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# Clover green manure productivity and weed suppression in an organic grain rotation

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## Abstract

Green manure crops must produce high biomass to supply biological N, increase organic matter and control weeds. The objectives of our study were to assess above-ground biomass productivity and weed suppression of clover (*Trifolium* spp.) green manures in an organic soybean [*Glycine max* (L.) Merr.]-winter wheat (*Triticum aestivum* L.)-corn (*Zea mays* L.) rotation in eastern Nebraska in three cycles (2011–12, 2012–13, 2013–14). Treatments were green manure species [red clover (*T. pratense* L.) and white clover (*T. repens* L.)] undersown into winter wheat in March and green manure mowing regime (one late summer mowing or no mowing). We measured wheat productivity and grain protein at wheat harvest, and clover and weed above-ground biomass as dry matter (DM) at wheat harvest, 35 days after wheat harvest, in October and in April before clover termination. Winter wheat grain yields and grain protein were not affected by undersown clovers. DM was higher for red than for white clover at most sampling times. Red clover produced between 0.4 and 5.5 Mg ha$^{-1}$ in the fall and 0.4–5.2 Mg ha$^{-1}$ in the spring. White clover produced between 0.1 and 2.5 Mg ha$^{-1}$ in the fall and 0.2–3.1 Mg ha$^{-1}$ in the spring. Weed DM was lower under red clover than under white clover at most sampling times. In the spring, weed DM ranged from 0.0 to 0.6 Mg ha$^{-1}$ under red clover and from 0.0 to 3.1 Mg ha$^{-1}$ under white clover. Mowing did not consistently affect clover or weed DM. For organic growers in eastern Nebraska, red clover undersown into winter wheat can be a productive green manure with good weed suppression potential.

**Key words:** red clover, white clover, green manures, undersowing, organic agriculture

## Introduction

Leguminous green manures are grown to increase soil nitrogen (N), soil organic matter and subsequent crop yields (Cherr et al., 2006; Schipanski and Drinkwater, 2011) and are crucial in organic systems where they constitute one of the main sources of N. They can be planted during the winter wheat phase of a soybean-winter wheat-corn rotation to take advantage of the fallow period between winter wheat harvest and corn planting. In the Western Corn Belt, soil moisture after winter wheat harvest can be insufficient, but spring soil moisture conditions are more favorable for green manure establishment. Thus, planting the green manure in early spring directly into winter wheat stands is regarded as an effective way of establishment (Snapp et al., 2005). In the literature, this system has been called relay intercropping (Amossé et al., 2013) or relay cropping (Cicek et al., 2014) but we will use the term undersowing as 'cropping' might imply that two marketable crops are produced. Undersowing in early spring is carried out by broadcasting the seed on frozen ground (frost-seeding), allowing the freeze-thaw cycle to work the seeds into the soil (Blaser et al., 2006). After winter wheat harvest, the green manure continues to grow in the field and is terminated, usually by killing it mechanically, either in the fall of the establishment year or the following spring before corn planting. Upon decomposition, leguminous green manures release N from above- and below-ground plant tissue replacing some or all N fertilizer for subsequent crops. The amount of N from fixation varies greatly depending on legume species and cultivar, soil mineral N, rhizobial inoculation and climate (Peoples et al., 2009) but is estimated at 25 kg for every Mg of legume above-ground dry matter (DM) (Peoples and Baldock, 2001).

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Replacing the fallow period with a green manure also eliminates tillage for weed control reducing labor and fuel needs and decreasing the risk of erosion (Carr et al., 2012). Even where the risk of erosion is small, the impacts of tillage on soil quality are stark: loss of soil organic matter, soil structure and aggregation, as well as the disruption of beneficial soil microorganisms such as fungi and earthworms (Triplett and Dick, 2008). In order to replace tillage as weed control, the green manure must inhibit weed emergence, growth and seed production to avoid intensifying weed problems in the subsequent years.

High biomass production of leguminous green manures is important, because it is highly correlated with N fixation (Peoples and Baldock, 2001), productivity of the following crop (Parr et al., 2011; Amossé et al., 2013) and weed suppression (Brust et al., 2014). High biomass accrual before the dormant season provides erosion control during winter and winter hardiness is necessary for early spring biomass production (Snapp et al., 2005). For undersowing into small grains, low-growing, non-vining legume species are well suited because they rarely interfere with small grain growth and harvest. Stute and Posner (1993) screened several forage legumes for their suitability to be intercropped with a small grain in Wisconsin conventional trials. Hairy vetch (*Vicia villosa* Roth) produced the most biomass but increased lodging of the small grain due to its vining growth habit. Red clover and white clover did not interfere with the small grain while still producing up to 3.1 Mg ha$^{-1}$ of DM and up to 1.8 Mg DM ha$^{-1}$, respectively. Sweet clover (*Melilotus officinalis* L.) produced up to 3.6 Mg ha$^{-1}$ DM but had very little regrowth if the small grain was cut low. Other authors also reported on the high productivity of red clover as a green manure, for example Cicek et al. (2014) in organic trials in Manitoba found that undersown red clover yielded more biomass than undersown sweet clover. White clover when grown as a perennial forage crop, has a higher rate of N fixation than red clover (Carlsson and Huss-Danell, 2003) and is occasionally used as an undersown green manure for small grain cropping systems in Europe (Bergkvist, 2003). Red and white clover rarely impact the winter wheat they are undersown into, however, N fertilization can mask effects of competition between the cereal and undersown legumes (Blaser et al., 2011). Red and white clover green manures with DM yields between 2 and 3 Mg ha$^{-1}$ at spring termination have been linked to increases in subsequent corn yields (Gentry et al., 2013; Amossé et al., 2014).

Undersown and overwintered red clover suppressed weed biomass by 99% compared with a control (no cover crop) in organic trials in South Dakota (Anderson, 2015). White clover has demonstrated the ability to control weeds when used as a living mulch in orchards and vineyards (Hartwig and Ammon, 2002), but might be less effective when grown for shorter periods of time. In living mulch vegetable systems in the Netherlands, white clover reduced weed biomass less than red clover, but also impacted the crop less than red clover (Den Hollander et al., 2007). Mowing red and white clover green manures is recommended to prevent weed seed set (Drangmeister, 2003) but impacts the green manures photosynthetic ability and storage of carbohydrates for winter survival (Black et al., 2009).

