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Winter oilseed production for biofuel in the U.S. Corn Belt: Opportunities and limitations

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Abstract

Interest from the U.S. commercial aviation industry and commitments established by the U.S. Navy and Air Force to use renewable fuels has spurred interest in identifying and developing crops for renewable aviation fuel. Concern regarding greenhouse gas emissions associated with land-use change and shifting land grown for food to feedstock production for fuel has encouraged the concept of intensifying current prominent cropping systems through various double cropping strategies. Camelina (*Camelina sativa* L.) and field pennycress (*Thlaspi arvense* L.) are two winter oilseed crops that could potentially be integrated into the corn (*Zea mays* L.)-soybean [(*Glycine max* (L.) Merr.] cropping system, which is the prominent cropping system in the U.S. Corn Belt. In addition to providing a feedstock for renewable aviation fuel production, integrating these crops into corn-soybean cropping systems could also potentially provide a range of ecosystem services. Some of these include soil protection from wind and water erosion, soil carbon sequestration, water quality improvement through nitrate reduction, and a food source for pollinators. However, integration of these crops into corn-soybean cropping systems also carries possible limitations, such as potential yield reductions of the subsequent soybean crop. This review identifies and discusses some of the key benefits and

constraints of integrating camelina or field pennycress into corn-soybean cropping systems and identifies generalized areas for potential adoption in the U.S. Corn Belt.

Introduction

Producing sustainable renewable fuels with little to no competition with land used for food production while simultaneously reducing society's carbon (C) footprint is an important goal of the second-generation biofuel crop industry. Land-use changes and potential subsequent greenhouse gas emission increases are main concerns associated with the production of crops for bioenergy (e.g., Fargione et al., 2008; Searchinger et al., 2008, Kim et al., 2009; Dale et al., 2011). The intensification of current cropping systems with a bioenergy crop through double or relay cropping is one strategy that may alleviate these concerns regarding land-use change (Heaton et al., 2013; Moore and Karlen, 2013). In the Corn Belt Region of the United States (Fig. 1), corn-based cropping systems dominate the agricultural landscape, and cropland is often fallow during the winter months (Fig. 2). Because of this, winter annual oilseed crops offer potential for biofuel production while co-existing with other crops grown for food [e.g., corn, soybean, wheat (*Triticum aestivum* L.)]. While the inclusion of winter oilseeds into cropping systems where corn is grown continuously may also be an option, this discussion is centered on corn-soybean cropping systems because it is the dominant cropping system in the U.S. Corn Belt, with an estimated area of 27 million hectares in the region (Table 1). In this cropping system, the oilseed crop would ideally be interseeded into corn before or immediately after corn harvest (Fig. 3) and would be harvested prior to soybean planting in a sequential double cropping system or while soybean is growing in a relay double cropping system. Benefits and limitations exist with winter oilseed crop integration into corn-soybean systems. However, the added value of winter cropping diversity and winter cash crops may also offer relief for some of the previously reported limitations. This review identifies and discusses agronomic, environmental, and socio-economic benefits and challenges associated with the possible implementation of this system.

Renewable Fuel Demands

The 2013 adjustment of the U.S. Renewable Fuel Standard (RFS2) requires 7.3 and 10.4 billion L of biomass-based diesel and advanced biofuels, respectively, in an effort to increase domestic fuel production and decrease reliance on foreign sources (EPA, 2013). The aviation industry also has significant interest in adopting renewable fuels that reduce carbon emissions while simultaneously being economically competitive with petroleum-based fuels. At the 2008 Aviation and Environment Summit, commitments were set to maintain current carbon emission levels by 2020 and halve emissions based on 2005 levels by 2050 (Air Transportation Action Group, 2015). In an attempt to shift its reliance to sustainable fuel, the U.S. Federal Aviation Administration established the goal of using approximately 4 billion L year^{-1} of renewable jet fuel by 2018 (FAA, 2011).The U.S. Air Force and U.S. Navy have also set renewable fuel consumption goals, where the Air Force goal is that 50% of non-contingency operations will use an alternative drop-in fuel blend by 2025 (U.S. Air Force, 2013). The Navy has set a target that 50% of total energy consumed will be from renewable sources by 2020 (U.S. Navy, 2010). Therefore, renewable fuels are planned to serve as an integral fuel source for ground- and air-based transportation in the near-future and beyond. Additionally, a recent report by the U.S.

Environmental Protection Agency has concluded that emissions from aircraft endangers human health because of their contribution to global warming (EPA, 2015), which will likely result in emission regulations imposed on the commercial aviation industry (Mouawad and Davenport, 2015).

Traditional oilseed feedstocks used for biofuel production include soybean, rapeseed/canola (*Brassica napus*), palm (*Elaeis guineensis*), and sunflower (*Helianthus annus*) (Moser, 2012). However, as noted by Moser (2012), the sole use of these traditional oilseed feedstocks will likely not meet production demands mandated by the RFS2. For example, Hill et al. (2006) estimated that dedicating all U.S. soybean production to biofuel would only satisfy 6% of the U.S. diesel demand. Additionally, the use of prominent crops like soybean for biofuel production diminishes its opportunity to be used for food (Cassman and Liska, 2007; Tilman, 2009; Karp and Richter, 2011), which is of increasing importance as world population is estimated to surpass nine billion by 2044 (U.S. Census Bureau, 2014). Additionally, soybean production has been reported to have adverse effects on the soil environment, specifically through greater wind and water erosion susceptibility and less soil organic carbon (SOC) when compared to corn-based cropping systems (Laflen and Moldenhauer, 1979; Varvel and Wilhelm, 2008; Varvel and Wilhelm, 2011).

Alternative Crops and Cover Crops

The aforementioned concerns have resulted in expansion of research on alternative oilseed crops for bio-based diesel and aviation fuel. Examples of second generation oilseed crops include camelina, field pennycress, crambe (*Crambe abyssinica*), cuphea, (*Cuphea* spp.) oilseed radish (*Raphanus sativus* L.), Ethiopian mustard (*Brassica carinata*), white mustard (*Sinapis alba* L.), and flax (*Linum usitatissimum* L.), to name a few (Johnson et al., 2007; Moser, 2012). These crops have several desirable characteristics including greater seed oil concentration than soybean, reported lower agricultural input requirements (Putnam et al., 1993, Zubr, 1996), and potential for little or no disruption when integrated into prominent cropping systems. They can also provide environmental benefits like protection from soil erosion, increased carbon inputs for potential SOC sequestration, and providing food resources and habitat for pollinators and other beneficial insects. Camelina and field pennycress are particularly viewed as attractive options for biodiesel or aviation fuel due to their desirable fatty acid profiles in addition to high oil contents (Moser et al., 2009; Boateng et al., 2010; Moser, 2012; Fan et al., 2013). Also, significant greenhouse gas emissions reductions are expected from second generation oilseed crops either for ground transportation or aviation fuels, especially when used in a double cropping system (Shonnard et al., 2010; Krohn and Fripp, 2012; Fan et al., 2013).

Double cropping strategies

Simply defined, double cropping is the agricultural practice of growing two crops on the same unit of land during the same growing season. In traditional double cropping systems, the second crop is planted following the harvest of the first. Double cropping of biomass crops has been viewed to be a potential option in northern areas of the U.S. Corn Belt (Iowa, Minnesota, and Wisconsin), where the traditional growing season is often regarded as short (Moore and Karlen, 2014). For example, Feyereisen et al. (2013) concluded that winter rye (*Secale cereale* L.) could be successfully grown in a corn-soybean cropping system across the U.S. Corn Belt, thus potentially alleviating the issue of displacing cereal crops with energy crops and avoiding significant land use change. Additionally, land area suitable for double cropping in the U.S. Corn Belt has increased in the last 30 years and is projected to further increase as a result of future climate change (Seifert and Lobell, 2015). A particular double cropping strategy that may help to mitigate risk, particularly in northern environments, is relay cropping. In this type of system, the second crop (summer annual) is interplanted into the first crop (winter annual) prior to maturity, which extends the growing season for the second crop (Fig. 3). Research in the North Central U.S. has shown promising results with this system. For example, Gesch et al. (2014) reported that soybean relay-cropped with winter camelina produced greater seed and more total gross income compared to a sequential soybean-camelina double cropping system and was economically competitive with full-season monocropped soybean. Moreover, relay cropping soybean with winter camelina was shown to produce at least 50% more seed oil per hectare than growing a sole full-season soybean crop. Research similar to that performed by Gesch et al. (2014) will need to be conducted in other environments and on other oilseed crops to identify double cropping strategies that maximize productivity and profitability.

Potential Ecosystem Value

While the intensification of corn-soybean cropping systems with a winter oilseed crop would be to primarily increase opportunities for renewable diesel or hydroprocessed renewable jet fuel, its inclusion may also indirectly affect cellulosic biofuel (ethanol) from agricultural residues. Corn stover, the aboveground biomass remaining after grain is harvested, is forecasted to be a primary feedstock for lignocellulosic biofuel production with estimated stover harvests ranging from 54 to 123 Tg yr^{-1} for the U.S. (Graham et al., 2007; Muth et al., 2013). However, harvesting corn stover, or other crop residues, without other organic amendments can have adverse effects on soil erosion susceptibility (Mann et al., 2002; Jin et al., 2015; Kenney et al., 2015), SOC (Wilhelm et al., 2004; Stetson et al., 2012; Schmer et al., 2014), and general soil fertility (Karlen et al., 1984; Blanco-Canqui and Lal, 2009; Sindelar et al., 2013). Our hypothesis is that the inclusion of winter oilseed crops into corn-soybean cropping systems where corn stover is harvested may reduce, or even potentially offset in some cases, organic C losses associated with corn stover removal. For example, Blanco-Canqui et al. (2014) found that the inclusion of a winter rye cover crop helped offset SOC losses when stover was removed in a continuous corn system in Nebraska. Osborne et al. (2014) reported that a winter lentil (*Lens culinaris* Medik.)/slender wheatgrass [*Elymus trachycaulus* (Link) Gould ex Shinners] cover crop combination reduced the impact of corn stover removal on SOC dynamics in a corn-soybean cropping system in South Dakota. Research is needed to determine if the response of oilseed cover crops would result in a deviation from this response. Corn stover removal has also been shown to increase residual nitrate-N in the soil profile following corn, particularly at N fertilizer rates that economically optimize grain yield since stover, that can often immobilize N, is absent from the soil surface (Sindelar et al., 2015). Strock et al. (2004) found that a corn-soybean cropping system with a winter rye cover crop reduced subsurface tile water drainage discharge and flow-weighted mean nitrate concentration. Drury et al. (2014) reported that the inclusion of a winter wheat cover crop in a corn-soybean cropping system reduced nitrate-N loss by 14 to 16%. A recent study by Kladivko et al. (2014) used the Root Zone Water Quality Model to simulate residual nitrate-N dynamics in the Mississippi River Basin and concluded that residual nitrate-N loadings would be reduced by approximately 20% if cover crops were integrated into corn-soybean cropping systems. In western Minnesota, Gesch (unpublished data) recently found that winter camelina seeded in late summer as a cover crop produced as much as 1544 kg ha^{-1} (DW) of aboveground biomass containing 50 kg ha^{-1} of N by the onset of winter. Therefore, there may be opportunity to mitigate the risk of N loss if a winter oilseed crop is integrated into a corn-soybean cropping system where corn stover is removed.

