Crop Residue and Residue Management Effects on *Armadillidium vulgare* (Isopoda: Armadillidiidae) Populations and Soybean Stand Densities

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ABSTRACT   In general, *Armadillidium vulgare* (Latreille) are considered nonpests of soybean [*Glycine max* (L.) Merrill], but changes in soil conservation practices have shifted the pest status of this organism from an opportunistic to a perennial, early-season pest in parts of central Kansas. As a result, soybean producers that rotate with corn (*Zea mays* L.) under conservation tillage practices have resorted to removing excess corn residue by using controlled burns. In a 2-yr field study (2009–2010), we demonstrated that residue removal in burned compared with unburned plots (measured as previous crop residue weights) had minimal impact on numbers of live and dead *A. vulgare*, soybean seedling emergence, and isopod feeding damage over time. Specifically, removal of residue by burning did not result in higher emergence rates for soybean stands or less feeding damage by *A. vulgare*. In a separate study, we found that number of live *A. vulgare* and residue weights had no consistent relationship with seedling emergence or feeding damage. Furthermore, seedling emergence was not impacted by higher numbers of *A. vulgare* in unburned plots, indicating that emergence in this study may have been influenced by factors other than *A. vulgare* densities. These studies demonstrate that removing residue through controlled burning did not impact seedling emergence in presence of *A. vulgare* and that residue and feeding damage to seedlings did not consistently relate to *A. vulgare* densities. Other factors that may have influenced a relationship between residue and live isopod numbers, such as variable moisture levels, are discussed.

KEY WORDS   soybean, *Glycine max*, isopod, *Armadillidium vulgare*, residue management

The benefits of reduced or conservation tillage management in cropping systems include enhanced retention of soil moisture, increased soil structure stability, and reduced input costs for producers (Gebhardt et al. 1985, NeSmith et al. 1986). In no-till soybean production, the presence of crop residue improves soil properties and reduces producer input costs (Doran et al. 1984). Presence of residue also reduces soil erosion, although increasing the infiltration and retention of soil moisture (Bruce and Kells 1990, Tebruegge and Duering 1999, Saxton et al. 2001). Moreover, residues increase soil organic matter, which is correlated with beneficial microbial activities of soil-inhabiting organisms (Cruse et al. 2003, Marriott and Wander 2006, Teasdale 2007). However, there may be potential risks associated with adopting conservation tillage practices like increased incidence of pests. For example, the undisturbed soil profile may be an optimal environment for increasing populations of soil-inhabiting pests (Stinner and House 1990). Specifically, soil-borne secondary pests (i.e., those not considered key perennial pests) may become problematic under conservation tillage systems.

Terrestrial isopods (Crustacea: Isopoda) are soil-dwelling arthropods that generally feed on decaying organic matter (Saska 2008), but also are reported to damage a number of agriculturally important crops, including alfalfa (*Medicago sativa* L.), cereals, soybean [*Glycine max* (L.) Merrill], and canola (Byers and Bierlein 1984, Paoletti et al. 2008). In particular, the isopod species *Armadillidium vulgare* (Latreille) has been found feeding on soybean, seeds and seedlings, causing a reduction in stand densities (Faberi et al. 2011). Damage to soybean seedlings occurs just after emergence where *A. vulgare* feed on the succulent stem tissue (hypocotyl) beneath the cotyledons of emerging soybean seedlings, which severs the cotyledons from the developing seedling and results in plant death (Whitworth et al. 2008). Under heavy isopod pressure, producers usually replant damaged fields to establish harvestable soybean stands. Generally, *A. vulgare* are considered nonpests of soybean; however, changes in production practices may be enabling a shift from an opportunistic pest to a perennial, early-season pest (Wallner 1987). Recently, damaging populations of early-season *A. vulgare* have been ob-

served in soybean fields in central Kansas, which typically are managed with conservation tillage practices. As such, soil conservation practices may be providing optimal conditions for development and reproduction of isopods (Saluso 2004, Mastronardi 2006).

Risk of seedling feeding damage can be increased with the presence of crop residues, which provides an ideal habitat for isopod development (Paris 1963). Presence of residues on the soil surface serves as a food source for isopods, which generally are considered decomposers of organic material (Rushton 1981, Rushton and Hassall 1983, Brody and Lawlor 1984, Morisawa et al. 2002). Moreover, residues provide shelter and protection from extreme fluctuations in ambient temperature and humidity (Davis 1984, Hassell and Dangerfield 1990), which isopods are highly susceptible to (Al-Dabbagh and Block 1981, Brody and Lawlor 1984, Refinetti 1984). It is thought that isopods are not generally problematic in conventional-tilled fields, which retain minimal amounts of organic matter on the soil surface. Rushton and Hassall (1987) reported that populations of *A. vulgare* exposed to decreasing amounts of organic matter tended to increase feeding competition within populations, although declining in overall isopod numbers. As such, presence of corn residues in soybean fields may be influencing isopod population densities, thus increasing feeding damage to soybean seedlings; the extent of this interaction is not known.

Rotating successive crops of soybean and corn (*Zea mays* L.) under conversation tillage management has become a widespread practice in Kansas and other parts of the north central United States. A component of such systems is the management of crop residue left in fields between rotations. An important requirement for residue management is maintaining sufficient residue levels from previous crops, which are designed to limit soil erosion, although allowing maximum seedling emergence for the next crop (Buchholz et al. 1993). In general, 60–70% ground cover from crop residue is desired, but also depends on crop and soil type (Buchholz et al. 1993). In some cases, excessive residues are removed either mechanically or by controlled burning, a common practice in conservation cropping systems of the northern Great Plains (Fasching 2001). Consequently, burning crop residue also has been a successful control measure for various pests in conservation systems (Hardison 1976, Miller 1979, McCullough et al. 1998, Young et al. 1998). Biederbeck et al. (1980) reported that the heat from burning residue penetrates the soil ≈1.3 cm. Therefore, soilborne insects that overwinter near the soil surface may be directly affected by burning. Conversely, indirect effects from burning may include a reduction in habitat availability for overwintering insects, reducing food resources, or both. (McCullough et al. 1998). Moreover, burning residue may expose arthropods to suboptimal climatic conditions, including fluctuations in temperature and humidity, which may disrupt their feeding activities (Hassall and Dangerfield 1990, Siemann et al. 1997, Moretti et al. 2004). As such, burning crop residues may be useful for controlling *A. vulgare*

in soybean but the overall effectiveness of burning, as a way to manage isopods, is not known.