Despite the potential benefits of undersown green manures in organic grain-based rotations, few studies have been conducted under organic management. Long-term organic-conventional farming system comparisons have found higher soil organic matter (Pimentel et al., 2005) and higher (Pimentel et al., 2005) or lower soil mineral N (Drinkwater et al., 1995) in organically managed fields, which could affect green manure DM yields as well as yields of intercropped winter wheat. Few studies measure undersown green manure DM production more than one time during the season, but are needed to understand peak green manure productivity and inform timing of management decisions such as when to mow or terminate.

This study aims to better understand the influence of legume species and mowing regime on undersown green manure DM production and winter wheat grain yield and grain quality in an organic soybean-winter wheat-corn rotation. Our hypotheses were (i) red clover and white clover will produce at least 2 Mg ha$^{-1}$ DM in the fall and following spring, (ii) red clover DM production will be greater than white clover; (iii) red clover will suppress weeds more than white clover; iv) mowing clover green manures will improve weed suppression and (v) winter wheat grain yields or grain protein contents will be unaffected by undersown clover species.

## Materials and Methods

### Site and soils

The site was located in eastern Nebraska at the Shelterbelt Research Area of the Agricultural Research and Development Center near Mead, Nebraska (41°29′N; 96°30′W; 354 m above mean sea level). All fields in this study have been organically certified under the National Organic Program, transitioning in 2006 and 2007. Since then, they have been in a soybean-winter wheat-corn rotation with cattle (*Bos taurus*) manure applications at a rate of 56 Mg ha$^{-1}$ (wet weight) after wheat harvest. Soils were mostly Yutan silty clay loam (fine-silty, mixed, superactive, mesic Mollic Hapludalf) with some Filbert silt loam (fine, smectic, mesic Vertic Argiallboll) and to a lesser extent Tomek silt loam (fine, smectic, mesic Pachic Argiudoll) with a slope of less than 5%.

### Experiment and treatment design

The first cycle of this study was initiated in 2011, the second in 2012 and the third in 2013, respectively, with the undersowing of green manures into winter wheat in early spring. In the first cycle, treatments were green manure species (red clover, white clover, or control) and mowing regime (mowed or not mowed), and were arranged as factorials in a completely randomized design with four replicates. The control treatment (wheat without undersown clover) was not randomly located but placed on the east side of the field for ease of management. Clovers were mowed at a height of 0.1 m 40 days after winter wheat harvest and clippings were left in place. Plots were 9 m wide by 69 m long. In the second cycle, the treatment was green manure species (red clover, white clover, or control) arranged in a randomized complete block design. Plots were not mowed because of very low clover DM production during the drought year of 2012. Due to smaller field size, plot length in this cycle was reduced to 30 m. In the third cycle, treatments were green manure species (red clover, white clover, or control), arranged in a randomized complete block design. The mowing treatment was randomly assigned to whole blocks instead of plots to facilitate management with the large farm equipment. Plots were 9 × 18 m long. The second cycle had 14 replications and the third cycle had ten replications. Not all replications were sampled at each time in the third cycle.

### Crop management

The semi-dwarf hard red winter wheat 'Overland' was no-till drilled into soybean stubble with a Sunflower 9410 drill (Beloit, KS) at a seeding rate of 100 kg ha$^{-1}$ equivalent to 400 seeds m$^{-2}$ in October in all 3 years (Table 1). No weed control was carried out in the winter wheat. Clover cultivars were planted into winter wheat stands the following March (Table 1) with a Vicon broadcast spreader (Merseyside, UK) at a rate of 22.4 kg ha$^{-1}$ for red clover 'Marathon' (600,000 seeds kg$^{-1}$, equivalent to 1300 seeds m$^{-2}$) and at a rate of 13.5 kg ha$^{-1}$ for white clover 'Rivendel' (1,700,000 seeds kg$^{-1}$, equivalent to 2300 seeds m$^{-2}$). The same cultivars were used each year and were chosen for high DM production capacity and winter hardiness. Red clover purity and germination were not available in the first cycle, and were 100 and 63% in the second cycle, and 100 and 90% in the third cycle, respectively. White clover purity and germination were 66 and 82% in the first, 99 and 80% in the second and 66 and 77% in the third cycle, respectively. Hard seed constituted 24 and 5% of the red clover seed in the second and third cycle, and 9, 11 and 13% of the white clover seed in the first, second and third cycle, respectively.

### Data collection

Emergence counts of clover were taken approximately 7 weeks after planting (WAP) (Table 1). Two to four areas per plot were randomly selected, a 0.1 m$^2$ metal square was placed on the ground, and all clover seedlings growing within the square were counted. Wheat plants were not counted.

Wheat was harvested at maturity with a Gleaner N combine (Duluth, GA) with a 4.6 m wide head in the first cycle and with a Case IH 1640 combine (Racine, WI) with a 6.1 m wide head in the other cycles. All grain from one pass through the center of each plot was weighed on a grain cart (Parker 450, Kalida, OH) with an accuracy of 4.5 kg to determine raw wheat grain yield. In the second and third cycle, plots were shorter and wheat grain from the center strip of each plot was emptied into a trash can and weighed on a truck scale with an accuracy of 1 kg.

Wheat grain moisture was not measured on the field, but is assumed to be similar between treatments. Wheat grain moisture (grain from all treatments combined) at the grain elevator was between 12 and 15% in each cycle. All wheat grain yields reported are raw yields, not adjusted for moisture. Wheat grain protein from each plot was analyzed with near-infrared transmittance technology with a Foss Infratec 1241 (Eden Prairie, MN) in the first and second cycle and a Perten DA 7250 (Springfield, IL) in the third cycle.

DM production of undersown clovers was measured by taking above-ground biomass samples starting at winter wheat harvest ('Harvest'), 35 days post-harvest to assess DM at mowing ('35 days post'), in the fall ('October') to reflect DM yields at a potential fall termination and in the overwintered plots to reflect DM yields at spring termination ('April') (Table 1). Winter wheat DM (above-ground biomass including seed head) was measured at 'Harvest' only. For biomass sampling, three areas per plot were randomly selected and all vegetation growing within a 0.1 m$^2$ quadrat was cut at ground level and sorted into clover, winter wheat and weeds. All dead plant material (except wheat) was discarded. Biomass was then dried at 65°C to constant weight and weighed. Weed biomass was not sampled in the control plots as they were kept weed-free by frequent tilling between wheat harvest and the following spring. Thus, there is no clover-free weedy control treatment to compare with red and white clover weed DM. However, our protocols reflect the cultivation practices of organic producers that do not use green manures for weed control.

