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Evaluating pest-regulating services under conservation agriculture: A case study in snap beans

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ABSTRACT

Although conservation agriculture (CA) practices including strip-tillage (ST) and cover cropping are promoted largely for their potential benefits for soil quality, uncertainty surrounding their short-term effects on pests often constrains adoption. Quantification of ecosystem services or dis-services associated with pests is an important step in identifying research and policy priorities for improving the performance of CA practices. Using insect, weed and yield data from snap beans in a three year vegetable rotation, we estimated the value of pest-regulating services associated with the adoption of CA, and compared it to establishment and management costs associated with implementing CA.

Experimental factors included tillage (full-width tillage [FWT] or ST), cover crops (winter rye [R] or none [NR]) and weed management intensity (low or high). The value of pest-regulating services associated with adoption of CA practices was estimated based on pesticide cost savings associated with reductions in pest densities given action thresholds typical of commercial snap bean production in the North Central United States. CA practices had no detectable impact on snap bean yields relative to FWT-NR, but resulted in significant tradeoffs in weed and insect abundance. For example, in at least one of two years, ST-R had lower densities of potato leafhopper, Powell amaranth and winter annual weeds, but greater densities of tarnished plant bug and large crabgrass compared to FWT-NR. CA practices had variable effects on natural enemies including ladybeetles, spiders and parasitoids, with no consistent impacts relative to FWT-NR. We estimated that CA practices resulted in net pest-regulating *dis*-services with costs of \$33 ha^{-1} for FWT-R, \$25 ha^{-1} for ST-NR, and \$14 ha^{-1} for ST-R. Under partial adoption of CA (ST-NR), pest-related costs were completely offset by savings in tillage costs, resulting in estimated short-term increases in net returns of \$26 ha^{-1}. In contrast, complete adoption of CA (ST-R) resulted in greater pest and cover crop management costs that outweighed savings due to reduced tillage, resulting in estimated short-term losses of \$165 ha^{-1}. In production systems for which effective, low-cost pesticides are unavailable (e.g. low-income countries) or prohibited (e.g. organic systems), the economic impact of pest regulation services is likely to be greater than our estimates suggest. Although CA practices provide several potential long-term ecosystem services at both the farm and landscape level, short-term impacts on pests and yields relative to the costs of implementation are likely to be the major determinant of grower adoption.

1. Introduction

Conservation agricultural (CA) practices including reduced tillage (RT), retention of crop or cover crop residues, and crop diversification, have been promoted because of their perceived benefits for soil conservation, profitability, food security and the environment (Hobbs, 2007; Reicosky, 2015). CA systems are reported to provide multiple ecosystem services including soil moisture retention (e.g. Hendrix et al., 2004), erosion and wind protection for vulnerable soils and crops (e.g. Brainard and Noyes, 2012; Overstreet and Hoyt, 2008), carbon sequestration (Ellert and Janzen, 1999; Reicosky and Lindstrom, 1993) and improvements in

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soil physical, chemical and biological properties (Reicosky, 2015). Despite these wide-ranging potential ecosystem services, adoption of CA practices in many crops has been limited in part due to lack of consistent benefits for crop yield and profitability (Giller et al., 2009; Pittelkow et al., 2015a). In some cases reductions in crop yield under CA practices are due to adverse effects of CA practices on weed, insect or disease pressure which may outweigh benefits for soils (Farooq et al., 2011; Kumar et al., 2013). Since optimization of decision making at both the farm and policy level depends on understanding the net impact of such ecosystem services, more detailed case studies quantifying ecosystem service tradeoffs are needed (Zhang et al., 2007; Pittelkow et al., 2015b).

Beans (*Phaseolus vulgaris*)—including both snap beans (also known as "green beans") and dry beans—are a critical source of nutrition for much of the world's poor and are grown on approximately 45 million acres worldwide (FAO, 2014). As large-seeded legumes, beans are relatively insensitive to problems of crop establishment and nitrogen deficiency that are sometimes associated with RT systems, and therefore represent a promising crop for realization of CA benefits. However, studies evaluating the impact of CA practices on beans show enormous variation in yield responses (Abdul-Baki and Teasdale, 1997; Pittelkow et al., 2015a). Several of these studies have reported responses of individual categories of pests to CA practices (e.g. Bottenberg et al., 1997), but few have attempted to quantify the overall impact of multiple pest responses to CA practices, or the economic implications of these pest-related effects.

Weeds represent one of the biggest pest-related constraints to adoption of CA practices. (Brainard et al., 2013; Hoyt et al., 1994; Kumar et al., 2008; NeSmith et al., 1994; Walters and Kindhart, 2002). Indeed, only with the advent of herbicide-resistant crops has adoption of CA practices taken off in many cropping systems (Givens et al., 2009). In RT systems, weed management effects are complex and vary considerably depending on weed species, weed life-stage, edaphic conditions, crop competitive ability, and the availability and effectiveness of alternative weed management strategies (Brainard et al., 2013). In general, RT systems result in lower rates of weed emergence, but higher rates of seedling survival. For example, reduced emergence of weeds under strip-till (ST), compared with full-width tillage (FWT), has been observed for summer annual species in pickling cucumber (Wang and Ngouajio, 2008), carrot (Brainard and Noyes, 2012), and corn (Hendrix et al., 2004). In contrast, weed seedling survival—particularly of winter annual or perennial species—is typically higher under RT systems, since tillage is not used to sever, uproot or bury seedlings (Brainard et al., 2013). The effects of tillage on weeds are further complicated by interactions with crop or cover crop residue that may be present on the soil surface in CA systems (Haramoto and Brainard, 2016). If residues have sufficient biomass to form a thick mulch they may inhibit weed emergence by excluding light, providing a physical barrier, or exuding allelochemicals Teasdale, 1998; Teasdale and Mohler, 2000). On the other hand, low levels of cover crop residue left on the soil surface may promote weed emergence by creating more favorable edaphic (e.g. higher moisture) conditions for seed germination without inhibiting growth (Brainard et al., 2013; Wallace and Bellinder, 1989). Despite its importance in determining the feasibility of successful adoption of CA systems, the effects of tillage, cover crop and herbicide interactions on weeds have received relatively little attention. For example, Pittelkow et al. (2015a,b) state that the absence of tillage in CA practices involving no-till "generally requires changes in herbicide management", but do not attempt to disentangle herbicide use or weed suppression as factors determining impacts of CA practices on crop yield.

CA effects on insects are also complex and may result in pest-regulating services or dis-services depending on the cropping system. Complex habitats, such as untilled strips with cover crop surface mulch, are expected to reduce pest populations by interfering with the movement, landing, and oviposition of pests in the field (Andow, 1988, 1990; Broad et al., 2008; Finch and Collier, 2000). According to the natural enemy hypothesis (Elton, 1958), complex habitats can provide refuge, alternative prey, additional resources, and protection from intraguild predation (Sunderland and Samu, 2000), leading to greater predation and parasitism (Andow, 1988; Landis et al., 2000; Letourneau, 1990; Schellhorn and Sork, 1997; Wilkinson and Landis, 2005). On the other hand, some beneficial insects are well adapted to disturbance (Shearin et al., 2007), and populations of plant pests including slugs (Luna and Staben, 2002), plant-parasitic nematodes (Overstreet et al., 2010), and insect pests such as the imported cabbage worm (*Pieris rapae*) sometimes increase in CA systems (Bryant et al., 2014). While tradeoffs associated with insect management have been discussed in previous work involving some components of CA adoption (Shipanski et al., 2014), few studies have attempted to quantify the economic value of insect-regulating services associated with CA.

Although CA practices have several potential long-term economic and environmental benefits, their widespread adoption is likely to depend critically on their short-term impact on profitability due to changes in both yield and input costs. RT is often reported to reduce labor and fuel costs relative to FWT, since fewer tractor passes are required (Archer and Reicosky, 2009; Haramoto, 2014; Luna and Staben, 2002). In contrast, cover cropping generally entails increases in costs associated with establishment and management, as well as opportunity costs in cases where cash crop revenue is forgone in order to accommodate the cover crop (Snapp et al., 2005). Costs of other inputs including herbicides or insecticides may increase or decrease depending on the impact of ST and cover crops on weed and insect pests. Given these important potential tradeoffs, surprisingly few studies have attempted to quantify the net effects of cover crops or tillage on pests or profitability.