Soybean producers lack management options to maintain soybean stands in the presence of damaging isopod densities. To avoid the added cost of replanting (seed, fuel, and time), reliable management options for *A. vulgare* in soybean must be explored. For the growing number of soybean producers that use conservation tillage practices with increased population densities of ground-dwelling arthropods, including *A. vulgare* (Stinner and House 1990), there is a need to measure the impact of residue management strategies on isopod numbers and resulting soybean plant densities. Specifically, it would be useful to determine if removal of corn residue reduces feeding damage to soybeans by directly reducing isopod populations.

It is important to determine if *A. vulgare* population levels relate to changes in field residue levels. We conducted two studies to test the hypothesis that existing amounts of residue are correlated with greater *A. vulgare* densities and higher levels of feeding damage to soybean seedling, whereas lower amounts of residue will result in reduced *A. vulgare* densities and less feeding damage. From a management perspective, is also important to determine if population densities and damage severity to soybean plant populations correlate with the amount of residue present, which can vary by field or even by climatic conditions. In separate study we sampled *A. vulgare* populations several times during the early growing season where soybean plants are most susceptible to damage (2–4 wk after planting) to determine how much populations were changing during this time. We hypothesized that lower residue levels along with lower early-season isopod densities will positively impact seedling emergence and reduce feeding damage throughout the early growing season (emergence period).

Although it is unclear whether increases in conservation management of soybean production systems are increasing the risk of damage from *A. vulgare*, control methods are sought to maintain stands in the presence of isopod feeding in fields with a history of damage. Therefore, the objectives of this study were to 1) quantify the direct effects of residue removal through burning on early-season *A. vulgare* populations and soybean stand densities, and 2) assess the effects of variable residue levels on *A. vulgare* populations over time and the impact on soybean stand densities. Improved stands, as either a reduction in plant damage or increased seedling emergence, were measured in open-plot field experiments along with *A. vulgare* numbers (live and dead) and dried residue weights in commercial soybean production fields to determine if burning residue can protect stands against isopod damage.

Methods and Materials

Two field studies were conducted to investigate the effects of crop residue on *A. vulgare* numbers and soybean densities in commercial production fields. The first study compared isopod densities and soybean

densities in presence and absence of residue (established by controlled burning), whereas the second study assessed the relationships between residue, *A. vulgare* densities, and soybean seedling emergence and isopod feeding damage. The first study consisted of a 2-yr experiment in four locations identified as fields 1 and 2 (2009) and fields 3 and 4 (2010). The second study was carried out only in fields 3 and 4 (2010), but used separate blocks within large unburned sections of the soybean fields used in 2010.

For all field sites, soybeans were under a long-term, corn–soybean rotation system managed with overhead irrigation and located 4–5 km apart south of Lindsborg, KS. Field sites were chosen based on soybean growers reporting poor stand establishment because of feeding by isopods in each of the 5 yr before conducting the experiments. In each study year, fields were planted to soybean ('Pioneer 94Y01') and were maintained according to the standard practices of the soybean producer. Before conducting experiments, live isopods were collected from each field for identification. Dorsal and lateral photos of field specimens were submitted to Dr. Stephano Taiti (Istituto per lo Studio degli Ecosistemi, Italy). All submitted specimens were identified as *A. vulgare;* these identified specimens were used to confirm all isopod samples collected from all field studies.

Controlled-Burn Study. Before planting, large sections of corn residue were removed by controlled burns. Several random sections or patches of residue were left unburned for all fields in either year. These unburned sections in a field ranged from 1,400 (25 by 56 m) to 19,200 (75 by 256 m) m^2 in size and were immediately adjacent to control-burned sections within a field. Therefore, a block contained a burned and unburned treatment pair, which was blocked by location within the field to account for differences in block size, residue heterogeneity, or differences in environmental conditions such as drainage or soil type. This experiment was arranged in a randomized complete block design (RCBD) for both years. Block number varied between field 1 ($n = 4$) and field 2 ($n = 6$) in 2009, and fields 3 and 4 ($n = 12$ for each location) in 2010, based on variable field size (ranging from 27.2 to 32.6 ha) and number of unburned patches within a field. Each treatment within a block was sampled using a 1- by 1-m quadrat made from 1.9 cm polyvinyl chloride (PVC). Quadrats were placed at interfacing edges of the burned and adjacent unburned areas and were spaced a minimum of 3–4 m apart. Within each quadrat or sample, we counted the number of *A. vulgare* (live and dead) and soybean seedlings (number of plants per m^2), which were subcategorized as either "emerged" (cotyledons intact) or "damaged" plants (cotyledons severed from the seedling). To show treatment effects, dry residue weights from quadrats were taken in 2010, but not 2009. In 2009, all blocks were sampled on 21 May, and 3 and 10 June for field 1; and 7 and 18 June for field 2. For 2010, responses to burn and unburned treatments were recorded on 28 May, and 7 and 10 June for field 3; and 2 and 28 June for field 4.

Residue Study. Because burning residue can have direct and indirect effects on isopod populations, we conducted a separate companion study to assess the interactions between unmanaged residue levels and existing *A. vulgare* populations. Therefore, we used large unburned sections of two soybean fields to minimize effects of burn treatments on adjacent isopod populations. This 1-yr study (2010) was arranged in an RCBD within fields 3 and 4. Although the same fields were used as the controlled burn study, this separate residue study used different blocks located in large sections of the field that were unburned (14 and 21 ha in fields 3 and 4, respectively). Blocks (spaced 50 to 100 m apart) within these unburned sections were located along a transect that spanned across each field. Block numbers varied between field 3 (four blocks) and field 4 (six blocks), because of variable sizes of these fields (fields 3 and 4 were 27.2 and 28.5 ha, respectively). Four subsamples were taken within each block by using a 1- by 1-m PVC quadrat (spaced 5–10 m apart in a grid pattern). We recorded the number of live and dead *A. vulgare* per m^2, plant counts (similar to the controlled burn study), and dry weight of residue (kg of residue per m^2). The number of live and dead *A. vulgare* was assessed by sorting through residue on the soil surface. Previous crop residue within each subsample then was removed by hand and placed in paper bags and transported to drying facilities located at the North Agronomy Farm in Manhattan, KS; samples were dried in conventional ovens for 5–7 d at 37°C and 0–5% RH. Finally, bags with dried residue and bag weights without residue were weighed on a digital balance (±0.1 mg). Final residue weights then were recorded as total weight minus bag weight. Samples for the residue study were taken on 16, 17, and 21 June for field 3; and 18, 21, 22, and 23 June for field 4.