Year-round climate data were available from the ARDC Mead climate station located in an area about 1 km away (Automated Weather Data Network, ID a255369, High Plains Regional Climate Network).

### Statistical analysis

Data were analyzed with ANOVA using PROC GLIMMIX in SAS 9.4 (SAS Institute, Cary, NC, SAS Institute, 2014). For DM and emergence measurements, the means of the subsamples were calculated using PROC MEANS before conducting the ANOVA. All the data were analyzed separately by cycle, as completely

**Table 1.** Measurement schedule for each cycle in chronological order.

| Measurement | First cycle | Second cycle | Third cycle |
|---|---|---|---|
| Winter wheat planting | October 13, 2010 | October 13, 2011 | October 10, 2012 |
| Clover broadcasting | March 24, 2011 | March 10, 2012 | March 19, 2013 |
| Clover and weed emergence counts | May 6–May 13 | May 10 | May 18 |
| Biomass sampling ('Wheat harvest') | July 18 & 19 | June 28 & 29 | July 17 & 18 |
| Winter wheat harvest[1] | July 18 and 19 | June 27 | July 16 |
| Biomass sampling ('35 days post-harvest') | August 23 | July 30 | August 23 |
| Clover mowing | September 1 | – | August 30 |
| Biomass sampling ('October') | October 11 | October 11 & November 9 | October 28 |
| Biomass sampling ('April') | April 26, 2012 | April 29, 2013 | April 16, 2014 |

[1] Winter wheat yield and grain samples for grain protein analysis were taken at harvest.
Planting, mowing and termination dates are given for reference. Clover green manure and weed biomass sampling started at winter wheat harvest and continued until spring of the following year. Clover was not mowed in the second cycle due to insufficient growth.

randomized design in the first cycle and randomized complete block design in the second and third cycle. Block (where applicable) was a random effect and the treatments were fixed effects. For unmowed clover and weed DM, sampling time was modeled as repeated measures. To assess the effects of mowing on clover and weed DM, a separate ANOVA with mowing regime and clover species as fixed effects was conducted for each sampling time after mowing ('October' and 'April'). In the first cycle, mowing and clover species were factorial treatments in a completely randomized design. In the third cycle, mowing was assigned to whole blocks and was analyzed as an incomplete randomized design. Least-square mean differences were compared with Fisher's test using a significance level of $\alpha = 0.05$.

## Results and Discussion

### Weather conditions

The weather during this study's duration was characterized by extreme variations from the 30-year means of temperature and precipitation (Figs 1 and 2). In the first cycle (2011–2012), above-normal precipitation between April and June 2011 was followed by below-normal precipitation combined with above-normal temperatures between October 2011 and March 2012. Dry and warm conditions continued in the second cycle (2012–2013), with temperatures 2.5°C above normal for April, 3.1°C for May and 2.2°C for June 2012. In July, the temperature reached 27.8°C, a record high, and only 2 mm of rain fell. Drought conditions prevailed in much of the area until April 2013, when precipitation was 11 mm above-normal, yet temperatures remained cooler than normal, especially during March 2013, which was 4.1°C below normal. Drought conditions improved in the third cycle (2013–2014), with precipitation in May 27 mm above normal, although July and August 2013 had below-average rainfall. Temperatures until September were within the normal range. The winter was very cold and dry, without precipitation or snow cover between December 2013 and March 2014. Temperatures in February were 4°C below normal, a record cold.

### Winter wheat DM production, grain yields and grain protein

Winter wheat DM was reduced by undersown red and white clover in the first cycle, but not in the other cycles (Table 2). Wheat grain yields and grain protein were not impacted by undersown clover in the first or second cycle. In the third cycle wheat grain yields were 0.61 Mg $ha^{-1}$ lower than the control in wheat undersown with white clover and wheat grain protein was 0.25% lower than the control in wheat undersown with red clover. To be marketed as bread wheat, wheat grain must have at least 12% protein (Mallory and Darby, 2013). In the last cycle, grain protein in both the control and wheat undersown with white clover was within 0.1% of the 12% threshold. Wheat grain protein and yields in our study were similar or greater than those of winter wheat under organic management from other studies (Miller et al., 2011; Mallory and Darby, 2013; Wortman et al., 2013) probably because of the frequency of soybean in the rotation and relatively high manure applications.

Other authors also report little or no influence on yields of winter wheat undersown with red clover (Blackshaw et al., 2010; Blaser et al., 2011; Amossé et al., 2013) or white clover (Amossé et al., 2013), because winter wheat has a competitive advantage over the later-planted legumes. However, Amossé et al. (2013) in a study under organic management, found that winter wheat grain protein was reduced by undersown red clover and black medic (*Medicago lupulina* L.) in some site years, especially when conditions were favorable for the undersown legumes. In the third cycle of our study, red clover had accumulated more DM (see below) by winter wheat harvest than in the other cycles, increasing its competitiveness with wheat

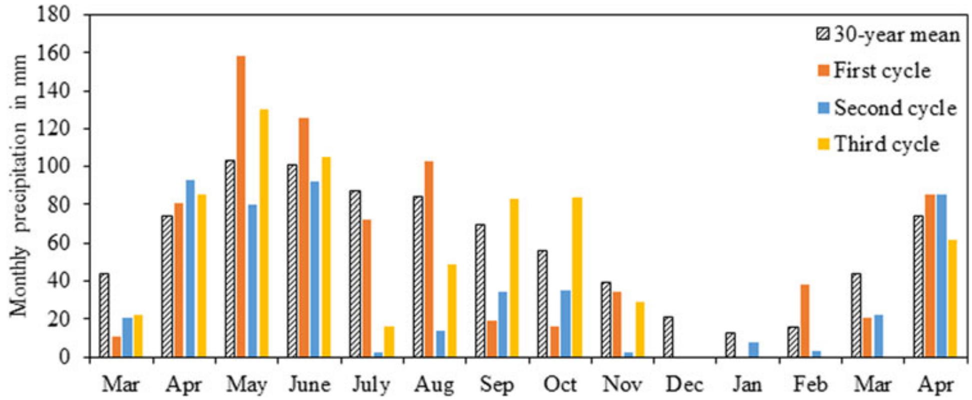


**Figure 1.** Monthly precipitation for each cycle, starting at the time of undersowing (March) and ending the following April.