A growing body of literature has attempted to value ecosystem services associated with natural pest control, but only a few such studies have addressed monetary values of pest control services at a farm scale, or net effects of multiple pests (e.g. Cleveland et al., 2006; Colloff et al., 2013). Most studies evaluate impacts on a single pest or category of pests (e.g. thrips in Toews et al., 2010 or winter annual weeds in Hayden et al., 2012) and thus provide limited information on potential pest management tradeoffs, and the net effects on pest-regulating services (Zhang et al., 2007). Several reviews have included general discussion of ecosystem services associated with various components of CA practices, including tradeoffs associated with the use of cover crops (Schipanski et al., 2014; Snapp et al., 2005). Among the challenges cited are inherent variability and uncertainty surrounding estimates, and difficulty assessing the relative functional significance of ecosystem service estimates (Schipanski et al., 2014). The cost-avoidance approach (Cleveland et al., 2006; Colloff et al., 2013) partially addresses the latter challenge by quantifying the functional significance of pest-regulating services in monetary terms. Under this approach, the value of pest-regulation of a particular practice is based on the costs (e.g. pesticide costs) and/or revenue losses (due to pest damage) that are avoided when adopting that practice (Cleveland et al., 2006; Colloff et al., 2013).

The primary goal of this study was to estimate the value of pest-regulating services associated with CA practices relative to the short-term costs of implementation of those practices. Specific objectives were to: 1) evaluate the interactive effects of tillage (FWT or ST), cover crops (none or winter rye [*Secale cereale*]) and weed management intensity (low or high) on weeds, insects, and yields in snap beans; 2) estimate the net value of insect and weed pest-regulating services associated with adoption of CA practices; and 3) compare the short-term value of natural pest control under CA practices to the costs associated with implementation. Using insect, weed and yield data from a snap bean field experiment, we illustrate a cost-avoidance approach for gaining insight into the value of pest-regulation services under CA.

2. Materials and methods

2.1. Study site

This study was conducted from September 2009 through August 2011 (encompassing two growing seasons) in Benton Harbor, MI, USA (42°04′N, 86°21′W), on two adjacent fields at the South West Michigan Research and Extension Center on an Oakville fine sand soil (Mixed, mesic Typic Udipsamment). Three factors, tillage (ST vs FWT), cover crop (none [NR] vs rye [R]) and weed management intensity (low vs high), were examined in $2 \times 2 \times 2$ factorial, split–split plot design with 4 replications. Tillage was the main plot factor, cover crop the sub-plot factor, and weed management intensity the sub–sub plot factor. Sub-sub plots measured 3.8×9.1 m, with 5 rows of snap beans spaced 76 cm apart between rows and approximately 7.5 cm apart in row. Our primary interest was comparison of standard grower practice (FWT-NR) with either partial adoption of CA practices (ST-NR) or full adoption of CA practices (ST-R). Because snap beans were grown in a 3–4 year rotation including sweet corn (*Zea mays*), cucurbit crops (*Cucumis sativus* or *Cucurbita moschata*) and/or fallow, the third component of CA—crop rotation—was not a factor in our experimental design, but rather an integral component of all treatments.

The timing of key field operations and data collection is presented in Table 1. Sweet corn was grown the year before snap beans in both fields. Following harvest in August, the sweet corn crop was mowed and lightly disked and winter rye was drilled into ST-R and FWT-R treatments with a John Deere 750 no-till grain drill (Deere and Company, Moline, IL) at 125 kg ha^{-1} on 9 September 2009 and 10 September 2010. In NR treatments, no additional tillage or herbicide management occurred in the fall, and winter annual weeds were allowed to grow. Weeds and cover crops were sprayed with glyphosate (2.24 kg ai ha^{-1}) on 17 May 2010 and 16 May 2011 to kill existing vegetation. The entire experimental area was flail-mowed on 24 May 2010 and 23 May 2011.

On 25 May 2010 and 1 June 2011, fertilizer was applied across the entire experimental area according to soil test recommendations for snap beans based on soil sampling conducted the previous fall (Warncke et al., 2004), with NPK fertilization levels of 81:100:69 and 78:28:112 kg ha^{-1} in 2010 and 2011 respectively. Tillage was performed immediately after fertilization. In ST treatments, a Hiniker® Model 6000 two-row strip-tiller (equipped with notched row-cleaning discs, cutting-coulter, shank-point assembly, berming disks and rolling basket) was used to create 25 cm wide × 25 cm deep strips at 76 cm between-strip spacing. Therefore, approximately 67% of the soil surface was left undisturbed in the ST systems, with either rye residue (ST-R) or winter annual weed residue (ST-NR) present on the soil surface between strips. FWT tillage was accomplished with a moldboard plow followed by two passes with tandem disks and one pass with a field cultivator.

Snap bean 'Provider' was planted in tilled strips on 26 May 2010 and 2 June 2011 using a MaterMac Series 8000 two-row vacuum precision planter. For weed management, the entire experimental area received a combination of S-metolachlor pre-emergence at 1.06 kg ai ha^{-1}, and clethodim at 0.076 kg ai ha^{-1} 35 days after planting (DAP). "High intensity" weed management treatments received an additional application of bentazon at 0.84 kg ai ha^{-1} 27–29 DAP. No fungicide or insecticide applications were made during the two growing seasons. Harvest occurred on 19 July 2010 and 26 July 2011.

2.2. Data collection

On 29 April 2010 and 10 May 2011, winter annual weeds were counted by species from two 0.25 m^2 quadrats per plot. Rye and weeds were then clipped at ground level, placed into paper bags, dried at 60 °C and weighed. To evaluate the effects of tillage and cover crops on emergence of summer annual weeds, approximately 600 seeds of common lambsquarters (*Chenopodium album*) and approximately 700 seeds of Powell amaranth (*Amaranthus powellii*) were sown in separate 0.25 m^2 quadrats in the between row zone of low weed management intensity plots. Emergence of weeds was evaluated on 21 June 2010 and 16 June 2011 by counting all individuals by species from these sown areas. Included in these counts were both sown species, as well as weeds emerging from the ambient seedbank, including primarily large crabgrass (*Digitaria sanguinalis*), which was abundant in both years. The final density and composition of weeds in the snap bean crop was evaluated by counting, by species the number of weeds taller than the crop canopy (overtopping weeds) on 19 July 2010 and 26 July 2011 from a 20 m^2 area in the center of each plot. Counts were conducted separately for the between-row and in-row zones. In snap bean fields dominated by summer annual weeds, the number of weeds overtopping the crop canopy is highly correlated with weed biomass, and provides a more efficient method of evaluating treatment effects on economically relevant levels of weed infestation (Brainard, unpublished).

Arthropod herbivores were evaluated by visually sampling all the leaves of 10 randomly selected plants per plot during the life of the bean plants. Natural enemies, due to their mobility, were sampled with yellow sticky cards (7.6 cm wide × 12.7 cm long, Great Lakes IPM, Vestaburg, MI, USA). One yellow card was placed at canopy level in the center of each sampled plot; sticky cards were removed for counting and replaced with fresh cards on the same day. Three samples (both visual and trap) were taken in 2010 on 1 July, 7 July and 16 July. In 2011 weekly sampling occurred between 16 June and 26 July, for a total of 7 sampling dates. The total number of arthropods, identified to order, family or species. Arthropods were sampled only from high weed management intensity plots with the two types of tillage and cover crop management treatments (4 treatments).

At harvest, twelve row-meters of snap beans from two of the center rows from each plot were clipped at soil level and weighed.

Table 1
Schedule of major field operations and data collection events, 2009/10 and 2010/11.

Event	Date	
	2009/10	2010/11
Rye planted	9-Sep	10-Sep
Winter annual weed density evaluated	29-Apr	10-May
Rye and weed biomass sampling	14-May	10-May
Glyphosate application	17-May	16-May
Flail mowing of rye	24-May	23-May
Fertilize/Plow/Disk/Harrow/Strip-till	25-May	1-Jun
Snap bean planting	26-May	2-Jun
S-metolachlor application	27-May	3-Jun
Weed emergence evaluation	21-Jun	16-Jun
Bentazon application[a]	24-Jun	29-Jun
Clethodim application	30-Jun	7-Jul
Insect evaluation	1-Jul to 16 Jul	16-Jun to 26 Jul
Final weed density evaluated	19-Jul	26-Jul
Snap bean harvest	19-Jul	26-Jul

[a] High weed management treatment only.