Statistical Analysis. Before analysis of variance (ANOVA) for either study, the means, standard errors, and assumptions of normality for variables were estimated and tested, respectively, according to the Shapiro–Wilk test statistic (PROC UNIVARIATE; SAS Institute, version 9.2; Cary, NC). Data followed a non-normal distribution; therefore response variables used in ANOVA models were assigned either a negative binomial (numbers of live and dead *A. vulgare*) or Poisson (numbers of damaged plants) distribution by using the link function (PROC GLIMMIX, SAS Institute 2012). Block effects were considered random factors in the model. In addition, residue weights were log$_{10}$ transformed before analysis but only transformed data are shown.

For the controlled burn study in fields 1 through 4, counts of emerged and damaged plants and counts of live and dead *A. vulgare* were analyzed using ANOVA for the main effects of sample date, treatment, and the two-way interaction (sample date × treatment); block was the random effect (PROC GLIMMIX, SAS Institute 2012). In the residue study for fields 3 and 4, counts of live and dead *A. vulgare*, counts of emerged and damaged plants, and previous crop residue weight were analyzed using ANOVA for the main effect of

Table 1. ANOVA results for isopod numbers and plant responses for effects of sample date (SD), treatment (burned and unburned areas), and the two-way interaction of SD × treatment for all fields sampled during the 2009 and 2010 controlled burn experiments. Significant effects are bolded ($P < 0.05$)

Location	Main effect	Live isopods			Dead isopods			Emerged plants			Damaged plants			Residue weights[a]		
		F	df	P	F	df	P	F	df	P	F	df	P	F	df	P
Field 1	SD	0.2	2,49	0.82	26.46	2,49	**<0.001**	30.56	2,49	**<0.0001**	6.68	2,49	**0.002**	—	—	—
	Treatment	70.51	1,49	**<0.0001**	1460	1,49	**<0.001**	33.06	1,49	**<0.0001**	14.96	1,49	**0.0003**	—	—	—
	SD × treatment	0.39	2,49	0.67	37.06	2,49	**<0.001**	0.62	2,49	0.54	3.84	2,49	**0.02**	—	—	—
Field 2	SD	0.98	1,13	0.34	4.01	1,13	0.06	0.73	1,13	**0.4**	4.44	1,13	**0.05**	—	—	—
	Treatment	0.02	1,13	0.9	61.85	1,13	**<0.0001**	2.47	1,13	0.14	4.44	1,13	**0.05**	—	—	—
	SD × treatment	0.27	1,13	0.6	95.3	1,13	**<0.0001**	27.42	1,13	**0.0002**	0.58	1,13	0.5	—	—	—
Field 3	SD	0.65	2,49	0.52	37.21	2,49	**<0.0001**	0.45	2,49	0.63	5.47	2,49	**0.007**	0.3	2,49	0.74
	Treatment	10.82	1,49	**0.001**	107.59	1,49	**<0.0001**	18.5	1,49	**<0.0001**	0.01	1,49	0.92	51.32	1,49	**<0.0001**
	SD × treatment	0.27	2,49	0.76	17.31	2,49	**<0.0001**	1.53	2,49	0.22	0.07	2,49	0.92	11.89	2,49	**<0.0001**
Field 4	SD	4.03	1,18	**0.05**	19.76	1,19	**0.0003**	29.94	1,19	**<0.0001**	0.01	1,19	0.9	0.18	1,19	0.67
	Treatment	7.36	1,18	**0.01**	47.46	1,19	**<0.0001**	2.36	1,19	0.14	0.85	1,19	0.36	11.21	1,19	**0.003**
	SD × treatment	3.19	1,18	0.09	17.04	1,19	**0.0006**	0.56	1,19	0.46	0.6	1,19	0.2	0.38	1,19	0.54

[a] Residue weights were not recorded in the 2009 locations (i.e., fields 1 and 2).

sample date and block as a random effect (PROC GLIMMIX, SAS Institute 2012). The LS MEANS statement (SAS Institute 2012) and adjusted Tukey were used to make multiple pair-wise treatment comparisons at alpha = 0.05. To determine the impact of live *A. vulgare* and residue weights on counts of emerged and damaged plants, a covariance model was used (PROC MIXED, SAS Institute 2012) between all sample dates for the covariate effects of live isopod numbers and residue weights on the number of emerged or damaged plants. Covariance analysis did not detect significant differences in slope or intercept estimates between sample dates (see Results), which meant that a common regression could be used to describe the relationship of emerged and damaged plants with live *A. vulgare* and residue weights across sample dates (PROC REG, SAS Institute 2012).

Results

Controlled-Burn Experiment. Block was not significant at all locations or response variables tested ($Ps \leq 0.05$), including plant counts (emerged and damaged), isopod counts (live or dead), and previous crop residue weights. In general, burning residue significantly impacted *A. vulgare* populations more often than sampling date (Table 1). Specifically, the number of live *A. vulgare* was affected significantly by controlled burns in fields 1, 3, and 4 ($P \leq 0.01$; Table 1), where numbers of live *A. vulgare* were 10–16-fold higher in unburned plots compared with burned plots (Fig. 1). Sample date significantly ($P < 0.05$) influenced the number of live *A. vulgare* observed but only in one location (field 4). Here, isopod numbers were five times higher on 28 June (55 ± 23 live *A. vulgare*) compared with the earlier sample date (11 ± 5 live *A. vulgare*) on 2 June.