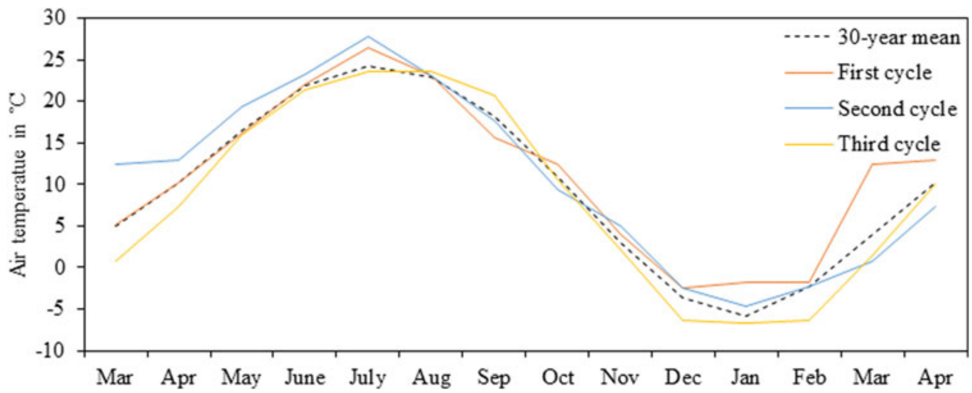


**Figure 2.** Daily air temperature (average of daily nighttime low and daytime high temperature) for each cycle, starting at the time of undersowing (March) and ending the following April.

for N and water, which could have lowered wheat yields in these plots.

## Clover emergence and DM production

The target seeding rate was 1300 seeds m$^{-2}$ for red clover and 2300 m$^{-2}$ for white clover in each cycle, but the actual seeding rate (ARS) differed from cycle to cycle due to differences in purity and germination rate of the clover seeds (Table 3). Red clover ARS was between 819 and 1170 seeds m$^{-2}$ and white clover ARS was between 1169 and 1822 m$^{-2}$. The percentage of emerged seeds at 7 WAP was higher for red than white clover in each cycle. Red clover emergence was 64% in the first and 92% in the third cycle, at least twice as high as white clover emergence. In the first cycle, snowfall immediately after clover broadcasting provided cover and moisture and in the third cycle, seeds were broadcast onto snow. Cool spring temperatures in March and April of 2013 did not hinder germination, as red clover germinates at 3°C and white clover at 5°C (Agriculture and Forestry Alberta, 2000).

The lowest percentage of seeds of both species emerged in the second cycle (49 and 14% for red and white clover, respectively), probably because the seed bed in March was frost-free, lacking the freeze-thaw mechanisms necessary to incorporate seeds into the soil where they can access moisture. The number of emerged red clover seeds ranged from 403 plants m$^{-2}$ in the second to 1079 plants m$^{-2}$ in the third cycle. The emergence rate and stand counts at 7 WAP in our study were high, and allowed for high biomass production. For example, Blaser et al. (2006) frost-seeded red clover at different seeding rates into winter wheat and triticale (X *Triticosecale* Wittmack) in a 2 year study under conventional management in Iowa. They found red clover ('Cherokee', 94% germination, 100% purity) target seeding rates of 1200 seeds m$^{-2}$ and 1500 seeds m$^{-2}$ achieved the highest biomass production, even though stand counts at 7 WAP were 90–107 plants m$^{-2}$ and 126–130 plants m$^{-2}$, respectively.

White clover is rarely sown alone, thus few studies have investigated white clover emergence in pure clover stands. In Alberta, 49% of white clover seeds broadcast as cover crops had emerged 10 WAP in a high-fertility site and 67% in a low-fertility site (Ross et al., 2001). Compared with Blaser et al. (2006) and Ross et al. (2001) plant populations 7 WAP in our study were very high and seeding

**Table 2.** Winter wheat whole plant dry matter (DM), grain yield and grain protein for winter wheat undersown with red clover or white clover and winter wheat without undersown clover (control).

| Treatment | DM Mg ha$^{-1}$ | Grain yield | Grain protein % | DM Mg ha$^{-1}$ | Grain yield | Grain protein % | DM Mg ha$^{-1}$ | Grain yield | Grain protein % |
|---|---|---|---|---|---|---|---|---|---|
| | First cycle | | | Second cycle | | | Third cycle | | |
| Wheat only | 11.93$^{a}$ (0.55) | 3.65$^{a}$ (0.08) | 11.75$^{a}$ (0.097) | 10.12$^{a}$ (0.64) | 3.64$^{a}$ (0.21) | 10.71$^{a}$ (0.12) | 13.66$^{a}$ (1.12) | 4.13$^{a}$ (0.26) | 11.96$^{a}$ (0.07) |
| Wheat + red clover | 9.94$^{b}$ (0.55) | 3.75$^{a}$ (0.10) | 11.48$^{a}$ (0.117) | 11.10$^{a}$ (0.64) | 3.82$^{a}$ (0.21) | 10.81$^{a}$ (0.12) | 10.87$^{a}$ (1.12) | 3.73$^{ab}$ (0.26) | 11.71$^{b}$ (0.07) |
| Wheat + white clover | 9.87$^{b}$ (0.55) | 3.79$^{a}$ (0.10) | 11.64$^{a}$ (0.117) | 11.45$^{a}$ (0.64) | 3.85$^{a}$ (0.21) | 10.99$^{a}$ (0.12) | 11.26$^{a}$ (1.12) | 3.52$^{b}$ (0.26) | 11.91$^{a}$ (0.07) |
| *P*-Value | 0.022 | 0.562 | 0.103 | 0.154 | 0.602 | 0.142 | 0.192 | 0.078 | 0.016 |

Grain yields are combine yields, not adjusted for moisture. The standard error is given in parentheses. Numbers followed by the same letter within a column indicate no significant difference between treatments at $\alpha = 0.05$.

rates can likely be reduced without affecting DM production. At our target seeding rates, red clover seed cost US \$188 ha$^{-1}$ and white clover cost US\$356 ha$^{-1}$. To save cost, farmers can frost-seed red and white clover at 75% of the rate used in this study. Hard seed was present in our clover seed at relatively high percentages, but clover emergence in subsequent years was not observed.