Winter oilseed crops may provide other ecosystem services beyond soil and water quality improvements, including weed and pest control, and insect and wildlife habitat (Heaton et al., 2013). Johnson et al. (2015) reported that pennycress reduced weed biomass by >80%. Although not explicitly discussed by the authors, this response may have been related to the presence of glucosinolates, a class of secondary metabolites found in mustards (Moser, 2012), which can inhibit growth of other plants (Gimsing and Kirkegaard, 2009). This might be of practical interest in organic production systems and may also serve as a use for co-products that remain following oil extraction. For example, Vaughn et al. (2005) found that defatted pennycress seed meal inhibited seedling germination and emergence of wheat and arugula [*Eruca vesicaria* (L.) Cav. Susp. *sativa* (Mill.) Thell.]. Control of pests by oilseed residue has also been reported. Mojtahedi et al. (1991) found that soils amended with rapeseed tissues had lower populations of root-knot nematode (*Meloidogyne* spp.).

Oilseed crops can also enhance beneficial insect populations and diversity, as several studies on the ecology of pollinators and mass-flowering crops have demonstrated. Bumble bee (*Bombus* spp.) density was found to be related positively to rapeseed availability on the landscape (Westphal et al., 2003), with a higher abundance in rapeseed fields compared to wheat and Miscanthus (*Miscanthus* × *giganteus*) (Stanley and Stout 2013). This effect can extend even to crops maturing later in the season; the density of bumble bees in late-flowering sunflower has been shown to be enhanced by early flowering rapeseed, an effect known as temporal spillover (Riedinger et al., 2014). Recently, Eberle et al. (2015) evaluated pollinator visitation and nectar production of camelina and pennycress grown as cover crops in Minnesota and found that visitation rates for these two oilseeds reached 67 and 22 insects min^{-1}, respectively (112 m^{2}-area). They also reported that, during the period of anthesis (Table 2), camelina and pennycress flowers produced 100 and 13 kg of sugar ha^{-1} in their nectar, respectively, the former of which was even greater than that of winter canola (84 kg ha^{-1}), a widely recognized pollinator-friendly plant. Both camelina and pennycress specifically were cited by the presidentially-mandated Pollinator Health Task Force (2015) as being useful early-season forage resources for pollinators, which may assist in improving health of both domesticated and wild pollinators.

Solitary bee biodiversity is also enhanced by mass flowering in agricultural habitats, including increased abundance (Holzschuh et al., 2013) and species richness (Diekotter et al., 2014) in nearby semi-natural areas, as well as increased species richness within rapeseed fields (Stanley and Stout, 2013). Pollination services rendered by bumble bees and solitary bees are increasingly important as they are recognized as more efficient pollinators in many crops and native plants compared to honey bees *(Apis* spp.), and in some cases the only pollinator (Klein et al., 2007, and sources therein). Furthermore, the declines in managed honey bee colonies as a result of a number of interacting factors (pests, disease, pesticides, stress, inadequate diet) places an increased burden on native pollinators for agricultural production and ecosystem function.

Mass flowering crops like rapeseed are likewise attractive to pollinating syrphid flies (*Syrphidae* spp.), whose ecosystem services also include biological control resulting from predaceous larval stages that consume crop pests such as aphids (*Aphis* spp.) (Haenke et al., 2014; Schmidt et al., 2003). Syrphids are major visitors of pennycress and camelina, with both plants serving as a foraging resource during times when few other crops or native plants are flowering (Groenveld and Klein, 2014). In a relay or double cropping system including a winter oilseed followed by soybean, there is potential for a temporal spillover of biological control of soybean aphid (*Aphis glycines*), analogous to the temporal spillover of bumble bees mentioned above. There is need for further study on this topic, as enhancement of natural enemies such as syrphid flies could provide a direct value by reducing pest populations and outbreaks, which in turn would reduce the economic and environmental costs of pesticide use. If oilseeds are to provide pollinator benefits, it will be important that they are incorporated into cropping systems in ways that enhance these benefits and do not negate them (e.g., by increasing need for insecticide applications).

Corn-Soybean Cropping System Demographics

A geographic analysis (2010-13) estimated that 21.6 and 5.5 million hectares are classified as 2-year (corn-soybean) and 3-year (corn-corn-soybean) cropping systems, respectively, in the U.S. Corn Belt (Table 1). The analysis also found that crop sequences in the 2-year system were quite consistent (51 and 49%). This indicates that there are no discernable temporal acreage fluctuations as a result of crop phase changes with this cropping system. When individual states were compared, Illinois and Iowa combined, accounted for 45% of the total 2-year corn-soybean system acreage in the U.S. Corn Belt, while Minnesota, Indiana, and Nebraska individually accounted for an additional 14, 11, and 10%, respectively. Conversely, North Dakota, Michigan, and Wisconsin (< 2.5%, individually) accounted for low proportions of the 2-year cropping system acreage. Further county-level extrapolation of the acreage data displayed dense areas of 2-year corn-soybean cropping systems in central Illinois, western Iowa, and southwestern Minnesota (Fig. 4A), with a high volume of counties with 2-year corn-soybean acreage ranging from 50,000 to 150,000 hectares. Additionally, at least ten counties in Nebraska and South Dakota had acreage ranging from 50,000 to 100,000 hectares. The prevalence of 2-year corn-soybean cropping systems was less than 1,000 hectares in western areas of North Dakota, South Dakota and Nebraska, northern areas of Minnesota, Wisconsin, and Michigan, and southeastern Ohio. This is a function of agricultural row crop production being limited in these areas with greater production of small grains and other shorter-season and less water-intensive crops, and as a result of the prevalence of grasslands (North Dakota, South Dakota, and Nebraska) and forests (Minnesota, Wisconsin, Michigan, and Ohio) in those areas.

Total acreage of the 3-year cropping system is approximately one-fourth of that observed for the 2-year system (Table 1). However, the spatial layout of dense areas of 3-year cropping systems was generally similar to those observed for the 2-year cropping system, with some slight differences (Fig. 4B). In this case, clusters of counties with the greatest 3-year cropping system acreage (>30,000 hectares) were located in south central Nebraska and northern Illinois. The analysis also indicated that all states except Michigan and Ohio had multiple counties that had at least 10,000 hectares of the 3-year cropping system.

Adoption Considerations and Potential Challenges

Several environmental, agronomic, and socioeconomic issues may exist as a result of intensifying a corn-soybean cropping system with a winter oilseed crop in the U.S. Corn Belt. Additionally, these constraints may be spatially dependent. Moore and Karlen (2014) concluded that double cropping may be a feasible cropping strategy in the north central U.S., pending further research. However, the system they discussed would be primarily biomass-driven, thus allowing both crops to be harvested prior to physiological maturity. The cropping system of interest in this review would require both crops (winter oilseed and soybean) to reach physiological maturity within the same calendar year, since seed/grain harvest is the primary goal of both crops. However, recent work in the north central U.S. has shown that double cropping winter oilseeds with soybean is attainable if agronomic management decisions (e.g., soybean cultivar selection) are modified appropriately (Gesch and Archer, 2013; Johnson et al., 2015). This will be discussed in detail later.

Environmental

The inclusion of a cover crop into a cropping system is formally the concept of double cropping, where two crops are grown during the same season on the same unit of land (Gesch and Archer, 2013; Moore and Karlen, 2013). The concept of a double cropping system is to better utilize the resources available during the active growing season, particularly growing degree unit (GDU) availability. Both Helsel and Wedin (1981) and Moore and Karlen (2013) concluded that areas in the north central region, where the growing season is often regarded as short when compared to other areas of the U.S., can support double cropping systems if at least one, if not both, of the crops is harvested for forage. The biomass harvest of the first crop would theoretically result in the planting of the second crop at a date that would not significantly deviate from a traditional planting date, barring unfavorable weather conditions (e.g., wet soils) that interfere with timely planting. Winter oilseed growth could help reduce the potential for planting delays in wet conditions by utilizing water during late fall and early spring periods and by improving soil structure to increase internal drainage and support field equipment.

In double cropping systems where the first crop is harvested for seed, planting of the second crop may often occur after the "traditional" planting window (Fig. 2). For example, Johnson et al. (2015) planted soybean following pennycress maturation in early- to mid-June in a 2-year study in Minnesota, while Gesch and Archer (2013) planted soybeans following camelina in late-June to early-July in a 2-year study in Minnesota. These dates were at least two to three weeks later than recommended for optimum soybean production in that state. In a research trial in Nebraska, soybeans were planted after pennycress maturation and harvest in early- to mid-June (Schmer and Sindelar, unpublished data). Since GDU availability will often be one of the primary limiting factors to grain production in double cropping systems, particularly in the north central U.S., its availability was estimated for the second crop based on 30-year normal temperature data from 15 June to the average first frost (≤ 0°C) date (Fig. 5A). This analysis found that GDU availability over this time period ranged from 956 to 3,070 GDU across the U.S. Corn Belt region, and 1,396 to 3,070 in counties with at least 1,000 hectares of 2-year corn-soybean cropping systems. The limited amount of GDUs over this time period in Wisconsin, Minnesota, and North Dakota may result in either a forage crop or soybean being the preferred second crop in a double cropping system. The selection of indeterminate soybean cultivars (those that continue vegetative growth during reproductive development) may be better suited for compressed growing seasons than other major crops with a determinate growth process [(e.g., corn, grain sorghum). Foley et al. (1986) evaluated yield performance of determinate and indeterminate soybean lines in Minnesota and found that yields of indeterminate lines were often greater. While quantification of GDU requirements of soybean is difficult, Kandel and Akyüz (2011) estimated that maturity group (MG) 00 soybean required at least 1,679 GDU to reach physiological maturity. Another report by Kandel and Akyüz (2011) estimated that the GDU requirement of a MG 0 soybean ranged from 1,542 to 1,837 GDU. While, the lower requirement of these ranges should not be considered to be the absolute minimum GDU requirement, it does at least suggest that there is some degree of risk that soybean growing in a double cropping system may not often reach physiological maturity in far northern areas of the U.S. Corn Belt. However, the risk of the growing season ending prior to the secondary crop reaching physiological maturity should decrease if a proper soybean cultivar is selected to account for the condensed growing season. This issue may become less problematic if relay cropping strategy is implemented. Gesch et al. (2014) demonstrated that soybean could be produced successfully by interplanting it into winter camelina in the spring at a normal or near-normal time for western Minnesota. Furthermore, this technique allowed the use of a standard Maturity Group soybean for the region (MG I), whereas sequential double cropping required the use of a shorter-maturity soybean variety (MG 00).

Water availability through precipitation is the other primary environmental variable that may influence the success of a double cropping system. However, the overall influence of cover crops on subsequent crop yields is conflicted. For example, Olson et al. (2014) found no negative effects of hairy vetch (*Vicia villosa* Roth) and rye cover crops on corn and soybean production, respectively, in Illinois. In Nebraska, a winter rye cover crop reduced subsequent corn grain yield in one of three years, but had no effect in the other two (Kessavalou and Walters, 1997). Acuña and Villamil (2014) evaluated the effects of several cover crop species and mixtures on subsequent soybean production in Illinois, and found that there was no yield reduction when compared to the conventional treatment. In South Dakota, seeding a cover crop mixture following wheat did not affect corn grain yield the following year in a low or high water stress environment, but did reduce yield at a site with moderate water stress (Reese et al., 2014). At this site, cumulative soil water in the 30- to 60-cm depth was reduced in treatments with the cover crop mixture by 15%. However, no soil water changes occurred in the low- or high-stress environments with the use of the cover crop mixture. Lastly, winter rye cover crops in Minnesota reduced soybean yield by one-third in one year, but had no influence in another for both short- and full season cultivars (Forcella 2013). With regard to winter oilseeds, in a camelina-soybean double cropping study, Gesch and Johnson (2015) found that water use for sequentially- and relay-cropped soybean in Minnesota was greater than continuous soybean, but absolute differences were not large. These authors concluded that these double cropping systems can be used feasibly in most rain-fed agricultural areas in the U.S. Corn Belt region.

