| Canola/clover | 7.75 bA | 7.88 aA | 9.90 aA |
| 2012 | | | |
| Soybean | 4.78 abB | 11.38 aA | 4.98 bB |
| Wheat/clover | 5.48 aA | 7.75 bA | 8.54 aA |
| Canola/clover | 2.85 bB | 6.50 bA | 8.70 aA |
| 2013 | | | |
| Soybean | 9.58 aA | 6.50 bA | 4.39 bA |
| Wheat/clover | 6.43 abB | 12.00 aA | 15.36 aA |
| Canola/clover | 2.80 bC | 10.75 aB | 20.68 aA |
| SE | 2.12 | 1.06 | 1.42 |
| Significance | | *P* value | |
| Year (Y) | 0.0136 | 0.8273 | 0.3339 |
| Previous crop (C) | 0.0352 | 0.9038 | 0.2792 |
| Y × C | 0.8293 | 0.0011 | 0.0447 |

† 10 May 2011, 11 May 2012, and 21 May 2013.
‡ 13 June 2011, 12 June 2012, 26 June 2013.
§ 11 Nov. 2011, 30 Oct. 2012, and 27 Oct. 2013.
¶ Means followed by different lowercase letters within a column by year and uppercase letters within a row by previous crop are significantly different at $P \leq 0.05$.

Table 4. Corn stalk nitrate concentrations and corn grain yields from 2011-2013. Stalk samples were collected on 7 Oct. 2011, 12 Oct. 2012, and 29 Sept. 2013. Grain was harvested on 30 Sept. 2011, 15 Oct. 2012, and 12 Oct. 2013.

| Year<br>Previous crop | Corn stalk [$NO_3$-N] †,‡ | Corn grain yield |
|---|---|---|
| 2011 | mg $NO_3$-N $kg^{-1}$ | Mg $ha^{-1}$ |
| Soybean | 719 (6.3) b§ | 12.91 a |
| Wheat/clover | 1557 (7.2) a | 11.30 b |
| Canola/clover | 1800 (7.3) a | 10.78 b |
| 2012 | | |
| Soybean | 111 (4.6) b | 8.35 a |
| Wheat/clover | 499 (5.7) a | 6.23 b |
| Canola/clover | 564 (6.3) a | 6.43 b |
| 2013 | | |
| Soybean | 48 (3.5) b | 7.35 a |
| Wheat/clover | 98 (4.2) a | 7.93 a |
| Canola/clover | 209 (4.9) a | 7.45 a |
| SE | (0.4) | 0.32 |
| Significance | *P* value | |
| Year (Y) | <0.0001 | <0.0001 |
| Previous crop (C) | 0.0009 | <0.0001 |
| Y × C | 0.1812 | 0.0017 |

† With respect to reaching corn yield potential, corn stalk $NO_3$-N concentration is considered low at < 250 mg $NO_3$-N $kg^{-1}$, marginal at 250-700 mg $NO_3$-N $kg^{-1}$, optimal at 700-2000 mg NO3-N $kg^{-1}$, and excessive at > 2000 mg $NO_3$-N $kg^{-1}$ (Blackmer and Mallarino, 1996).

‡ Data were log(x)-transformed before analysis of variance. Means and standard errors of transformed data are shown in parentheses.

§ Means followed by different lowercase letters within a column by year are significantly different at $P \leq 0.05$.

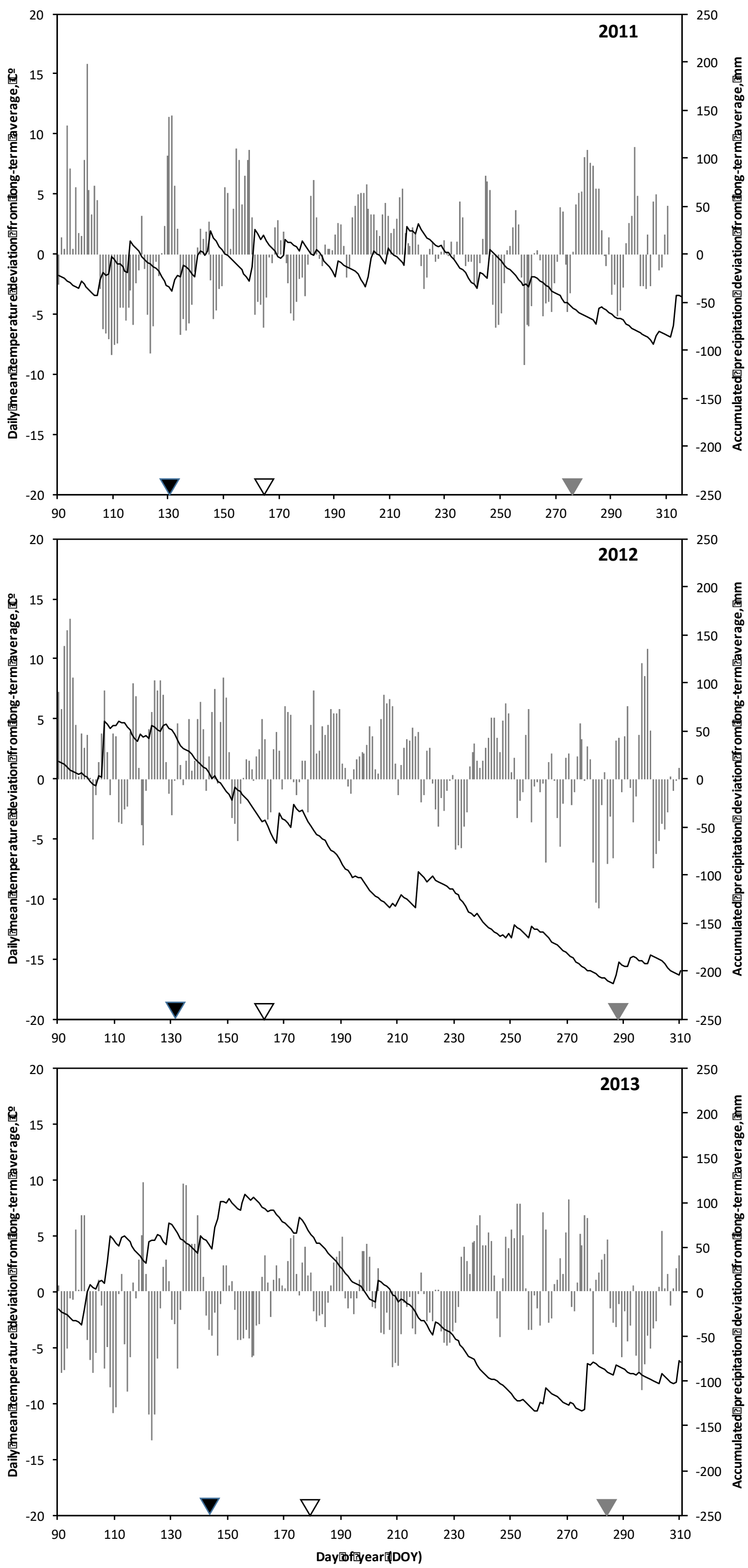


Figure 1. Deviation from the long-term (1951-2013) average in daily mean temperature (vertical bars) and accumulated precipitation (continuous line) during the 2011-2013 growing seasons near Ames, IA. Daily air temperature and precipitation were recorded at a weather station located 3.2 km from the experimental site. ▼ indicates date of corn planting; ∇indicates date of LSNT sample; ▼ indicates date of corn grain harvest.

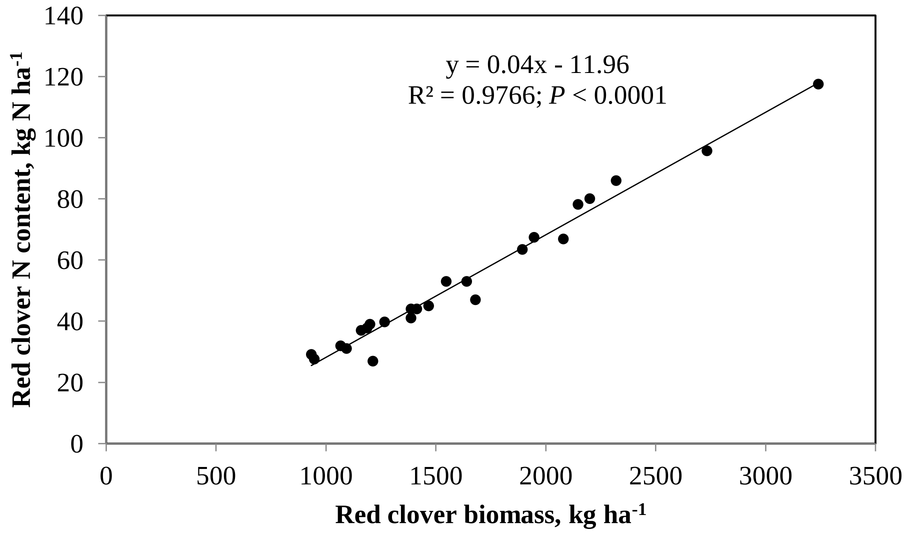


Figure 2. Linear regression and prediction equation for red clover N content response to aboveground biomass across the wheat/clover and canola/clover systems for 2011-2013.

# CHAPTER 3. COOL-SEASON CROPPING SEQUENCES FEATURING CANOLA AND WHEAT

A paper to be submitted to Field Crops Research

Stefans R. Gailans

## Abstract

When included in extended crop rotations, cool-season crops, such as canola (*Brassica napus* L.) and wheat (*Triticum aestivum* L.), and legume green manures, such as red clover (*Trifolium pratense* L.), exhibit beneficial environmental characteristics due to their extensive rooting systems and active growth habits during the fall and spring months. This chapter considers two cool-season crop sequences (spring canola-winter wheat/red clover vs. spring wheat-winter canola/red clover) over the course of three periods (2010-2011, 2011-2012 and 2012-2013) in central Iowa. These two-crop sequences were part of a larger study that compared three cropping systems: corn (*Zea mays* L.)-spring canola-winter wheat/red clover, corn-spring wheat-winter canola/red clover, and corn-soybean (*Glycine max* [L.] Merr.). The two canola-wheat sequences were selected to determine which would perform better in the context of a potential alternative, diverse crop rotation in the Upper U.S. Corn Belt. The winter varieties of canola and wheat consistently out-yielded the spring counterparts. When combined within a sequence, canola+wheat yields for each sequence were equivalent for each of the three periods. Canola oil content and wheat protein concentration were consistently superior in the spring wheat-winter canola/red clover sequence. Across all periods, red clover aboveground biomass production, C concentration, and N concentration following the harvest of the winter crop in both sequences was equivalent for the two crop sequences at the end of the growing season. Weed

biomass observed in the two sequences was generally equivalent, but across the sequences, the canola crops were weedier than the wheat crops. Ultimately, the superiority of either sequence is probably best determined by a grower's goals, which could include maximum grain or straw production or grain quality and oil production.

## Introduction

Crop rotations that include cool-season crops with corn and soybeans have been shown to improve productivity, profitability and environmental quality in the Upper U.S. Corn Belt (Davis et al., 2012; Cambardella et al., 2015; Hunt et al., 2017). Diversifying corn-soybean production systems in this region to include cool-season crops such as small grains and legume green manures can reduce nutrient leaching potential and improve soil quality. Studies comparing corn-soybean and corn-soybean-oat+legume cropping systems in northeast Iowa (Kanwar et al., 2005) and central Iowa (Tomer and Liebman, 2014) have shown reduced concentrations of nitrate in drainage water and soil solution in the extended system during the growing season, thus reducing the potential for nitrate losses through leaching. These same studies also reported that extended rotations with cool-season grain crops and legume green manures improved yields of corn and soybean relative to rotations only containing corn and soybean (Kanwar et al., 2005; Liebman et al., 2008; Davis et al., 2012).

Cool-season crops and legume green manures can serve as ideal cover crops in crop rotations in the northern Corn Belt. Cool-season crops, such as canola and wheat, exhibit beneficial cover crop characteristics. Due to their extensive rooting systems and active growth habits during the fall and spring months, cool-season crops can reduce soil erosion (Kessavalou and Walters, 1997) and nitrate leaching (Strock et al., 2004; Kaspar et al., 2007; Qi and Helmers, 2010; Qi et al., 2011; Kaspar et al., 2012). In addition to improved soil nutrient management, legume green manures contribute to reducing soil erosion (Hussain et al., 1988), increasing soil organic matter (Reicosky and Forcella, 1998), and improving weed management (Buhler et al., 1998).

Despite the promising results of the research findings outlined above, the absence of cool-season crops on the northern Corn Belt farming landscape prevails. According to the most recent Census of Agriculture (USDA, 2014), of the 10.5 million hectares of cropland in Iowa, cover crops were seeded onto only approximately 162,000 hectares in 2012. Cropland dedicated to small grains and hay (cool-season crops) production collectively in 2012 amounted to nearly 405,000 hectares (USDA, 2014).

In 2010, three crop rotations were established in central Iowa as part of a cropping systems experiment. Two of these systems represent extended rotations with cool-season crops that may be suitable to the region: a three-year, spring canola-winter wheat/red clover-corn rotation and a three-year spring wheat-winter canola/red clover-corn rotation. A two-year, soybean-corn rotation was also included as it is typical of cash grain farming systems in the Midwest United States. This chapter primarily concerns the spring crop-winter crop/red clover sequences of the two three-year rotation systems for the periods 2010-2011, 2011-2012 and 2012-2013. These cropping sequences were designed to determine the best combination of wheat, canola and red clover in terms of wheat and canola yield and quality, red clover aboveground biomass and C and N characteristics, and weed aboveground biomass.

## Materials and Methods

*Plot background, experimental design, and crop management*

The experiment was conducted during 2010-2013 at the ISU Agronomy and Agricultural Engineering Farm located in Boone County, IA (42°0' N; 93°0' W; 354 m above sea level). Predominant soils at the site are Clarion loam (fine-loam, mixed, superactive, mesic Typic Hapludolls) and Webster silty clay loam (fine-loamy, mixed, superactive, mesic, Typic Endoaquolls). Soil samples collected to a depth of 15 cm in the fall of 2009 indicated a mean P concentration (via Bray-1 procedure) of 6 mg $kg^{-1}$, a mean K concentration (via Mehlich-3 extraction) of 115 mg $kg^{-1}$, a mean organic matter concentration (via combustion analysis) of 41 g $kg^{-1}$, a mean pH of 5.8, and a mean buffer pH of 6.5. The experiment was arranged in a randomized complete block design with four replications in the periods 2010-2011, 2011-2012, and 2012-2013. Plot size was 9 by 40 m. The experiment was established following soybean for the period 2010-2011 and corn for the periods 2011-2012 and 2012-2013. Weather data from within 4 km of the experimental site were compiled from the Iowa Environmental Mesonet for 2010, 2011, 2012, 2013, and the period 1950-2013.

The experiment consisted of two cropping sequences involving a spring annual crop followed by a winter annual crop in each period; all crops in both sequences were present each year. In one sequence, spring canola was followed by winter wheat (spring canola-winter wheat); in the other spring wheat was followed by winter canola (spring wheat-winter canola). On the basis of the results of soil tests, spring crop plots were fertilized with 137 kg P $ha^{-1}$ (as monoammonium phosphate), 114 kg K $ha^{-1}$ (as muriate of potash), and 417 kg lime $ha^{-1}$ (as calcium carbonate) and then tilled with a field cultivator to a 7-cm depth on 1 April 2010. Spring crop plots were fertilized at the time of planting with 57 kg N ha$^{-1}$ (as urea) on 1 April 2010, 1 April 2011, and 28 March 2012.