Pods were removed by hand and weighed. A harvest index was calculated by dividing pod weight by total aboveground plant weight for each treatment. Pods from a 500 g subsample from each plot were visually assessed and rated for insect damage and other defects. Roots were also inspected for signs of root rot pathogens, with none detected, so no further quantification was conducted.

2.3. Statistical analysis

The fixed effects of tillage, cover crop and weed management intensity on bean yield, harvest index and weed density were evaluated using the PROC Mixed procedures of SAS (SAS, 2014), with block (replicate) treated as a random effect. All responses were analyzed separately by year as initial testing indicated significant zone by treatment and year by treatment interactions. Weed responses in the in-row and between-row zones were analyzed separately. Since weed emergence and insect responses were evaluated for only one weed management intensity level, only the fixed effects of tillage and cover crops were assessed for these responses. Winter annual weed counts and biomass were evaluated prior to implementation of tillage and weed management intensity treatments, therefore only the fixed effect of cover crop was evaluated, with replicate and year treated as random effects. For arthropods, the response variable was mean density across all sampling dates. For tarnished plant bug (*Lygus lineolaris*) in 2010, and potato leafhopper (*Empoasca fabae*) in 2011, additional analysis was conducted at each individual sampling date in order to assess densities relative to published action threshold recommendations. For both weed and insect densities, data were log or square-root transformed as necessary to improve assumptions of normality and equal variance of population distributions.

2.4. Estimation of economic value of pest-regulating services and total input costs

2.4.1. Cost avoidance methodology

In order to estimate the costs and benefits associated with pest-regulation services associated with CA practices, we followed a cost-avoidance approach in which the value of pest-regulation is based on the costs that are avoided when adopting practices which provide natural pest control (Cleveland et al., 2006; Colloff et al., 2013). These avoided costs may include the value of the crop that would have been lost due to pests in the absence of adoption of CA, as well as reduced pesticide costs attributable to reduced pest abundance under CA (Cleveland et al., 2006; Colloff et al., 2013). We did not attempt to quantify changes in social and environmental costs associated with different levels of pesticide use, although others have included such estimates in their analyses (Cleveland et al., 2006; Kovach, 2003; Pimentel et al., 1991)

Changes in pesticide costs (including both the pesticide itself and application costs) associated with CA adoption can be calculated based on pest densities relative to estimated action thresholds (Cleveland et al., 2006). In our case, we assessed impacts of CA practices on the density of multiple insect and weed pests. For each insect or weed observed in our field study, we compared densities in each alternative treatment (Da) with their density in the FWT-NR control treatment (Dc). For pests whose densities were influenced by treatment in at least one year of our field study (Da $\neq$ Dc), we considered four outcomes (O1-O4), representing four possible relationships between the density of pest in the control and alternative treatments and specific published action threshold estimates (Dt):

O1: Da < Dt and Dc < Dt (Pest density below threshold in both treatments)

O2: Da < Dt and Dc > Dt (Pest density below threshold only in the alternative treatment)

O3: Da > Dt and Dc < Dt (Pest density below threshold only in the control treatment)

O4: Da > Dt and Dc > Dt (Pest density above threshold in both treatments)

We assumed that pesticides would be applied if and only if pest densities exceeded the action threshold and therefore that differences in pesticide use between the alternative and control treatments would only occur if observed densities exceeded the threshold in one treatment but not the other (O2 or O3). Under this assumption, the expected pesticide cost saving associated with the alternative treatment (Sa) for a specific pest was calculated according to:

$$Sa = P_2{}^*Cp - P_3{}^*Cp - AC \quad (1)$$

where P_2 is the probability of O2; P_3 is the probability of O3; and Cp is the cost of the pesticide used to control the pest (price of pesticide times the quantity used) and AC is the application cost.

Based on our assumptions regarding action thresholds (Table A1 and Section 2.4.2), and observed pest densities in our field studies, we assigned probabilities for each outcome (P_2 and P_3 in Eq. (1)) of either 0, 0.5 or 1 (Table A2). A probability of 0.5 for a given outcome indicated that it occurred in one of two years, while a probability of 1 indicated that outcome occurred in both years. The values of total pest management services were then calculated by summing the estimated changes in pesticide costs of each weed and insect pest from Eq. (1).

2.4.2. Action threshold assumptions

Action threshold estimates were based on information from published studies and grower guides (Table A1). For large crabgrass, our threshold estimate was based on the work of Aguyoh and Masiunas (2003a), who found that snap bean yield was reduced by between 10 and 60%, and that large crabgrass was capable of producing between 1000 and 3000 seeds per plant depending on the density and time of emergence relative to the snap bean crop. They concluded that infestations of greater than two plants per m-row (approximately eight plants m^{-2}), should be controlled to avoid yield loss and seed production. Thresholds for broadleaf weeds were based on Aguyoh and Masiunas (2003b) and Harrison (1990) whose studies suggest that densities of species such as redroot pigweed (*Amaranthus retroflexus*, a close relative of Powell amaranth) and common lambsquarters of as little as 0.5–2 per m row (approximately 2–4 plants m^{-2}) can reduce yield, interfere with harvest efficiency or produce sufficient seeds to justify herbicide application. No published thresholds are available for winter annual weeds prior to snap bean production, but we utilized personal observations to inform our assumption that biomass of greater than 100 g m^{-2} would trigger spring herbicide applications. Although winter annual weeds can provide valuable ecosystem services such as erosion control and recycling of residual nutrients (Jordan and Vatovec, 2004), their net impact in early spring is generally perceived by growers as negative, since they can interfere with crop establishment, reduce yields, and host insect and disease pests (Norris and Kogan, 2005; Wisler and Norris, 2005). If seed production of these species is not prevented, winter annuals can reduce yields and contaminate rotational crops including peas (Ogg et al., 1993) and wheat (Conley and Bradley, 2005).

Assumptions for insect pest thresholds were based on a variety of studies and pest management guides used by growers in the North Central US (Table A1). For potato leaf hopper, thresholds are variously reported as one nymph per 10 leaves (Delahaut, 2005), or 16 per m of row (Cook et al., 2004). Given our plant density and bean leaf number, these thresholds translate into approximately 1–1.5 nymphs per plant at later growth stages. Threshold densities for tarnished plant bug and aphids (superfamily Aphidoidea) were assumed to be 0.2 insects per plant and 1.0 per leaf, respectively, based on the reported ranges in Bird et al. (2014) and yield loss data from Khattat and Stewart (1975) and Stewart and Khattat (1980).

2.4.3. Input cost estimates

Assumed changes in costs directly associated with tillage and rye cover cropping were based on custom machine work rates from Stein (2011) for moldboard plowing, strip tillage, disking, harrowing, planting, mowing and pesticide application. Costs for rye seed, herbicides and insecticides were estimated based on price lists from local dealers, combined with recommended use rates from grower guides (Zandstra, 2011; Bird et al., 2014). Details of these assumptions are provided in Tables A1 and 7.

3. Results and discussion

3.1. Rye cover crop and winter annual weeds

At the time of glyphosate application in the spring, rye shoot dry weight was 530 g m^{-2} in 2010, and 380 g m^{-2} in 2011 (Fig. 1). Winter annual weed dry weight in non-cover crop treatments at this time was 100 g m^{-2} in 2010 and 240 g m^{-2} in 2011; thus rye reduced the dry weight of winter annual weeds by 90% in 2010, and 67% in 2011. The most abundant winter annuals were common chickweed (*Stellaria media*), henbit (*Lamium amplexicaule*), purple deadnettle (*Lamium purpureum*) and mouse-ear cress (*Arabidopsis thaliana*) in 2010, and knawel (*Scleranthus annus*) in 2011 (Table 2). The presence of rye reduced the density of henbit, purple deadnettle and mouse-ear cress, but not common chickweed or knawel.