The region of interest in this review exhibits a considerable range in average annual precipitation, with as little as 33 cm received in western Nebraska to 124 cm in Illinois (or 41 to 124 cm within the region that supports 1,000 ha county^{-1} corn-soybean cropping system) (Fig. 5B). When in-season precipitation was calculated according to the same parameters explained for GDU availability, a spatial precipitation gradient from west to east that was similar to annual precipitation was observed (Fig. 5C). Over the hypothetical growing season for soybean, in-season precipitation ranged from 20 to 60 cm across the region (24 to 60 cm within 1,000-hectare county^{-1} corn-soybean geography). While in-season and annual precipitation can serve as an initial gauge, the overall suitability will ultimately be determined by water demand by the combined needs of crop (T) and evaporative demand (E), which is defined as evapotranspiration (ET). Since water demand can fluctuate on both macro- (Robinson and Nielsen, 2015) and micro-scales (Sadler et al., 2002), to explicitly identify or rule out suitable areas at this point would be extremely difficult, if not inappropriate. However, since evaporative demand generally decreases as the distance from the southern U.S. Plains increases, a logical hypothesis is that the core area of the U.S. Corn Belt would be under less restriction. Furthermore, we speculate that locations restricted by water availability will primarily be located in central and western areas of Nebraska, South Dakota, and North Dakota. However, even exclusion of areas in these states is not necessarily certain nor appropriate at this point because of the confounding influence of supplemental irrigation. According to the USDA-National Agricultural Statistics Service (2008), approximately 3.5 million hectares of agricultural land is irrigated in Nebraska, accounting for 15% of total irrigated land in the U.S. In comparison, 1.25 million hectares are irrigated in the remaining nine states in the U.S. Corn Belt, combined. Therefore, opportunities for cropping system intensification with winter oilseed cover crops will likely exist in many areas in the western Corn Belt, particularly in Nebraska, as a result of supplemental irrigation. In these areas, the potential increase in water demand would need to be weighed against any limitations in irrigation water supply. Further identification of irrigated land in these regions would be necessary in order to identify acreage where cropping system intensification would not be practical.

Finally, landscape attributes, specifically slope, could also affect land availability for a corn-soybean cropping system with stover removal and winter oilseed crop inclusion. In several areas in the U.S. Corn Belt, scenarios exist where at least 1,000 hectares of corn-soybean cropping systems reside in areas with landscape slopes of 6% or greater (Fig. 6). A point of emphasis by many has been that corn stover removal rates need to be at levels that simultaneously maintain SOC and control wind and water erosion, and that areas exist where corn stover removal may not be appropriate (e.g., Mann et al., 2002; Nelson, 2002; Wilhelm et al., 2007; Johnson et al., 2010). Since water erosion is affected by landscape slope, this becomes a critical attribute for determining landscape suitability for such a cropping system. Graham et al.

(2007) reported that the area appropriate for corn stover removal decreases significantly as erosion susceptibility increases.

Coincidentally, however, there may be situations where the addition of a winter oilseed crop may allow for stover removal when previously declared unacceptable as a result of landscape erosion constraints. In a 2-year study at a sloped site in Iowa, Kaspar et al. (2001) found that a winter rye cover crop interseeded with soybean reduced interrill erosion and runoff in both years, while an oat (*Avena sativa* L.) cover crop reduced erosion and runoff in one year. Bonner et al. (2014) used an integrated modeling framework to evaluate the effect of cover crops on corn stover supplies and found that their inclusion would increase sustainable stover removal rates across a range of slope gradients, although it became less impactful at slopes >4%. Therefore, based on initial results from this study, it seems that the amount of harvestable stover in this scenario may still be rather small.

Agronomic

From a production standpoint, soybean yield reduction associated with delaying the planting of the crop in a double cropping system is probable, regardless of geographic location. The review of 17 studies where soybean planting was delayed revealed a clear yield response when planting was delayed by at least 19 days, though the magnitude varied among sites (Table 3). In this review, all but four site-years exhibited a yield loss of 4 to 28% when planting was delayed. Two cases existed where no yield losses occurred with delayed planting in Minnesota and Wisconsin, though planting was delayed into late-May by 19 and 20 days, respectively (Lueschen et al., 1992; Pedersen and Lauer, 2003). Two studies used in this review evaluated soybean production in double cropping systems (LaMahieu and Brinkman, 1990; Gesch and

Archer, 2013). In Wisconsin, LeMahieu and Brinkman (1990) reported that planting in late-June (delay of 41 days) as a result of growing a winter rye crop for biomass reduced subsequent soybean yield by 26%. In comparison delaying soybean planting over the same period without a double crop reduced soybean yield by 27%. In Minnesota, Gesch and Archer (2013) reported that soybean yield decreased by 20% when it was planted following camelina harvest when compared to continuous soybean sown in early-May (52-day difference between planting dates). Based on these results, producers must be aware of and amendable to probable soybean yield reductions associated with grain-based double cropping systems, regardless of location in the U.S. Corn Belt. However, it is important to consider is that the reduction in soybean yield may not necessarily equate to net profit loss for the cropping system when the economic value of the oilseed crop is considered.

Several authors (e.g., Carter and Boerma, 1979; Wilcox and Frankenberger, 1987; Specht et al., 2012) have stated that reductions in soybean yield as a function of delayed planting is a result of the reduction of main stem nodes. Specht et al. (2012) also noted that a new node is produced on the main stem every 3.7 days, regardless of planting date. Therefore, soybean plants planted after "traditional" planting dates have less opportunity for nodal development. An observed reduction in main stem node number reported by Carter and Boerman (1979) also coincided with a reduction in plant height by 14 to 39% when planting was delayed. Because of this physiological response and the aforementioned planting date studies, there are likely limited scenarios where delaying soybean planting to mid- to late-June would not result in some degree of yield reduction. However, additional research is clearly needed to identify crop management practices that reduce this yield gap as a result of delayed planting in double cropping systems.

An agronomic-associated landscape constraint for winter oilseed adoption may be temporal and spatial proximity to alfalfa (*Medicago sativa* L.)-based cropping systems. Cropping systems where alfalfa precedes at least one year of corn can be quite attractive as a result of the legume N credit supplied to the subsequent corn crop (Fox and Piekielek, 1988; Bundy and Andraski, 1993), and scenarios can exist where second-year corn following alfalfa does not require additional N fertilizer (Yost et al., 2014). Alfalfa with high protein concentration is of particular value to the dairy industry, as it has been shown to increase milk production (Wu and Satter, 2000; Olmos Colmenero and Broderick, 2006), among other reasons. Therefore, areas or states with a prominent dairy industry and subsequent large areas of alfalfa production (Table 1, Fig. 4C) will require thoughtful planning and placement of cropping systems utilizing some types of winter oilseed crops (e.g., pennycress and camelina). This is because their temporal or spatial "escape" into an alfalfa-based cropping system may negatively influence quality and/or palatability. Although most research on the reduction of alfalfa forage quality is dedicated to other common weeds, a general conclusion is that polycultures of alfalfa and non-target plant species often produce less dry matter, have lower forage quality, and are less palatable than monoculture alfalfa (Temme et al., 1979; Marten at al., 1987; Fisher et al., 1988). Moyer and Hironaka (1993) reported that the proportion of digestible crude protein by sheep and subsequent digestible energy of pennycress was lower than that with alfalfa, despite crude protein concentration being similar between the two plant species. Pennycress can also have adverse effects on livestock and their corresponding milk and meat products if excess quantities are consumed due to high erucic acid levels in its seed oil and glucosinolates, specifically sinigrin, in its seed and vegetative tissues (Best and McIntyre, 1975; Warwick et al., 2002; Sedbrook et al., 2014). For example, consumption of large quantities of plants containing glucosinolates by dairy cattle can result in off-flavored milk products (Fenwick et al., 1982). Beef cattle carcasses had slight to strong odor when cattle were fed high proportions of pennycress seed immediately before processing, yet no discernable odor existed when the time period between feeding and processing was 24 hours or greater (Whiting et al., 1958) Despite this effect on animals and corresponding products, myrosinase, the enzyme responsible for the degradation of sinigrin into the toxic compounds isothiocynate and allyl isothiocynate, can be successfully deactivated through a heat treatment prior to seed crushing (Sedbrook et al., 2014). Furthermore, Hojilla-Evangelista et al. (2014) reported that two protein recovery methods, saline extraction and acid precipitation, performed on defatted pennycress seed also can effectively recover protein extracts that are sinigrin-free. This finding is significant, as protein content in pennycress seed meal can range from 20 to 27% (Hojilla-Evangelista et al., 2013; Selling et al., 2013), and thus could be a serviceable livestock feed. Conversely, camelina should be less problematic than pennycress in this regard. Research has shown that camelina seed meal is low in glucosinolates (Schuster and Friedt, 1998), can serve as a potential livestock feed (Korsrud et al., 1978; Moriel et al., 2011; Szumacher-Strabel et al., 2011; Colombini et al., 2013), and is approved by the U.S. Food and Drug Administration for use in cattle and chicken feeds (up to 10% of total ration). Long-term management plans in addition to short-term strategies should also be considered in areas with dense dairy production or fields that may be seeded to alfalfa in the near future. However, a counterpoint to this issue is the recent availability of glyphosate-tolerant alfalfa cultivars that can aid in control of non-target plants. Therefore, any issues regarding winter oilseed production in or near alfalfa-based cropping systems may be alleviated if widespread adoption of glyphosate-tolerant alfalfa cultivars occurs.

Both pennycress and camelina are considered minor weeds to select crops. For pennycress, most yield losses associated with its presence have been reported with canola, wheat, and safflower (*Carthamus tinctorius* L.) in Canada (Warwick et al., 2002). Camelina is a minor weed in flax (Putnam et al., 1993), resulting in its alternate name as *false flax*. Despite both crops being historically regarded as a weed and a recent risk assessment by the USDA-Animal and Plant Health Inspection Service (APHIS) classifying pennycress as a high risk potential for spread and impact (USDA-APHIS, 2015), we hypothesize their impact as a volunteer weed on corn and soybean production to be low. This is because chemical control of both plants is historically quite successful. Francis and Warwick (2009) concluded that agronomic impact of camelina in corn-soybean cropping systems should not be an issue when proper herbicide chemistries are used. Pennycress is also quite susceptible to multiple herbicide chemistries (Warwick et al., 2002), including glyphosate and glufosinate (Sedbrook et al., 2014). Therefore, a pre-emergence herbicide application at corn or soybean planting should provide adequate control of most pennycress or camelina seeds as they germinate, and any escapes can be managed with post-emergence chemistries. Additionally, the majority of soybean currently grown in the U.S. Corn Belt has resistance to glyphosate. In other situations, herbicide chemistries such as 2,4-Dichlorophenoxyacetic acid, imazethpyr and aciflurfen should also successfully control escapes.

From a field management standpoint, a critical practice associated with oilseed and cover crop productivity is proper stand establishment. Studies that have evaluated a winter oilseed-soybean double cropping system have typically followed wheat (Phippen and Phippen, 2012; Gesch and Archer, 2013). Depending on type, wheat harvest occurred no later than mid-August, thus allowing adequate time for fall growth of the winter oilseed when direct-seeded into the soil.