Dates of field operations are presented in Table 1. Spring canola (‘Pioneer 45H73’) was seeded at 8 kg pure live seed (PLS) ha$^{-1}$ and spring wheat (‘Faller’) was seeded at 130 kg PLS ha$^{-1}$ both in 19-cm rows following fertilization and tillage (in 2010 and 2012 only) in late March or early April each year. The intent of the study was to not use herbicides, but spring canola plots received a single postemergence application of imazamox (0.14 kg a.i. ha$^{-1}$) on 25 May 2012 due to poor crop establishment and subsequent weed infestation. Excepting this application, plots did not receive any herbicide applications. Both spring crops were harvested for grain in mid-July with straw removed from spring wheat plots shortly following grain harvest each year. Prior to planting winter crops, spring crop stubble was mowed one or two times to control weeds.

Winter crops were fertilized with 24 kg N ha$^{-1}$ (as urea), and on the basis of soil test results, 91 kg P ha$^{-1}$ (as triple super phosphate) and 91 kg K ha$^{-1}$ (as muriate of potash) before planting each year. Both winter crops were fertilized the following year in March just before spring green up with an additional 34 kg N ha$^{-1}$ (as urea). Winter canola (‘Sitro’) was planted in early September each year following spring wheat grain and straw harvest, stubble mowing, and tandem disk tillage. Winter canola was seeded at 10 kg PLS ha$^{-1}$ in 19-cm rows. Winter wheat (‘Expedition’) was planted in early October each year following spring canola harvest, stubble mowing, and disk tillage. Winter wheat was seeded in 19-cm rows at 159 kg PLS ha$^{-1}$ in 2010 and 128 kg PLS ha$^{-1}$ in 2011 and 2012. Additionally, both winter crops were interseeded with red clover at 23 kg seed ha$^{-1}$ at the time of spring N application. Red clover was interseeded with a broadcast seeder and was managed as a green manure cover crop for the remainder of the growing season following winter crop harvest. Winter wheat and winter canola were combine harvested in June or July (Table 1). Straw was removed from winter wheat plots shortly following grain harvest.

*Crop and soil sampling and data analysis*

Upon emergence of winter wheat and winter canola in the fall, stands were determined by counting the number of plants along six randomly selected one-meter row lengths in each plot. After allowing time for new spring growth the following year, this same procedure was conducted in order to determine the percentage of plants that survived the winter.

Grain yields of spring wheat and winter wheat were determined from the central 24 rows (180 $m^2$) of each plot using a combine equipped with a grain tank on a load cell. Spring canola and winter canola were hand-harvested from three randomly placed quadrats (0.25 $m^2$) in each plot just prior to machine harvest. Upon hand-harvest, samples were placed in paper bags and air-dried for at least 5 d. After drying, canola seed was threshed using a stationary thresher and then hand-sieved and weighed. Yields of spring wheat and winter wheat straw were determined by weighing bales harvested from each individual plot. Grain yields were adjusted for moisture levels of 100 g $kg^{-1}$ for spring and winter canola, 130 g $kg^{-1}$ for spring and winter wheat, and 110 g $kg^{-1}$ for straw. Protein and oil concentration of spring and winter canola grain was determined by calibrated near infrared spectroscopy at the University of Minnesota in St. Paul, MN. Protein concentration of spring and winter wheat grain was determined by calibrated near infrared spectroscopy at the Iowa State University Grain Quality Lab.

Aboveground biomass of red clover interseeded with winter wheat and winter canola was determined at the time of winter wheat and winter canola harvest (at-harvest sample) by clipping shoot material at the ground level from three randomly located 0.25-$m^2$ quadrats in each plot on

5 July 2011, 19 June 2012, and 10 July 2013. Upon clipping of red clover, samples were composited within plots, dried at 60ºC for at least 4 d, and weighed. End-of-season aboveground biomass of red clover was determined in the same manner on 11 Nov. 2011, 9 Nov. 2012, and 10 Nov. 2013. The C and N concentrations of red clover biomass were determined by the Iowa State University Soil and Plant Analysis Laboratory.

*Weed sampling*

Aboveground weed biomass was determined by clipping all non-crop shoot material at ground level from three 0.25-$m^2$ quadrats in each plot near the time of grain harvest. In spring crop plots, this occurred on 4 Aug. 2010 after grain harvest and on 20 July 2011 and 12 July 2012, just prior to grain harvest. In winter crop plots, this occurred on 5 July 2011, 19 June 2012, and 10 July 2013, just prior to grain harvest. Upon clipping, samples were composited within plots and weed shoot material was separated by grasses and broadleaves, placed in a forced-air oven at 60ºC until dry, and weighed.

*Statistical analysis*

Crop, soil, and weed data were analyzed with mixed-effect models in the Fit Model procedure of JMP 10.0 statistical software (SAS Institute, Cary, NC 2012). Analysis of variance was conducted with period, crop sequence, and their interaction considered fixed factors while block was considered a random factor. Mean separations among crop sequence × period combinations were assessed using linear contrasts. Unless otherwise indicated, values were considered significant at $P < 0.10$.

## Results and Discussion

### *Climate*

Climatic conditions during the 2010-2013 growing seasons and how they compared to long-term (1893-2013) trends are shown in Table 2 (Iowa Environmental Mesonet, 2016). Monthly temperatures for the spring and winter crop phases in the periods 2010-2011, 2011-2012, and 2012-2013 did not tend to deviate from the long-term average. While the mean temperature in March 2012 was 9ºC above average, temperatures for the remainder of that year were similar to the long-term average. In the spring crop phase of each crop sequence, total precipitation was greatest in 2010 and least in 2012 for the period of April-July. Total precipitation for June and July in the spring crop phase of each crop sequence was 457 mm in 2010 compared to 227 mm in 2011 and 112 mm in 2012. Excessive precipitation continued after harvest and into August 2010 resulting in mild flooded conditions for several days that month. In the winter crop phase of each crop sequence, total precipitation was least in 2011-2012 for the periods September-October and March-June. This was especially true during the establishment period of the winter crop as total precipitation for September and October was 73 mm in 2011 compared to 179 mm in 2010 and 106 mm in 2012. Below average monthly precipitation totals began in August 2011 and continued for the majority of 2012 resulting in extremely dry conditions. While total precipitation for September-October in 2012 was below average, total precipitation in March-June 2013 was above average. For the months of April, May, and June during the final winter crop phase of each crop sequence, total precipitation was 404 mm in 2013 compared to 356 mm in 2011 and 259 mm in 2012.

*Crop yields*

The winter crops in both crop sequences sufficiently overwintered in each of the periods. Winter wheat survival rate averaged 95%; winter canola survival rate tended to vary across the periods: 89% (2010-2011); 93% (2011-2012); 42% (2012-2013) (data not shown).

Canola yields were greater in the spring wheat-winter canola sequence ($P$ = 0.0014) while wheat yields were greater in the spring canola-winter wheat sequence ($P$ = 0.0003) across periods (Table 3). This is not surprising as winter varieties of canola and wheat tend to possess greater yield potential than their spring variety counterparts (Terman et al., 1979; Brown et al., 2007). In the two sequences studied, winter canola and winter wheat were always planted following spring wheat and spring canola, respectively. Spring canola and spring wheat were planted following soybean for the 2010-2011 period and corn for the 2011-2012 and 2012-2013 periods. Johnston et al. (2002) and Kirkegaard et al. (2008) both describe superior wheat yields when following *Brassica* crops (such as canola) compared to other grass or cereal crops. Tanaka et al. (2007) saw no difference in canola yields following wheat compared to corn. In the present study, winter canola did tend to establish better following wheat than the spring canola did following corn (data not shown). This was especially true for the spring canola in 2012-2013 period which suffered from very poor emergence through corn residue and very likely contributed to low yield (Table 3). Winter canola followed spring wheat, but after straw removal and light disking, which might have resulted in a less stressful environment for the seedling to emerge from compared to the spring canola seedlings emerging through corn residue.

Wheat straw yields were generally greater in the spring canola-winter wheat sequence except for the 2010-2011 period resulting in the period × crop sequence interaction (Table 3). The 2010-2011 period resulted in the least amount of harvested straw from wheat in the spring canola-winter wheat sequence among all the periods. The 2010-2011 period was also the only instance in which straw yield was greater in the spring wheat-winter canola sequence than in the spring canola-winter wheat sequence (Table 3). This was attributed to a large amount of growth by the interseeded red clover in the winter wheat in the spring canola-winter wheat sequence in 2011, which necessitated cutting the wheat higher above the soil surface for harvest than in other periods.

When combining grain yields of canola+wheat for both sequences, period had an effect but neither sequence nor the interaction had an effect (Table 3). Combined yields for both sequences were greatest for the 2010-2011 period. Regardless of sequence, combined yields of canola+wheat were equivalent.

*Yield quality*

Canola grain protein and oil concentration were influenced by the period × crop sequence interaction (Table 4). Excepting the 2010-2011 period, canola in the spring canola-winter wheat sequence had a higher concentration of protein in the grain compared to the canola in the spring wheat-winter canola sequence. In oilseed crops like canola, protein and oil concentration in the grain are inversely related (Brennan et al., 2000; Rathke et al., 2005; Gao et al., 2010). In the present study, canola in the spring wheat-winter canola sequence had a higher concentration of oil, save for the 2010-2011 period. Oil content was calculated as the product of canola grain yield and canola grain oil concentration. Both period ($P$ = 0.0014) and sequence ($P$ = 0.0044) significantly affected oil content of canola (Table 4). Greatest oil contents were recorded in the 2010-2011 period. The spring wheat-winter canola sequence always produced more canola oil than the spring canola-winter wheat sequence. This was true even though canola grain yields

(Table 3) and oil concentrations (Table 4) were not always significantly greater in the spring wheat-winter canola sequence across the periods. Only when these two variables were considered together to calculate oil content was the spring wheat-winter canola sequence consistently superior.

Wheat grain protein concentration was affected by the sequence and period × crop sequence interaction (Table 4). Wheat protein concentration was consistently greater for the spring wheat-winter canola sequence with the 2011-2012 period likely accounting for the significant interaction. In that period, wheat protein concentration for the spring wheat-winter canola sequence exceeded that for the spring canola-winter wheat sequence by 43 g $kg^{-1}$ compared to 21 g $kg^{-1}$ in 2010-2011 and 31 g $kg^{-1}$ in 2012-2013. Spring wheat varieties were shown to have higher grain protein concentrations than winter varieties (Fowler, 2003). This is primarily owing to the higher grain yield potentials of winter varieties and the negative relationship between grain yield and protein concentration (Terman et al., 1969; Terman, 1979). In the present study, wheat in the spring canola-winter wheat sequence consistently out-yielded wheat in the spring wheat-winter canola sequence (Table 3) with the reverse being true for grain protein concentration (Table 4). Both wheat varieties selected for this study (‘Faller’ spring wheat; ‘Expedition’ winter wheat) are classified as hard red wheat varieties. Protein concentration is important for the marketability of the wheat. For the purposes of bread making, bakers generally desire a protein concentration of at least 120 g $kg^{-1}$ in the wheat grain (Mallory et al., 2012). The wheat in the spring wheat-winter canola sequence consistently made this protein concentration level, while the wheat in the spring canola-winter wheat sequence consistently fell short (Table 4).

*Red clover aboveground biomass*

Red clover was interseeded into the winter crops in both crop sequences in March at the same time of N fertilizer application. Red clover aboveground biomass production by the time of winter crop harvest in June-July was affected by crop sequence (Table 5). More red clover biomass was produced by the time of winter crop harvest in the spring wheat-winter canola sequence compared to the spring canola-winter wheat sequence. By the end of the season in November, only the effect of period on red clover aboveground biomass was significant (Table 5). The least amount of red clover biomass was observed in the 2011-2012 sequence coinciding with recorded precipitation levels far below the long-term average for 2012 (Table 2). Irrespective of period, red clover aboveground biomass production by the end of the season was equivalent for the two crop sequences. Red clover biomass production by the end of the season in both sequences was similar to those observed following winter cereal grains in central Iowa by Blaser et al. (2006; 2007).

*Red clover C and N*

Neither red clover biomass C concentration nor N concentration was affected by the crop sequence but N concentration was affected by period (Table 5). Red clover biomass C:N ratio, however, was affected by both period ($P$ = 0.0018) and crop sequence ($P$ = 0.0083). When used as a green manure ahead of a succeeding cash crop, C:N ratio of red clover biomass is an important consideration for growers. Typically, a ratio greater than 25 results in net immobilization of soil inorganic N, while a ratio less than 25 is deemed suitable for N release by way of soil microbial decomposition (Tisdale et al., 1993; Dou et al., 1995; Seiter and Horwath, 2004). Regardless of period or sequence, red clover biomass C:N ratios were less than 25, with the spring wheat-winter canola sequence consistently producing a lesser ratio (18.0 vs. 19.3) (Table 5). Red clover biomass C:N ratios at the end of the growing season in mid-November were similar to those observed by Bruulsema and Christie (1987) in south-central Ontario, Vyn et al. (2000) in south-central Ontario, and Liebman et al. (2012) in northeast Iowa.

*Weed biomass*

Weed biomass was assessed just prior to harvest of each crop in both crop sequences. Predominant weed species observed included foxtail (*Setaria* spp.), common lambsquarters (*Chenopodium album* L.), common waterhemp (*Amaranthus rudis* Sauer), and smartweed (*Polygonum* spp.). Weed biomass comparisons were made separately between the two spring crops of both sequences and the two winter crops of both sequences. Additionally, total weed biomass observed across each period was compared between the two sequences.

The period × crop sequence interaction affected grass weeds more so than broadleaf weeds for both the spring and winter crops in the sequences (Table 6). Between the two sequences, grass weeds were more prevalent in canola than wheat. Generally, broadleaf weed biomass did not differ between the two spring crops or the two winter crops in the sequences. Spring canola generally had more total weed biomass than spring wheat and winter canola always had more weed biomass than winter wheat. When weed biomass was combined across both crops for both sequences, the sequences differed only in the 2010-2011 period. During that period, more total weed biomass was observed in the spring canola-winter wheat sequence than in the spring wheat-winter canola sequence (Table 6). Overall, weed biomass between the two sequences was generally equivalent, but across the sequences the canola crops were weedier than the wheat crops.

Though no chemical weed management was originally intended, poor seedling emergence of spring canola in 2012 necessitated a rescue application of postemergence herbicide. This was also the only year in which weed biomass was equivalent between spring canola and spring wheat. As such, because spring canola tended to be less naturally competitive with weeds than spring wheat, a higher level of weed management is probably required for spring canola. As stated earlier, the red clover interseeded with the winter canola and winter wheat phases in both sequences precluded chemical weed management for those crops. However, because grass weeds were particularly more problematic for winter canola compared to winter wheat, an herbicide specific to grass weeds may have in fact been an option in retrospect.

## Conclusion

This experiment evaluated two cropping sequences that mirrored each other: spring wheat-winter canola and spring canola-winter wheat. Over the course of three periods included in this study, the cropping sequences were equivalent in terms of total Mg grain $ha^{-1}$ produced when combining canola+wheat yields (Table 3). Likewise, the amount of biomass and N produced by the red clover green manure interseeded with the winter crops in the two sequences were equal for each period (Table 6). This is especially important because corn is the intended crop to succeed the red clover green manure for both sequences. The canola phases of both sequences tended to result in more grass weed biomass than the wheat phases, but total weed biomass for the two sequences was similar in two of the three periods (Table 7). As such, grass-specific chemical weed control may need to be a serious consideration for spring or winter canola production in Iowa.