Burning residue effectively reduced isopod populations, as the number of dead *A. vulgare* between burned and unburned treatments were significantly different in all fields ($Ps < 0.0001$; Table 1). When comparing the main effect of burn treatment across sample dates, dead isopod numbers were significantly 3.5 ($F = 38.2$; df = 1,49; $P < 0.0001$); 4.3 ($F = 10.4$; df = 1,49; $P < 0.0001$); and 1.8 ($F = 6.8$; df = 1,49; $P < 0.0001$), times higher for burned compared with unburned plots in fields 1, 3, and 4, respectively (Figs. 2 and 3). Conversely, dead isopod numbers were significantly greater ($F = 7.8$; df = 1,49; $P < 0.0001$) in unburned plots (35 ± 12 dead *A. vulgare*) compared
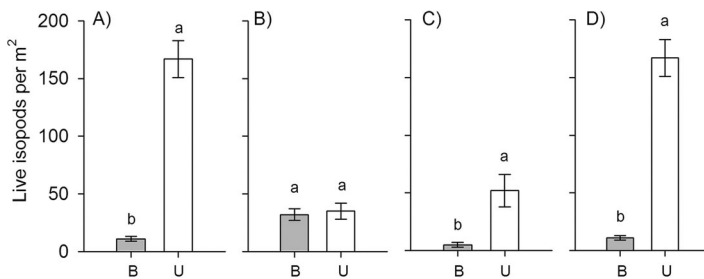

Fig. 1. Results from controlled burn study measuring changes in mean number of live isopods for burned (B, gray bars) and unburned (U, white bars) treatments in fields 1 (A) and 2 (B) in 2009; and fields 3 (C) and 4 (D) in 2010 ($n = 4$) across sample dates. Mean comparisons are denoted with lowercase letters; bars having the same letter are not significantly different from each other ($P < 0.05$). Error bars represent mean standard error.
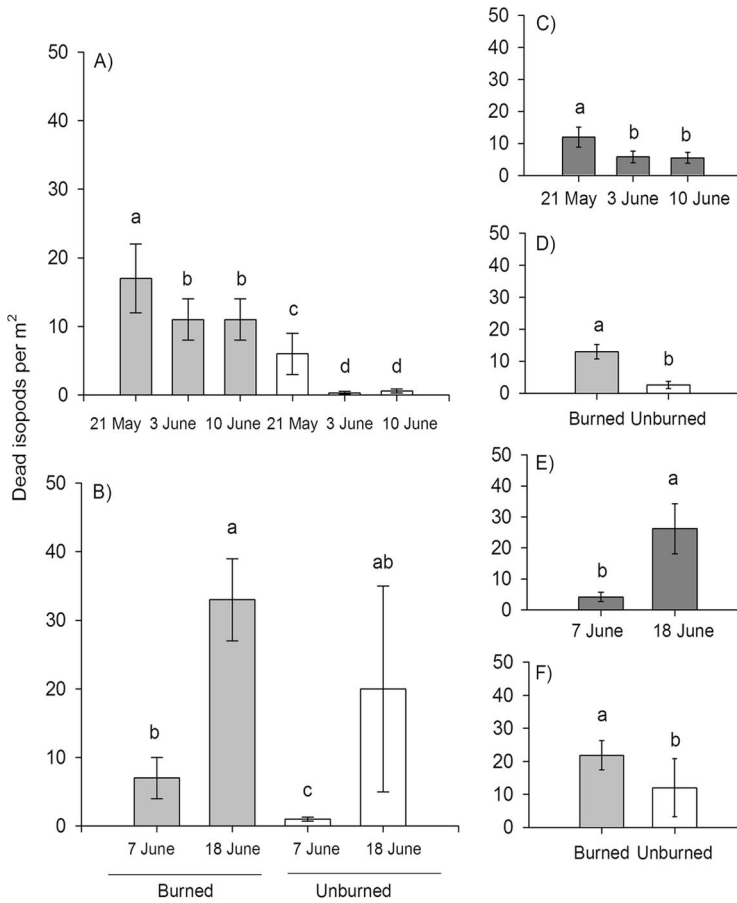
Fig. 2. Results from controlled burn study measuring changes in mean number of dead isopods for all sample date × treatment combinations of burned (gray bars) and unburned (white bars) treatments in field 1 (A) and field 2 (B) in 2009 ($n = 4$). Small graphs (C–F) indicating main effects of sample date (dark gray bars) or burn treatment by year are shown at the right of the interaction plots (A–B). Mean comparisons are denoted with lowercase letters; bars having the same letter are not significantly different from each other ($P < 0.05$). Error bars represent mean standard error.

with burned plots (23 ± 7 dead *A. vulgare*) in field 2 (Fig. 2B). Number of dead *A. vulgare* also changed through time ($Ps < 0.001$; Table 1), however the effect was not consistent between fields (Figs. 2 and 3). For example, dead isopod numbers were six ($F = 41.2$; df = 2,49; $P < 0.0001$) to 11% ($F = 43.4$; df = 2,49; $P < 0.0001$) greater for later sample dates in field 1 but 13-fold greater ($F = 8.71$; df = 1,49; $P < 0.0001$) in field 4 for the late (28 June) compared with early (2 June) sample date. Conversely, there were twice as many dead *A. vulgare* ($F = 12.5$; df = 2,49; $P < 0.0001$) in field 3 on the earliest sample date (28 May) compared with later dates (seven or 10 June). Soybean density (number of emerged plants) was significantly affected by the burn treatment, but the effect was not consistent between fields (Table 1). Specifically, number of emerged plants was significantly different ($P < 0.0001$) for burned and unburned plots in field 1, where burned plots (27 ± 2 plants per m^2) had 50% more soybean plants then unburned plots (18 ± 2 plants per m^2). In contrast, field 3 tended to have 31% more soybean plants ($P < 0.0001$) in the unburned