Green manure DM production was significantly greater in red than white clover for the majority of sampling times in all the three cycles (Fig. 3). There was a significant interaction between clover species and sampling time in two of the three cycles (Table 4). In the first cycle, red clover increased its DM significantly between each sampling time until October but white clover had significant increases only between August and October. Both clovers grew slowly within the winter wheat canopy, producing less than 0.4 Mg ha$^{-1}$ in approximately 4 months between planting and wheat harvest. After wheat harvest, red clover grew rapidly, increasing its DM by 1.8 Mg ha$^{-1}$ 35 days after harvest. White clover produced only 0.6 Mg DM ha$^{-1}$ during the same time. At the end of the growing season in October, red clover DM was 5.5 Mg ha$^{-1}$, the highest DM yield obtained during the study. White clover DM was significantly lower at 2.2 Mg ha$^{-1}$. Red and white clover die back after hard freezes, and regrow in the spring, so all spring DM is new growth. Early warm temperatures supported fast regrowth of overwintered clover in the first cycle, with both white and red clover DM yields of more than 3 Mg ha$^{-1}$ in April.

Clover planted in the second cycle was affected by drought conditions that prevailed during the growing season. Wheat harvest was 3 weeks earlier than in the other cycles, and clover DM at that time was very low. Red clover DM peaked at 0.8 Mg ha$^{-1}$ 35 days after wheat harvest and then decreased, indicating that plants died. White clover DM was below 0.2 Mg ha$^{-1}$ at each sampling time.

In the third cycle, red clover DM and white clover DM varied similarly across sampling times, with red clover DM always higher than white clover DM. Red clover DM was 1.1 Mg ha$^{-1}$ at wheat harvest, but both red and white clover DM 35 days after wheat harvest and in October were comparable with those obtained in the first cycle. However, the following April, red clover DM was only 0.7 Mg ha$^{-1}$ and white clover DM 0.3 Mg ha$^{-1}$ likely due to winter-kill during the very cold and dry period between December 2013 and February 2014.

A one-time mowing in early September impacted subsequent clover DM yields only in the first cycle (Table 5). Mowed red clover had 2.4 Mg DM ha$^{-1}$ less than unmowed red clover in October (Fig. 3). However, by the following April, mowed red clover yielded 1.5 Mg ha$^{-1}$ more DM than unmowed red clover. At the same sampling time, mowed white clover yielded 1.2 Mg ha$^{-1}$ less DM than unmowed white clover. In

**Table 3.** Actual seeding rate (ASR) and emergence for each cycle approximately 7 weeks after planting (WAP).

| Species | ASR Seeds m$^{-2}$ | Emergence Plants m$^{-2}$ | Emergence % |
|---|---|---|---|
| | | First cycle | |
| Red clover | 992 | 632 (95) | 64 (8) |
| White clover | 1245 | 359 (95) | 29 (8) |
| *P*-value | – | 0.061 | 0.011 |
| | | Second cycle | |
| Red clover | 819 | 403 (37) | 49 (4) |
| White clover | 1822 | 247 (37) | 14 (4) |
| *P*-value | – | <0.001 | <0.001 |
| | | Third cycle | |
| Red clover | 1170 | 1079 (106) | 92 (9) |
| White clover | 1169 | 512 (106) | 44 (9) |
| *P*-value | – | <0.001 | <0.001 |

Emergence is given as count in m$^{-2}$ as well as percentage of ARS that emerged. Standard error for emergence counts is given in parentheses. In each cycle, the target seeding rate was 1300 seeds m$^{-2}$ for red clover and 2300 seeds m$^{-2}$ for white clover. Actual seeding rate = target seeding rate × (% purity/100) × (%germination/100). Hard seed percentage was not included in the ASR.

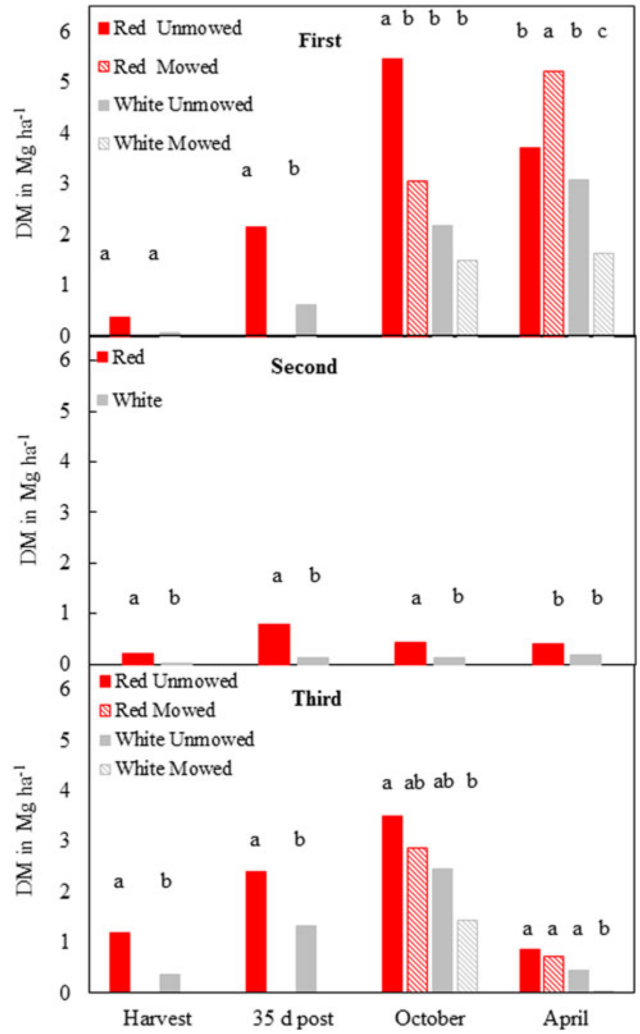


**Figure 3.** Red clover and white clover dry matter for each cycle. Bars within a sampling time with the same letter indicate no significant difference at α = 0.05. Where bars are not visible, clover dry matter (DM) was below 0.1 Mg ha$^{-1}$. Clover DM was taken at winter wheat harvest (‘Harvest’), 35 days after winter wheat harvest (‘35 days post’), in the fall of the establishment year (‘October’) and in the spring of the second year (‘April’).

the second cycle, clovers were not mowed because of their very low DM production. In the fall of the third cycle, compared with the unmowed treatment, mowed red clover yielded 0.6 Mg ha$^{-1}$ less and mowed white clover yielded 1.1 Mg ha$^{-1}$ less DM, but these differences were not significant.