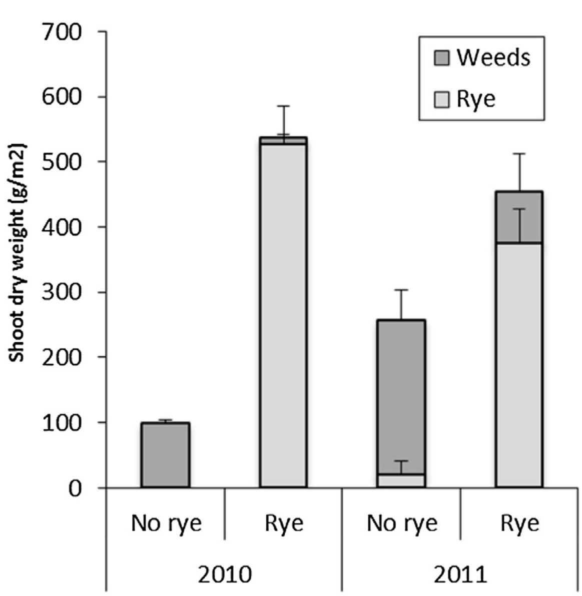

Fig. 1. Mean (+se) shoot dry weight of winter rye cover crop and winter annual weeds, 2010 and 2011.

Table 2
Winter annual weed density, April 2010 and 2011.

	LAMAM[a]		LAMPU[a]		STEME[a]		SCRAN[a]		ARBTH[a]	
	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
	(plants m^{-2})									
Cover Crop										
None	40a	24a	13a	0	41	5	3	391	326a	16a
Rye	9b	2b	4b	0	40	15	2	260	127b	4b

Statistical significance (p = 0.05) is indicated by different letters within the same column.
[a] LAMAM = Henbit; LAMPU = Purple deadnettle; STEME = common chickweed; SCRAN = knawal; ARBTH = mouse-ear thale.

The level of suppression of winter annual weed biomass by rye in this study was lower than the 95–98% reported by Hayden et al. (2012), despite similar levels of rye biomass accumulation (300–600 g m^{-2}). This discrepancy may have been due in part to a different community of winter annual weeds. Hayden et al. (2012) reported that rye generally suppressed mustard family weeds more than non-mustards. With the exception of mouse-ear cress—a relatively small mustard family weed—all winter annuals in this study were non-mustards.

3.2. Summer annual weeds

3.2.1. Emergence

Emergence of both common lambsquarters and large crabgrass was affected by tillage or tillage by cover crop interactions (Table 3). In contrast, the emergence of Powell amaranth was not affected by tillage, cover crops or their interaction in either year. For common lambsquarters, the effect of tillage depended on whether or not rye was present (significant tillage by cover crop interaction). In particular, common lambsquarters emergence was reduced by approximately 80% in 2010 and 57% in 2011 in ST-R compared to either ST-NR or FWT. For large crabgrass, no effects of treatment on emergence were detected in 2010, likely due to large variability in crabgrass density. In 2011, large crabgrass emergence was higher in ST, and ranked as follows from lowest to highest: FWT-NR < FWT-R = ST-R < ST-NR. In other words, the presence of rye suppressed emergence of large crabgrass within the ST system, but stimulated emergence when FWT was used.

Table 3
Mean emergence of weeds, 2010 and 2011.

Tillage	CHEAL[a,b]		AMAPO[a,b]		DIGSA[a,c]	
	2010	2011	2010	2011	2010	2011
	#/m²					
Full-width						
No-rye	72a	35ab	47	69	17	0d
Rye	63a	57ab	25	69	52	12bc
Strip-tillage						
No-rye	70a	65a	15	85	200	26a
Rye	14b	28b	4	55	14	11c
ANOVA	Significance					
Tillage (T)	NS	NS	NS	NS	NS	0.0007
Cover (C)	0.003	NS	NS	NS	NS	NS
T × C	0.011	0.044	NS	NS	NS	0.0125

Statistical significance (p = 0.05) is indicated by different letters within the same column.
[a] CHEAL = common lambsquaters; AMAPO = Powell amaranth; DIGSA = large crabgrass.
[b] Weed seeds were sown at planting.
[c] Ambient weed population.

Such suppression of weed emergence from rye surface mulch has been previously observed in many studies, and was likely the result of a combination of physical and chemical properties of rye mulch (Teasdale and Mohler, 2000). More surprising was the apparent promotion of large crabgrass emergence in the presence of rye under FWT in 2011. This effect may have been the result of reduced efficacy of S-metolachlor in the presence of incorporated rye. Crop and cover crop residues may reduce the efficacy of chloroacetamides, including S-metolachlor through interception or adsorption (Banks and Robinson, 1986; Locke and Bryson, 1997). Although this effect might have been expected to be higher under ST with rye surface mulch, any reduction in herbicide efficacy from surface rye may have been outweighed by the allelopathic or physical suppressive effects of rye mulch.

3.2.2. Final weed density

In 2010, the final density of common lambsquarters and Powell amaranth individuals that were taller than the bean crop canopy at harvest was not affected by tillage, cover crop, or weed management intensity (Table 4). However, large crabgrass densities in the crop row were higher under ST compared to FWT, and higher in rye treatments compared to non-rye treatments. In 2011, weed management intensity influenced the final density of both common lambsquarters and Powell amaranth; not surprisingly, lower densities of both species were present in high compared to low intensity weed management treatments. Tillage and cover crop factors also influenced final weed density in 2011 in some cases. In particular, large crabgrass final density in the crop row was almost four times higher under ST compared to FWT. In 2011, Powell amaranth final density between crop rows was suppressed by rye, regardless of tillage system. However, no effects of tillage or cover crops on final common lambsquarters density were detected in either year or location.

3.3. Insects

Tillage influenced the number of potato leafhoppers in 2011, but had no detectable effect on other insect pests including tarnished plant bug, aphids or thrips (order Thysanoptera) in either year (Table 5). In 2011, ST treatments had 31% fewer potato leafhoppers than FWT (Table 5 and Fig. 2). Contrary to expectations, ST in combination with rye surface residue resulted in reductions in beneficial lady beetles (*Coccinellidae*) and parasitoids in 2010, although these effects were not observed in 2011.

In 2010, the presence of a rye cover crop resulted in a 4-fold increase in tarnished plant bug density and a 2.5-fold increase in aphid density, but had no detectable effect on other insect pests or beneficials (Table 5). In 2011, rye had no detectable effect on insect pests, but resulted in an increase in lady beetle abundance and a decrease in spider (*Araneae*) abundance relative to non-rye treatments. It is likely that our small plot size may have been limiting in capturing consistent treatment effects on mobile arthropods, such as lady beetles and spiders, since these can easily move among experimental plots.

Such inconsistent impacts of RT on specific insect pests and beneficials have been reported in previous studies (Bryant et al., 2014; Luna and Staben, 2002; Overstreet et al., 2010; Shearin et al., 2007). The use of grass family cover crops in the absence of RT systems can exacerbate insect pests including several lepidopteran species in corn based systems (Schipanski et al., 2014), but had minimal effects on insect pests in a broccoli cropping system (Wyland et al., 1996). In snap beans, Bottenberg et al. (1999) observed a reduction in potato leafhopper abundance under no-till with a rye surface mulch compared to FWT, but because yields were also reduced, it is unclear whether this effect was the direct result of CA practices, or an indirect effect of crop quality.

Table 4
Mean density of summer annual weeds overtopping the bean canopy at harvest, 2010–2011.