plots (50 ± 2 plants per m^2) compared with the burned plots (38 ± 1 plants per m^2). In addition, the number of emerged plants was significantly different by sample date in fields 1 and 4 ($P < 0.0001$; Table 1). In field 1 (Fig. 4A) and 4 (Fig. 4D), the number of emerged soybean plants was 10–50% higher on the later sample dates compared with earlier dates. The number of damaged plants was also affected by the main effects of sample date and burn treatment (Table 1). As with the number of emerged soybean plants, these effects were inconsistent between fields. For example, number of damaged plants was significantly different ($P < 0.0001$) for burned and unburned plots in field 1 ($P = 0.0003$) and 2 ($P = 0.05$), where unburned plots (4 ± 0.5 plants per m^2) had threefold more damaged soybean plants than burned plots (1 ± 0.2 plants per m^2) in field 1. In contrast, field 2 tended to have more soybean plants in the unburned plots (0.3 ± 0.2 plants per m^2) compared with the burned plots (0 ± 0 plants per m^2). Number of damaged plants was significantly affected by sample date; however, this effect was inconsistent (Fig. 5). In field 1 (Fig. 5A) and 2 (Fig. 5B),
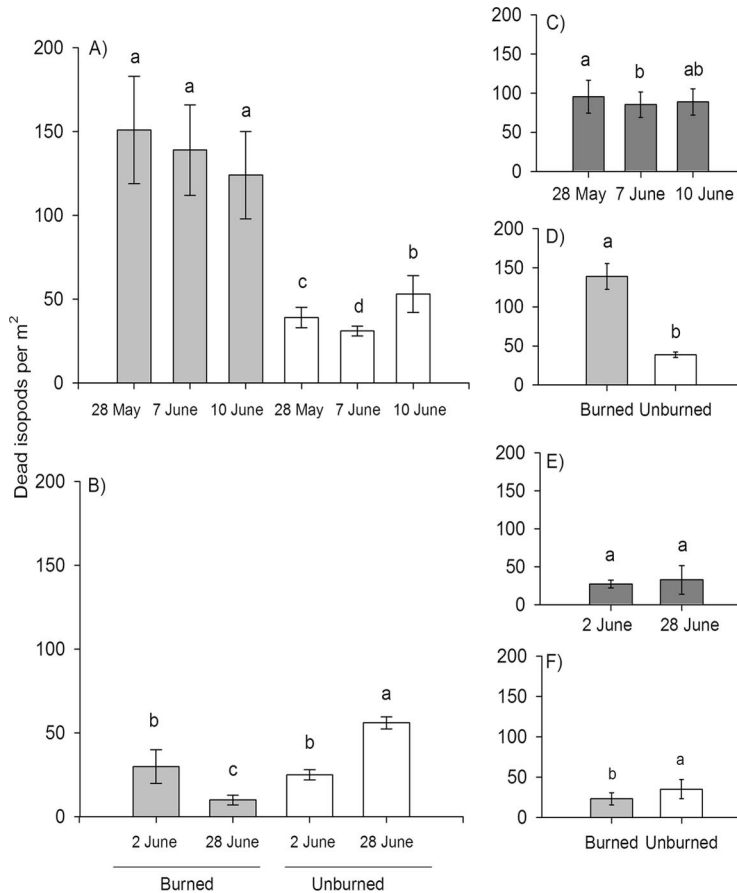
Fig. 3. Results from controlled burn study measuring changes in mean number of dead isopods for all sample date × treatment combinations of burned (gray bars) and unburned (white bars) treatments in field 3 (A) and field 4 (B) in 2010 ($n = 4$). Small graphs (C–F) indicating main effects of sample date (dark gray bars) or burn treatment by year are shown at the right of the interaction plots (A–B). Mean comparisons are denoted with lowercase letters; bars having the same letter are not significantly different from each other ($P < 0.05$). Error bars represent mean standard error.

significantly more damage occurred on later sample dates (field 1: 21 May and 10 June; field 2: 7 June) compared with earlier sample dates, which occurred on 3 May and 18 June, respectively. Conversely, fewer damaged soybean plants were observed in field 3 (Fig. 5C) with each successive sample date.

For fields 1, 2, and 3, the number of damaged plants was significantly different by sample date ($Ps \leq 0.05$; Table 1), numbers were higher at the later sample dates compared with the earlier sample date in fields 1 and 2 (Fig. 5). For field 3, the number of damaged plants was higher for the early sample date compared with late or mid sample dates (Fig. 5). Not surprisingly, the burn treatment significantly reduced ($Ps < 0.001$) the amount of residue from previous crops collected from experimental plots in fields 3 and 4; recall, residue data were only collected in the 2010 field locations. Dried residue weights were significantly higher (3.8–5.6-fold higher) in fields 3 and 4 ($Ps < 0.001$; Table 1) in unburned plots (field 3: 1267 ± 2; field 4: 1583 ± 187 g per m^2) compared with plots that were burned (field 3: 330 ± 63; field 4: 282 ± 50 g

per m^2). Therefore, controlled burns were successful in establishing residue differences between treatments.

There was a significant burn treatment × sample date interaction for the number of dead *A. vulgare* observed in all fields ($Ps < 0.001$; Table 1). In fields 1 (Fig. 2A) and 3 (Fig. 3A), the number of dead *A. vulgare* was 10-fold greater in burned plots compared with unburned plots. A similar effect was observed in field 2; however, the number of dead *A. vulgare* was only twofold to threefold higher in unburned plots on 28 June compared with the previous sampling date for unburned plots or either sample date in burned plots (Fig. 2B). In field 4 (Fig. 3B), the number of dead *A. vulgare* was sixfold higher in burned and unburned plots on 18 June, compared with burned and unburned plots that were sampled 11 d prior. In general, the effect of the burn treatment was not consistent across sample dates for three of the four fields sampled in this experiment.

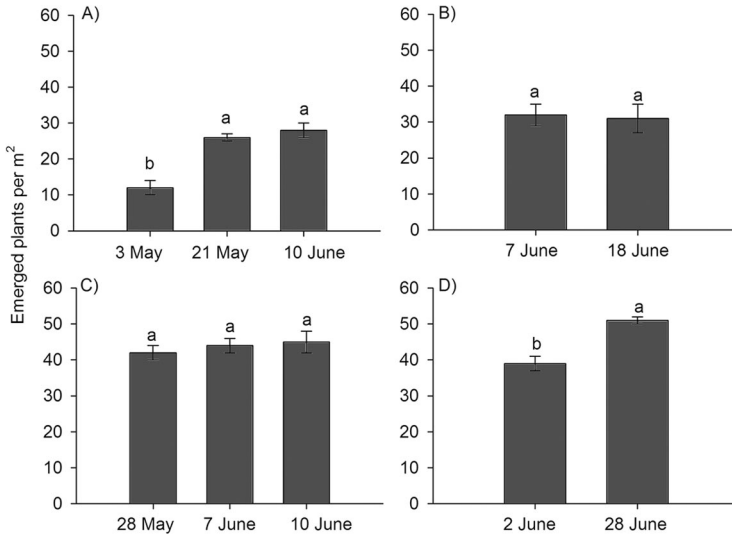There was also a significant sample date × treatment interaction ($P = 0.0002$; Table 1) for number of