The spring wheat-winter canola sequence produced more canola grain and oil than the spring canola-winter wheat sequence (Tables 3 and 4, respectively). The spring canola-winter wheat sequence did typically produce more wheat grain and straw (Table 3), however, the wheat in the spring wheat-winter canola sequence always possessed a higher concentration of protein (Table 5). Moreover, the wheat in the spring wheat-winter canola sequence consistently exceeded the minimum protein concentration deemed suitable for bread baking (120 g $kg^{-1}$; Mallory et al., 2012). Canola is typically grown for its oil, while protein concentration for bread baking is a major consideration for hard red wheat. If these yield quality characteristics (oil and protein) are paramount, then the spring wheat-winter canola sequence should is superior to the spring canola-winter wheat sequence. If, however, total grain and straw produced in a period is of most importance, then the superior sequence is likely the one that can net the greater financial returns. In this case, a grower would do well to plan a cropping sequence consisting of canola and wheat with regard for expected crop prices based on the results above. For instance, if canola is worth considerably more than wheat, the sequence with maximum potential for canola production could be considered superior, and vise-versa.

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Table 1. Chronology of field operations from 2010-2013, Boone County, IA.

| Field operation | Period 1 (2010-2011) | Period 2 (2011-2012) | Period 3 (2012-2013) |
|---|---|---|---|
| Spring crop N fertilizer applied | April 1, 2010 | April 1, 2011 | March 28, 2012 |
| Disk tillage | -- | -- | March 28, 2012 |
| Spring crops planted | April 1, 2010 | April 1, 2011 | March 29, 2012 |
| Spring crops harvested | July 14, 2010 | July 26, 2011 | July 12, 2012 |
| Spring wheat straw baled | July 14, 2010 | July 26, 2011 | July 16, 2012 |
| Spring crop stubble mowing | August 16, 2010 | August 9, 2011 | August 6, 2012 |
| Winter crop fertilizer applied | Aug. 31, 2010; March 2, 2011 | Sept. 7, 2011; March 9, 2012 | Sept. 6, 2012; April 2, 2013 |
| Disk tillage | September 7, 2010 | September 7, 2011 | September 6, 2012 |
| Winter canola planted | September 8, 2010 | September 7, 2011 | September 6, 2012 |
| Winter wheat planted | September 30, 2010 | September 30, 2011 | October 1, 2012 |
| Red clover interseeded | March 2, 2011 | March 9, 2012 | March 28, 2013 |
| Winter crops harvested | July 7, 2011 | June 29, 2012 | July 12, 2013 |
| Winter wheat straw baled | July 7, 2011 | July 2, 2012 | July 12, 2013 |

Table 2. Total monthly precipitation and air temperature in 2010–2013 and long-term averages (1950–2013), at the experimental site.

| | Total monthly precipitation (mm) | | | | | Mean monthly air temperature (ºC) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | 2010 | 2011 | 2012 | 2013 | Long-term avg. | 2010 | 2011 | 2012 | 2013 | Long-term avg. |
| January | 28 | 18 | 7 | 15 | 20 | -10 | -9 | -2 | -5 | -7 |
| February | 19 | 33 | 44 | 20 | 24 | -9 | -4 | -1 | -4 | -5 |
| March | 55 | 20 | 60 | 38 | 45 | 3 | 3 | 11 | -1 | 2 |
| April | 93 | 111 | 122 | 148 | 82 | 14 | 10 | 13 | 8 | 10 |
| May | 92 | 117 | 62 | 180 | 112 | 16 | 16 | 19 | 16 | 16 |
| June | 284 | 128 | 75 | 76 | 123 | 22 | 22 | 23 | 21 | 21 |
| July | 173 | 99 | 37 | 26 | 93 | 24 | 26 | 26 | 23 | 24 |
| August | 285 | 91 | 74 | 55 | 101 | 24 | 23 | 22 | 23 | 22 |
| September | 167 | 51 | 47 | 30 | 91 | 18 | 17 | 18 | 20 | 18 |
| October | 12 | 22 | 59 | 64 | 61 | 13 | 13 | 10 | 11 | 11 |
| November | 58 | 68 | 23 | 35 | 39 | 4 | 5 | 5 | 2 | 3 |
| December | 20 | 57 | 26 | 9 | 27 | -6 | -1 | -2 | -8 | -4 |

Table 3. Yields of canola, wheat grain and wheat straw from both crop sequences for periods 2010-2011, 2011-2012, and 2012-2013.

| Source of variation | Canola | Wheat | Wheat straw | Canola + wheat |
|---|---|---|---|---|
| Period | ---------- | ---------- | Mg ha$^{-1}$ | ---------- |
| Crop sequence | | | | |
| 2010-2011 | | | | |
| Spring canola-winter wheat | 1.9 b† | 3.6 a | 1.0 b | 5.5 |
| Spring wheat-winter canola | 2.5 a | 2.4 b | 2.4 a | 4.9 |
| 2011-2012 | | | | |
| Spring canola-winter wheat | 1.0 b | 3.3 a | 1.6 a | 4.3 |
| Spring wheat-winter canola | 1.6 a | 2.3 b | 1.0 b | 3.9 |
| 2012-2013 | | | | |
| Spring canola-winter wheat | 0.1 b | 2.8 a | 1.2 a | 2.9 |
| Spring wheat-winter canola | 1.7 a | 2.1 b | 0.9 b | 3.8 |
| SE | 0.2 | 0.2 | 0.1 | 0.3 |
| Significance | | | *P* value | |
| Period (P) | 0.0039 | 0.0376 | 0.0008 | 0.0017 |
| Crop sequence (C) | 0.0014 | 0.0003 | 0.0748 | 0.5019 |
| P × C | 0.1417 | 0.4284 | <0.0001 | 0.2209 |

† Within a column, means followed by different lowercase letter within a period are significantly different at $P < 0.10$.

Table 4. Protein concentration, oil concentration, and oil content of canola and protein concentration of wheat from both crop sequences from 2010 to 2013.

| | Canola | | | Wheat |
|---|---|---|---|---|
| Source of variation | Protein conc. | Oil conc. | Oil cont. | Protein conc. |
| Period | ---------------- $g\ kg^{-1}$ ---------------- | | $Mg\ ha^{-1}$ | $g\ kg^{-1}$ |
| Crop sequence | | | | |
| 2010-2011 | | | | |
| Spring canola-winter wheat | 219 | 479 a† | 0.89 b | 110 b† |
| Spring wheat-winter canola | 214 | 438 b | 1.19 a | 131 a |
| 2011-2012 | | | | |
| Spring canola-winter wheat | 232 a | 437 | 0.46 b | 87 b |
| Spring wheat-winter canola | 183 b | 451 | 0.72 a | 130 a |
| 2012-2013 | | | | |
| Spring canola-winter wheat | 259 a | 259 b | 0.01 b | 118 b |
| Spring wheat-winter canola | 233 b | 330 a | 0.59 a | 149 a |
| SE | 3 | 5 | 0.11 | 2 |
| Significance | | *P* value | | |
| Period (P) | 0.0001 | <0.0001 | 0.0014 | <0.0001 |
| Crop sequence (C) | 0.0003 | 0.0575 | 0.0044 | <0.0001 |
| P × C | 0.0011 | 0.0010 | 0.4151 | 0.0044 |

† Within period, means followed by different lowercase letter within a column are significantly different at $P < 0.10$.

Table 5. Aboveground biomass of red clover at grain harvest of winter wheat or winter canola and end of season and C and N concentrations of red clover at end of season from both crop sequences from 2010 to 2013.

| Source of variation | At-harvest of winter crop† | End of season‡ | End of season clover C conc. | End of season clover N conc. | End of season clover C:N ratio |
|---|---|---|---|---|---|
| Period | ---------------- kg ha$^{-1}$ | ---------------- | g C kg$^{-1}$ | g N kg$^{-1}$ | |
| Crop sequence | | | | | |
| 2010-2011 | | | | | |
| Spring canola-winter wheat | 108 b§ | 2450 | 423.5 | 23.5 | 18.0 a |
| Spring wheat-winter canola | 325 a | 2400 | 418.8 | 25.5 | 16.4 b |
| 2011-2012 | | | | | |
| Spring canola-winter wheat | 75 b | 1475 | 410.4 | 31.6 | 19.1 a |
| Spring wheat-winter canola | 320 a | 1225 | 412.5 | 27.9 | 18.3 b |
| 2012-2013 | | | | | |
| Spring canola-winter wheat | 273 b | 2250 | 420.5 | 20.3 | 20.8 a |
| Spring wheat-winter canola | 479 a | 1950 | 400.9 | 20.8 | 19.3 b |
| SE | 56 | 148 | 5.2 | 1.6 | 0.5 |
| Significance | | | *P* value | | |
| Period (P) | 0.2172 | 0.0027 | 0.1380 | <0.0001 | 0.0018 |
| Crop sequence (C) | 0.0017 | 0.1326 | 0.1136 | 0.7748 | 0.0083 |
| P × C | 0.9452 | 0.6825 | 0.1565 | 0.2435 | 0.6220 |

† Winter wheat harvest in the spring canola-winter wheat sequence and winter canola harvest in the spring wheat-winter canola sequence. Sampling occurred on 5 July 2011, 19 June 2012, and 10 July 2013.

‡ Winter wheat stubble in the spring canola-winter wheat sequnce and winter canola stubble in the spring wheat-winter canola sequence. Sampling occurred on 11 Nov. 2011, 9 Nov. 2012, and 10 Nov. 2013.

§ Within period, means followed by different lowercase letter within a column are significantly different at $P < 0.10$.

Table 6. Biomass of grass, broadleaf, and total weeds at grain harvest in both crop sequences from 2010 to 2013.

| | Spring crop in sequence | | | Winter crop in sequence | | | Both crops |
|---|---|---|---|---|---|---|---|
| Source of variation | Grasses† | Broadleaves† | Total† | Grasses† | Broadleaves† | Total† | Total† |
| Period | | | | $g\ m^{-2}$ | | | |
| Crop sequence | | | | | | | |
| 2010-2011 | | | | | | | |
| Spring canola-winter wheat | 117 (4.7) a¶ | 21 (3.0) | 138 (4.9) a | 2 (0.8) b | 6 (1.8) | 7 (1.9) b | 146 (5.0) a |
| Spring wheat-winter canola | 20 (2.9) b | 12 (2.5) | 32 (3.5) b | 10 (2.2) a | 15 (2.1) | 25 (2.8) a | 57 (4.0) b |
| 2011-2012 | | | | | | | |
| Spring canola-winter wheat | 76 (4.1) a | 131 (4.7) | 207 (5.2) a | 1 (0.8) b | 15 (2.4) | 16 (2.5) b | 223 (5.3) |
| Spring wheat-winter canola | 12 (2.1) b | 80 (4.1) | 93 (4.3) b | 8 (2.2) a | 53 (3.9) | 61 (4.1) a | 153 (4.9) |
| 2012-2013 | | | | | | | |
| Spring canola-winter wheat | 20 (2.5) b | 28 (3.1) a | 48 (3.8) | 15 (2.2) b | 118 (4.2) | 133 (4.6) b | 181 (5.1) |
| Spring wheat-winter canola | 52 (3.9) a | 1 (0.5) b | 53 (3.9) | 210 (5.8) a | 112 (4.1) | 322 (5.5) a | 372 (5.7) |
| SE‡ | (0.4) | (0.4) | (0.2) | (0.2) | (0.5) | (0.4) | (0.2) |
| Significance | | | | *P* value | | | |
| Period (P) | 0.3728 | <0.0001 | 0.0109 | 0.0003 | 0.0120 | 0.0006 | 0.0115 |
| Crop sequence (C) | 0.0395 | 0.0070 | 0.0029 | <0.0001 | 0.2351 | 0.0119 | 0.2240 |
| P × C | 0.0030 | 0.0773 | 0.0216 | 0.0047 | 0.3019 | 0.6442 | 0.0334 |

† Means of untransformed and log(x+1)-transformed data. The latter are in parentheses.

‡ Standard errors of log(x+1)-transformed data.

¶ Within period, means followed by different lowercase letter within a column are significantly different at $P < 0.10$.

# CHAPTER 4. AGRONOMIC, ECONOMIC, AND VEGETATIVE GROUNDCOVER PERFORMANCE OF ALTERNATIVE CROPPING SYSTEMS IN IOWA

A paper to be submitted to Agronomy Journal

Stefans R. Gailans

## Abstract

Over the period of 2011-2013, I compared three distinct crop rotation systems in central Iowa. One rotation system represented the contemporary norm in Iowa of corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) (C-Sb). The two other rotation systems represented alternatives to the norm that included cool-season crops and forage legume green manures. These alternative systems were a corn-spring canola (*Brassica napus* L.)-winter wheat (*Triticum aestivum* L.)/red clover *Trifolium pratense* L.) rotation (C-SC-WW/RC) and a corn-spring wheat-winter canola/red clover rotation (C-SW-WC/RC). All three rotations included applications of liquid swine (*Sus scrofa domesticus*) manure, synthetic fertilizers, and chemical pesticides but biological N fixation by the red clover and crop competitiveness with weeds was more heavily relied on in the two alternative cropping systems. Corn yields were greatest in the C-Sb system compared to the two alternative systems in 2011 (12.91 vs. 11.04 Mg ha$^{-1}$) and 2012 (8.35 vs. 6.33 Mg ha$^{-1}$) but similar across all systems in 2013 (7.58 Mg ha$^{-1}$). Canola yields were consistently greater in the C-SW-WC/RC system than in the C-SC-WW/RC system (1.9 vs. 0.41 Mg ha$^{-1}$, respectively). Winter wheat yield in the C-SC-WW/RC rotation (3.23 Mg ha$^{-1}$) was consistently greater than spring wheat yield in the C-SW-WC/RC rotation (2.06 Mg ha$^{-1}$). Financial returns were generally greatest in the C-Sb system ($1,359.50 ha$^{-1}$), intermediate in the C-SW-WC/RC system ($852.59 ha$^{-1}$), and least in the C-SC-WW/RC system ($562.31 ha$^{-1}$). These trends were due to the stronger performance of corn in the C-Sb system and the poor

performance of spring canola in the C-SC-WW/RC system. In 2013, the C-SW-WC/RC system did outperform the C-Sb system (\$846.90 $ha^{-1}$ vs. \$752.21 $ha^{-1}$) as corn yields were similar but synthetic N use was less in the C-SW-WC/RC system that year. Despite the greater amount of tillage used in the alternative systems, for incorporation of fertilizer and seedbed preparation for winter wheat and winter canola, mean annual duration of vegetative cover was 33% greater in the alternative cropping systems compared to the C-Sb system. During April-June, the C-Sb system was 70% more prone to erosion than the alternative systems. Alternative cropping systems have great potential to reduce potential for soil erosion compared to the commonly used C-Sb system in Iowa, but achieving consistent productivity and economic performance remain as challenges.

## Introduction

In Iowa, cropping systems are largely characterized by two primary crops—corn and soybeans—grown on 93% of all arable land in the state; approximately 55% and 38%, respectively (USDA, 2014). These crops typically are grown in monoculture systems with alternating production of corn and soybeans, or with only corn year after year. The sustainability and resiliency of these production systems, however, is called into question given the large negative impacts to the environment and society in terms of soil erosion and loss of nutrients into surface waters.

The Daily Erosion Project at Iowa State University currently estimates an average of over 11 Mg soil is lost per hectare from croplands in the state each year (ISU Agronomy, 2017). Moreover, the domination of the corn-soybean production system across the Iowa landscape over the past 50 years has been linked to increased sediment deposition into the state's lakes as a result of soil erosion from croplands (Heathcote et al., 2013). Those authors determined that the amount of sediment coming off croplands and ending up in lakes began to increase in the 1970s. At this time crop diversity in Iowa began to steadily decline as less land was dedicated to small grain and hay production in favor of corn and soybean (USDA, 2017). With the loss of small grain and hay crops from production systems also came the loss of crop species that actively grow during the spring and fall months. As a result, croplands are mostly bare during this period in the common corn-soybean and continuous corn production systems prevalent today, leaving them vulnerable to soil loss via erosion. Cropping systems that maintain ground cover in the form of living plants or crop residues are considered vital to mitigating soil erosion (Renard et al., 1994).