	Common lambsquarters				Powell amaranth				Large crabgrass				TOTAL			
	Between-row		In-row		Between-row		In-row		Between-row		In-row		Between-row		In-row	
	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
	weeds m^{-2}															
Tillage main effect																
Full-width tillage	0.64	1.03	2.02	0.45	0.08	0.08	0.66	0.33	0.00	0.02	1.97a	0.78a	0.72	1.13	4.65	1.56a
Strip-tillage	0.64	0.26	1.97	0.45	0.19	0.14	0.81	0.25	0.32	0.04	4.54b	3.03b	1.15	0.64	7.33	4.02b
Cover crop main effect																
No rye	0.83	0.60	1.86	0.41	0.16	0.22a	0.82	0.29	0.27	0.00	2.30a	1.68	0.69	0.44	4.98	2.38
Rye	0.46	0.69	2.13	0.49	0.11	0.02b	0.66	0.29	0.06	0.06	4.21b	2.13	0.27	0.06	7.00	3.20
Weed Management main effect																
Low	0.54	1.29a	2.46	0.70a	0.13	0.22a	0.82	0.49	0.11	0.00	3.28	1.85	0.78	1.51a	6.56	3.32
High	0.75	0.00b	1.53	0.21b	0.13	0.00b	0.66	0.08	0.21	0.06	3.23	1.97	1.10	0.26b	5.41	2.25
Tillage × cover																
Full-width tillage																
No rye	0.91	0.72	2.62	0.41	0.11	0.16ab	0.87	0.33	0.00	0.00	0.77	0.57	1.02	0.88	4.26	1.31
Rye	0.38	1.33	1.42	0.49	0.05	0.00b	0.44	0.33	0.00	0.04	3.17	0.98	0.43	0.04	5.03	1.80
Strip-tillage																
No rye	0.75	0.48	1.09	0.41	0.21	0.28a	0.77	0.25	0.54	0.00	3.83	2.79	0.35	0.00	5.69	3.44
Rye	0.54	0.04	2.84	0.49	0.16	0.04b	0.87	0.25	0.11	0.08	5.25	3.28	0.11	0.08	8.97	4.59
ANOVA	Significance															
Tillage (T)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.0458	0.0001	NS	NS	NS	0.0040
Cover (C)	NS	NS	NS	NS	NS	0.0340	NS	NS	NS	NS	0.0387	NS	NS	NS	NS	NS
Weed Man. (W)	NS	<0.0001	NS	0.0004	NS	0.0030	NS	NS	NS	NS	NS	NS	NS	0.0030	NS	NS
T × C	NS	NS	NS	NS	NS	0.0340	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
T × W	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C × W	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.0370	NS	NS
T × C × W	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Statistical significance (p = 0.05) is indicated by different letters within the same column.

Table 5
Effects of tillage and rye cover crops on insect pests and natural enemies.

Tillage	Insect pests								Natural enemies									
	PLH[a]		TPB[b]		Aphid		Thrip		Striped thrips		Ladybeetles		Spiders		Pentatomids		Parasitoids	
	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
	Mean number per 10 plants[c]																	
Cover Crop Main Effect																		
None	0.00	8.74	0.77a	0.70	1.87a	2.32	3.67	7.31	3.38	0.70	1.45	0.05a	0.51	0.20a	0.06	0.02	1.54	0.21
Rye	0.00	8.36	3.17b	0.59	4.60b	2.43	6.17	6.66	7.05	0.71	0.33	0.16b	0.22	0.07b	1.39	0.02	0.72	0.13
Tillage × Cover																		
Full-width tillage																		
None	0.00	11.07 A	1.17	0.57	2.50	1.71	2.77	7.83	4.75	0.93ab	1.00a	0.07	0.25	0.21	0.00	0.00	1.08ab	0.21a
Rye	0.00	9.11	3.33	0.82	4.77	2.29	8.00	6.43	5.00	0.39b	0.67ab	0.11	0.33	0.11	0.33	0.00	1.44a	0.00b
Strip tillage																		
None	0.00	6.40 B	0.22	0.82	1.00	2.93	4.57	6.79	2.00	0.46ab	1.90a	0.04	0.78	0.18	0.11	0.04	2.00a	0.21a
Rye	0.00	7.61	3.00	0.36	4.43	2.57	4.33	6.90	9.10	1.04a	0.00b	0.21	0.11	0.04	2.44	0.04	0.00b	0.25a
ANOVA																		
Tillage (T)	NS	0.0097	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.0300
Cover (C)	NS	NS	0.0110	NS	0.0677	NS	NS	NS	NS	NS	0.0229	0.0293	NS	0.0107	NS	NS	NS	NS
T × C	NS	0.0793	NS	NS	NS	NS	NS	NS	NS	0.0375	0.0283	NS	NS	NS	NS	NS	0.0131	0.0315

Statistical significance ($p = 0.05$) is indicated by different letters within the same column.
[a] Potato leafhopper (nymphs and adults).
[b] Tarnished plant bug (nymphs and adults).
[c] Plants were sampled 3 times in 2010, and 7 times in 2011. Analysis was conducted on mean number per sampling date. See Figs. 2 and 3 for more detail on PLF and TPB.

3.4. Crop yield and harvest index

Snap bean yield was not affected by tillage, cover crop, weed management intensity nor their interactions in either year (Table 6). Mean bean yields were 5.01 T/ha in 2010 and 5.16 T/ha in 2011, compared to MI statewide averages for fresh snap beans of 5.05 ha^{-1} and 6.18 ha^{-1} in 2010 and 2011 respectively. Bean harvest index (pod weight divided by total plant weight × 100) was also unaffected by treatments with mean values of 42.7% in 2010 and 33.7% in 2011. The lack of detectable treatment effects on snap bean yield and harvest index suggest that the observed impacts of tillage and cover crops on both insect pests and natural enemies in our study were not the result of indirect effects on crop size or above ground carbon-partitioning.

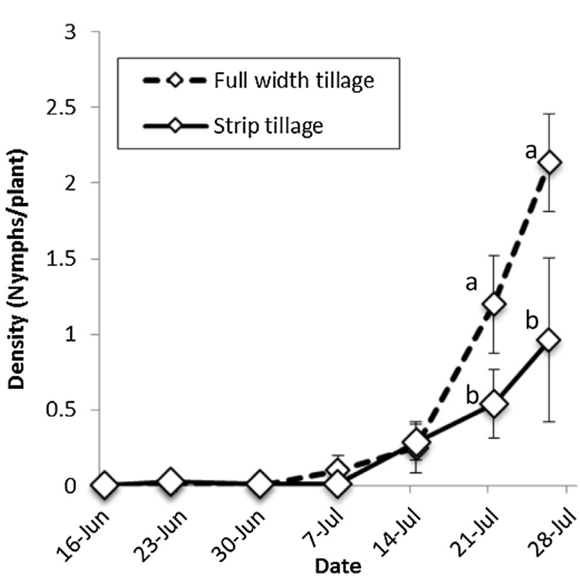

Fig. 2. Main effect of tillage on mean (±se) density of potato leafhopper nymphs, 2011.

It should be noted that a lack of detectable treatment effects on yield does not imply that weed or insect pests did not have a negative effect on yield, nor that growers would not be justified in managing these pests. Crop yield is likely to be influenced both by pests, and by changes in edaphic conditions that are often influenced by CA practices. For example, benefits associated with improved moisture retention in ST systems (Haramoto and Brainard, 2012; Hendrix et al., 2004) may offset costs associated with insects or weeds, resulting in non-detectable yield effects. Moreover, management of pests may be justified based on potential negative impacts unrelated to yield. For example, weeds that have no impact on yield may host disease or insect pests or produce seeds that are detrimental to future crops.

Previous studies have reported improved yields and/or profitability of ST relative to both no tillage (NT) or FWT in many crops (Hoyt et al., 1996; Lonsbary et al., 2004; Luna and Staben, 2002; Luna et al., 2012; Mochizuki et al., 2007, 2008; Wang and Ngouajio, 2008), although reductions in crop yields in ST compared to FWT have been observed in some cases (Bryant et al., 2013; Hoyt, 1999). In snap beans, yield responses to tillage have been variable. For example, Bottenberg et al. (1999) found that yields under ST were improved relative to NT, but lower compared to FWT in some years. In contrast, Abdul-Baki and Teasdale (1997) reported improvements in snap bean yields under NT with cover crop residue compared to FWT without residue. Based on a meta-analysis of 166 studies evaluating the impact of CA practices on yields of legumes (including beans), Pittelkow et al. (2015b) reported large variability in yield responses, with a tendency towards improved yields occurring only under dry, rainfed conditions. The same analysis applied to the subset of 26 studies involving only beans gave similar results, with no overall yield response to CA practices detected, and responses varying widely across production zones (Pittelkow, personal communication). However, it should be noted that Pittelkow et al. (2015a) included paired comparisons of CA vs non-CA treatments which also differed in their herbicide use, so it is unclear whether yield differences were due to CA practices per se, or differences in weed management across these systems.

Table 6
Mean (+-se) bean yield and harvest index, 2010 and 2011.