Gesch and Cermak (2011) demonstrated that although stand establishment of winter camelina can differ by year and tillage system (e.g., conventional versus no-till) in the northern U.S. Corn Belt, they found that final plant population density varied little by planting date when seeded from early September to mid-October. However, the greatest seed yields and oil content were generally obtained for plants seeded in late September to early October. Similar results have been obtained for pennycress (Gesch, unpublished data). Winter camelina has also been successfully established in North Dakota in September and even as a dormant seeding in late October (Archer, unpublished data). Moreover, Gesch et al. (2014) have shown that winter camelina seeded in mid- to late October in west central Minnesota, just weeks before permanent soil freezing occurred, exhibited adequate winter survival and spring growth. This indicates that, in some of the southern regions of the U.S. Corn Belt (e.g., Iowa, Illinois, and Nebraska), it may be possible to successfully establish winter camelina and pennycress following harvest of corn for grain. Nevertheless, this type of management schedule may not be applicable to many corn-soybean cropping systems unless 1) the entire corn plant is harvested for silage prior to reaching physiological maturity, or 2) an early-maturing hybrid is used. Typically, corn hybrids are selected based on maturities that best exploit the growing season when grain yield optimization is the primary goal. This practice, in turn, results in little growing season remaining after the corn plants reach physiological maturity, grain is allowed to dry to an appropriate moisture content, and harvest occurs (Fig. 2). Therefore, aerially seeding of the winter oilseed crop may be necessary in most areas, particularly for crops/cultivars that require vernalization. In comparison, Baker and Griffis (2009) concluded that aerial seeding of winter rye in northern areas of the U.S. Corn Belt may help mitigate growth limitations imposed by a short growing season. A survey by Singer (2008) found that 8% of cover crops were aerially seeded in a portion of the Corn Belt

(Illinois, Indiana, Iowa, and Minnesota), compared to 68 and 21% for direct drilling and broadcast spreading, respectively. However, 62% of cover crops in this area were not harvested. Though not explicitly discussed by Singer (2008), we speculate that the proportion of cover crops aerially seeded in this area is a function of cost, and that seed from few, if any, of these cover crops would have been harvested. Additionally, we hypothesize this proportion would increase if cash-positive winter crops were used or if incentives for cover crops are provided.

Benefits do exist for aerially seeding winter cover crops when compared to other traditional methods. These include offering a greater temporal window for seeding, elimination of machinery traffic, which may help to reduce soil compaction, and less time requirement since aerial seeding can often be performed in a shorter amount of time than other traditional methods (Wilson et al., 2013). To some, however, the disadvantages outweigh the benefits. These include a short time period for fall growth, cost of aerial application, seed predation, and proper stand establishment (Wilson et al., 2014). Barnett and Comeau (1980) evaluated aerial seeding effects on the germination of wheat, oat, and barley (*Hordeum vulgare* L.) and found that the number of plants germinated was substantially less than direct-seeded or broadcast treatments. Therefore, in order to compensate for poor germination of aerially-seeded crops, seeding rates may need to be increased, which would subsequently increase input costs. However, both camelina and pennycress have very small seeds compared, for example, to winter rye (about 0.8, 0.8, and 33 g 1000^{-1} seeds, respectively), which would serve to lower aerial seeding costs on a unit-area basis (Robinson 1987, Phippen et al. 2010, and Miedaner et al. 2014).

Other considerations include information and techniques needed in managing these crops, and the need for continued breeding efforts to improve characteristics of these crops. For example, risk of seed loss due to shatter can be a serious concern for camelina and pennycress, with complete yield loss potentially occurring in a single untimely rain and wind event (Archer, unpublished data). Fortunately, genetic similarities of camelina and pennycress with *Arabidopsis* has resulted in expedited progress towards the genomic understanding of both crops (Gehringer et al., 2006; Dorn et al., 2013; Nguyen et al., 2013; Dorn et al., 2015). For pennycress, this can potentially accelerate its domestication through improvement of several traits including seed oil quality and quantity improvement, reduction of glucosinolates, seed dormancy manipulation, flowering and senescence synchronization, and pod shatter reduction (Sedbrook et al., 2014). Also, availability of herbicides labeled for use in these crops is limited, presenting a challenge for in-season weed management, particularly in no-till production systems. One possible solution to this issue is herbicide-resistant cultivars, such as camelina with resistance to acetolactate synthase inhibitor (ALS) herbicides (Walsh et al., 2012). While initial research has demonstrated that management practices can be adjusted to overcome some of these constraints (e.g., Gesch et al., 2014), additional crop development and agronomic management research is clearly needed.

Socio-economic

Despite most cover crop research generally occurring in the past quarter century, its benefits have long been recognized (e.g., Odland and Knoblauch, 1938; Beale et al., 1955; Moschler et al., 1967; Mitchell and Teel, 1977). Some of these include erosion control (Kaspar et al., 2001), soil organic matter additions (Ding et al. 2006), nitrate-N leaching reductions (Kladviko et al., 2014), and weed suppression (Teasdale, 1996). Furthermore, the addition of a cover crop into a corn-based cropping system with stover removal may help to offset some of the adverse effects on soil properties (Fronning et al., 2008; Blanco-Canqui et al., 2014), and may even increase profitability of these cropping systems (Pratt et al, 2014). However, despite these advantages, adoption by farmers is low to date. A survey by Singer et al. (2007) found that 18% of farmers in Illinois, Indiana, Iowa, and Minnesota had used a cover crop, and only 6% of the land area for the average-sized farm was seeded to cover crops in 2005. When farmers do indeed integrate cover crops into their cropping systems, it is because of the benefits associated with cropping system diversification, erosion control, organic matter addition, weed suppression, and N addition by leguminous cover crops (Mallory et al., 1998; Stivers-Young, 1999; Snapp et al., 2005; Singer et al., 2007). However, as at least partially reflected in low adoption rates, many farmers feel the disadvantages outweigh the benefits. A farmer survey by Mallory et al. (1998) identified cost, potential influence on the subsequent crop, and weed problems as main concerns. Surveys by Stivers-Young (1999) and Snapp et al. (2005) also identified cost as a concern. Despite the cash crop potential of winter oilseed crops, the limited market for their seed still makes these cover crops a cost concern. Additionally, prospective winter oilseed crops like pennycress and camelina are regarded as weeds in some cropping systems. This may further dissuade farmers from adopting these crops, particularly since pennycress seed requires a maturation period, which can increase its persistence in the seedbank (Warwick et al., 2002). However, use of non-dormant pennycress cultivars (Isbell et al., 2015) may decrease this persistence, and both camelina and pennycress are easily controlled by commercially-available herbicides.

From a direct-cost standpoint, cropping systems integrating winter cover or oilseed crops may be less profitable, especially if they have adverse effects on subsequent crops. Bollero and Bullock (1994) estimated a net loss of \$11 hectare^{-1} when a hairy vetch cover crop preceded corn and grain sorghum [*Sorghum bicolor* (L.) Moench] in Illinois. Mallory et al. (1998) reported that when only the sole N value of a legume cover crop was considered, it was not economically advantageous when compared to fertilizer N. However, recent research has shown that corn-based cropping systems with stover removal maintain or increase profitability when an annual ryegrass (*Lolium multiflorum* Lam.) or crimson clover (*Trifolium incarnatum* L.) cover crop is added to the cropping system (Pratt et al., 2014). Gesch et al. (2014) reported lower net return for a sequential double crop camelina-soybean system when compared to monoculture soybean. However, in that same study, they also reported similar net returns between monoculture soybean and a relay-cropped camelina-soybean system when the camelina was treated with glyphosate seven to ten days before harvest. Therefore, market values of winter oilseeds likely will need to be established before an increase in adoption of winter oilseed crops occurs. These initial findings are promising and certainly warrant further research on the topic, particularly with winter oilseed crops that may further provide monetary value.

Conclusion

Inclusion of winter oilseed crops into corn-soybean cropping systems in the U.S. Corn Belt may simultaneously provide a cash-positive commodity crop used for renewable diesel or hydroprocessed aviation fuel in addition to the wide range of ecosystem services often observed with cover crops. The geographic analysis conducted for this discussion identified 21.5 and 5.6 million hectares that are grown in corn-soybean and corn-corn-soybean cropping systems in the U.S. Corn Belt, with the densest areas generally located in Illinois, Iowa, and southern Minnesota. However, what remains unknown is the proportion of these cropping systems that ultimately would be used since adoption of biomass cover crops in the U.S. Corn Belt is low to date. A survey by Singer et al. (2007) reported 56% of farmers would adopt cover crops if financial cost sharing for the cover crop was available. Consequently, the additional value of the seed from a winter oilseed crop quite possibly may incentivize farmers to adopt these crops.

Environmental, agronomic, and socioeconomic obstacles resulting from integrating winter oilseed crops into Midwestern corn-soybean cropping systems do exist, and further research is needed in all of these areas in an attempt to reduce or minimize them. Initial research has already demonstrated that management practices can be adjusted to overcome some of these constraints (e.g., Gesch et al., 2014). Management practices for a winter oilseed crop plausibly may vary slightly among areas within the U.S. Corn Belt, much like management practices for corn and soybean can often vary slightly across the region. Regardless of these constraints, a corn-soybean cropping system where corn stover is removed and a winter oilseed crop is grown theoretically offers great potential to produce multiple independent sources for food, fuel, and fiber. However, more research is needed regarding the environmental and economic viability and sustainability of this intensified cropping system over a larger geographical area throughout the Corn Belt region and other areas in the U.S.

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References

Acuña JCM, Villamil MB (2014) Short-term effects of cover crops and compaction on soil properties and soybean production in Illinois. *Agronomy Journal*, **106**, 860-870.

Air Transport Action Group (2015) *Our climate plan*. Available at: http://aviationbenefits.org/environmental-efficiency/aviation-and-climate-change/our-climate-plan/ (Assessed 21 March 2015).

Anderson LR, Vasilas BL (1985) Effects of planting date on two soybean cultivars: Seasonal dry matter accumulation and seed yield. *Crop Science*, **25**, 999-1004.

Baker JM, Griffis TJ (2009) Evaluating the potential use of cover crops in corn-soybean systems for sustainable co-production of food and fuel. *Agricultural and Forest Meteorology*, **149**, 2120-2132.

Barnett GM, Comeau JE (1980) Seeding cereals by air and ground. *Canadian Journal of Plant Science*, **60**, 1147-1155.

Beale OW, Nutt GB, Peele TC (1955) The effects of mulch tillage on runoff, erosion, soil properties, and crop yields. *Soil Science Society of America Journal, **19**,* 244-247.

Beaver JS, Johnson RR (1981) Response of determinate and indeterminate soybeans to varying cultural practices in the northern USA. *Agronomy Journal*, **73**, 833-838.

Best KF, MCIntyre GI (1975) The biology of Canadian weeds. 9. *Thlaspi arvense* L. *Canadian Journal of Plant Science*, **55**, 279-292.

Beuerlein JE (2013) Yield of indeterminate and determinate semidwarf soybean for several planting dates, row spacings, and seeding rates. *Journal of Production Agriculture*, **4**, 300-303.

Blanco-Canqui H, Ferguson RB, Jin VL, Schmer MR, Wienhold BJ, Tatarko J (2014) Can cover crop and manure maintain soil properties after stover removal from irrigated no-till corn? *Soil Science Society of America Journal*, **78**, 1368-1377.

Blanco-Canqui H, Lal R (2009) Crop residue removal impacts on soil productivity and environmental quality. *Critical Reviews in Plant Sciences*, **28**, 139-163.

Bollero GA, Bullock DG (1994) Cover cropping systems for the central Corn Belt. *Journal of Production Agriculture.* **7**, 55-58.

Boateng AA, Mullen CA, Goldberg NM (2010) Producing stable pyrolysis liquids from the oil-seed presscakes of mustard family plants: Pennycress (*Thlaspi arvense* L.) and camelina (*Camelina sativa*). *Energy Fuels*, **24**, 6624-6632.