Fig. 4. Results from controlled burn study measuring changes in mean number of emerged plants per m^2 for the effect of sample date in fields 1 (A) and 2 (B) in 2009; and fields 3 (C) and 4 (D) in 2010 ($n = 4$). Mean comparisons are denoted with lowercase letters; bars having the same letter are not significantly different from each other ($P < 0.05$). Error bars represent mean standard error.

emerged plants in field 2. Here, plant densities were 48 and 91% greater for burned plots on 18 June (40 ± 3 plants per m^2) and unburned plots on 7 June (46 ± 4 plants per m^2), respectively, compared with burned plots at the later sample date (27 ± 4 plants per m^2) or unburned plots at the early sample date (24 ± 1 plants per m^2). For the number of damaged plants, there was a significant sample date × treatment interaction in field 1 only ($P = 0.02$; Table 1), where twice as much damage was observed in unburned plots

on 3 May (5 ± 1 plants per m^2) compared with other plots and sample dates, which ranged from 0 to three plants per m^2. There was also a significant sample date × treatment interaction for field 3 ($P < 0.0001$; Table 1), where residue weights were highest on 10 June in unburned plots compared with other plots and sample dates.

Residue Study. As in the previous study, block was not significant in either field 3 or 4 and for any of the response variables tested ($Ps \leq 0.05$; Table 2). Isopod
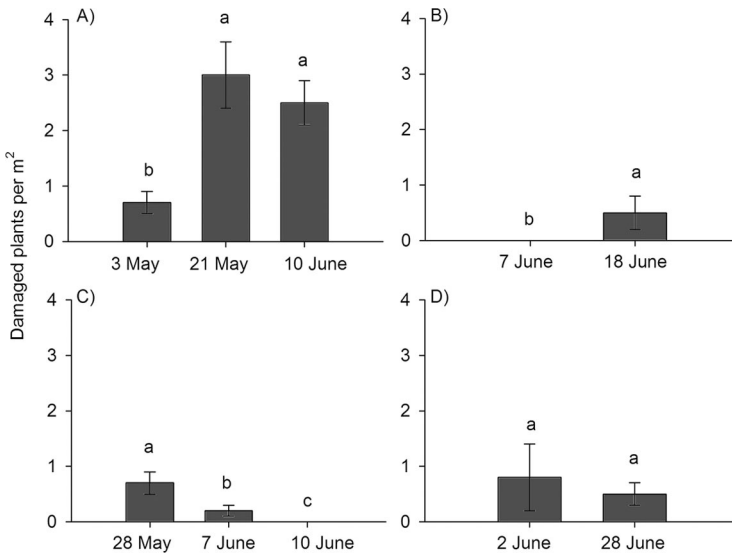

Fig. 5. Results from controlled burn study measuring changes in mean number of damaged plants per m^2 for the effect of sample date in fields 1 (A) and 2 (B) in 2009; and fields 3 (C) and 4 (D) in 2010 ($n = 4$). Mean comparisons are denoted with lowercase letters; bars having the same letter are not significantly different from each other ($P < 0.05$). Error bars represent mean standard error.

Table 2. ANOVA results for isopod numbers, plant responses, and residue dry weights for effects of sample date (SD) and block in field 3 and 4 during the 2010 residue study. Significant effects are bolded ($P < 0.05$)

Location[a]	Main effect	Live isopods			Dead isopods			Emerged plants			Damaged plants			Residue weight		
		F	df	P	F	df	P	F	df	P	F	df	P	F	df	P
Field 3	Block	1.21	3,47	0.51	0.77	3,47	0.51	0.66	3,47	0.58	1.67	3,47	0.18	0.77	3,47	0.51
	SD	6.92	2,51	**0.002**	0.88	2,51	0.42	0.42	2,51	0.65	0.31	2,51	0.73	0.03	2,51	0.97
Field 4	Block	0.36	3,55	0.78	1.19	3,55	0.32	0.6	3,55	0.61	0.28	3,55	0.83	0.3	3,55	0.82
	SD	7.78	3,55	**0.0002**	2.81	3,55	**0.04**	4.37	3,55	**0.007**	0.94	3,55	0.42	5.09	3,55	**0.003**

[a] Only locations (fields 3 and 4) from the 2010 field season were used in the residue study; residue data from fields 1 and 2 in 2009 were not collected for this study.

density (number of live *A. vulgare* per m^2) was the only response variable that was significantly affected by sample date in both fields ($Ps \leq 0.001$; Table 2), where *A. vulgare* numbers were 2–threefold higher for early sample dates compared with later sample dates for fields 3 and 4 (Fig. 6). The number of dead *A. vulgare* varied by sample date in field 4 only ($P = 0.04$; Table 2), where numbers were higher on 18 June (5 ± 1 *A. vulgare* per m^2) compared with 21, 22, and 23 June sample dates (ranging from 1 to 4 *A. vulgare* per m^2; data not shown). Soybean density (number of emerged plants per m^2) also changed with sample date for field 4 only ($P = 0.007$; Table 2), where soybean emergence was higher on 22 June (36 ± 2 plants per m^2) compared with 18, 21, and 23 June, where emerged seedlings ranged from 25 to 31 plants per m^2 (data not shown). Number of damaged plants was not affected by sample date in either field ($Ps > 0.05$). Conversely, residue weights varied significantly by sample date in field 4 ($P = 0.003$; Table 2), but not field 3 ($P = 0.97$). In field 4, residue weights were significantly greater ($F = 59.3$; df = 3,55; $P < 0.0001$) on the 18, 21, and 23 June sample dates ($1,565 \pm 104$, $1,307 \pm 101$, and $1,432 \pm 101$ g/m^2, respectively) compared with the 22 June sample date (877 ± 62 g/m^2).