Tillage	Yield		Harvest index	
	2010	2011	2010	2011
	T/ha		%	
Tillage (T)				
Full width tillage	5.04	5.29	43.5	33.3
Strip tillage	4.98	5.02	41.8	33.4
Cover crop (C)				
No rye	5.09	5.31	42.9	34.1
Rye	4.94	5.01	42.5	32.7
Weed management (W)				
Low	5.14	5.24	43.2	34.1
High	4.89	5.07	42.1	32.6
ANOVA	Significance			
Tillage (T)	NS	NS	NS	NS
Cover crop (C)	NS	NS	NS	NS
Weed man (W)	NS	NS	NS	NS
T × C	NS	NS	NS	NS
T × W	NS	NS	NS	NS
C × W	NS	NS	NS	NS
T × C × W	NS	NS	NS	NS

Table 7
Estimated changes in costs of pest management, tillage and cover cropping in FWT-R, ST-NR and ST-R c ompared to FWT-NR.

	Estimated costs (+) or savings (−)		
	FWT-R	ST-NR	ST-R
	$ ha^{-1}		
Pest management costs[a]			
Weeds			
Winter annuals	0.0	29.9	0.0
Large crabgrass	14.1	14.1	14.1
Powell amaranth	0.0	0.0	0.0
Common lambsquarters	0.0	0.0	0.0
Insects			
Potato leaf hopper	0.0	−18.6	−18.6
Tarnished plant bug	18.6	0.0	18.6
TOTAL Weed	*14.1*	*44.0*	*14.1*
TOTAL Insect	*18.6*	*−18.6*	*0.0*
TOTAL PEST (Weeds + Insects)	*32.7*	*25.3*	*14.1*
Cover crop management costs			
Rye seed[b]	88.7	0.0	88.7
Rye planting (drill)[c]	25.3	0.0	25.3
Glyphosate product[d]	44.9	0.0	44.9
Glyphosate application[c]	13.5	0.0	13.5
Rye mowing[c]	0.0	0.0	29.2
Total Rye Management	*172.4*	*0.0*	*201.6*
Tillage costs			
Strip till[b]	0.0	38.2	38.2
Moldboard plow[b]	0.0	−42.9	−42.9
Disk[b,e]	27.0	−27.0	−27.0
Harrow[b]	0.0	−19.5	−19.5
Total tillage	*27.0*	*−51.2*	*−51.2*
GRAND TOTAL	*232.1*	*−25.8*	*164.5*

Abbreviations: FWT = Full width tillage; R = Rye cover crop; NR = No rye cover crop; ST = Strip tillage.
[a] See Tables A.1 and A.2 for underlying threshold and cost assumptions.
[b] Assumes rye sown at 125 kg ha^{-1} and rye seed cost of $0.71 kg^{-1}; assumes no additional tillage required in the fall to sow rye since growers typically disk for weed and disease management even when rye is not being planted.
[c] Estimates from Stein (2011).
[d] Assumes 3.36 kg ha^{-1} application rate and product cost of $13.36 kg^{-1}.
[e] Assumes an extra disking is required in FWT-R to more fully incorporate rye biomass which exceeds that of winter annual weeds (see Fig. 1).

3.5. Pest-regulating services

3.5.1. Rye cover cropping

Relative to standard practice of not using a cover crop, the inclusion of a rye cover crop in snap bean production under conventional full-width tillage (FWT-R) resulted in an estimated total pest-regulating *dis-service* of $32.7 ha^{-1} due to higher costs associated with management of large crabgrass and tarnished plant bug (Table 7). For large crabgrass, we estimated a cost of $14.1 ha^{-1} associated with FWT-R compared to FWT-NR based on an observed increase in density in one of two years (Table 3) that was sufficient to require an additional pesticide application based on our threshold assumptions (Outcome 3; Tables A1 and A2). Similarly, for tarnished plant bug we estimated a cost of $18.6 ha^{-1}, based on an observed increase in density in FWT-R compared to FWT-NR in one of two years (Table 5 and Fig. 3), that was sufficient to require an additional pesticide application (Outcome 3; Tables A1 and A2). For all other weed and insect pests, FWT-R either had no effect, or did not influence densities sufficiently to result in either pesticide costs or savings compared to FWT-NR given our threshold assumptions (Outcomes 1 or 4).

The estimated impacts of rye cover cropping on pest regulating services in our study contrast to some extent with previous studies. For example, in FWT corn-soybean-wheat cropping systems, Schipanski et al. (2014) estimated—based on model simulations and "expert opinion"—that an incorporated rye cover would suppress spring weeds by 24%, and summer weeds in subsequent crops by 14%. They concluded that these effects constituted a pest-regulating ecosystem service, although no information is provided on whether these reductions in weed density would actually improve yield or reduce weed management costs. With respect to insects, Schipanski et al. (2014) noted that rye cover cropping exacerbated important lepidopteran pests in corn-soybean cropping systems, but did not consider this effect strong enough to constitute an ecosystem dis-service, given potential positive effects on beneficial insects.

When compared to the considerable costs associated with establishment and maintenance of rye, we found that pest regulating effects were small (Table 7). In particular, we estimated that the cost associated with rye cover cropping in the FWT system was approximately $199 ha^{-1}. This total estimate included costs associated with planting and terminating rye ($172), as well as the costs associated with incorporating rye following termination ($27). When combined with the estimated economic cost of pest management dis-services associated with rye, this system resulted in a net short-term economic loss of $232 ha^{-1}. Our estimate of the costs associated with rye cover cropping are almost identical to

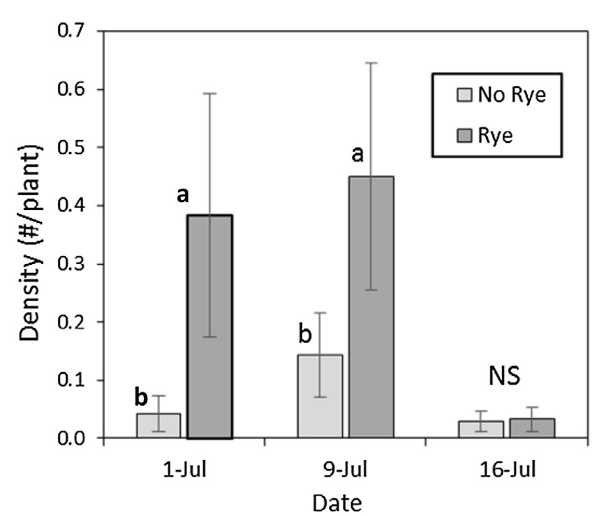

Fig. 3. Main effect of rye cover crop on mean (±se) density of tarnished plant bug, 2010.

those of Schipanski et al. (2014), although their estimate excluded costs associated with termination of rye. Wyland et al. (1996) estimated that the cost of rye cover cropping represented 5% of the costs required to produce a broccoli crop. However, their estimate did not include seed costs, and no dollar value was provided.

3.5.2. Strip-tillage

Partial adoption of CA practices in the form of strip tillage alone (ST-NR) resulted in estimated total pest-regulating *dis-service* of $25.3 ha^{-1} due to higher costs associated with management of winter annual weeds and large crabgrass, which more than offset the estimated cost-savings associated with reduced potato leafhopper densities (Table 7). For winter annual weeds, we estimated a pesticide cost of $29.9 ha^{-1} associated with ST-NR compared to FWT-NR based on an observed increase in biomass in both years (Fig. 1) that was sufficient to require an additional pesticide application based on our threshold assumptions (Outcome 3; Tables A1 and A2). Under FWT-NR, winter annual weeds also exceeded thresholds, but would not require a pesticide application because spring tillage operations were assumed to provide sufficient suppression. For large crabgrass management, we estimated a pesticide cost of $14.1 ha^{-1} associated with ST-NR compared to FWT-NR based on higher emergence observed in one of two years (Table 3), warranting an additional pesticide application given our threshold assumptions (Outcome 3; Tables A1 and A2). In contrast, for potato leafhopper, we estimated a pesticide cost savings of $18.6 ha^{-1} based on an observed reduction in ST-NR compared to FWT-NR in one of two years (Fig. 2) that saved a pesticide application (Outcome 2; Tables A1 and A2). For all other weed and insect pests, ST-NR either had no effect, or did not influence densities sufficiently to result in either pesticide costs or savings compared to FWT-NR (Outcomes 1 or 4).