Bonner IJ, Muth DJ, Koch JB, Karlen DL (2014) Modeled impacts of cover crops and vegetative barriers on corn stover availability and soil quality. *BioEnergy Research*, **7**, 576-589.

Bundy LG, Andraski TW (1993) Soil and plant nitrogen availability tests for corn following alfalfa. *Journal of Production Agriculture*, **6**, 200-206.

Carter TE, Boerma HR (1979) Implications of genotype × planting date and row spacing interactions in double-cropped soybean cultivar development. *Crop Science*, **19**, 607-610.

Cassman KG, Liska AJ (2007) Food and fuel for all: realistic or foolish? *Biofuels, Bioproducts, & Biorefining*, **1**, 18-23.

Colombini S, Broderick GA, Galasso I, Martinelli T, Rapetti L, Russo R, Reggiani R (2013) Evaluation of *Camelina sativa* (L.) Crantz meal as an alternative protein source in ruminant rations. *Journal of the Science of Food and Agriculture*, **94**, 736-743.

Coulter JA, Sheaffer CC, Haar MJ, Wyse DL, Orf JH (2011) Soybean cultivar response to planting date and seeding rate under organic management. *Agronomy Journal*, **103**, 1223-1229.

Dale VH, Kline KL, Wright LL, Perlack RD, Downing M, Graham RL (2011) Interactions among bioenergy feedstock choices, landscape dynamics, and land use. *Ecological Applications*, **21**, 1039-1054.

De Bruin JL, Pedersen P (2008) Soybean seed yield response to planting date and seeding rate in the Upper Midwest. *Agronomy Journal*, **100**, 696-703.

Diekotter T, Peter F, Jauker B, Wolters V, Jauker F (2014) Mass-flowering crops increase richness of cavity-nesting bees and wasps in modern agro-ecosystems. *Global Change Biology Bioenergy*, **6**:219-226.

Ding G, Liu X, Herbert S, Novak J, Amarasiriwardena D, Xing B (2006) Effect of cover crop management on soil organic matter. *Geoderma*, **130**, 229-239.

Dorn, KM, Fankhauser JD, Wyse DL, Marks MD (2013) *De novo* assembly of the pennycress (*Thlaspi arvense*) transcriptome provides tools for the development of a winter cover crop and biodiesel feedstock. *The Plant Journal*, **75**, 1028-1038.

Dorn, KM, Fankhauser JD, Wyse DL, Marks MD (2015) A draft genome of field pennycress (*Thlaspi arvense)* provides tools for the domestication of a new winter biofuel crop. *DNA Research*, **22**, 121-131.

Drury CF, Tan CS, Welacky TW *et al.* (2014) Reducing nitrate loss in tile drainage water with cover crops and water-table management systems. *Journal of Environmental Quality*, **43**, 587-598.

Eberle CA, Thom MD, Nemec KT *et al.* (2015) Using cash cover crops: pennycress, camelina, and canola to provision pollinators. *Industrial Crops and Products*, doi:10.1016/j.indcrop.2015.06.026.

Elmore RW (1990) Soybean cultivar response to tillage systems and planting date. *Agronomy Journal,* **82**, 69-73.

Fan J, Shonnard DR, Kalnes TM, Johnsen PB, Rao S (2013) A life cycle assessment of pennycress (*Thlaspi arvense* L.)-derived jet fuel and diesel. *Biomass and Bioenergy*, **55**, 87-100.

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science* **319**, 1235-1238.

Federal Aviation Administration (2011). *FAA Desination 2025*. Available at: http://www.faa.gov/about/plans_reports/media/Destination2025.pdf (Assessed 19 March 2015).

Fenwick GR, Heaney RK, Mullin WJ, VanEtten CH (1982). Glucosinolates and their breakdon products in food and food plants. *Critical Reviews in Food Science and Nutrition*, **18**, 123-201.

Feyereisen GW, Camargo GGT, Baxter RE, Baker JM, Richard TL (2013) Cellulosic biofuel potential of a winter rye double crop across the U.S. corn-soybean belt. *Agronomy* Journal, **103**, 631-642.

Fisher AJ, Dawson JH, Appleby AP (1988) Interference of annual weeds in seedling alfalfa (*Medicago sativa*). *Weed Science*, **36**, 583-588.

Foley TC, Orf JH, Lambert JW (1986) Performance of related determinate and indeterminate soybean lines. *Crop Science*, **26**, 5-8.

Forcella F (2013) Short- and full-season soybean in stale seedbeds versus rolled-crimped winter rye mulch. *Renewable Agriculture and Food Systems* **29**, 92-99.

Fox RH, Piekielek WP (1988) Fertilizer N equivalence of alfalfa, birdsfoot trefoil, and red clover for succeeding corn crops. *Journal of Production Agriculture*, **1**, 313-317.

Francis A, Warwick SI (2009) The biology of Canadian weeds. 142. *Camelina alyssum* (Mill.) Thell.; *C microcarpa* Andrz. Ex DC.; *C. sativa* (L.) Crantz. *Canadian Journal of Plant Science*, **142**, 791-810.

Fronning BE, Thelen KD, Min D-H (2008) Use of manure, compost, and cover crops to supplant crop residue carbon in corn stover removed cropping systems. *Agronomy Journal*, **100**, 1703-1710.

Gehringer A, Friedt W, Lühs W, Snowdon RJ (2006) Genetic mapping of agronomic traits in false flax (*Camelina sativa* subsp. *sativa*). *Genome*, **49**, 1555-1563.

Gesch, RW, Allen BL, Archer DW *et al.* (2014) Agronomic comparisons of several Brassica species in the U.S. Corn Belt as feedstock for hydrotreated jet fuel. Association for the Advancement of Industrial Crops, 26th Annual Meeting, Athens, Greece.

Gesch RW, Archer DW (2013) Double-cropping with winter camelina in the northern Corn Belt to produce fuel and food. *Industrial Crops and Products*. **44**, 718-725.

Gesch RW, Johnson JMF (2015) Water use in a winter camelina-soybean dual cropping systems. *Agronomy Journal,* **107**, 1098-1104.

Gimsing AL, Kirkegaard JA (2009) Glucosinolates and biofumigation: fate of glucosinolates and their hydrolysis products in soil. *Phytochemistry Review*, **8**, 299-310.

Graham RL, Nelson R, Sheehan J, Perlack RD, Wright LL (2007) Current and potential U.S. corn stover supplies. *Agronomy Journal*, **99**, 1-11.

Grau CR, Oplinger ES, Adee EA, Hinkens EA, Martinka MJ (1994) Planting date and row width effect on severity of brown stem rot and soybean productivity. *Journal of Production Agriculture*, **7**, 347-351.

Groeneveld JH, Klein A-M (2014) Pollination of two oil-producing plant species: Camelina (*Camelina sativa* L. Crantz) and pennycress (*Thlaspi arvense* L.) double-cropping in Germany. *GCB Bioenergy*, **6**, 242-251.

Groeneveld JH, Lührs HP, Klein Alexandra-Maria (2014) Pennycress double-cropping does not negatively impact spider diversity. *Agric Forest Entomol*. doi: 10.1111/afe.12100.

Haenke S, Kovacs-Hostyanszki A, Frund J, Batary P, Jauker B, Tscharntke T, Holzschuh A (2014) Landscape configuration of crops and hedgerows drives local syrphid fly abundance. *Journal of Applied Ecology*, **51**:505-513.

Heaton EA, Schulte LA, Berti M, Langeveld H, Zegada-Lizarazu W, Parrish D, Monti A (2013) Managing a second-generation crop portfolio through sustainable intensification: Examples from the USA and the EU. *Biofuels, Bioproducts, & Biorefining*, **7**, 702-714.

Helms TC, Hurburgh CR, Lussenden RL, Whited DA (1990) Economic analysis of increased protein and decreased yield due to delayed planting of soybean. *Journal of Production Agriculture*, **3**, 367-371.

Helsel ZR, Wedin WF (1981) Harvested dry matter from single and double-cropping systems. *Agronomy Journal*, **73**, 895-900.

Hill J, Nelson E, Tilman D, Polasky S, Tiffany D (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences*, **103**, 11206-11210.

Hojilla-Evangelista MP, Evangelista RL, Isbell TA, Selling GW (2013) Effects of cold-pressing and seed cooking on functional properties of protein in pennycress (*Thlaspi arvense* L.) seed and press cakes. *Industrial Crops and Products*, **45**, 223-229.

Hojilla-Evangelista MP, Selling GW, Berhow MA, Evangelista RL (2014) Preparation, composition, and functional properties of pennycress (*Thlaspi arvense* L.) seed protein isolates. *Industrial Crops and Products*, **55**, 173-179.

Holzschuh A, Dormann CF, Tscharntke T, Steffan-Dewenter I (2013) Mass-flowering crops enhance wild bee abundance. *Oecologia*, **172**, 477-484.

Isbell TA, Cermak SC, Dierig DA, Eller FJ, Marek LF (2015) Registration of Katelyn *Thlaspi arvense* L. (pennycress) with improved nondormant traits. *Journal of Plant Registrations*, **9**, 212-215.

Jin VA, Schmer MR, Wienhold BJ, Stewart CE *et al.* (2015) Twelve years of stover removal increases soil erosion potential without impacting yield. *Soil Science Society of America Journal*, **79**, 1169-1178.

Johnson GA, Kantar MB, Betts KJ, Wyse DL (2015) Field pennycress production and weed control in a double crop system with soybean in Minnesota. *Agronomy Journal*, **107**, 532-540.

Johnson JMF, Coleman MD, Gesch R, Jaradat A, Mitchell, Reicosky D, Wilhelm WW (2007): Biomass-bioenergy crops in the United States: a changing paradigm. *The Americas Journal of Plant Science and Biotechnology*, **1**, 1-28.

Johnson JMF, Karlen DL, Andrews SS (2010) Conservation considerations for sustainable bioenergy feedstock production: If, what, where, and how much? *Journal of Soil and Water Conservation*, **65**, 88A-91A.

Kandel H, Akyüz FA (2011) *Heat units and development stages of soybean*. North Dakota State University Extension Service. Available at: http://www.ag.ndsu.edu/cpr/plant-science/heat-units-and-development-stages-of-soybean-7-7-11. (Assessed 13 March 2015).

Kandel H, Akyüz FA (2012) *Growing degree model for North Dakota soybean*. North Dakota State University Extension Service. Available at: http://www.ag.ndsu.edu/cpr/plant-science/growing-degree-day-model-for-north-dakota-soybean-6-28-12 (Assessed 13 March 2015).

Karlen DL, Hung PG, Campbell RB (1984) Crop residue removal effects on corn yield and fertility of a Norfolk sandy loam. *Soil Science Society of America Journal*, **48**, 868-872.

Karp A, Richter GM (2011) Meeting the challenge of food and energy security. *Journal of Experimental Botany*, **62**, 3263-3271.

Kaspar TC, Radke JK, Laflen JM (2001) Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. *Journal of Soil and Water Conservation*, **56**, 160-164.

Kenney I, Blanco-Canqui H, Presley DR, Rice CW, Janssen K, Olson B (2015) Soil and crop response to stover removal from rainfed and irrigated corn. *GCB Bioenergy*, **7**, 219-230.

Kessavalou A, Walters DT (1997) Winter rye as a cover crop following soybean under conventional tillage. *Agronomy Journal*, **89**, 68-74.

Kim H, Kim S, Dale BE (2009) Biofuels land use change, and greenhouse gas emissions: Some unexplored variables. *Environmental Science & Technology*, **43**, 961-967.

Kladivko EJ, Kaspar TC, Jaynes DB, Malone RW, Singer J, Morin XK, Searchinger T (2014) Cover crops in the upper midwestern United States: potential adoption and reduction of nitrate leaching in the Mississippi River Basin. *Journal of Soil and Water Conservation*, **69**, 279-291.