Diversifying crop rotation systems in the U.S. Corn Belt to include small grains, other cool-season crops and forage legume green manure cover crops have been shown to improve crop yields while also reducing reliance on N fertilizer and herbicides (Liebhardt et al., 1989; Porter et al., 2003; Kanwar et al., 2005; Liebman et al., 2008; Davis et al., 2012; Gaudin et al., 2015a, 2015b). As such, these more diversified cropping systems are also associated with improved and less variable profitability (Davis et al., 2012). Additionally, the more diversified cropping systems provide long periods of vegetative cover and active, deep root systems throughout the year, which reduces the likelihood of sediment delivery and nutrient pollution to ground and surface waters (Randall et al., 2008; Burkhart and Stoner, 2008).

Diversified cropping systems, however, are not without caveats. Porter et al. (2003) cite challenges associated with soil fertility and weed management which must first be overcome in cropping systems intended to rely more on legume green manures and crop competition for such services. Red clover green manure crops can supply 80-180 kg N $ha^{-1}$ to a subsequent crop (Bruulsema et al., 1987; Hesterman et al., 1992; Liebman et al., 2012; Gaudin et al., 2013). In order to reduce reliance on synthetic fertilizers, these rotations require the synchronous release of N from the decomposing legume green manure and uptake by the succeeding cash crop (Gaudin et al., 2013). Dense stands of small grains, other cool-season crops, and forage legumes, seeded in narrow rows, are required early in the growing season to outgrow and outcompete weeds (Liebman and Davis, 2009). Success on these levels hinges on management ability; and, to some degree, suitable climatic conditions that permit the timely termination of legume green manures and planting of densely-seeded small grains, cool-season crops, and forage legumes. Failure to accomplish these can result in poorer agronomic and economic performance compared to contemporary cropping systems (Porter et al., 2003).

Given the potential benefits of diversifying cropping systems in the U.S. Corn Belt to include small grains, cool-season crops, and forage legume green manures, an experiment was conducted to compare alternative crop rotation systems that were expanded to include wheat, canola, and red clover with the prevailing corn-soybean system. The specific objectives were to determine (i) crop productivity; (ii) financial costs and returns; and (iii) temporal vegetative ground cover dynamics and soil erosion potential of alternative crop rotation systems relative to the corn-soybean system typical to the region. I hypothesized that the two alternative systems would reduce the requirement for N fertilizer and chemical weed control inputs as well as provide greater amounts of vegetative ground cover throughout the growing season relative to the corn-soybean system.

## Materials and Methods

*Plot background, experimental design, and rotation systems*

The experiment was conducted during 2011-2013 at the ISU Agronomy and Agricultural Engineering Farm located in Boone County near Ames, IA (42°0’ N; 93°0’ W; 354 m asl). Predominant soils at the site are Clarion loam (fine-loam, mixed, superactive, mesic Typic Hapludolls) and Webster silty clay loam (fine-loamy, mixed, superactive, mesic, Typic Endoaquolls). Soil samples collected to a depth of 15 cm in the fall of 2009 indicated concentrations of available P (Bray-1) of 6 mg $kg^{-1}$, K (Mehlich-3 extraction) of 115 mg $kg^{-1}$, organic matter (combustion analysis) of 41 g $kg^{-1}$, pH of 5.8, and buffer pH of 6.5.

Three crop rotation systems were included in the study. One was a corn-soybean rotation (C-Sb) that is typical of cash grain farming systems in the midwestern United States. The other two rotation systems represent diversified, alternative rotations that may be suitable to the region: corn-spring canola-winter wheat/red clover (C-SC-WW/RC) and corn-spring wheat-winter canola/red clover (C-SW-WC/RC). The experiment was arranged in a randomized complete block design with four replications with each crop phase of each rotation system present every year. Individual plot size was 9 by 40 m.

The entire site was planted to soybean in spring 2009 and the plots were established following harvest in the fall of that year. The 2010 growing season acted as the rotation system establishment year. The experimental period began with the onset of the 2011 growing season.

Weather data from within 3.2 km of the experimental site were compiled from the Iowa Environmental Mesonet for 2011, 2012, 2013, and the period 1951-2013.

*Crop management*

Crop identities, planting and harvest dates, seeding rates, and row spacings are shown in Table 1. Glyphosate-tolerant corn was used in all three systems, glyphosate-tolerant soybeans were used in the C-Sb system, and imidazolinone-tolerant spring canola was used in the C-SC-WW/RC system. Red clover was frost-seeded in early March into winter canola in the C-SW-WC/RC system and frost-seeded into winter wheat in the C-SC-WW/RC system. In both of these systems, red clover acted solely as a green manure for the succeeding corn crop. Soybean and red clover seeds were inoculated with appropriate *Bradyrhizobium* and *Rhizobium* treatments before planting. Corn stalks were chopped in all systems following grain harvest in 2010 and 2011 but not in 2012. Spring and winter wheat straw was baled and removed following grain harvest each year.

Synthetic fertilizers, applied at rates based on soil tests, as well as liquid swine manure were applied to all rotation systems (Table 2). Liquid swine manure was injection applied in November of each year at a target rate of 114 kg N $ha^{-1}$ into soybean stubble in the C-Sb system and standing red clover in the two alternative systems. With injection application, we assumed 98% of the N and 100% of the P and K in the manure to be available for the crop year immediately following application (Sawyer and Mallarino, 2008). This corresponded to fresh manure applications of 20,820 L $ha^{-1}$ in fall 2010, 16,635 L $ha^{-1}$ to blocks 1 and 2 and 15,265 L $ha^{-1}$ to blocks 3 and 4 in fall 2011, and 14,905 L $ha^{-1}$ in fall 2012. Application rates of N, P, and K in liquid swine manure were based on analyses conducted by MVTL Laboratories, Inc. (Nevada, IA) (Table 2). Post-emergence side-dress N applications to corn in all systems were determined using the late spring nitrate test (Blackmer et al., 1997). Winter canola and winter wheat crops received a split application of N with 24 kg N $ha^{-1}$ applied at planting and an additional 34 kg N $ha^{-1}$ applied the following year in March at the time of frost-seeding red clover.

Chemical weed management in corn and soybean in the C-Sb system and corn in the two alternative systems was based on conventional rates of labeled herbicides (Table 3). Prior to planting corn in the two alternative systems, a combination of 2,4-D amine and glyphosate as isopropylamine salt was used to terminate previously established red clover in those plots in April in each year. Spring canola plots in the C-SC-WW/RC system received a single postemergence application of imazamox as ammonium salt on 25 May 2012 due to poor crop establishment and subsequent weed infestation. Save for this application, canola, wheat, and red clover crops did not receive any chemical weed management in the two alternative systems. Stubble of spring crops and established red clover following winter crop harvest were occasionally mowed to suppress weeds in the two alternative systems (Table 3).

Tillage was used to incorporate fertilizer and terminate weeds and tillage implements used differed among the systems (Table 3). The C-Sb system was mostly managed with no tillage except in 2013 to incorporate dry phosphorus fertilizer in corn and soybean plots prior to planting. In 2012 and 2013, corn plots in the two alternative systems were strip tilled prior to planting in order to better achieve proper seed placement in chemically terminated red clover mulch. In 2012, spring canola and spring wheat plots were tandem disked to incorporate chopped corn stalks from the previous fall and provide a suitable seedbed. This was not done in 2013, as corn stalks were not chopped in fall 2012. In winter wheat and winter canola plots, tandem disk tillage prior to planting was used to incorporate dry phosphorus and potassium fertilizer as well as to terminate late-summer emerging weeds following spring canola and spring wheat harvest.

In establishing the experiment during fall 2009 following the harvest of soybeans that were planted to the entire site, cropping patterns similar to those described above were used with one exception. Spring canola (cv. Pioneer 45H73), interseeded with red clover, was seeded on 1 Apr. 2010 in place of winter canola in the C-SW-WC/RC system that year, as the soybeans were harvested too late in fall 2009 to permit the seeding of winter canola. As such, the 2011 corn crop followed a red clover green manure crop that was established with spring canola rather than winter canola as the corn did in 2012 and 2013.

Grain yields of corn were determined from the central four rows of each plot using a combine equipped with a grain tank on a load cell. Yields of soybean were determined the same way from the central six rows of each plot. Grain yields of winter wheat and spring wheat were determined the same way from the central 24 rows of each plot. Yields of winter canola and spring canola were determined by hand-harvesting plants from three randomly located quadrats (0.25 $m^2$) in each plot just prior to machine harvest. Upon hand-harvest of canola, replicate samples were combined, placed in paper bags, and air-dried for at least 5 d. After drying, canola seed was machine-threshed using a stationary research thresher and then hand-sieved and weighed. Yields of winter and spring wheat straw were determined by weighing bales harvested from entire plots. Yields were adjusted to moisture levels of 155 g $kg^{-1}$ for corn, 130 g $kg^{-1}$ for soybean, 130 g $kg^{-1}$ for winter and spring wheat, 100 g $kg^{-1}$ for winter and spring canola, and 110 g $kg^{-1}$ for wheat straw.

*Economic analysis*

Economic returns to land and management for the three crop rotation systems were assessed using production costs associated with machinery operations and inputs as well as gross revenues associated with crop yields. Production costs for machinery operations, fertilizers, land, labor, and crop insurance for corn and soybeans were accessed from Iowa State University farm management databases (Duffy, 2013 and previous years; Hanna, 2001). Seed costs associated with spring wheat, winter wheat, and spring canola were calculated based on values from North Dakota (Swenson and Haugen, 2013 and previous years) and for winter canola based on values from Kansas (Dumler et al., 2012), as no established budgets currently exist for these crops in central Iowa. Red clover seed costs and herbicide costs were gathered from local agricultural dealers. Crop insurance costs associated with wheat and canola were calculated from the average annual premium cost from Minnesota (USDA-RMA, 2013 and previous years). Gross revenues for 2011-2013 were calculated based on Iowa prices for corn, soybean, and wheat and Minnesota prices for canola (USDA-NASS, 2013). Revenues associated with wheat straw yields were calculated based on average prices from several hay and straw auctions in Iowa (Iowa State University Extension, 2013 and previous years). Established cost and price values from states outside of Iowa represented those in closest proximity to our study site and using these values allowed us to make the most accurate comparisons of the rotation systems as possible (Kliebenstein, pers. comm.).

*Vegetative cover sampling*

To determine temporal patterns of vegetative cover among the three crop rotation systems, the proportion of photosynthetically active radiation (PAR) intercepted by the crop canopies was measured approximately every two weeks throughout the growing season in each plot. Measurements were initiated in April of each year at the time of winter crop green-up and continued until a killing frost in late October or early November. A 1-m quantum sensor bar (LI-COR Biosciences, Lincoln, NE) was used to measure below-canopy PAR transmission, and a LI-COR point quantum sensor was used to measure above-canopy PAR. Measurements were taken as 5 sec averages on sunny days between 10:00 and 14:00 h, with three measurements per plot on each sampling date. Vegetative cover on each sampling date was calculated as follows:

$$PC = \frac{(above\text{-}canopy\ PAR) - (below\text{-}canopy\ PAR)}{(above\text{-}canopy\ PAR)} \qquad [1]$$

where PC is the proportion of vegetative cover (e.g., the proportion of PAR intercepted by the crop canopy). Values for PC were averaged across crops among crop rotation on each sampling date for analysis.

Differences in the duration of vegetative cover among the three crop rotations were assessed by calculating the time-integrated PC over the growing season, similar to an approach described by Jarchow and Liebman (2012). Time-integrated PC was calculated by finding the area under the curve generated by the mean PC values observed for each rotation system on each sampling date throughout the growing season. Curves began on 1 March and ended on 30 November for each growing season, which was before and after any crop growth was observed, respectively. The PC values were artificially set to zero for 1 March and 30 November to mark the beginning and end of the growing season.

The potential for soil erosion resulting from each of the three rotations was estimated for each sampling date based on an exponential relationship described by Gyssels et al. (2005) as follows:

$$Er = e^{-0.0492 \bullet \mathrm{PC}(\%)}$$

[2]

where Er is the relative amount of soil loss compared to a bare surface and PC is expressed as a percentage. Er value ranges between 0.0 and 1.0, with 1.0 representing the greatest potential for soil erosion.

Differences in the duration of erosion potential among the three crop rotations were assessed by calculating the time-integrated Er over the growing season, similar to the approach used to calculate the differences in the duration of vegetative cover. Time-integrated Er was calculated by finding the area under the curve generated by the mean Er values calculated for each rotation system on each sampling date throughout the growing season. As with time-integrated PC, Er curves began on 1 March and ended on 30 November for each growing season, which was before and after any crop growth was observed, respectively. Er values were artificially set to 1.0 for 1 March and 30 November to mark the beginning and end of the growing season.

*Data analysis*

Crop rotation system effects on measured, calculated, and estimated data were analyzed with mixed-effect models using the Fit Model procedure in JMP Pro 10.0 statistical software (SAS Institute, Cary, NC, 2012). Analysis of variance was conducted with crop rotation system considered a fixed factor while year and block were considered as random factors. Two orthogonal contrasts were used for analyses across the three rotation systems: (i) the C-Sb system vs. the average of the C-SC-WW/RC and C-SW-WC/RC systems and (ii) the C-SC-WW/RC system vs. C-SW-WC/RC system. Unless otherwise indicated, values were considered significant at $P \leq 0.05$.

## Results and Discussion

*Weather conditions*

Precipitation and temperature conditions during the 2011-2013 growing seasons and how they compared to long-term (1951-2013) trends are shown in Table 4 (ISU Mesonet, 2017). In 2011, temperature and precipitation did not tend to deviate from the long-term trends for much of the growing season. Beginning in August, predominantly dry conditions prevailed into the fall that year. The 2012 growing season was marked by above-normal temperatures and extremely dry conditions beginning in May. In 2013, March, April, and May were predominantly wetter than normally observed. Predominantly dry conditions prevailed for much of the summer growing season in 2013, beginning in June.

*Herbicide, synthetic N fertilizer, and fuel use in the rotation systems*

Herbicide use, on a kg a. i. $ha^{-1}$ basis, was consistently greater in the C-Sb system than in the C-SC-WW/RC and C-SW-WC/RC systems (Fig. 1a). This owed to the fact that corn and soybean routinely received herbicides in the C-Sb system; generally, only the corn in the two alternative systems received herbicides (Table 3). The corn in the alternative systems received more herbicide (a.i. $ha^{-1}$) than the corn in the C-Sb system because the red clover green manure preceding the corn each year required termination. Across years, herbicide use in corn in the C-Sb system was 2.66 kg a.i. $ha^{-1}$ $yr^{-1}$ compared to 3.65 kg a.i. $ha^{-1}$ $yr^{-1}$ in both of the alternative systems. Mean herbicide use in soybeans in the C-Sb system was 3.60 kg a.i. $ha^{-1}$ $yr^{-1}$. Spring canola in the C-SC-WW/RC system did receive an herbicide application in 2012, but for the most part the canola and wheat grown in the alternative systems did not receive herbicides (Table 3) as weed competition did not appear to be an issue. Instead, these crops relied on their row spacings, planting densities, and cool-season lifecycles (i.e., rapid growth early in the season) to compete with the summer annual weeds which dominated the weed community. On average, herbicide use in the C-Sb system was more than twice that in either alternative system (Fig. 1a).