To our knowledge, no previous studies have attempted to quantify the value or cost of the pest regulating-impacts of strip tillage. Previous studies documented differences in abundance of weeds (Brainard and Noyes, 2012; Hendrix et al., 2004; Wang and Ngouajio, 2008) or insects (Bryant et al., 2014; Overstreet et al., 2010) associated with strip tillage, but did not compare these densities to action thresholds to estimate their likely economic impact.

In contrast to rye cover cropping, ST resulted in tillage-related cost savings compared to FWT-NR that outweighed costs associated with pest-regulating dis-services (Table 7). Tillage cost savings were estimated at $51.2 ha^{-1} due to elimination of plowing, disking and harrowing operations which were greater than the cost associated with strip tillage (Table 7). These estimates are consistent with previous studies in which estimated tillage cost savings associated with ST ranged from $20 to 84 ha^{-1} (Archer and Reicosky, 2009; Haramoto, 2014; Luna and Staben, 2002) depending on assumptions regarding scale of equipment, purchasing price, fuel requirements, labor costs, interest rates, and the number of tillage operations in the FWT control. Taking both tillage and pesticide costs into account, the overall short-term cost savings of ST-NR compared to FWT-NR in our study was estimated at $25.8 ha^{-1} (Table 7).

3.5.3. Strip tillage and rye cover cropping

Full adoption of CA practices (ST-R) was estimated to result in a pest-regulating *dis-service* with an estimated cost of $14.1 ha^{-1} compared to FWT-NR. This overall pest-regulating dis-service was due to increased costs associated with management of large crabgrass and tarnished plant bug, which offset savings associated with lower densities of potato leafhopper (Table 7). For large crabgrass, densities in ST-R increased relative to FWT-NR in one of two years (Table 3), and the increase was sufficient to require an additional pesticide application based on our threshold assumptions (Outcome 3; Tables A1 and A2), with an estimated expected cost of $14.1 ha^{-1}. For tarnished plant bug, densities in ST-R were higher than those in FWT-NR in one of two years (Table 5 and Fig. 3), and sufficiently high to require an additional pesticide application based on our threshold assumptions (Outcome 3; Tables A1 and A2) with an estimated cost of $18.6 ha^{-1}. In contrast, ST-R resulted in a reduction in potato leafhopper densities (Table 5 and Fig. 2), resulting in a savings of $18.6 ha^{-1} associated with pesticide avoidance (Outcome 2; Tables A1 and A2).

For all other weed and insect pests, ST-R either had no effect, or did not influence densities sufficiently to result in either pesticide costs or savings compared to FWT-NR under our threshold assumptions (Outcomes 1 or 4; Table A2). For example, although ST-R resulted in a reduction of common lambsquarters emergence in both years (Table 3), the resulting densities remained greater than the estimated action threshold (Table A1), so did not result in any pesticide avoidance (Outcome 4; Table A2). Similarly, rye suppressed winter annual weeds compared to FWT-NR, but did not result in pesticide avoidance since tillage was assumed to manage these weed species (Outcome 1; Table A2).

When compared to the costs associated with establishment and maintenance of rye, the impact of pest regulating effects of ST-R were small (Table 7). Cover crop costs exceeded cost savings associated with tillage. Overall, we estimated that complete adoption of CA practices (ST-R) increased short-term management costs by $165 ha^{-1} compared to FWT-NR, with pest regulating effects accounting for less than 10% of these costs. Thus, complete adoption of CA practices in snap beans did not provide sufficient synergistic benefits for pest-regulation to improve short-term economic performance relative to adoption of strip tillage alone.

3.6. Implications beyond North Central US production systems

3.6.1. Impacts of CA in absence of pesticides

It is important to note that our estimates of the value (or cost) of pest-regulating services (or dis-services) are based on two major sets of assumptions: 1) the pesticides listed in Table A1 are highly effective at managing their associated pests, and available to growers at the specified price; and 2) that the use of these pesticides is based on observed pest densities in relation to action thresholds. Although we believe these assumptions are reasonable for snap bean production regions of the North Central US, they have more limited applicability in regions and cropping systems for which pesticides are unavailable, prohibited, or limited in effectiveness. In such cases it is likely that observed differences in pest density associated with CA practices will have a larger impact on costs or crop yields then our pesticide-based estimates might suggest.

To illustrate how the value of pest regulation of CA practices might differ in systems without pesticide use, published estimates of changes in yield associated with differences in pest density are helpful. In the absence of pesticides, increases in pest density are likely to result in either increased costs associated with non-chemical management (e.g. hand weeding) or losses in yield and revenue due to the pest, or both. For example, based on estimates of yield losses due to large crabgrass (Aguyoh and Masiunas, 2003a) and our emergence data from 2011 (Table 3), growers without herbicides would either need to rely on cultivation and hand weeding to reduce densities or face yield losses of 30–50%. Gianessi and Reigner (2007) estimated without herbicides, at least 30 h ha^{-1} of hand weeding and two cultivation passes would typically be used to manage weeds in snap beans, and that yield losses of 20% would still occur due to weed escapes. Under these circumstances, the costs associated with higher crabgrass density under ST would likely far exceed the $14.1 ha^{-1} associated with herbicide applications in our pesticide-based estimates.

Similarly, in the absence of insecticides, the impact of insect-regulating effects of CA are likely to increase substantially. For example, using yield loss data associated with varying densities of tarnished plant bug from Khattat and Stewart (1975) we estimate that higher densities of this insect associated with rye cover cropping in our study (Fig. 3) would result in yield losses of approximately 5% compared to FWT-NR in the absence of control measures. Given typical bean prices and yields for the North Central US (Ho et al., 2011), this yield loss equates to approximately $\$50–135\,ha^{-1}$. In contrast, based on potato leafhopper effects on yields reported in Wisconsin (US) snap bean studies (Gonzalez and Wyman, 1991), reductions in potato leafhopper density observed under ST in our study (Fig. 2), might be expected to result in improvements in yields of between 0 and 50% depending on the year, planting timing, and snap bean cultivar. Assuming an intermediate yield improvement of 25%, and typical snap bean prices and yields for the North Central US (Ho et al., 2011), the value of suppression of potato leafhopper under ST in the absence of insecticides would be approximately $\$250–675\,ha^{-1}$.

These examples suggest that when pesticides are not available, adoption of rye cover cropping appears less attractive then when pesticides are available, since observed pest effects were primarily negative with rye, and since more expensive control options would be required to address them. In contrast, in the absence of pesticides, the economic impact of complete adoption of CA (ST-R) is more difficult to predict, since cost avoidance associated with reduced potato leafhopper and common lambsquarters densities might outweigh the increased costs associated with large crabgrass control.

3.6.2. Importance of pest communities

Because CA practices have variable effects on specific pests, the composition and relative abundance of weed, insect, and disease communities will clearly have an important impact on pest regulation services associated with CA. The pests observed in our field study are ubiquitous in the North Central bean production systems, but their relative importance varies both spatially and temporally depending on climate and cropping system. For example, potato leafhopper abundance varies substantially from year to year in North Central bean production systems (Gonzalez and Wyman, 1991). Therefore, the potential benefits associated with natural control of this pest under ST will also vary. Pest complexes in beans in other parts of the world may also be very different from those found in the North Central US (e.g. Abate and Ampofo, 1996), and will likely entail distinct pest-regulating tradeoffs with different net short-term impacts than those evaluated in our study. Finally, it should be noted that in our trials, we did not observe any effects of CA on plant diseases, but pathogens can be a major problem in beans production systems worldwide (e.g. Naseri and Mousavi, 2015), and may be either exacerbated or suppressed under CA practices (Page et al., 2013).

3.6.3. Implications of alternative price and yield assumptions

To put our estimates in economic perspective, it is useful to consider the yield increases that would be required to offset costs associated with rye cover cropping, and how they might vary under different production systems and markets. For example, to offset the estimated cost of full adoption of CA (ST-R) in processing snap beans in the North Central US, yield increases of 5–15% would be required given typical yields (5–9 T/ha) and prices ($\$200\text{-}300T^{-1}$) provided in Ho et al. (2011). In contrast, yield increases of as little as 2–4% would be required for fresh market snap beans, since they typically have prices 4–5 times greater than processing beans (ERS, 2011).