Klein A-M, Vaissière BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, Tscharntke T (2007) Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*, **274**:303-313.

Korsrud, GO, Keith, MO, Bell, JM (1978) A comparison of the nutritional value of crambe and camelina seed meals with egg and casein. *Canadian Journal of Animal Science*, **58**, 493-499.

Krell RK, Pedigo LP, Rice ME, Westgate ME, Hill JH (2005) Using planting date to manage bean pod mottle virus in soybean. *Crop Protection*. **24**, 909-914.

Krohn BJ, Fripp M (2012) A life cycle assessment of biodiesel derived from the "niche filling" energy crop camelina in the USA. *Applied Energy*, **92**, 92-98.

Laflen JM, Moldenhauer WC (1979) Soil and water losses from corn-soybean rotations. *Soil Science Society of America Journal*, **43**, 1213-1215.

LeMahieu PJ, Brinkman MA (1990) Double-cropping soybean after harvesting small grains as forage in the north central USA. *Journal of Production Agriculture*, **3**, 385-389.

Lueschen WE, Ford JH, Evans SD *et al.* (1992) Tillage, row spacing, and planting date effects on soybean following corn or wheat. *Journal of Production Agriculture*, **5**, 254-260.

Mallory EB, Posner JL, Baldock JO (1998) Performance, economics, and adoption of cover crops in Wisconsin cash grain rotations: On-farm trials. *American Journal of Alternative Agriculture*, **13**, 2-11.

Mann L, Tolbert V, Cushman J (2002) Potential environmental effects of corn (*Zea mays* L.) stover removal with emphasis on soil organic matter and erosion. *Agriculture, Ecosystems & Environment*, **89**, 149-166.

Marten GC, Sheaffer CC, Wyse DL (1987) Forage nutritive value and palatability of perennial weeds. *Agronomy Journal*, **79**, 980-986.

Miedaner T, Schwegler DD, Wilde P, Reif JC (2014) Association between line per se and testcross performance for eight agronomic and quality traits in winter rye. *Theoretical and Applied Genetics*, **127**, 33-41.

Mitchell WH, Teel MR (1977) Winter-annual cover crops for no-tillage corn production. *Agronomy Journal*, **69**, 569-573.

Mojtahedi H, Santo GS, Hang AN, Wilson JH (1991) Suppression of root-knot nematode populations with selected rapeseed cultivars as green manure. *Journal of Nematology***, 23**, 170-174.

Moore KJ, Karlen DL (2013) Double cropping opportunities for biomass crops in the north central USA. *Biofuels*, **4**, 605-615.

Moriel, P, Nayigihugu, V, Cappellozza *et al.* (2011) Camelina meal and crude glycerin as feed supplements for developing replacement beef heifers. *Journal of Animal Science*, **89**, 4314-4324.

Moschler WW, Shear GM, Hallock DL, Sears RD, Jones GD (1967) Winter cover crops for sod-planted corn: Their selection and management. *Agronomy Journal*, **59**, 547-551.

Moser BR (2012) Biodiesel from alternative oil feedstocks: camelina and field pennycress. *Biofuels*, **3**, 193-209.

Moser BR, Knothe G, Vaughn SF, Isbell TA (2009) Production and evalutation of biodiesel from field pennycress (*Thlaspi arvense* L.) oil. *Energy & Fuels*, **23**, 4149-4155.

Mouawad, J, Davenport, C (2015). E.P.A. takes step to cut emissions from planes. *The New York Times*. 10 June, 2015. Available at: http://www.nytimes.com/2015/06/11/business/energy-environment/epa-says-it-will-set-rules-for-airplane-emissions.html

Moyer JR, Hironaka R (1993) Digestible energy and protein content of some annual weeds, alfalfa, bromegrass, and tame oats. *Canadian Journal of Plant Science*, **73**, 1305-1308.

Muth, D.J. Jr., K.M. Bryden, R.G. Nelson. 2013. Sustainable agricultural residue removal for bioenergy: a spatially comprehensive US national assessment. *Applied Energy,* **102**, 403-417.

Nelson RG (2002) Resource assessment and removal analysis for corn stover and wheat straw in the Eastern and Midwestern United States - rainfall and wind-induced soil erosion methodology. *Biomass and Bioenergy*, **22**, 349-363.

Ngjyen HT, Silva JE, Podicheti R, Macrander J (2013) Camelina seed transcriptome: a tool for meal and oil improvement and translational research. *Plant Biotechnology Journal*, **11**, 759-769.

Odland TE, Knoblauch HC (1938) The value of cover crops in continuous corn culture. *Journal of the American Society of Agronomy*, **30**, 22-29.

Olmos Colmenero JJ, Broderick GA (2006) Effect of dietary crude protein concentration on milk production and nitrogen utilization in lactating dairy cows. *Journal of Dairy Science*, **89**, 1704-1712.

Olson K, Ebelhar SA, Lang JM (2014) Long-term effects of cover crops on crop yields, soil organic stocks and sequestration. *Open Journal of Soil Science*, **4**, 284-292.

Oplinger ES, Philbrook BD (1992) Soybean planting date, row width, and seeding rate response in three tillage systems. *Journal of Production Agriculture*, **5**, 94-99.

Osborne SL, Johnson JMF, Jin VL, Hammerbeck AL, Varvel GE, Schumacher TE (2014) The impact of corn residue removal on soil aggregates and particulate organic matter. *Bioenergy Research*, **7**, 559-567.

Pedersen P, Lauer JG (2003) Soybean agronomic response to management systems in the Upper Midwest. *Agronomy Journal*, **95**, 1146-1151.

Perez-Bidegain M, Cruse RM, Ciha A (2007) Tillage system by planting date interaction effects on corn and soybean yield. *Agronomy Journal*, **99**, 630-636.

Phippen WB, John B, Phippen ME, Isbell T (2010) Planting date, herbicide, and soybean rotation studies with field pennycress (*Thlaspi arvense* L.). Association for the Advancement of Industrial Crops, 22nd Annual Meeting, Ft Collins, Colorado, USA.

Pollinator Health Task Force (2015) *Pollinator Research Action Plan.* Available at: https://www.whitehouse.gov/sites/default/files/microsites/ostp/Pollinator%20Research%20Action%20Plan%202015.pdf (Assessed 17 June 2015).

Phippen WB, Phippen ME (2012) Soybean seed yield and quality as a response to field pennycress residue. *Crop Science*, **52**, 2767-2773.

Pratt MR, Tyner WE, Muth DJ, Kladivko EJ (2014) Synergies between cover crops and corn stover removal. *Agricultural Systems*, **130**, 67-76.

Putnam DH, Budin JT, Field LA, Breene WM (1993) Camelina: A promising low-input oilseed. In: *New crops* (eds Janick J, Simon JE) pp. 314-322, Wiley, New York, USA.

Reese CL, Clay DE, Clay SA, Bich AD, Kennedy AC, Hansoen SA, Moriles J (2014) Winter cover crops impact on corn production in semiarid regions. *Agronomy Journal*, **106**, 1479-1488.

Robinson AP, Conley SP, Volenec JJ, and Santini JB (2009) Analysis of high yielding, early-planted soybean in Indiana. *Agronomy Journal*, **101**, 131-139.

Robinson C, Nielsen D (2015) The water conundrum of planting cover crops in the Great Plains: When is an inch not an inch? *Crops & Soils*, **48**, 25-31.

Robinson RG (1987) Camelina: *A Useful Research Crop and a Potential Oilseed Crop*. University of Minnesota Agricultural Experiment Station Bulletin, **579-1987**, 1-12.

Sadler EJ, Camp CR, Evans DE, Millen JA (2002) Spatial variation of corn response to irrigation. *Transactions of the American Society of Agricultural Engineers*, **45**, 1869-1881.

Schmer MR, Jin VL, Wienhold BJ, Varvel GE, Follett RF (2014) Tillage and residue management effects on soil carbon and nitrogen under irrigated continuous corn. *Soil Science Society of America Journal*, **78**, 1987-1996.

Schmidt MH, Lauer A, Purtauf T, Thies C, Schaefer M, Tscharntke T (2003) Relative importance of predators and parasitoids for cereal aphid control. *Proceedings of the Royal Society B-Biological Sciences*, **270**:1905-1909.

Schuster, A, Friedt, W (1998) Glucosinolate content and composition as parameters of quality of *Camelina* seed. *Industrial Crops and Products*, **7**, 297-302.

Searchinger T, Heimlich R, Houghton RA *et al.* (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, 1238-1240.

Sedbrook JC, Phippen WB, Marks MD (2014) New approaches to facilitate rapid domestication of a wild plant to an oilseed crop: Example pennycress (*Thlaspi arvense* L.). *Plant Science*, **227**, 122-132.

Seifert, CA, Lobell DB (2015) Response of double cropping suitability to climate change in the United States. *Environmental Research Letters*. doi:10.1088/1748-9326/10/2/024002.

Selling GW, Hojilla-Evangelista MP, Evangelista RL, Isbell T, Price N, Doll KN (2013) Extraction of proteins from pennycress seeds and press cake. *Industrial Crops and Products*, **41**, 113-119.

Shonnard DR, Williams L, Kalnes TN (2010) Camelina-derived jet fuel and diesel: Sustainable advanced biofuels. *Sustainable Energy* **29**, 382-392.

Sindelar AJ, Coulter JA, Lamb JA, Vetsch JA (2015) Nitrogen, stover, and tillage management affect nitrogen use efficiency in continuous corn. *Agronomy Journal*, **107**, 843-850.

Sindelar AJ, Lamb JA, Sheaffer CC, Rosen CJ, and Jung HG (2013) Fertilizer nitrogen rate effects on nutrient removal by corn stover and cobs. *Agronomy Journal*, **105**, 437-445.

Singer JW (2008) Corn Belt assessment of cover crop management and preferences. *Agronomy Journal*, **100**, 1670-1672.

Singer JW, Nusser SM, Alf CJ (2007) Are cover crops being used in the US Corn Belt? *Journal of Soil and Water Conservation*, **62**, 353-358.

Snapp SS, Swinton SM, Labarta R *et al.* (2005) Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agronomy Journal*, **97**, 322-332.

Specht JE, Rees JM, Zoubek GL *et al.* (2012) *Soybean planting date-When and why*. University of Nebraska Extension Bulletin, **EC145**, 1-7.

Stanley DA, Stout JC (2013) Quantifying the impacts of bioenergy crops on pollinating insect abundance and diversity: a field-scale evaluation reveals taxon-specific responses. *Journal of Applied Ecology*, **50**, 335-344.

Stetson SJ, Osborne SL, Schumacher TE *et al.* (2012) Corn residue removal impact on topsoil organic carbon in a corn-soybean rotation. *Soil Science Society of America Journal,* **76**, 1399-1406.

Stivers-Young LJ, Tucker FA (1999) Cover-cropping practices of vegetable producers in western New York. *HortTechnology*, **9**, 459-465.

Strock JS, Porter PM, Russelle MP (2004) Cover cropping to reduce nitrate loss through subsurface drainage in the northern U.S. corn belt. *Journal of Environmental Quality,* **33**, 1010-1016.

Szumacher-Strabel, M, Cieślak, A, Zmora, P, Pers-Kamczyc, E, Bielińska, S, Stanisz, M, Wójtowski, J (2011) Camelina sativa cake improved unsaturated fatty acids in ewe's milk. *Journal of the Science of Food and Agriculture* **91**, 2031-2037.

Teasdale JR (1996) Contribution of cover crops to weed management in sustainable agricultural systems. *Journal of Production Agriculture*, **9**, 475-479.