Red clover reached 2 Mg ha$^{-1}$ DM by 35 days post-harvest in 2 cycles, similar to or higher than reported in other winter wheat-clover undersowing studies. Blaser et al. (2006, 2011) in a conventional study in Iowa had similar red clover DM yields at wheat harvest and 35 days after wheat harvest. Amossé et al. (2014) in a study under organic management in France reported red clover DM of 2.9 Mg ha$^{-1}$ in the fall. An organic study in Manitoba found red clover yields of 3.5 Mg DM ha$^{-1}$ in October in 2 of 5 site years (Cicek et al., 2014). White clover grew slower, but exceeded 2 Mg ha$^{-1}$ DM by October. Amossé et al. (2014) also found that under-sown white clover had the lowest DM yields at wheat harvest, but had 3.6 Mg DM ha$^{-1}$ by the fall, outyielding red clover. White clover phyllochron is shorter and its leaf expansion faster than red clover (Black et al., 2009), which helps explain the relatively high white clover DM in the fall despite very low initial DM yields. At two of three spring termination times, DM of both clover species was low, which limits N available for subsequent corn. Terminating clover several weeks later can increase clover DM production.

Water availability likely had the greatest influence on green manure DM production. How much total water green manures use depends on their productivity and evapotranspiration rates (Robinson and Nielsen, 2015). In North Dakota, sole-cropped red clover planted in May and terminated in October with DM yields between 2.3 and 4.3 Mg ha$^{-1}$ used between 222 and 388 mm of total water (Badaruddin and Meyer, 1989).

We did not measure soil water, but precipitation between May and October in our study was 491, 257 and 467 mm in the first, second and third cycle, respectively. Timing of precipitation may be more important than total precipitation in explaining DM accumulation of clover at consecutive sampling times. From July through August, with full access to sunlight and soil nutrients, green manures enter a period of rapid growth if rainfall and soil moisture are adequate. Precipitation during

**Table 4.** *P*-values for main effects and interaction of clover species and time from repeated measures analysis for unmowed clover dry matter (DM) and weed DM under unmowed clover in each cycle.

| Variable | Clover *P*-value | Weeds |
|---|---|---|
| | First cycle | |
| Species | 0.009 | 0.013 |
| Time | <0.001 | 0.087 |
| Species × time | 0.013 | 0.257 |
| | Second cycle | |
| Species | <0.001 | <0.001 |
| Time | <0.001 | <0.001 |
| Species × time | 0.002 | 0.114 |
| | Third cycle | |
| Species | 0.002 | <0.001 |
| Time | <0.001 | <0.001 |
| Species × time | 0.668 | <0.001 |

**Table 5.** *P*-values for main effects and interaction of clover species and mowing at the October and April sampling times.

| Variable | Clover | | Weeds | |
|---|---|---|---|---|
| | October | April *P*-value | October | April |
| | | First cycle | | |
| Species | <0.001 | <0.001 | 0.146 | <0.001 |
| Mowing | 0.015 | 0.935 | 0.002 | 0.056 |
| Species × mowing | 0.142 | 0.003 | 0.560 | 0.064 |
| | | Third cycle | | |
| Species | 0.061 | <0.001 | 0.043 | 0.524 |
| Mowing | 0.149 | 0.063 | 0.313 | 0.560 |
| Species × mowing | 0.674 | 0.090 | 0.406 | 0.192 |

Clover was mowed 40 days after winter wheat harvest but not mowed in the second cycle.

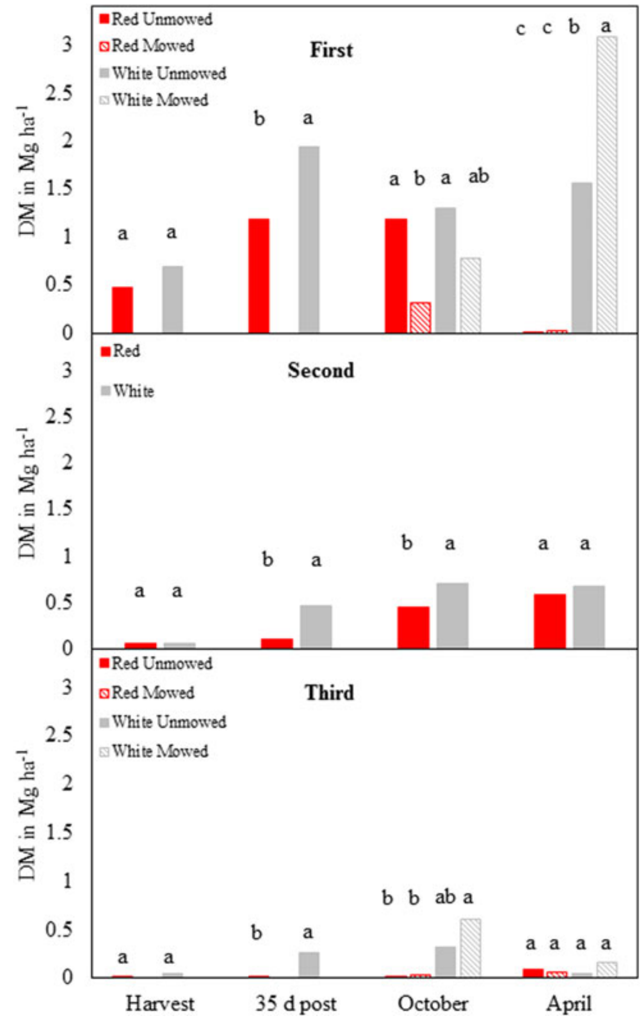


**Figure 4.** Weed dry matter (DM) under red and white clover for each cycle. Bars within a sampling time with the same letter indicate no significant difference at $\alpha = 0.05$. Where bars are not visible, weed DM was below 0.1 Mg ha$^{-1}$. Weed DM was taken at winter wheat harvest ('Harvest'), 35 days after winter wheat harvest ('35 days post'), in the fall of the establishment year ('October') and in the spring of the second year ('April').

that time was highest in the first cycle (similar to the 30-year mean), supporting high fall DM.