Nitrogen fertilizer application was consistently greater in the two alternative systems compared to the C-Sb system (Fig. 1b). Post-emergence N fertilizer rates for corn as recommended by late spring soil nitrate tests (Blackmer et al., 1997) differed by system and by year, but not their interaction (Table 2). Corn in all three systems received similar N rates in 2011; corn in the alternative systems received a higher rate in 2012; and corn in the C-Sb system received a higher rate in 2013. Averaged across years, however, corn in all three systems received 91 kg N $ha^{-1}$ of synthetic N fertilizer. The spring and winter varieties of canola and wheat grown in the alternative systems received 57 kg N $ha^{-1}$ of N fertilizer each year while the soybeans grown in the C-Sb system received 26 kg N $ha^{-1}$ as monoammonium phosphate in 2013 only (Table 2). Averaged across rotation systems and years, mean synthetic N fertilizer use in the

C-Sb system was 45 kg N $ha^{-1}$ $yr^{-1}$ compared to 68 kg N $ha^{-1}$ $yr^{-1}$ in both of the alternative systems.

Diesel fuel use for each of the rotation systems was calculated using established values for machinery operations from Iowa State University farm management databases (Hanna, 2001). Diesel fuel use in both of the alternative systems was greater than in the C-Sb system in 2011 and 2012, while fuel use in 2013 was nearly identical among systems (Fig. 1c). Averaged across years, diesel use in producing corn was slightly less in the C-Sb system (35.3 L $ha^{-1}$ $yr^{-1}$) compared to the alternative systems (38.7 L $ha^{-1}$ $yr^{-1}$). Mean diesel fuel use across years for producing soybeans in the C-Sb system was 19.8 L $ha^{-1}$ $yr^{-1}$. Management of the alternative systems required a greater number of machinery passes through the field compared to the C-Sb system. These included passes associated with raking and baling wheat straw as well as the multiple stubble mowings to control weeds and tillage passes to incorporate fertilizer, control weeds and prepare seedbeds prior to the seeding of winter canola and winter wheat each year in the alternative systems (Table 3). Averaged across years, diesel fuel use in producing spring canola and winter wheat in the C-SC-WW/RC system was 20.9 L $ha^{-1}$ $yr^{-1}$ and 35.4 L $ha^{-1}$ $yr^{-1}$, respectively; diesel fuel use in producing spring wheat and winter canola in the C-SW-WC/RC system was 27.3 L $ha^{-1}$ $yr^{-1}$ and 29.1 L $ha^{-1}$ $yr^{-1}$, respectively.

*Crop yields*

Corn yields were influenced by year, crop rotation system, and the interaction of year and crop rotation system (Table 5). Greatest corn yields for each of the systems were observed in 2011. Abnormally dry conditions during the growing season in 2012 and 2013 was likely the cause for corn yields in all systems being less than 10.96 Mg $ha^{-1}$, 10-year average for Boone County (USDA-NASS, 2015). Corn yields in the alternative systems were similar in each year, but the corn in the C-Sb system out-yielded or yielded similarly to the corn in the C-SC-WW/RC and C-SW-WC/RC systems each year. Low corn yields in the two alternative systems in 2011 and 2012 was attributed to poor seedling emergence due to insufficient termination of red clover and the subsequent difficulty of planting corn in those systems. In 2013, complete chemical termination of red clover was achieved and likely resulted in both better corn seedling emergence and release of N from red clover residue than in the previous years. That year, corn yields among all systems were similar (Table 5) despite the corn in the C-SC-WW/RC and C-SW-WC/RC rotations receiving less N fertilizer (Table 1).

Soybeans were grown only in the two-year, C-Sb system. Soybean yields differed among years with greatest yields observed in 2011 and lowest yields observed in 2013 (Table 5). The dry conditions in 2012 and 2013 were possible reasons for soybean yields being slightly less than the 10-year Boone County average of 3.32 Mg $ha^{-1}$ (USDA-NASS, 2015).

Canola yields differed between the C-SC-WW/RC and C-SW-WC/RC systems and among years (Table 5). Winter canola yield in the C-SW-WC/RC system was significantly greater than spring canola yield in the C-SC-WW/RC system in each year. This was attributed to the inherent greater yield potential of winter canola relative to spring canola and to the poor emergence of spring canola drilled into corn stubble. While stand counts were not conducted, it appeared that the small-seeded canola emerged through wheat stubble (as in the C-SW-WC/RC rotation) far better than it did through corn stubble (as in the C-SC-WW/RC rotation). Greatest canola yields from both systems occurred in 2011 while lowest yields occurred in 2012. Winter canola yields in the C-SW-WC/RC rotation were greater than the average canola yields in Minnesota and North Dakota for the period 2004-2013 (1.70 Mg $ha^{-1}$) (USDA-NASS, 2015) in 2011 and just shy of this average in 2012 and 2013 (Table 5). Spring canola yields in the C-SC-

WW/RC rotation never approached the average yields observed in these states. Minnesota and North Dakota were chosen for comparison because they represent regions nearest in proximity to our study site with USDA canola production statistics.

Wheat yields differed between the C-SC-WW/RC and C-SW-WC/RC rotations system but not by year (Table 5). Mean winter wheat yields in the C-SC-WW/RC system (3.22 Mg $ha^{-1}$) were significantly greater than mean spring wheat yields in the C-SW-WC/RC system (2.06 Mg $ha^{-1}$) in each year. As with canola, the winter variety of wheat possessed a greater inherent yield potential than the spring variety. Winter wheat yields in the C-SC-WW/RC rotation were generally similar to the average wheat yield in Iowa for the period 2004-2013 (3.40 Mg $ha^{-1}$) (USDA-NASS, 2015). Spring wheat yields in the C-SW-WC/RC rotation, however, were generally less than the Iowa average during this same period. Wheat straw yields in the three-year systems were influenced by year, rotation system, and the interaction of year and rotation system (Table 5). Straw yields between the two alternative systems were similar in 2011. In 2012, wheat straw yield in the C-SC-WW/RC system was greater than wheat straw yield in the C-SW-WC/RC system, though, the opposite occurred in 2013 (Table 5).

*Economic performance of rotation systems*

Gross revenue, production costs, labor required, and returns to land and management were generated each year for each crop grown in the rotation systems using annually established values from Iowa State University farm management databases (Duffy, 2013 and previous years). In each year, gross revenue was greatest in the C-Sb system, intermediate in the C-SW-WC/RC system, and least in the C-SC-WW/RC system (Table 6). Only in 2013 were gross revenues for corn greater in the alternative systems than in the C-Sb system and this is associated with significantly greater corn yields in the alternative systems compared to the C-Sb system that year (Table 5). Of all crops, spring canola in the C-SC-WW/RC system consistently resulted in the least revenue. Revenue from soybeans in the C-Sb system generally exceeded revenues from canola and wheat in the alternative systems except in 2013 when winter canola resulted in the greatest revenues among all crops in all rotation systems (Table 6).

Production costs, excluding labor, were consistently least for the C-SW-WC/RC system, intermediate for the C-SC-WW/RC system, and greatest for the C-Sb system (Table 6). Reductions in production costs have also been documented in Iowa in systems that contain small grains such as oats (*Avena sativa* L.) and forage legume green manures such as alfalfa (*Medicago sativa* L.) in rotation with corn owing to reduced costs associated with fertilizer and herbicides (Chase and Duffy, 1991; Liebman et al., 2008; Davis et al., 2012; Poffenbarger et al., 2017). In the present study, the reduction in production costs associated with the two alternative systems was most directly related to herbicide use among the rotation systems (Table 3; Fig. 1a). On average, costs associated with purchased herbicides were \$66.51 $ha^{-1}$ $yr^{-1}$ for the C-Sb system, \$9.27 $ha^{-1}$ $yr^{-1}$ for the C-SC-WW/RC system, and \$7.92 $ha^{-1}$ $yr^{-1}$ for the C-SW-WC/RC system. While N fertilizer use was greater in the two alternative systems than the C-Sb system (Table 2; Fig. 1b), the associated costs did not differ nearly as much as with herbicide use. On average, costs associated with purchased N fertilizer were \$56.50 $ha^{-1}$ $yr^{-1}$ in the C-Sb system and \$82.47 $ha^{-1}$ $yr^{-1}$ in the alternative systems. Phosphorus and potassium fertilizers were applied on the basis of soil tests between harvest of spring canola and planting of winter wheat in the C-SC-WW/RC system and between the harvest of spring wheat and planting of winter canola in the C-SW-WC/RC system (Table 2). Phosphorus fertilizer was applied to corn and soybean in the C-Sb system in 2013 on the basis of soil tests (Table 2). Averaged over the years, the cost associated with purchased P and K fertilizers in the two alternative systems was \$14.35 $ha^{-1}$ $yr^{-1}$ and \$20 $ha^{-1}$ $yr^{-1}$ for the C-Sb system.

Required labor was least for the C-Sb system compared to the alternative systems (Table 6). On average, the C-Sb system required 1.52 h $ha^{-1}$ $yr^{-1}$ while the alternative systems required 2.34 h $ha^{-1}$ $yr^{-1}$. Much of this owed to the fact that the alternative systems required more machinery passes through the field (Fig. 1c), and thus more labor, associated with planting operations and harvesting (grain and wheat straw) than the C-Sb system. Similar instances of increased labor requirements associated with diversified cropping systems in the Upper U.S. Corn Belt have also been documented by Liebman et al. (2008), Davis et al. (2012), and Poffenbarger et al. (2017).

Despite greatest production costs, the C-Sb system resulted in greatest returns to land and management in 2011 and 2012 compared to the three-year system (Table 6). In 2013, however, returns were greatest for the C-SW-WC/RC system, intermediate for the C-Sb system, and least for the C-SC-WW/RC system (Table 6). Though revenue for the C-Sb system exceeded that for the C-SW-WC/RC system by \$68.79 $ha^{-1}$, the C-SW-WC/RC system resulted in \$168.23 $ha^{-1}$ less in production costs and only required 0.38 $h^{-1}$ $ha^{-1}$ in additional labor than the C-Sb system that year. As with gross revenue, returns for winter canola in the C-SW-WC/RC system were greater than for any other crop in 2013. Spring canola, on the other hand, consistently resulted in the least returns among all crops with negative returns occurring in 2012 and 2013 (Table 6). The margin between returns for winter wheat in the C-SC-WW/RC system and spring wheat in the C-SW-WC/RC system was narrowest in 2013 (Table 6). Despite greater returns from wheat grain in the C-SC-WW/RC system, returns from wheat straw were \$209.34 $ha^{-1}$ in the C-SW-WC/RC system compared to \$181.43 $ha^{-1}$ in the C-SC-WW/RC system as spring wheat resulted in significantly greater straw yield than winter wheat that year (Table 5).

*Temporal patterns of vegetative cover*

Temporal patterns of vegetative cover were assessed by determining the mean PC for each of the three crop rotation systems on a bi-monthly basis during the growing season (Fig. 2). The two alternative systems produced a greater mean PC during April, May, and June and at the end of the growing season in late October than the C-Sb system. This was because C-SC-WW/RC and C-SW-WC/RC systems contained spring annual species (spring canola and spring wheat, respectively), winter annual species (winter wheat and winter canola, respectively), and a red clover green manure cover crop. The C-Sb system, on the other hand, was comprised of two crop species (corn and soybeans) with similar summer annual growth patterns. The C-Sb system did, however, produce a greater mean PC than the two alternative systems during July, August, and September. This can be attributed to the removal of wheat grain and straw and canola grain with the summer harvest (Table 1) as well as the ensuing stubble mowings and tillage passes (Table 3) in those two systems. Both of these activities reduced mean PC in the C-SC-WW/RC and C-SW-WC/RC systems during the summer.

Mean annual duration of vegetative cover (expressed as time-integrated PC) was consistently greater in the C-SC-WW/RC and C-SW-WC/RC systems compared to the C-Sb system (Fig. 3). The C-SC-WW/RC and C-SW-WC/RC systems were comprised of multiple crop species exhibiting spring, summer, and winter annual life cycles while the C-Sb system was comprised of two species, both exhibiting summer annual life cycles. The PC was calculated as the proportion of PAR intercepted by a living crop canopy. Other methods of assessing ground cover by plant foliage, such as the Normalized Difference Vegetation Index (NDVI), have previously been found related to the proportion of PAR intercepted by living plant canopies (Hatfield et al., 1984; Goward et al., 1985; Goward et al., 1987). Moreover, Pinter et al. (1981) and Tucker et al. (1981) describe strong relationships between time-integrated NDVI and crop biomass production and duration of living canopy cover, respectively. With this in mind, it is safe to say that the greater amount of time-integrated PC observed in the C-SC-WW/RC and C-SW-WC/RC systems reflects the fact that those systems contained living crops (foliage and roots) for a longer period of time during the year than the C-Sb system.

Soil erosion potential, relative to a bare surface, was calculated for each date that PC was measured (Gyssels et al., 2005). Those authors describe the potential for soil erosion to decrease exponentially as the amount of vegetative cover increased. In a review of several studies, they attribute soil holding principles to both the foliage and living roots associated with vegetative cover. Figure 4 depicts the average erosion potential throughout the growing season of the three rotation systems. Erosion potential is inversely related to PC (Fig. 2). During April–June, the C-Sb system was estimated to be 70% more prone to erosion than the alternative systems. At this time of year, the spring and winter annual species in the C-SC-WW/RC and C-SW-WC/RC systems provide ample canopy cover while the corn and soybeans in the C-Sb system are just emerging from the soil providing very little cover. This time of year also coincides with a period of substantial rainfall in central Iowa (Table 4), which is considered among the chief causes of soil erosion (Wischmeier and Smith, 1978). As the C-Sb system closed the canopy with increased PC during July (Fig. 2), the potential for erosion fell below those for the two alternative systems. This coincided with wheat and canola harvest (Table 1) as well as tillage passes used to incorporate fertilizer and prepare seedbeds for winter wheat and winter canola in the alternative systems (Table 3). By late October at the end of the season, the two alternative systems possessed less erosion potential than the C-Sb system owing to the PC provided by the red clover and winter annual crops in those systems. Moreover, mean annual duration of erosion potential (expressed as time-integrated Er) was consistently less in the C-SC-WW/RC and C-SW-WC/RC systems compared to the C-Sb system (Fig. 5). Cropping systems that include plants that provide living, vegetative cover of the soil for the majority of the growing season are widely recognized for their low probability of soil loss through erosion (Renard et al., 1994; Connor et al., 2011). Thus, because of the temporal patterns of PC associated with the C-SC-WW/RC and C-SW-WC/RC systems, it is these systems that offer much greater protection from soil erosion than the C-Sb system.

**Summary**

Compared to the C-Sb system, the C-SC-WW/RC and C-SW-WC/RC systems might not have been as successful agronomically (Table 5) or economically (Table 6), but they did provide more environmental benefit in terms of increased vegetative cover (Figs. 2 and 3) reduced soil erosion potential (Fig. 4). The two alternative systems also resulted in reduced herbicide use (Fig. 1a). Nitrogen fertilizer and diesel fuel usage, however, were typically greater in the alternative systems (Figs. 1b and 1c). On average, financial returns were generally greatest in the C-Sb system (\$1,359.50 ha$^{-1}$), intermediate in the C-SW-WC/RC system (\$852.59 ha$^{-1}$), and least in the C-SC-WW/RC system (\$562.31 ha$^{-1}$). These trends were due to stronger performance on average of corn in the C-Sb system and the poor performance of spring canola in the C-SC-WW/RC system. In the context of these rotation systems, and how they performed over the course of this project, these financial returns indicate that improved soil conservation would come with a high cost.