Covariance analysis was used to determine if there were significant differences in slope or intercept estimates in either field across sample dates to relate the number of emerged and damaged plants with numbers of live *A. vulgare* and residue weights. In either field, differences were not detected between sample dates ($Ps > 0.05$; data not shown); however, regressions across sample dates revealed that emerged plants in field 4 had a significant relationship with residue weight ($F = 10.8$; df = 2,69; $P < 0.0001$; $R^2 = 0.23$), where decreases in residue weight positively impacted plant emergence (Fig. 7). A similar relationship was not found in field 3, nor were relationships detected for numbers of damaged plants with numbers of live *A. vulgare* and residue weights.

Discussion

In parts of central Kansas, soybean producers must contend with managing perennial isopod populations in production soybean fields, although management information and effective, economical control tactics are limited for controlling *A. vulgare* in soybean. Under heavy densities, it is not uncommon for growers to replant soybean fields multiple times within a growing season to get a harvestable stand in the fall. As a result, some soybean growers have resorted to the use of controlled or prescribed burns in conservation systems to mitigate stand losses caused by this opportunistic species. In our studies, removing residue by burning did not result in soybean stands with higher emergence rates or even less damage from isopod feeding. For soybeans under conservation management, the impact of removing residue by burning to protect stands against *A. vulgare* does not likely outweigh the benefits (soil stability, improved structure, or water retention) producers receive from the presence of crop residues (Gebhardt et al. 1985, NeSmith et al. 1986).

In our study, controlled burning of residue did impact *A. vulgare* populations but, not surprisingly, also
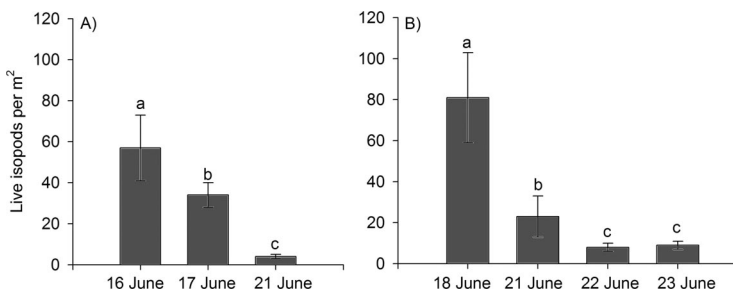

Fig. 6. Results from residue study measuring changes in mean number of live isopods for field 3 (A) and field 4 (B) in 2010 ($n = 4$) across sample dates. Mean comparisons are denoted with lowercase letters; bars having the same letter are not significantly different from each other ($P < 0.05$). Error bars represent mean standard error.
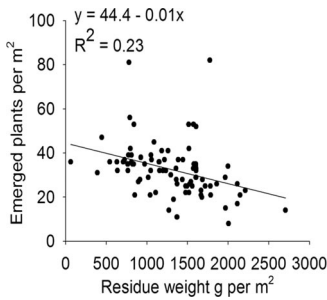
Fig. 7. Linear relationship between the number of emerged plants and previous crop residue weight (g) sampled in m^2 quadrats from field 4 during 2010 across sample dates ($n = 72$ quadrats).

reduced previous corn residue levels. A physical control method like prescribed burning has been used to manage other agricultural pest species (Vincent et al. 2003), where excessive heat can cause direct mortality to target pest populations. In the soybean system, removal of crop residue also can be indirectly affecting isopod populations, as presence of crop residues is positively associated with the protection of arthropod pests by providing shelter and alternative food sources (Kogan and Turnipseed 1987, Wallner 1987, Bugg 1991, Koul et al. 2004). In our study, we only assessed the short-term or within-season affects of burning on *A. vulgare* populations. However, long-term effects of prescribed burning on isopod populations are not known, and environmental as well as economical impacts on soybean production need further investigation for growers seeking sustainable management options to mitigate losses caused by damaging isopod populations.

From the residue study, it appeared that residue levels had minimal impact on *A. vulgare* numbers and feeding damage in the fields that were sampled. This finding does not support our original hypothesis that higher levels of residue should correlate with higher numbers of *A. vulgare* and increased levels of damage to seedlings, reduced seeding emergence, or both. However, for field 4, there was a negative relationship between emerged soybean seedlings and residue weights per m^2 (Fig. 7). Because this relationship is independent of isopod numbers, it suggests that high residue levels could have a negative impact on seedling emergence. Soybean seedling emergence is optimal in soil types that are well-drained (Berglund and Helms 2003). It is known that wet field conditions tend to result in poor stands that take longer to emerge, typically because of the increase in damping-off diseases (Berglund and Helms 2003). Moreover, emerging seedlings in this study may have been damaged by other herbivores in addition to *A. vulgare*, which also may have varied by field, year sampled, or both. Although there are other early-season chewing insects in soybean such as various species of Lepidopteran larvae (Whitworth et al. 2008), none were observed in this study (B.P.M., unpublished data).

Based on results from the residue study, it appears that residue levels alone did not adequately predict *A.*

vulgare density, seedling emergence, or feeding damage in sampled fields. This finding also does not support our original hypothesis, where higher residue levels should correlate with greater isopod numbers and increased levels of damage to seedlings, reduced seeding emergence, or both. In general, residue levels explained only 23% of the variability in numbers of emerged plants in field 4, which suggests there are other factors influencing the degree to which isopod populations become damaging. For example, variable field conditions such as soil moisture may have influenced isopod feeding activities. Specifically, the impact of moisture on corn residue may affect the chemical composition that determines its value as a food source, shelter site, or both for *A. vulgare* (Zimmer 2004). Corn residues are known to release large amounts of ferulic and *p*-coumaric acids (Schreiner and Reed 1908). Although the effects of consuming these acids are unknown for *A. vulgare*, they are known to slow growth and development and prolong feeding for other arthropod species (Dixon and Paiva 1995, Felton 1996). Consequently, these acids are quickly neutralized by hydrolysis in presence of moisture and thus may have impacted corn residues as a food source for isopods in this study. Although the quality of corn residue as a food source in these experiments was not assessed, moisture and resulting residue quality may have impacted feeding shifts from residue to soybean seedlings differently based on variable moisture levels from field to field. In May and June of 2009, there were 5 d of precipitation totaling 18.9 cm; whereas in May and June of 2010, there were 4 d of precipitation totaling only 7.6 cm (Knapp 2012). As such, future work should focus on food quality and residue moisture levels that may be influencing isopod feeding behavior and changes in population numbers occurring in soybean production fields under conservation management. Moreover, it is known that increases in moisture increase isopod reproduction (Zimmer 2004). Therefore, it also would be beneficial to include comparisons of isopod densities between irrigated and dryland soybean fields.