Although we observed no yield impacts associated with CA practices in our study, other studies have shown either yield reductions (Bottenberg et al., 1999) or improvements (Abdul-Baki and Teasdale, 1997) in response to CA practices in beans in US cropping systems. Similarly variable responses have been reported in studies from around the world (Pittelkow et al., 2015a). Depending on bean prices and input costs associated with bean production in different production areas, yield improvements in response to CA practices may justify adoption of CA even if pest effects and costs associated with residue retention are similar to those observed in our study.

4. Summary and conclusions

Our study evaluated the short-term impact on yields, pests, and costs of CA practices (reduced tillage and residue retention) compared to standard grower practices in snap bean production systems typical of the North Central US. Overall, we found that CA practices had (i) no effect on yields; (ii) significant effects on the abundance of economically important insects (e.g. tarnished plant bug and potato leafhopper) and weeds (e.g. large crabgrass, Powell amaranth); but (iii) the estimated net economic impact of these pest effects was relatively small in comparison to the costs of establishment and maintenance of cover crops.

Overall, our results suggest that partial adoption of CA practice in the form of reduced tillage (ST-NR) is likely to have immediate economic benefits for snap bean growers (Table 7). Yields under ST were comparable to those under FWT-NR, while savings in input costs were estimated to be $\$24\,ha^{-1}$ due to reductions in tillage and insecticide costs which outweighed increased herbicide costs. Therefore, the potential risks associated with increasing weed density under ST appear to be low for commercial snap bean producers, while potential short-term benefits are substantial. In contrast, we estimated that rye cover cropping alone (FWT-R) or in combination with strip tillage (ST-R) would result in short-term reductions in profitability for snap bean producers of more than $\$150\,ha^{-1}$ due to seed and maintenance costs that outweigh impacts associated with weed and insect pests (Table 7).

Although our study provides a useful approximation of the short-term impact of CA practices on pests and profits for snap bean production in the North Central US, we caution that our results have limited applicability to cropping systems with restricted access to pesticides, different pest complexes, and different relative input costs. In particular, pest-regulating effects of CA are likely to take on greater importance in cropping systems and regions in which pesticide use is limited. In such systems, the costs of pest-regulating dis-services observed in our study would likely increase substantially depending on the cost and effectiveness of alternative pest management practices, and the impact on yields (and profits) of pests escaping those management practices (see Section 3.6.1). Overall, we speculate that grower incentives for adopting CA practices may be lower in these alternative systems, given their general tendency to exacerbate pest problems.

Although pest regulating services and dis-services are often extremely important in explaining grower adoption or dis-adoption of CA practices (Farooq and Siddique, 2015; Neill and Lee, 2001), they must be viewed in the larger context of wide-ranging ecosystem service tradeoffs (Zhang et al., 2007). In some cases, non-pest-regulating ecosystem services of CA may overshadow pest effects. For example, soil moisture retention may be a particularly critical service provided by CA practices in regions with limited rainfall or access to irrigation, resulting in yield improvements for crops (Pittelkow et al., 2015b) that outweigh costs associated with pests and CA implementation. Similarly, reduced tillage and cover cropping practices may protect soils and crops from extreme weather events and enhance soil physical and biological properties that ultimately improve yields (Hobbs, 2007; Palm et al., 2014; Snapp et al., 2005). Although documented yield benefits from non-legume cover crops—including cereal rye—are often small or absent in the short term, longer term increases in soil organic matter or reductions in N losses may justify their adoption (Miguez and Bollero, 2005). However, the duration required to realize yield benefits associated with CA practices, is often more than 3 years, and short term yield losses resulting from CA practices may represent a major barrier to adoption in many cropping systems (Pittelkow et al., 2015b). Short-term reductions in risk associated with crop yield loss under extreme weather conditions may be a particularly important factor for grower adoption of CA practices in some cropping systems (e.g. Abdul-Baki and Teasdale, 1997; Brainard et al., 2012; Overstreet and Hoyt, 2008), and this factor is likely to increase in importance as the incidence of extreme weather events increases (Rosenzweig and Tubiello, 2007). Future studies quantifying longer-term economic and environmental tradeoffs associated with pest and non-pest regulating services are important for developing a broader understanding of the impacts of these practices on agricultural sustainability (Zhang et al., 2007). Nonetheless, such long-term benefits are unlikely to be realized, if short-term improvements in profitability of these practices—such as those evaluated in this study—cannot be clearly demonstrated.

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Appendix A.

See Tables A1 and A2.

Table A1
Pest management threshold, rate and cost assumptions.

Pest	Threshold Assumptions and Sources[a]		Pesticide product, rate and cost assumptions when thresholds are exceeded					
	Action threshold	Source(s)	Product	Product Costs[b] ($/kg ai)	Rate (kg ai/ha)[c]	Product cost	Application cost[d]	Total cost
						$/ha		
Crabgrass	8 plants m^{-2}	Aguyoh and Masiunas, 2003a	Clethodim	192.75	0.08	14.68	13.46	28.14
Common lambsquarters	3 plants m^{-2}	Aguyoh and Masiunas, 2003b; Harrison, 1990	Bentazon	48.26	0.98	47.30	13.46	60.76
Powell amaranth	3 plants m^{-2}	Aguyoh and Masiunas, 2003b	Fomesafen	120.14	0.28	33.64	13.46	47.10
Winter annual weeds	100 g m^{-2}	Ogg et al., 1993; Conley and Bradley, 2005	Glyphosate	13.36	2.24	29.94	0	29.94
Potato leaf hopper	1 nymph/plant	Delahaut, 2005; Cook et al., 2004; Bird et al., 2014	lambda-cyhalothrin	14.91	1.60	23.80	13.46	37.26
Tarnished plant bug	0.2 adults/plant	Bird et al., 2014; Stewart and Khattat, 1980; Khattat and Stewart, 1975	lambda-cyhalothrin	14.91	1.60	23.80	13.46	37.26

[a] Threshold assumptions were based on sources listed in combination with our personal observations of snap bean management in MI (see text for details). For summer annual weeds, threshold values were converted from m-row to m^{-2} by multiplying by 4 (assumes 0.25 in-row zone).
[b] Product costs are from local MI pesticide dealer and represent typical prices paid by MI snap bean growers.
[c] Pesticide application rates are from Zandstra (2011) for weeds, and from Bird et al. (2014) for insects.
[d] From Stein (2011). For glyphosate, it is assumed that no additional application costs would be incurred, because the pesticide could be tank mixed with pre-emergence herbicides (e.g. s-metolachlor) that would be applied regardless of treatment.

Table A2
Assumed probabilities of different pest density outcomes relative to threhsolds for strip tillage and cover crop practices.[a]

Pest	Probability of Outcome[b]			
	O1	O2	O3	O4
	Both below threshold[c]	Pesticide avoided	Pesticide required	Both above threshold
FWT-R				
Winter annual weeds	1.0			
Large crabgrass			0.5	0.5
Powell amaranth				1.0
Common lambsquarters				1.0
Potato leaf hopper				1.0
Tarnished plant bug	0.5		0.5	
ST-NR				
Winter annual weeds			1.0	
Large crabgrass			0.5	0.5
Powell amaranth				1.0
Common lambsquarters				1.0
Potato leaf hopper	0.5	0.5		
Tarnished plant bug	1.0			
ST-R				
Winter annual weeds	1.0			
Large crabgrass			0.5	0.5
Powell amaranth				1.0

Table A2 (*Continued*)

Pest	Probability of Outcome[b]			
	O1	O2	O3	O4
	Both below threshold[c]	Pesticide avoided	Pesticide required	Both above threshold
Common lambsquarters				1.0
Potato leaf hopper	0.5	0.5		
Tarnished plant bug	0.5		0.5	

[a] Abbreviations: FWT = Full width tillage; R = Rye cover crop; NR = No rye cover crop; ST = Strip tillage.
[b] See text. O1: Pest density in the control treatment (Dc) and the pest density in the alternative treatment (Da) are both less than the threshold density (Dt); O2: Dc > Dt and Da < Dt; O3: Dc < Dt and Da > Dt; O4: Dc > Dt and Da > Dt.
[c] See Table A.1 for threshold assumptions; Pobabilities are based on observed weed (Table 3 and Fig. 1) and insect (Table 5 and Figs. 2 and 3) abundance relative to thresholds.

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