## *Weed DM production*

Our study did not contain a weedy control treatment, and thus inferences about the weed suppression potential of clovers are limited to a comparison of the two species with each other. Weed pressure was high in the first cycle and very low in the third cycle. In the first cycle, weed DM was influenced by clover species, but not by sampling time (Fig. 4, Table 4). Weed DM across all sampling times under white clover was 1.44 Mg ha$^{-1}$, more than twice as high as under red clover. In April, weeds in the red clover plots were completely suppressed (no weed biomass), whereas weed DM in the white clover plots was 1.57 Mg ha$^{-1}$. Weed productivity was influenced by clover species and sampling time in the second cycle, but weed DM yields were below 0.35 Mg ha$^{-1}$ at any sampling time, reflecting the drought conditions. Weed DM was lowest in the third cycle, and lower in red than in white clover. Under red clover, weed DM was less than 0.04 Mg ha$^{-1}$ at any sampling time. Under white clover weed DM reached a maximum of 0.36 Mg ha$^{-1}$ in October, but was below 0.06 Mg ha$^{-1}$ at the other sampling times. A one-time mowing reduced weed DM in red clover plots by 0.88 Mg ha$^{-1}$ in October of the first cycle and increased weed DM by 1.51 Mg ha$^{-1}$ in white clover plots in April (Fig. 4), but mowing had no effect on weed DM in the third cycle (Table 5).

Weed DM was lower in red clover than in white clover plots at most sampling times in each cycle. Red clover is taller and has faster canopy closure, enabling it to compete better with weeds than white clover (Ross et al., 2001). Weed pressure at the same sampling time varied by one to two orders of magnitude between cycles, likely influenced by the rate at which clovers accumulated DM. In the first cycle, clover DM was low at winter wheat harvest, and subsequent weed DM was above 1 $Mg\ ha^{-1}$ at each sampling time until fall. In contrast, high clover DM at wheat harvest in the third cycle gave it a competitive advantage, reducing weed DM for the reminder of the cycle. Similar findings were reported from South Dakota, where weed DM in undersown red clover was less than 0.01 $Mg\ ha^{-1}$ in mid-September and red clover DM was about 1.5 $Mg\ ha^{-1}$ at the same time (Anderson, 2015). A weed-suppressing effect of red clover has been detected even when red clover DM in the fall was less than 2 $Mg\ ha^{-1}$, however, weed DM was still 1.1 $Mg\ ha^{-1}$ (Mutch et al., 2003). Green manure weed suppression also depends on weed species. We did not identify weed species, but observed that the most common species after wheat harvest were pigweed (*Amaranthus* ssp.), lambsquarters (*Chenopodium album* L.) and volunteer wheat (self-sown kernels lost at wheat harvest). In the spring of the first cycle, weed DM in the white clover was mostly volunteer wheat. White clover is not competitive with grasses (Black et al., 2009). Volunteer wheat can harbor a number of disease vectors, for example aphids which transmit Barley Yellow Dwarf virus and eriophyid mites which spread Wheat Streak Mosaic virus (Brakke, 1987). To avoid disease infestations of newly planted winter wheat fields, producers must prevent volunteer wheat emergence. A dense clover canopy after wheat harvest, as observed in the third cycle, limited volunteer wheat growth. While mowing did not consistently lower weed DM, it can prevent weed seed formation. Mowing affects weeds depending on their growth stage, for example Ross et al. (2001) found that annual weeds mowed at late flowering did not regrow.

Measuring both clover and weed biomass throughout the season, as opposed to a one-time sampling at the end of the season revealed the effects of clover on weeds over time. It is likely that high early-season clover productivity is a key in lowering weed DM throughout the rest of the cycle. Mowing might be more effective in preventing weeds emerging in late summer or early spring. Undersown clover management, such as mowing regime and time of termination (fall or spring) might thus have implications for the survival of summer and winter annual weeds in these farming systems.

## Conclusion

Both red and white clover emerged at high rates when undersown into winter wheat, but red clover was more productive than white clover at most sampling times. Red clover produced high fall DM, making it a good option for farmers who want to terminate green manure in the fall of its establishment year. When terminating red clover in the spring after overwintering, termination may have to be delayed, as red clover DM in early spring can be low. Weed suppression was better in red clover than in white clover, and early-season clover productivity may be a key to the level of weed suppression, independent of species. Mowing green manures can reduce weed DM and should be part of the green manure management to prevent weed seed setting and dispersal. Both clover species had minimal growth in a drought year, and as dry and hot summer weather conditions are predicted to increase in the Western Corn Belt, drought-tolerant green manure species may become more suitable than red or white clover. Undersown winter wheat grain yields and grain protein were reduced in only one cycle, thus making undersowing an effective method of green manure establishment.

Whether organic producers will adopt undersown green manures, will ultimately depend on the green manure's ability to improve subsequent crop yields. Future research should focus on management to increase undersown green manure DM production by including drought-tolerant species and varying timing of mowing and termination.

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## References

**Agriculture and Forestry Alberta.** 2000. Soil temperature for germination. Available at Web site http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1203.

**Amossé, C., Jeuffroy, M.H., and David, C.** 2013. Relay intercropping of legume cover crops in organic winter wheat: Effects on performance and resource availability. Field Crops Research 145:78–87.

**Amossé, C., Jeuffroy, M.H., Mary, B., and David, C.** 2014. Contribution of relay intercropping with legume cover crops on nitrogen dynamics in organic grain systems. Nutrient Cycling in Agroecosystems 98:1–14.

**Anderson, R.L.** 2015. Suppressing weed growth after wheat harvest with underseeded red clover in organic farming. Renewable Agriculture and Food Systems 31:185–190.