Temme DG, Harvey RG, Fawcett RS, Young AW (1979) Effects of annual weed control on alfalfa forage quality. *Agronomy Journal*, **71**, 51-54.

Tilman D, Socolow R, Foley JA *et al.* (2009) Beneficial biofuels- the food, energy, and environment trilemma. *Science*, **325**, 270-271.

United States Air Force (2013) *Air Force energy strategic plan*. Available at: http://www.safie.hq.af.mil/shared/media/document/AFD-091208-027.pdf (Assessed 21 April 2015)

United States Census Bureau (2014) *International database, world population: 1950-2050.* Available at: http://www.census.gov/population/international/data/idb/worldpopgraph.php (Accessed 12 March 2015).

United States Environmental Protection Agency (2013) *Regulatory announcement: EPA finalizes 2013 renewable fuel standards*. EPA-420-F-13-048. Available at: http://www.epa.gov/otaq/fuels/renewablefuels/documents/420f13048.pdf (Accessed 20 March 2015).

United States Environmental Protection Agency (2013) *Proposed finding that greenhouse gas emissions from aircraft cause or contribute to air pollution that may reasonability be anticipated to endanger public health and welfare and advance notice of proposed rulemaking*. EPA-HQ-OAR-2014-0828. Available at: http://epa.gov/otaq/documents/aviation/aircraft-ghg-pr-anprm-2015-06-10.pdf (Assessed 11 June 2015).

United States Navy (2010) *A Navy energy vision for the 21st century*. Available at: http://dtic.mil/ndia/2010navy/Cullom_Revised.pdf (Assessed 21 April 2015)

USDA-APHIS (2015) *Weed risk assessment for Thlaspi arvense L. (Brassicacae) – Field pennycress*. Available at: http://www.aphis.usda.gov/plant_health/plant_pest_info/weeds/downloads/wra/Thlaspi-arvense.pdf (Accessed 21 April 2015).

USDA-NASS (2008) 2007 *Farm and ranch irrigation survey*. Available at: http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/index.php (Assessed 11 March 2015).

Varvel GE, Wilhelm WW (2008) Soil carbon levels in irrigated western Corn Belt rotations. *Agronomy Journal*, **100**, 1180-1184.

Varvel GE, Wilhelm WW (2011) No-tillage increases soil profile carbon and nitrogen under long-term rainfed cropping systems. *Soil & Tillage Research*, **114**, 28-36.

Vaughn SF, Isbell TA, Weisleder D, Berhow MA (2005) Biofumigant compounds released by field pennycress (*Thlaspi arvense*) seedmeal. *Journal of Chemical Ecology*, **31**, 167-177.

Walsh, DT, Babiker EM, Burke IC, Hulbert SH (2012) Camelina mutants resistant to acetolactate synthase inhibitor herbicides. *Molecular Breeding*, **30**, 1053-1063.

Warwick SI, Francis A, Susko DJ (2002) The biology of Canadian weeds. 9. *Thlaspi arvense* L. (updated). *Canadian Journal of Plant Science*, **82**, 803-823.

Westphal C, Steffan-Dewenter I, Tscharntke T (2003) Mass flowering crops enhance pollinator densities at a landscape scale. *Ecology Letters*, **6**:961-965.

Whiting F, Young D, Phillips AH, Munro WB, Steves HL (1958) The effects on the odour and flarvour of the meat of feeding refuse screenings with a high stinkweed (*Thlaspi Arvense* L.) content to fattening cattle. *Canadian Journal of Animal Science*, **38**, 48-52.

Wilcox JR, Frankenberger EM (1987) Indeterminate and determinate soybean responses to planting date. *Agronomy Journal*, **79**, 1074-1078.

Wilhelm WW, Johnson JMF, Hatfield JL, Voorhees WB, Linden DR (2004) Crop and soil productivity response to corn residue removal. *Agronomy Journal*, **96**, 1-17.

Wilhelm WW, Johnson JMF, Karlen DL, Lightle DT (2007) Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy Journal*, **99**, 1665-1667.

Wilson ML, Allan DL, Baker JM (2014) Aerially seeding cover crops in the northern US Corn Belt: Limitations, future research needs, and alternative practices. *Journal of Soil and Water Conservation*, **69**, 67A-72A.

Wilson ML, Baker JM, Allan DL (2013) Factors affecting successful establishment of aerially seeded winter rye. *Agronomy Journal*, **105**, 1868-1877.

Wu Z, Satter LD (2000) Milk production during the complete lactation of dairy cows fed diets containing different amounts of protein. *Journal of Dairy Science*, **83**, 1042-1051.

Yost MA, Morris TF, Russelle MP, Coulter JA (2014) Second-year corn after alfalfa often requires no fertilizer nitrogen. *Agronomy Journal*, **106**, 659-669.

Zubr J (1997) Oil-seed crop: *Camelina sativa*. *Industrial Crops and Products*, **6**, 113-119.

Supporting Information

Table S1. User accuracy of corn, soybean, and alfalfa classification by USDA-NASS Cropland Data Layers, 2010-13.†

Table 1. Acreage estimates for 2- and 3-year corn-soybean and alfalfa-based cropping systems in the U.S Corn Belt from 2009-13.†

	Corn-soybean		Corn-corn-soybean		Alfalfa-based	
State	Area	Distribution‡	Area	Distribution	Area	Distribution
	- hectares -	-- % --	- hectares -	-- % --	- hectares -	-- % --
Illinois	4,281,810	19.8	1,153,150	21.1	31,550	1.4
Iowa	5,417,130	25.1	1,164,080	21.3	140,410	6.0
Minnesota	2,923,730	13.5	661,830	12.1	363,020	15.6
North Dakota	517,060	2.4	87,070	1.6	124,830	5.4
Ohio	1,337,550	6.2	153,190	2.8	60,650	2.6
South Dakota	1,732,970	8.0	311,320	5.7	220,290	9.5
Indiana	2,353,080	10.9	466,910	8.5	29,450	1.3
Michigan	426,590	2.0	151,780	2.8	384,950	16.6
Nebraska	2,161,620	10.0	1,024,380	18.7	258,800	11.1
Wisconsin	428,490	2.0	301,570	5.5	707,850	30.5
Total	21,580,030		5,475,280		2,321,800	

† Classification accuracy of corn, soybean, and alfalfa area by USDA-NASS Cropland Data Layers is available in a supplemental table (Table S1).

‡ Distribution is the proportion of a cropping system for a given state compared to the U.S. Corn Belt region.

Table 2. Anthesis interval of winter oilseeds in Morris, Minnesota, and Brookings, South Dakota, 2011-14.†

		Camelina		Pennycress		Canola	
Location	Year	Start	Stop	Start	Stop	Start	Stop
Morris, MN	2011	28 May	3 July	-	-	-	-
	2012	23 April	29 May	7 May	29 May	7 May	19 June
	2013	7 June	25 June	7 June	25 June	23 May	7 July
	2014	23 May	4 June	23 May	9 June	27 May	9 July
Brookings, SD	2013	19 June	3 July	19 June	3 July	-	-
	2014	23 May	3 June	-	-	-	-

† Ground coverage of flowers ≥ 1%

Table 3. Reported responses of soybean grain yield to delayed planting across the U.S. Corn Belt.

State	Site(s)	Study length, years	Average planting date		Yield change (D_1 - D_2), kg ha^{-1}	Reference
			Date 1 (D_1)	Date 2 (D_2)		
Illinois	Urbana	3	13 May	18 June	-458 (13%)	Beaver and Johnson, 1981
	Brownston	2	20 May	14 June	+478 (28%)	Beaver and Johnson, 1981
Illinois	Urbana	2	12 May	14 June	-715 (22%)	Anderson and Vasilas, 1985
Indiana	West Lafayette	3	12 May	22 June	-531 (21%)	Wilcox and Krankenberger, 1987
Indiana	West Lafayette	2	10 May	10 June	-620 (15%)	Robinson et al., 2009
Iowa	Ames	3	14 May	8 June	-205 (8%)	Krell et al., 2005
Iowa	Newton	3	11 May	7 June	-200 (7%)	Perez-Bidegain et al., 2007
Iowa	Ames, Crawfordsville, De Witt, Nashua, Nevada, Whiting	4	29 April	8 June	-1,055 (25%)	De Bruin and Pedersen, 2008
Minnesota	Morris	4	3 May	22 May	-215 (7%)†	Leuschen et al., 1992
	Lamberton	3	4 May	25 May	+38 (2%)	Leuschen et al., 1992
	Waseca	4	8 May	28 May	-303 (10%)	Leuschen et al., 1992
Minnesota	Waseca, Lamberton, Madison, Rosemount	3	15 May	14 June	-590 (23%)	Coulter et al., 2011
Minnesota‡	Morris	2	8 May	29 June	-463 (20%)	Gesch and Archer, 2013
Nebraska	Clay Center	3	7 May	15 June	-390 (13%)	Elmore, 1990
North Dakota	Fargo, Casselton	2	21 May	17 June	-820 (26%)	Helms et al., 1990
Ohio	Hoytville, South Charlston	3	1 May	10 June	-834 (25%)	Beurlein, 1988
Wisconsin§	Arlington	2	12 May	22 June	-1,004 (27%	LeMahieu and Brinkman, 1990
		2	12 May	22 June	-941 (26%)	LeMahieu and Brinkman, 1990
Wisconsin	Arlington	4	15 May	13 June	-572 (17%)	Oplinger and Philbrook, 1992
Wisconsin	Hancock	2	1 May	30 May	-565 (21%)	Grau et al., 1994
Wisconsin	Arlington	4	5 May	25 May	-170 (4%)	Pedersen and Lauer, 2003
	Hancock	4	10 May	30 May	-600 (14%)†	Pedersen and Lauer, 2003

† Authors reported no statistical change.

‡ Soybeans were double cropped, with camelina being the preceding crop.

§ Soybeans were double cropped, with barley being the preceding crop.

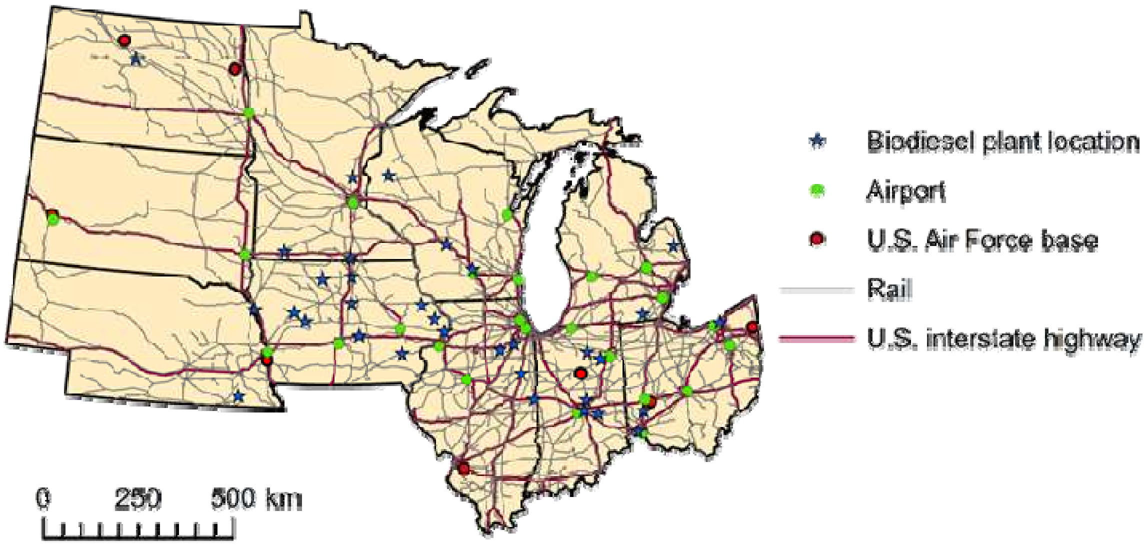


Figure 1. Select infrastructure for biodiesel production in the U.S. Corn Belt. Airports were those with enplanements of ≥250,000 people.