These crop rotation system treatments were initiated in 2010 and the experimental period included the crop years of 2011, 2012 and 2013. Past experiments on diversified and expanded crop rotation systems in Pennsylvania (Liebhardt et al., 1989) and Minnesota (Porter et al., 2003) have documented initially lesser crop yields in rotation systems that rely more on biological inputs, like animal manure and legume green manures, than conventional systems receiving synthetic N fertilizer inputs. By the third year of the present study (2013), corn yields were equivalent among the rotation systems (Table 5). That year, the C-SW-WC/RC system outperformed the C-Sb system (\$846.90 vs. \$752.21 $ha^{-1}$) as corn yields were similar but with 33% less N fertilizer used for corn in the C-SW-WC/RC system. Liebhardt et al. (1989) suggest small grain and hay crops as most appropriate for the early years of transitioning to a cropping system that primarily relies on biological sources of soil fertility. These crops have a lower N requirement, or fix their own N, compared to corn. Those authors found delaying corn until the third or fourth year of such a system resulted in comparable yields to conventional systems that solely relied on synthetic sources of fertility. In the present study, 2013 was the first year that the corn in the two alternative systems was preceded by a full cycle of the non-corn phases of those rotation systems. That corn yields equivalent to the conventional C-Sb system occurred in the two alternative systems in 2013 could be a function of an adequate build up of soil fertility following the canola, wheat and red clover crops that preceded the corn in those rotations. Moreover, unlike in the previous two years, sufficient termination of the red clover green manure was achieved ahead of corn planting in the two alternative systems in 2013, which may have resulted in the first instance that the N release by the red clover closely matched uptake by the corn in the alternative systems. This likely contributed to the lesser amount of N fertilizer required to the corn in the two alternative systems that year (Table 2) while producing yields equivalent to the C-Sb system.

The C-SC-WW/RC and C-SW-WC/RC systems provided vegetative cover over a longer period during the year than the C-Sb system (Fig. 3). On average, mean annual duration of vegetative cover was 33% greater in the alternative cropping systems compared to the C-Sb system (Fig. 4). Furthermore, the alternative systems provided more vegetative cover than the C-Sb system during the spring and fall months when just over half of the mean annual rainfall occurs in central Iowa (ISU Mesonet, 2017) and the prevailing corn-soybean cropping system in the region leaves much of the landscape vulnerable to soil loss. Despite the greater use of tillage (Table 3), the alternative systems were estimated to be much less susceptible to soil erosion (Fig. 5).

It is clear that the alternative C-SC-WW/RC and C-SW-WC/RC rotation systems possess the potential to stem soil erosion compared to the C-Sb system typical of the upper U.S. Corn Belt. This typical system is generally considered the primary culprit for the soil losses documented by the Iowa Daily Erosion Index (ISU Agronomy, 2017) and the associated negative environmental effects on the state’s surface waters reported by Heathcote el al. (2013). The alternative systems, however, brought with them increased levels of management and, at first, lower yields, increased N fertilizer use, and lower financial returns. Other cropping systems experiments conducted in Iowa documented agronomic and financial success on par with or exceeding the typical corn-soybean system (Liebman et al., 2008; Davis et al., 2012; Hunt et al., 2017) while also documenting improved environmental performance by the alternative systems in terms of reduced freshwater pollution via reduced nutrient loss through the soil (Tomer and Liebman, 2014) and reduced herbicide use (Hunt et al., 2017). These studies involved three- and four-year rotations that received manure or compost and included oats, red clover, and alfalfa along with corn and soybeans. While somewhat similar in nature and design, the alternative systems in the present study included winter and spring varieties of canola and wheat; crops with little to no history of being cultivated in Iowa. These crops, along with the red clover, are responsible for much of the increased vegetative cover through the growing season relative to the C-Sb system, but the canola, wheat and, red clover are also somewhat responsible for the poorer agronomic and financial performances of the alternative systems. Chase and Duffy (1991) and Porter et al. (2003) suggest that challenges associated with alternative crop management and biological fertility inputs as the primary barriers to success in the upper U.S. Corn Belt. As such, the alternative C-SC-WW/RC and C-SW-WC/RC rotation systems in the present study will require improved crop managerial skills before they can be as agronomically and economically successful as the typical C-Sb system.

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Table 1. Crop identities, planting and harvest dates, and row spacings for rotation systems in 2011-2013.

| Year | Rotation system | Rotation entry point | Crop | Hybrid or cultivar | Planting date | Harvest date | Seed mass | Seed density | Interrow spacing |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | g ha$^{-1}$ | seeds ha$^{-1}$ | cm |
| 2011 | C-Sb | 1 | Corn | Channel 209-76r | 10 May | 21 Oct. | | 80,500 | 76 |
| | C-Sb | 2 | Soybean | Pioneer 92Y60 | 18 May | 7 Oct. | | 402,500 | 76 |
| | C-SC-WW/RC | 1 | Corn | Channel 209-76r | 10 May | 21 Oct. | | 80,500 | 76 |
| | C-SC-WW/RC | 2 | Spring canola | 45H73 | 1 Apr. | 26 July | | | 19 |
| | C-SC-WW/RC | 3 | Winter wheat | Expedition | 30 Sept., 14 Oct. 2010 | 7 July | 59 | | 19 |
| | C-SC-WW/RC | | Red clover | Mammoth | 2 Mar. | | 20 | | broadcast |
| | C-SW-WC/RC | 1 | Corn | Channel 209-76r | 10 May | 21 Oct. | | 80,500 | 76 |
| | C-SW-WC/RC | 2 | Spring wheat | Faller | 1 Apr. | 26 July | 30 | | 19 |
| | C-SW-WC/RC | 3 | Winter canola | Sitro | 7 Sept. 2010 | 7 July | 10 | | 19 |
| | C-SW-WC/RC | | Red clover | Mammoth | 2 Mar. | | 20 | | broadcast |
| 2012 | C-Sb | 1 | Soybean | Pioneer 92Y60 | 14 May | 27 Sept. | | 402,500 | 76 |
| | C-Sb | 2 | Corn | Channel 209-76r | 11 May | 23 Oct. | | 80,500 | 76 |
| | C-SC-WW/RC | 1 | Spring canola | 45H73 | 29 Mar. | 8 July | | | 19 |
| | C-SC-WW/RC | 2 | Winter wheat | Expedition | 30 Sept. 2011 | 9 June | 59 | | 19 |
| | C-SC-WW/RC | | Red clover | Mammoth | 9 Mar. | | 20 | | broadcast |
| | C-SC-WW/RC | 3 | Corn | Channel 209-76r | 11 May | 23 Oct. | | 80,500 | 76 |
| | C-SW-WC/RC | 1 | Spring wheat | Faller | 29 Mar. | 12 July | 30 | | 19 |
| | C-SW-WC/RC | 2 | Winter canola | Sitro | 7 Sept. 2011 | 29 June | 10 | | 19 |
| | C-SW-WC/RC | | Red clover | Mammoth | 9 Mar. | | 20 | | broadcast |
| | C-SW-WC/RC | 3 | Corn | Channel 209-76r | 11 May | 23 Oct. | | 80,500 | 76 |
| 2013 | C-Sb | 1 | Corn | Channel 209-76r | 24 May | 23 Oct. | | 80,500 | 76 |
| | C-Sb | 2 | Soybean | Pioneer 92Y60 | 12 June | 9 Oct. | | 402,500 | 76 |
| | C-SC-WW/RC | 1 | Winter wheat | Expedition | 1 Oct. 2012 | 12 July | 59 | | 19 |
| | C-SC-WW/RC | | Red clover | Mammoth | 28 Mar. | | 20 | | broadcast |
| | C-SC-WW/RC | 2 | Corn | Channel 209-76r | 24 May | 23 Oct. | | 80,500 | 76 |
| | C-SC-WW/RC | 3 | Spring canola | 45H73 | 8 Apr. | 25 July | | | 19 |
| | C-SW-WC/RC | 1 | Winter canola | Sitro | 6 Sept. 2012 | 10 July | 10 | | 19 |
| | C-SW-WC/RC | | Red clover | Mammoth | 29 Mar. | | 30 | | broadcast |
| | C-SW-WC/RC | 2 | Corn | Channel 209-76r | 24 May | 23 Oct. | | 80,500 | 76 |
| | C-SW-WC/RC | 3 | Spring wheat | Faller | 8 Apr. | 1 Aug. | 30 | | 19 |

Table 2. Synthetic fertilizer and swine manure amendments for crops grown in rotation systems in 2011-2013.

| Rotation | Crop | 2011 | 2012 | 2013 |
|---|---|---|---|---|
| C-Sb | Corn | 114 kg N ha$^{-1}$ + 34 kg P ha$^{-1}$ + 83 kg K ha$^{-1}$ as liquid swine manure before planting; 102 kg N ha$^{-1}$ as UAN†, side-dressed | 114 kg N ha$^{-1}$ + 32 kg P ha$^{-1}$ + 78 kg K ha$^{-1}$ as liquid swine manure before planting; 68 kg N ha$^{-1}$ as UAN, side-dressed to blocks 1 and 2 ;114 kg N ha$^{-1}$ + 77 kg P ha$^{-1}$ + 83 kg K ha$^{-1}$ as liquid swine manure before planting; 68 kg N ha$^{-1}$ as UAN, side-dressed to blocks 3 and 4 | 114 kg N ha$^{-1}$ + 36 kg P ha$^{-1}$ + 66 kg K ha$^{-1}$ as liquid swine manure and 26 kg N ha$^{-1}$ and 114 kg P ha$^{-1}$ as MAP‡ before planting; 102 kg N ha$^{-1}$ as UAN, side-dressed |
| C-Sb | Soybean | none | none | 26 kg N ha$^{-1}$ and 114 kg P ha$^{-1}$ as MAP before planting |
| C-SC-WW/RC | Corn | 114 kg N ha$^{-1}$ + 34 kg P ha$^{-1}$ + 83 kg K ha$^{-1}$ as liquid swine manure before planting; 102 kg N ha$^{-1}$ as UAN, side-dressed | 114 kg N ha$^{-1}$ + 32 kg P ha$^{-1}$ + 78 kg K ha$^{-1}$ as liquid swine manure before planting; 102 kg N ha$^{-1}$ as UAN, side-dressed to blocks 1 and 2 ;114 kg N ha$^{-1}$ + 77 kg P ha$^{-1}$ + 83 kg K ha$^{-1}$ as liquid swine manure before planting; 102 kg N ha$^{-1}$ as UAN, side-dressed to blocks 3 and 4 | 114 kg N ha$^{-1}$ + 36 kg P ha$^{-1}$ + 66 kg K ha$^{-1}$ as liquid swine manure before planting; 68 kg N ha$^{-1}$ as UAN, side-dressed |
| C-SC-WW/RC | Spring canola | 57 kg N ha$^{-1}$ as urea at planting | 57 kg N ha$^{-1}$ as urea at planting | 57 kg N ha$^{-1}$ as urea at planting |
| C-SC-WW/RC | Winter wheat/ Red clover | 24 kg N ha$^{-1}$ + 91 kg P ha$^{-1}$ + 91 kg K ha$^{-1}$ as urea, triple super phosphate, and potash at planting in fall 2010; 34 kg N ha$^{-1}$ as urea in spring at frost-seeding | 24 kg N ha$^{-1}$ + 91 kg P ha$^{-1}$ + 91 kg K ha$^{-1}$ as urea, triple super phosphate, and potash at planting in fall 2011; 34 kg N ha$^{-1}$ as urea in spring at frost-seeding | 24 kg N ha$^{-1}$ + 91 kg P ha$^{-1}$ + 91 kg K ha$^{-1}$ as urea, triple super phosphate, and potash at planting in fall 2012; 34 kg N ha$^{-1}$ as urea in spring at frost-seeding |
| C-SW-WC/RC | Corn | 114 kg N ha$^{-1}$ + 34 kg P ha$^{-1}$ + 83 kg K ha$^{-1}$ as liquid swine manure before planting; 102 kg N ha$^{-1}$ as UAN, side-dressed | 114 kg N ha$^{-1}$ + 32 kg P ha$^{-1}$ + 78 kg K ha$^{-1}$ as liquid swine manure before planting; 102 kg N ha$^{-1}$ as UAN, side-dressed to blocks 1 and 2 ;114 kg N ha$^{-1}$ + 77 kg P ha$^{-1}$ + 83 kg K ha$^{-1}$ as liquid swine manure before planting; 102 kg N ha$^{-1}$ as UAN, side-dressed to blocks 3 and 4 | 114 kg N ha$^{-1}$ + 36 kg P ha$^{-1}$ + 66 kg K ha$^{-1}$ as liquid swine manure before planting; 68 kg N ha$^{-1}$ as UAN, side-dressed |
| C-SW-WC/RC | Spring wheat | 57 kg N ha$^{-1}$ as urea at planting | 57 kg N ha$^{-1}$ as urea at planting | 57 kg N ha$^{-1}$ as urea at planting |
| C-SW-WC/RC | Winter canola/ Red clover | 24 kg N ha$^{-1}$ + 91 kg P ha$^{-1}$ + 91 kg K ha$^{-1}$ as urea, triple super phosphate, and potash at planting in fall 2010; 34 kg N ha$^{-1}$ as urea in spring at frost-seeding | 24 kg N ha$^{-1}$ + 91 kg P ha$^{-1}$ + 91 kg K ha$^{-1}$ as urea, triple super phosphate, and potash at planting in fall 2011; 34 kg N ha$^{-1}$ as urea in spring at frost-seeding | 24 kg N ha$^{-1}$ + 91 kg P ha$^{-1}$ + 91 kg K ha$^{-1}$ as urea, triple super phosphate, and potash at planting in fall 2012; 34 kg N ha$^{-1}$ as urea in spring at frost-seeding |

† UAN: urea ammonium nitrate.

‡ MAP: monoammonium phosphate.

Table 3. Mechanical and chemical weed management practices for crops grown in crop rotations in 2010-2013. Dosages of herbicide active ingredients (kg ha$^{-1}$) are shown in parentheses.

| Rotation | Crop | 2011 | 2012 | 2013 |
|---|---|---|---|---|
| C-Sb | Corn | PRE†, broadcast: dimethenamid-P (1.06), glyphosate as isopropylamine salt (0.91); POST‡, broadcast: glyphosate as isopropylamine salt (1.15) | PRE, broadcast: dimethenamid-P (1.06), glyphosate as isopropylamine salt (0.91); POST, broadcast: glyphosate as isopropylamine salt (0.91) | disk tillage/fertilizer incorporattion (1x); PRE, broadcast: dimethenamid-P (1.06), glyphosate as isopropylamine salt (0.91) |
| C-Sb | Soybean | PRE, broadcast: dimethenamid-P (1.06), glyphosate as isopropylamine salt (0.91); POST, broadcast: glyphosate as isopropylamine salt (1.15); POST, broadcast: glyphosate as isopropylamine salt (1.30) | PRE, broadcast: dimethenamid-P (1.06), glyphosate as isopropylamine salt (0.91); POST, broadcast: glyphosate as isopropylamine salt (1.15); POST, broadcast: glyphosate as isopropylamine salt (1.30) | disk tillage/fertilizer incorporattion (1x); PRE, broadcast: dimethenamid-P (1.06), glyphosate (0.91) |
| C-SC-WW/RC | Corn | PRP§, broadcast: 2,4-D amine (0.28), glyphosate as isopropylamine salt (0.91); POST, broadcast:glyphosate as isopropylamine salt (1.15) (2x) | strip tillage (1x); PRP, broadcast: 2,4-D amine (0.28), glyphosate as isopropylamine salt (0.91); PRE, broadcast: dimethenamid-P (1.06), glyphosate as isopropylamine salt (0.91); POST, broadcast: glyphosate as isopropylamine salt (1.15) | strip tillage (1x); PRP, broadcast: 2,4-D amine (0.28), glyphosate as isopropylamine salt (0.91); PRE, broadcast: dimethenamid-P (1.06), glyphosate as isopropylamine salt (0.91) |
| C-SC-WW/RC | Spring canola | stubble mowing (2x) | POST, broadcast: imazamox as ammonium salt (0.14); stubble mowing (2x) | stubble mowing (2x) |
| C-SC-WW/RC | Winter wheat/ Red clover | disk tillage/fertilizer incorporation (1x, fall 2010); stubble mowing (1x) | disk tillage/fertilizer incorporation (1x, fall 2011); stubble mowing (1x) | disk tillage/fertilizer incorporation (1x, fall 2012); stubble mowing (1x) |
| C-SW-WC/RC | Corn | PRP, broadcast: 2,4-D amine (0.28), glyphosate as isopropylamine salt (0.91); POST, broadcast: glyphosate as isopropylamine salt (1.15) (2x) | strip tillage (1x); PRP, broadcast: 2,4-D amine (0.28), glyphosate as isopropylamine salt (0.91); PRE, broadcast: dimethenamid-P (1.06), glyphosate as isopropylamine salt (0.91); POST, broadcast: glyphosate as isopropylamine salt (1.15) | strip tillage (1x); PRP, broadcast: 2,4-D amine (0.28), glyphosate as isopropylamine salt (0.91); PRE, broadcast: dimethenamid-P (1.06), glyphosate as isopropylamine salt (0.91) |
| C-SW-WC/RC | Spring wheat | stubble mowing (2x) | stubble mowing (2x) | stubble mowing (2x) |
| C-SW-WC/RC | Winter canola/ Red clover | disk tillage/fertilizer incorporation (1x, fall 2010); stubble mowing (1x) | disk tillage/fertilizer incorporation (1x, fall 2011); stubble mowing (2x) | disk tillage/fertilizer incorporation (1x, fall 2012); stubble mowing (1x) |

† PRE: pre-emergence application.
‡ POST: post-emergence application.
§ PRP: pre-plant application.