**Badaruddin, M. and Meyer, D.W.** 1989. Water use by legumes and its effect on soil water status. Crop Science 29:2012–2016.

**Bergkvist, G.** 2003. Perennial clovers and ryegrass as understory crops in cereals. PhD dissertation, Swedish University of Agricultural Sciences, Uppsala, Sweden.

**Black, A.D., Laidlaw, A.S., Moot, D.J., and O'Kiely, P.** 2009. Comparative growth and management of white and red clovers. Irish Journal of Agricultural and Food Research 48: 149–166.

**Blackshaw, R.E., Molnar, L.J., and Moyer, J.R.** 2010. Suitability of legume cover crop-winter wheat intercrops on the semi-arid Canadian prairies. Canadian Journal of Plant Science 90:479–488.

**Blaser, B.C., Gibson, L.R., Singer, J.W., and Jannink, J.L.** 2006. Optimizing seeding rates for winter cereal grains and frost-seeded red clover intercrops. Agronomy Journal 98: 1041–1049.

**Blaser, B.C., Singer, J.W., and Gibson, L.R.** 2011. Winter cereal canopy effect on cereal and interseeded legume productivity. Agronomy Journal 103:1180–1185.

**Brakke, M.K.** 1987. Virus diseases of wheat. Wheat and Wheat Improvement 13:585–624.

**Brust, J., Claupein, W., and Gerhards, R.** 2014. Growth and weed suppression ability of common and new cover crops in Germany. Crop Protection 63:1–8.

**Carlsson, G. and Huss-Danell, K.** 2003. Nitrogen fixation in perennial forage legumes in the field. Plant and Soil 253: 353–372.

**Carr, P.M., Mäder, P., Creamer, N.G., and Beeby, J.S.** 2012. Editorial: Overview and comparison of conservation tillage practices and organic farming in Europe and North America. Renewable Agriculture and Food Systems 27:2–6.

**Cherr, C.M., Scholberg, J.M.S., and McSorley, R.** 2006. Green manure approaches to crop production. Agronomy Journal 98:302–319.

**Cicek, H., Entz, M.H., Thiessen Martens, J.R., and Bullock, P. R.** 2014. Productivity and nitrogen benefits of late-season legume cover crops in organic wheat production. Canadian Journal of Plant Science 94:771–783.

**Den Hollander, N.G., Bastiaans, L., and Kropff, M.J.** 2007. Clover as a cover crop for weed suppression in an intercropping design: II. Competitive ability of several clover species. European Journal of Agronomy 26:104–112.

**Drangmeister, H.** 2003. Tipps für einen erfolgreichen Kleegrasanbau im Öko-Landbau. In German. Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft.

**Drinkwater, L.E., Letourneau, D.K., Workneh, F., Van Bruggen, A.H.C., and Shennan, C.** 1995. Fundamental differences between conventional and organic tomato agroecosystems in California. Ecological Applications 5:1098–1112.

**Gentry, L.E., Snapp, S.S., Price, R.F., and Gentry, L.F.** 2013. Apparent red clover nitrogen credit to corn: Evaluating cover crop introduction. Agronomy Journal 105:1658–1664.

**Hartwig, N.L. and Ammon, H.U.** 2002. Cover crops and living mulches. Weed Science 50:688–699.

**Mallory, E.B. and Darby, H.** 2013. In-season nitrogen effects on organic hard red winter wheat yield and quality. Agronomy Journal 105:1167–1175.

**Miller, P.R., Lighthiser, E.J., Jones, C.A., Holmes, J.A., Rick, T. L., and Wraith, J.M.** 2011. Pea green manure management affects organic winter wheat yield and quality in semiarid Montana. Canadian Journal of Plant Science 91:497–508.

**Mutch, D.R., Martin, T.E., and Kosola, K.R.** 2003. Red clover (*Trifolium pratense*) suppression of common ragweed (*Ambrosia artemisiifolia*) in winter wheat (*Triticum aestivum*). Weed Technology 17:181–185.

**Parr, M., Grossman, J.M., Reberg-Horton, S.C., Brinton, C., and Crozier, C.** 2011. Nitrogen delivery from legume cover crops in no-till organic corn production. Agronomy Journal 103: 1578–1590.

**Peoples, M.B. and Baldock, J.A.** 2001. Nitrogen dynamics of pastures: Nitrogen fixation inputs, the impact of legumes on soil nitrogen fertility, and the contributions of fixed nitrogen to Australian farming systems. Animal Production Science 41:327–346.

**Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., and Sampet, C.** 2009. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis 48:1–17.

**Pimentel, D., Hepperly, P., Hanson, J., Douds, D., and Seidel, R.** 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. BioScience 55:573–582.

**Robinson, C. and Nielsen, D.** 2015. The water conundrum of planting cover crops in the Great Plains: When is an inch not an inch? Crops Soils 48:24–31.

**Ross, S.M., King, J.R., Izaurralde, R.C., and O'Donovan, J.T.** 2001. Weed suppression by seven clover species. Agronomy Journal 93:820–827.

**SAS Institute.** 2014. User's Guide: Statistics. SAS Inst., Cary, NC.

**Schipanski, M.E. and Drinkwater, L.E.** 2011. Nitrogen fixation of red clover interseeded with winter cereals across a management-induced fertility gradient. Nutrient Cycling in Agroecosystems 90:105–119.

**Snapp, S.S., Swinton, S.M., Labarta, R., Mutch, D., Black, J.R., Leep, R., and O'Neil, K.** 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agronomy Journal 97:322–332.

**Stute, J.K. and Posner, J.L.** 1993. Legume cover crop options for grain rotations in Wisconsin. Agronomy Journal 85:1128–1132.

**Triplett, G.B., Jr and Dick, W.A.** 2008. No-tillage crop production: A revolution in agriculture! Agronomy Journal 100:S-153–S-165.

**Wortman, S.E., Francis, C.A., Galusha, T.D., Hoagland, C., Van Wart, J., Baenziger, P.S., Hoegemeyer, T., and Johnson, M.** 2013. Evaluating cultivars for organic farming: Maize, soybean, and wheat genotype by system interactions in Eastern Nebraska. Agroecology and Sustainable Food Systems 37:915–932.