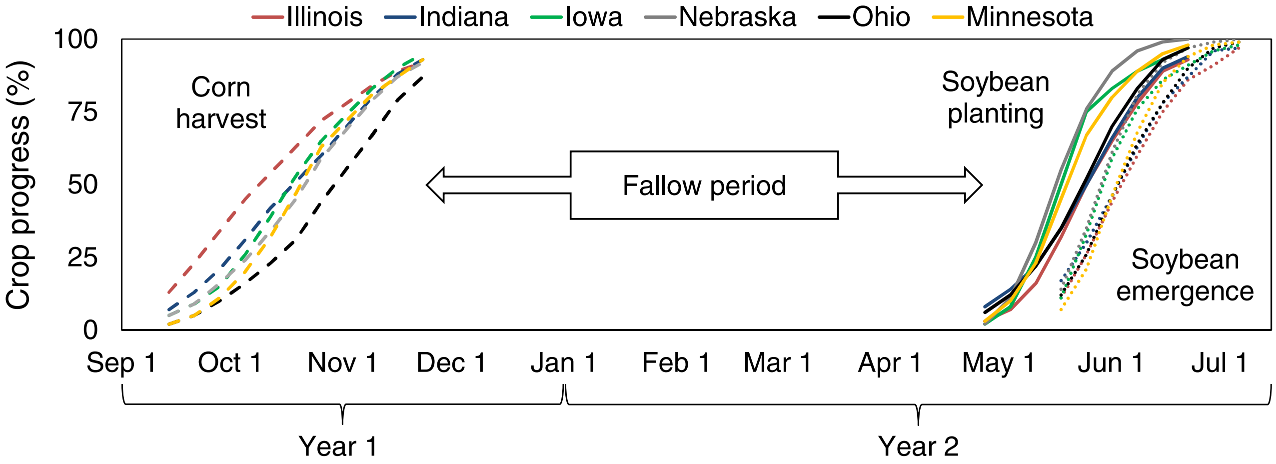
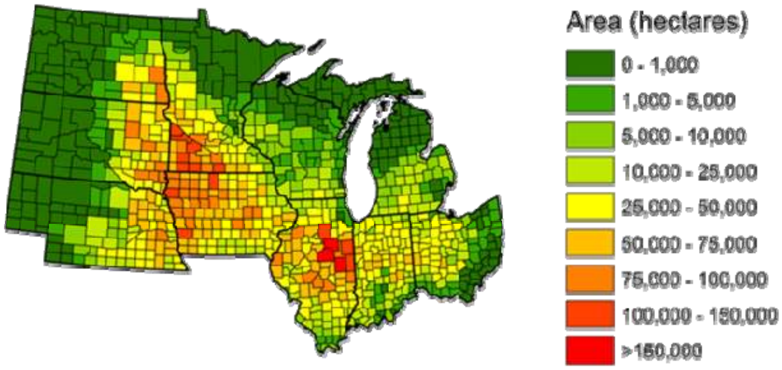


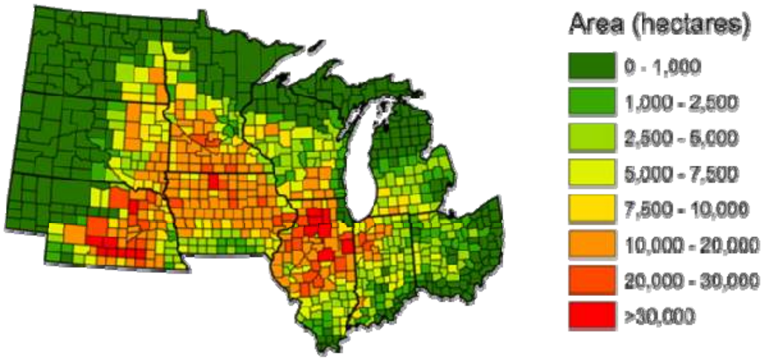
Figure 2. Average (2009-13) corn harvest progress (long dash line), soybean planting progress (solid line), and soybean emergence progress (short dash line) for selected states in the U.S. Corn Belt (www.nass.usda.gov).

Figure 3. Pennycress growth following corn in a double cropping system near Ithaca, NE (top), and simultaneous camelina and soybean growth in a relay cropping system near Morris, MN (bottom).

A. Corn-soybean



B. Corn-corn-soybean



C. Alfalfa-based

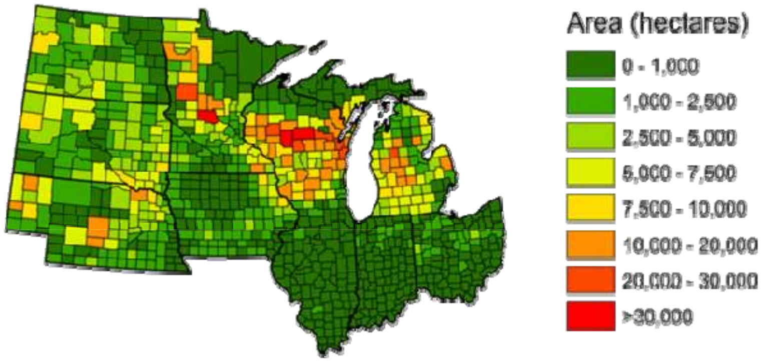


Figure 4. Acreage estimates (2010-13) by county in the U.S. Corn Belt for A) 2-year corn-soybean, B) 3-year corn-soybean and C) alfalfa-based cropping systems.

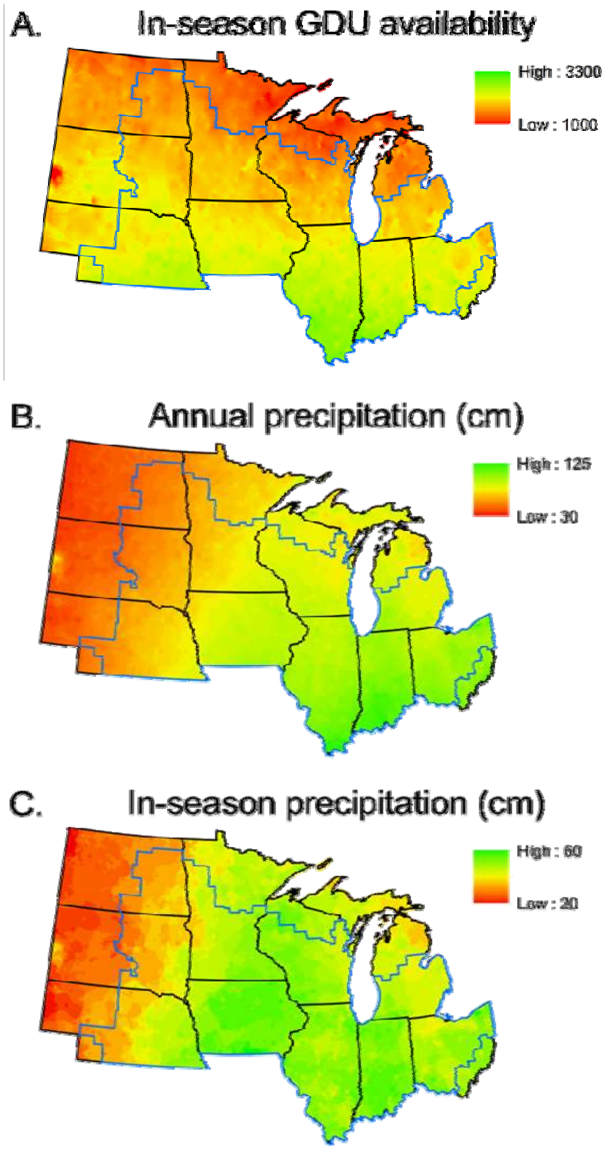


Figure 5. Long-term (30-year) A) in-season growing degree unit (GDU) availability, B) annual precipitation, and C) in-season precipitation in the U.S. Corn Belt. Area within the blue outline identifies the generalized geography of ≥1,000 hectares county^{-1} of 2-year corn-soybean cropping systems.

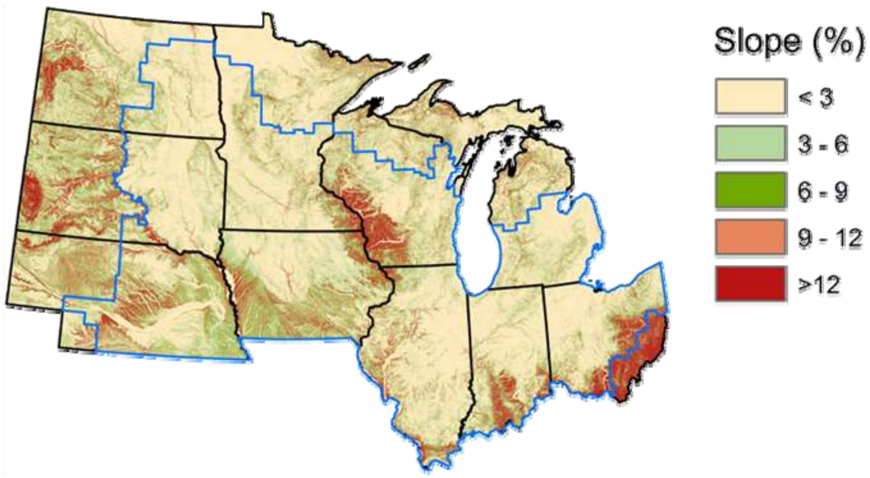


Figure 6. Landscape slope in the U.S. Corn Belt. Area within the blue outline identifies the generalized geography of ≥1,000 hectares of 2-year corn-soybean cropping systems.

Table S1. User accuracy of corn, soybean, and alfalfa classification by USDA-NASS Cropland Data Layers, 2010-13.†

	Corn				Soybean				Alfalfa			
State	2010	2011	2012	2013	2010	2011	2012	2013	2010	2011	2012	2013
	%											
Illinois	98.16	97.89	96.01	98.44	97.16	96.16	94.66	97.57	69.21	65.39	59.62	81.63
Indiana	97.02	96.81	94.35	96.34	96.64	96.38	94.05	97.05	71.01	91.64	62.32	77.59
Iowa	97.55	98.37	98.29	98.23	97.32	97.76	96.95	96.70	68.90	58.29	68.06	80.37
Michigan	92.07	96.38	94.14	94.86	91.95	96.40	94.38	93.24	77.42	81.27	71.85	82.67
Minnesota	97.90	98.16	97.96	98.00	97.20	96.95	96.94	96.71	82.04	63.38	69.29	85.36
Nebraska	98.03	96.83	96.60	97.20	97.97	95.34	95.99	96.95	92.53	95.18	88.98	85.85
North Dakota	95.24	93.89	92.34	94.14	95.89	93.59	93.57	92.24	75.04	61.51	64.28	71.68
Ohio	95.97	97.69	91.81	96.79	96.33	98.59	93.56	97.08	73.64	93.88	63.89	80.03
South Dakota	92.94	93.34	93.47	95.22	94.49	95.55	94.59	95.89	58.73	61.45	65.26	72.98
Wisconsin	94.19	96.71	93.87	90.89	92.40	96.47	93.28	88.98	83.65	93.81	85.88	84.00

†Metadata for individual state × crop years is available at: http://www.nass.usda.gov/research/Cropland/metadata/meta.htm.