Table 4. Total monthly precipitation and air temperature in 2010–2013 and long-term averages (1950–2013), at the experimental site.

| | Total monthly precipitation (mm) | | | | Mean monthly air temperature (ºC) | | | |
|---|---|---|---|---|---|---|---|---|
| Month | 2011 | 2012 | 2013 | Long-term avg. | 2011 | 2012 | 2013 | Long-term avg. |
| January | 18 | 7 | 15 | 20 | -9 | -2 | -5 | -7 |
| February | 33 | 44 | 20 | 24 | -4 | -1 | -4 | -5 |
| March | 20 | 60 | 38 | 45 | 3 | 11 | -1 | 2 |
| April | 111 | 122 | 148 | 82 | 10 | 13 | 8 | 10 |
| May | 117 | 62 | 180 | 112 | 16 | 19 | 16 | 16 |
| June | 128 | 75 | 76 | 123 | 22 | 23 | 21 | 21 |
| July | 99 | 37 | 26 | 93 | 26 | 26 | 23 | 24 |
| August | 91 | 74 | 55 | 101 | 23 | 22 | 23 | 22 |
| September | 51 | 47 | 30 | 91 | 17 | 18 | 20 | 18 |
| October | 22 | 59 | 64 | 61 | 13 | 10 | 11 | 11 |
| November | 68 | 23 | 35 | 39 | 5 | 5 | 2 | 3 |
| December | 57 | 26 | 9 | 27 | -1 | -2 | -8 | -4 |

Table 5. Yields of corn, soybean, canola, and wheat grain, wheat straw, and content of oilseed crops from experimental plots from 2011 to 2013.

| Year<br>Rotation system | Corn | Soybean | Canola† | Wheat‡ | Straw‡ |
|---|---|---|---|---|---|
| 2011 | ---------- | ---------- | Mg ha$^{-1}$ | ---------- | ---------- |
| C-Sb | 12.91 a¶ | 3.88 | - | - | - |
| C-SC-WW/RC | 11.30 b | - | 0.97 b | 3.63 a | 0.98 a |
| C-SW-WC/RC | 10.78 b | - | 2.50 a | 2.25 b | 0.95 a |
| 2012 | | | | | |
| C-Sb | 8.35 a | 3.13 | - | - | - |
| C-SC-WW/RC | 6.23 b | - | 0.08 b | 3.30 a | 1.70 a |
| C-SW-WC/RC | 6.43 b | - | 1.60 a | 2.10 b | 0.90 b |
| 2013 | | | | | |
| C-Sb | 7.35 a | 2.78 | - | - | - |
| C-SC-WW/RC | 7.93 a | - | 0.18 b | 2.75 a | 1.30 b |
| C-SW-WC/RC | 7.45 a | - | 1.62 a | 1.83 b | 1.50 a |
| SE | 0.32 | 0.08 | 0.23 | 0.21 | 0.03 |
| Significance | | | *P* value | | |
| Year (Y) | <0.0001 | 0.0001 | 0.0087 | 0.1138 | <0.0001 |
| Rotation system (R) | <0.0001 | - | 0.0001 | <0.0001 | <0.0001 |
| Y × R | 0.0017 | - | 0.9817 | 0.2378 | <0.0001 |

† Spring canola in the C-SC-WW/RC rotation and winter canola in the C-SW-WC/RC rotation.
‡ Winter wheat in the C-SC-WW/RC rotation and spring wheat in the C-SW-WC/RC rotation.
§ Soybean in the C-Sb rotation, spring canola in the C-SC-WW/RC rotation, and winter canola in the C-SW-WC/RC rotation.
¶ Means followed by different lowercase letters within a column by year are significantly different at $P \leq 0.05$.

Table 6. Crop prices, gross revenues, production costs, labor requirements, and returns to land and management for the rotation systems, 2011-2013.

| Rotation system<br>Crop | Crop price† | Gross revenue | Production costs‡ | Labor requirement | Return to land and management§ |
|---|---|---|---|---|---|
| 2011 | \$ $Mg^{-1}$ | \$ $ha^{-1}$ $yr^{-1}$ | | h $ha^{-1}$ $yr^{-1}$ | \$ $ha^{-1}$ $yr^{-1}$ |
| C-Sb | | | | | |
| Corn | 246.09 | 3182.15 | 680.09 | 1.17 | 2488.53 |
| Soybean | 463.05 | 1814.40 | 452.43 | 1.45 | 1345.15 |
| Rotation avg. | | 2498.28 | 566.26 | 1.31 | 1916.84 |
| C-SC-WW/RC | | | | | |
| Corn | 246.09 | 2785.35 | 645.29 | 1.84 | 2118.68 |
| Spring canola | 533.61 | 520.30 | 307.75 | 1.40 | 196.31 |
| Winter wheat/clover | 235.57 | 996.29 | 442.08 | 3.19 | 517.17 |
| Rotation avg. | | 1433.98 | 465.04 | 2.14 | 944.06 |
| C-SW-WC/RC | | | | | |
| Corn | 246.09 | 2656.70 | 601.99 | 1.84 | 2033.34 |
| Spring wheat | 235.57 | 659.76 | 318.14 | 1.81 | 320.61 |
| Winter canola/clover | 533.61 | 1321.93 | 379.76 | 3.03 | 907.07 |
| Rotation avg. | | 1546.13 | 433.30 | 2.23 | 1087.01 |
| 2012 | | | | | |
| C-Sb | | | | | |
| Corn | 283.50 | 2390.40 | 708.74 | 1.17 | 1668.02 |
| Soybean | 525.53 | 1669.53 | 501.67 | 1.45 | 1150.89 |
| Rotation avg. | | 2029.96 | 605.20 | 1.31 | 1409.45 |
| C-SC-WW/RC | | | | | |
| Corn | 283.50 | 1778.40 | 842.86 | 2.27 | 909.02 |
| Spring canola | 582.12 | 36.30 | 381.93 | 1.88 | -367.57 |
| Winter wheat/clover | 257.25 | 1166.19 | 494.50 | 3.50 | 630.71 |
| Rotation avg. | | 993.63 | 573.10 | 2.55 | 390.72 |
| C-SW-WC/RC | | | | | |
| Corn | 283.50 | 1929.60 | 815.09 | 2.27 | 1088.00 |
| Spring wheat | 257.25 | 697.92 | 356.34 | 2.10 | 317.04 |
| Winter canola/clover | 582.12 | 932.25 | 430.27 | 3.03 | 466.59 |
| Rotation avg. | | 1186.59 | 533.90 | 2.46 | 623.88 |
| 2013 | | | | | |
| C-Sb | | | | | |
| Corn | 196.88 | 1456.25 | 806.63 | 1.71 | 628.73 |
| Soybean | 525.53 | 1483.63 | 581.39 | 2.17 | 875.69 |
| Rotation avg. | | 1469.94 | 694.01 | 1.94 | 752.21 |
| C-SC-WW/RC | | | | | |
| Corn | 196.88 | 1572.50 | 785.90 | 2.09 | 760.99 |
| Spring canola | 1181.88 | 308.20 | 382.92 | 1.41 | -92.01 |
| Winter wheat/clover | 282.61 | 948.74 | 518.99 | 3.45 | 387.48 |
| Rotation avg. | | 943.15 | 562.61 | 2.32 | 352.15 |
| C-SW-WC/RC | | | | | |
| Corn | 196.88 | 1476.25 | 750.90 | 2.09 | 699.74 |
| Spring wheat | 282.61 | 743.99 | 367.89 | 1.84 | 353.50 |
| Winter canola/clover | 1181.88 | 1983.20 | 458.54 | 3.04 | 1487.46 |
| Rotation avg. | | 1401.15 | 525.78 | 2.32 | 846.90 |

† Price for wheat straw was \$132.54 $Mg^{-1}$ in 2011, \$142.09 $Mg^{-1}$ in 2012, and \$139.56 $Mg^{-1}$ in 2013.

‡ Costs included machinery passes, handling, hauling, and for corn, drying grain. Land and labor costs were not included.

§ Labor charge was \$11.60 $h^{-1}$ in 2011, \$11.70 $h^{-1}$ in 2012, and \$12.25 $h^{-1}$ in 2013.

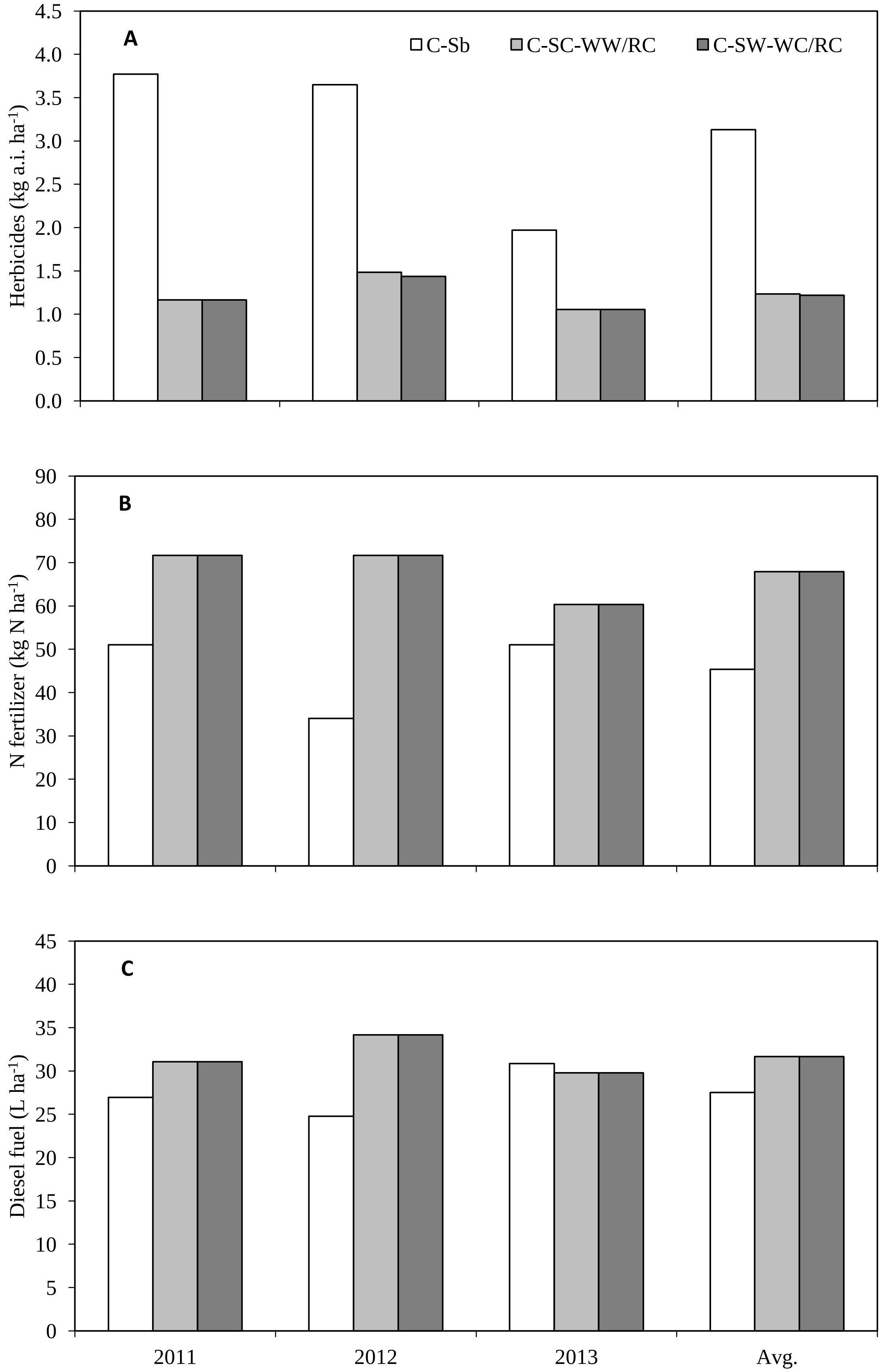


Fig 1. Annual and three-year average amount of (A) herbicide active ingredients (a.i.) applied, (B) N fertilizer applied, and (C) diesel fuel usage for each of the three crop rotation systems.

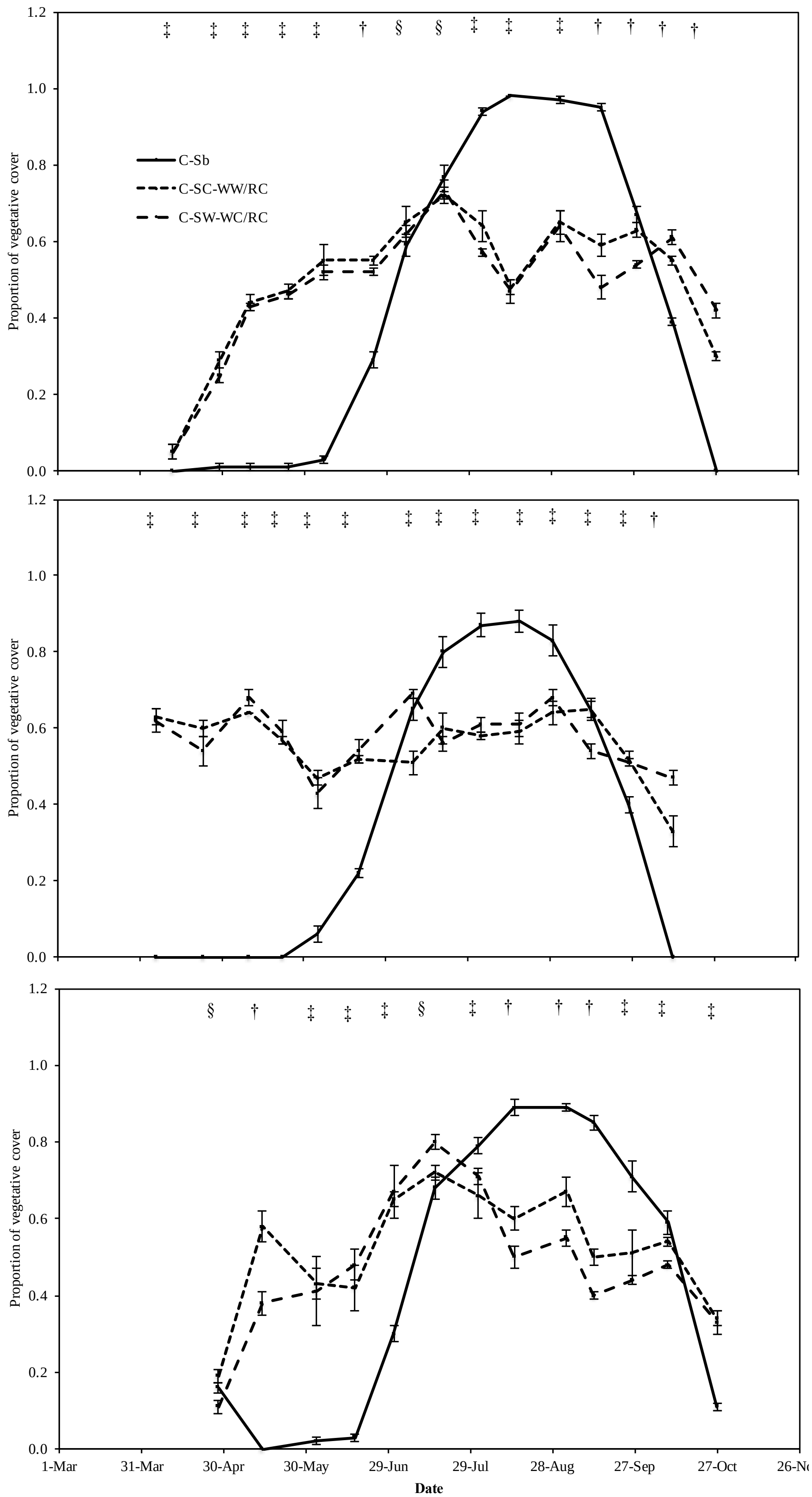


Fig. 2. Mean (±SE) proportion of vegetative cover for each of the three crop rotation systems for 2011–2013. † = all three treatments are different; ‡ = any two treatments are different; § = no differences among treatments.

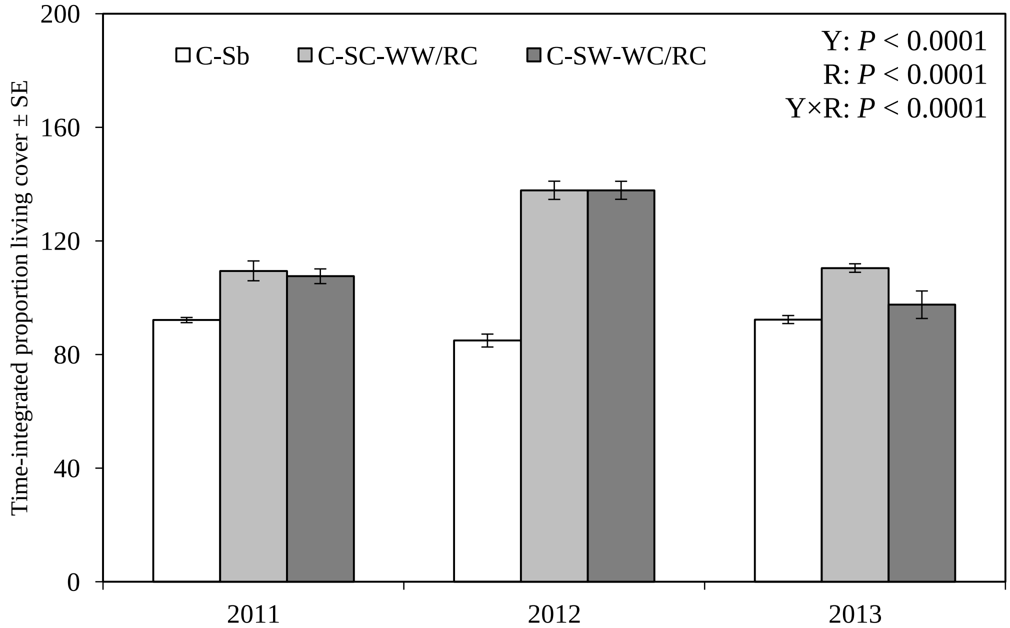


Fig. 3. Mean (±SE) annual duration of vegetative cover (as expressed as time-integrated proportion vegetative cover) for each of the rotation systems, 2011–2013.

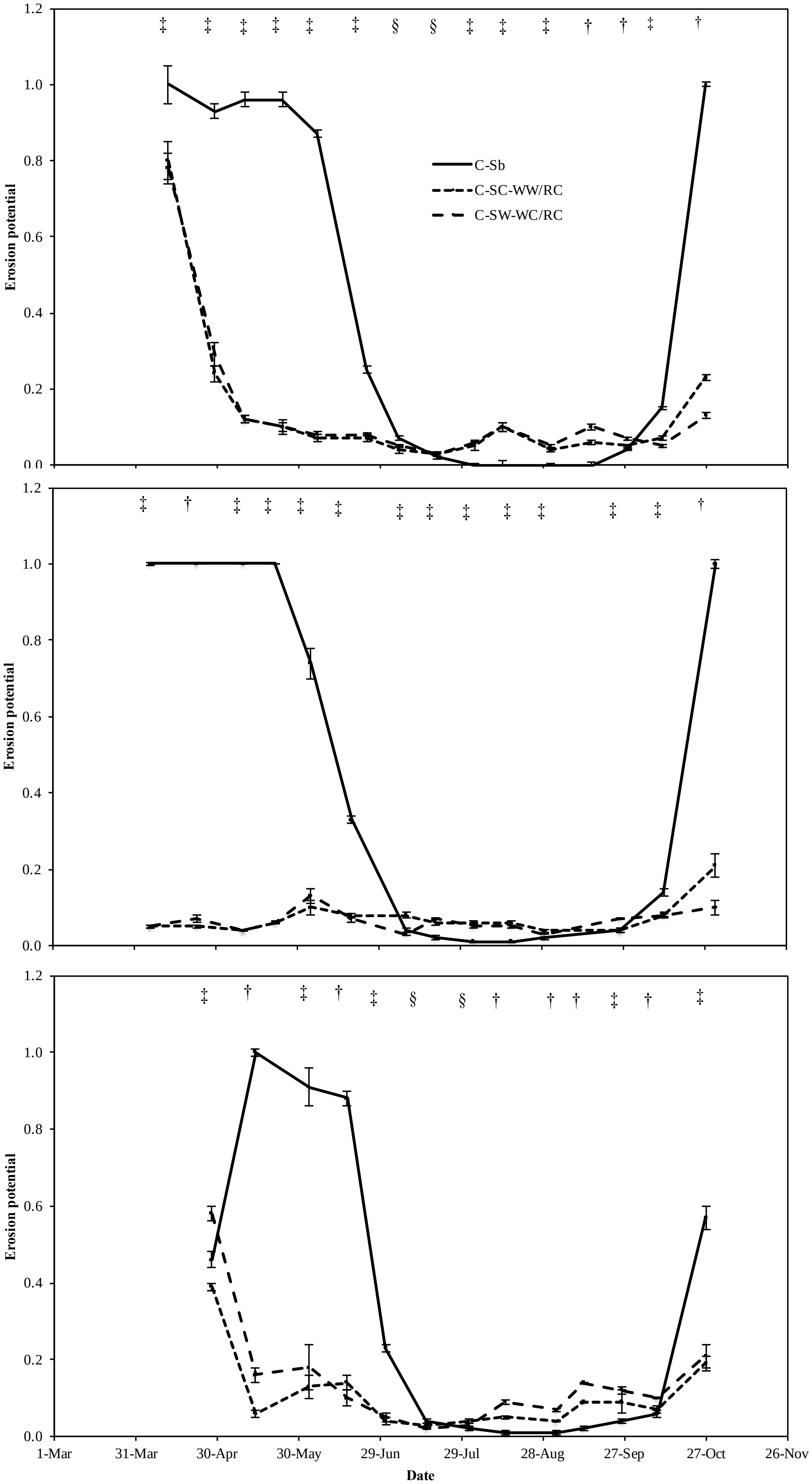


Fig. 4. Mean (±SE) soil erosion potential for each of the three crop rotation systems, 2011–2013. Erosion potential relative to a bare surface (1.0) was calculated after Gyssels et al. (2005). † = all three treatments are different; ‡ = any two treatments are different; § = no differences among treatments.

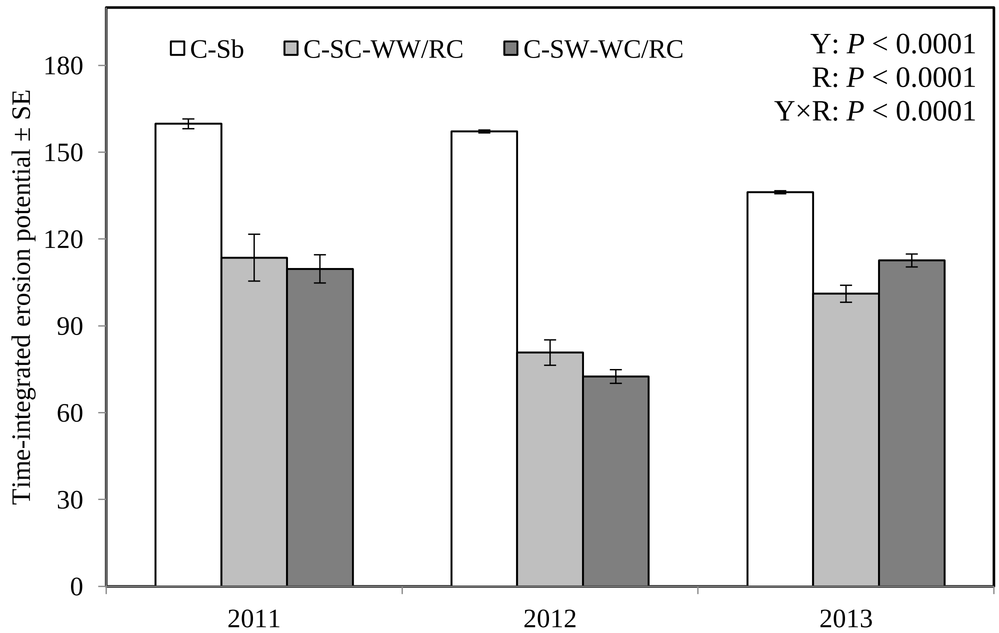


Fig. 5. Mean (±SE) annual duration of erosion potential (as expressed as time-integrated Er) for each of the rotation systems, 2011–2013.

# CHAPTER 5. GENERAL CONCLUSION

The purpose of my dissertation research was to investigate cropping systems that would reintroduce crop species diversity on the Iowa farming landscape. Each of the preceding articles addressed important components of diversified crop rotations in comparison to the prevailing contemporary corn-soybean system. The first article (Chapter 2) addressed the effects of adding a red clover green manure (frost-seeded with a winter annual crop) on the productivity of corn. The second article (Chapter 3) focused on the crops (canola and wheat) in the three-year rotation systems that earned those rotation systems the general title of "alternative cropping system" in Iowa. The third article (Chapter 4) assessed the productivity, economic performance, and potential for soil erosion of each of the three crop rotation systems studied over the course of the period 2011-2013. My results portray the potential benefits, challenges, and shortcomings of extended, alternative cropping systems compared to a two-year, corn-soybean system. Though the two alternative systems were not as competitive on a production or economic basis compared to the contemporary corn-soybean system, they did show tremendous promise in terms of reducing the potential for soil erosion associated with the commonly used corn-soybean system in Midwestern agriculture.

Corn yields were greatest in the corn-soybean system compared to the two alternative systems in 2011 (12.91 vs. 11.04 Mg $ha^{-1}$) and 2012 (8.35 vs. 6.33 Mg $ha^{-1}$) but similar across all systems in 2013 (7.58 Mg $ha^{-1}$). Taken together these results reemphasize the importance of synchronicity between soil available N and corn N uptake for optimal corn yields. Replacing synthetic N applied to corn with N from green manures like red clover can be achieved provided adequate environmental conditions for chemical termination and subsequent microbial decomposition of red clover residue. Insufficient termination of red clover green manure due to cool temperatures and rainfall that interfered with chemical termination resulted in lower corn yields than when corn followed soybean in rotation as was observed in this study in 2011 and 2012. The likely culprits for these lower yields were early competition by the dying red clover with the emerging corn and the N from the decomposing red clover residue becoming available too late in the growing season for the corn to benefit from it.

Canola yields were consistently greater in the C-SW-WC/RC system than in the C-SC-WW/RC system primarily owing to the greater yield potential of winter canola compared to spring canola. Moreover, winter canola yields in the C-SW-WC/RC rotation more closely resembled average yields in states where canola is contemporarily grown, namely Minnesota and North Dakota (1.50 Mg $ha^{-1}$). Spring canola yields in the C-SC-WW/RC rotation were very low and we attribute this to canola not fitting well in a crop rotation after a high residue producing crop like corn. Low spring canola yields likely stemmed from poor stands resulting from problems seeding canola into corn stubble. Similar trends to canola were observed for wheat production between the two alternative systems. Mean winter wheat yield in the C-SC-WW/RC rotation (3.23 Mg $ha^{-1}$) was consistently greater than mean spring wheat yield in the C-SW-WC/RC rotation (2.06 Mg $ha^{-1}$). Winter wheat yields more closely resembled the 10-year average wheat yield for Iowa, 3.40 Mg $ha^{-1}$.

Compared to the corn-soybean system, the two alternative systems provided more vegetative cover for a longer period of time throughout the year. On average, the two alternative systems provided at least 70% vegetative cover between October and May when over 50% of precipitation occurs in central Iowa. Because rainfall occurring when much of the soil in Iowa lays bare is a major driver of soil loss, the alternative systems offer a compelling strategy to reduce soil erosion. The alternative systems also saw on average less herbicide applied per year than the corn-soybean system. In the two alternative systems, herbicide was generally only applied during the corn phase as those systems relied on the natural competitiveness of the spring and winter annual crops with weeds commonly adapted to corn-soybean production systems of

Iowa. Thus, farmers looking to reduce the amount of herbicide applied could look to cropping systems that include a diverse array of crop life cycles. Financial returns, however, generally favored the corn-soybean system. Though, in 2013, corn yields across the three systems were equivalent and returns to land and management were greatest in the corn-spring wheat-winter canola/red clover system.

Given that the cropping history of the experimental site was a corn-soybean rotation, my results depict what could be considered the first years of transitioning away from the contemporary system to an alternative cropping system. The crops harvested in 2013 from the three-year systems were the first to follow each of the previous two crops and to have gone through the entire rotation cycle. Corn grain yields in the three-year systems were less than those in the corn-soybean system in 2011 and 2012, but they were equivalent in 2013. This might suggest a "lag time" before improved crop productivity can be realized in alternative cropping systems. As such, research into crop management techniques that will maintain or improve crop yields during the period while transitioning into alternative cropping systems should be a priority. These might include:

i. Investigating the application of a small amount of N fertilizer at the time of corn planting when no-till or strip-till planting into a desiccated red clover green manure to overcome potential soil N deficiencies;

ii. Screening varieties of wheat and canola that might perform better than those included in this dissertation research;

iii. Including only one "alternative" crop (e.g., canola or wheat) as well as soybeans in alternative rotations to limit potential financial sacrifices of such rotations.

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