Inconsistency in numbers of emerged and damaged plants between years and fields may have been impacted by *A. vulgare* feeding behaviors or preferences that were not measured in this study, such as shifts in resource usage (i.e., previous crop residue to emerging soybean seedlings). *Armadillidium vulgare* is considered a generalist decomposer, feeding mainly on decaying organic material but occasionally consuming living green tissues as well (Paris and Pitelka 1962, Warburg 1993, Wolters and Ekschmitt 1997, Lavy et al. 2001). In addition, *A. vulgare* survivorship and overall development is increased when individuals consume dead dicotyledonous leaves rather than monocotyledonous material such as corn residue (Crawley 1983, Rushton and Hassall 1983). Attractiveness of corn residue as a food source, compared with soybean seedlings, for *A. vulgare* is unknown.

An unexpected result from the second study (residue study) was the variation in isopod densities between sample dates. Given the proximity in dates, we

did not expect numbers to change as much as we had observed. Recall, resident isopod densities fluctuated 0–10 fold within a span of 5 or 6 d in fields 3 and 4 (Fig. 6). Residue levels remained unaffected by sample date (Table 2), yet isopod densities changed significantly through time. It is possible that considerable fluctuations in vertical distribution of *A. vulagre* within the soil (Paris and Pitelka 1962) impacted our ability to detect and record population numbers between sample dates. Isopods are known to move on a diurnal basis to greater soil depths to minimize desiccation risk when soil surface temperatures and moisture levels are not optimal (Frouz et al. 2004). Moreover, *A. vulgare* is most active at night, which likely impacted our ability to record their numbers (Rapp 2001).

From these studies, controlled burning does not appear to be an ideal or sustainable management option for maintaining soybean stands at risk of isopod feeding damage. In addition, previous crop residue levels did not appear to increase isopod numbers or seedling susceptibility to feeding. It is unclear if residue levels can negatively impact isopod feeding, or whether composition of residue (i.e., moisture, crop type) impacts feeding behaviors by *A. vulgare* in soybean agroecosystems. Future studies should aim to quantify factors determining *A. vulgare* feeding preference for soybean tissues in presence of varying types of crop residues and production practices.

Acknowledgments

References Cited

Al-Dabbagh, K. Y., and W. Block. 1981. Population ecology of a terrestrial isopod in two Breckland grass heaths. J. Anim. Ecol. 50: 61–77.

Berglund, D. R., and T. C. Helms. 2003. Soybean production. North Dakota State University Extension Service. Publication #A-250. North Dakota State University, Fargo, ND.

Biederbeck, V. O., C. A. Campbell, K. E. Bowren, M. Schnitzer, and R. N. McIver. 1980. Effect of burning cereal straw on soil properties and grain yields in Saskatchewan. Soil Sci. Soc. Am. J. 44: 103–111.

Brody, M. S., and L. R. Lawlor. 1984. Adaptive variation in offspring size in the terrestrial isopod, *Armadillidium vulgare.* Oecologia 61: 55–59.

Bruce, J. A., and J. J. Kells. 1990. Horseweed (*Conyza canadensis*) control in no-tillage soybeans (*Glycine max*) with preplant and preemergence herbicides. Weed Technol. 4: 642–647.

Buchholz, D. D., E. Palm, G. Thomas, and D. L. Pfost. 1993. No-till planting systems. University of Missouri Extension. Publication #G4080. University of Missouri, Columbia, MO.

Bugg, R. L. 1991. Cover crops and control of arthropod pests of agriculture. (http://www.swcs.org/documents/filelibrary/CCCW9.pdf).

Byers, R. A., and D. L. Bierlein. 1984. Continuous alfalfa: invertebrate pests during establishment. J. Econ. Entomol. 77: 1500–1503.

Crawley, M. J. 1983. Herbivory. The dynamics of plant-animal interactions. Blackwell Scientific Publications, Oxford, United Kingdom.

Cruse, R., J. Neppel, J. Kost, and K. T. Eleki. 2003. Encyclopedia of water science, erosion control, tillage/residue methods. Nature 1076: 205.

Davis, R. C. 1984. Effects of weather and habitat structure on the population dynamics of isopods in a dune grassland. Oikos 42: 387–395.

Dixon, R. A., and N. L. Paiva. 1995. Stress-induced phenylpropanoid metabolism. Plant Cell 7: 1085–1097.

Doran, J. W., W. W. Wilhelm, and J. F. Power. 1984. Crop residue removal and soil productivity with no-till corn, sorghum, and soybean. Soil Sci. Soc. Am. J. 48: 640–645.

Faberi, A. J., N. Alicia, N. L. Lopez, C. Manetti, and P. L. Menetti. 2011. Importance of diet in the growth, survivorship and reproduction of the no-tillage pest *Armadillidium vulgare* (Crustacea: Isopoda). Rev. Chilena de Historia Natural 84: 407–417.

Fasching, R. A. 2001. Burning-effects on soil quality. Agronomy Technical Note #150.16. Natural Resources Conservation Service, Bozeman, MT.

Felton, G. W. 1996. Nutritive quality of plant protein: sources of variation and insect herbivore responses. Arch. Int. Physiol. Biochem. 32: 107–130.

Frouz, J., A. Ali, J. Frouzova, and R. J. Lobinske. 2004. Horizontal and vertical distribution of soil macroarthropods on spatio-temporal moisture gradient in subtropical central Florida. Environ. Entomol. 33: 1282–1295.

Gebhardt, M. R., T. C. Daniel, E. E. Schweizer, and R. R. Allmaras. 1985. Conservation tillage. Science 230: 625.

Hardison, J. R. 1976. Fire and flame for plant disease control. Annu. Rev. Plant Pathol. 14: 355–379.

Knapp, M. 2012. Kansas State Weather Data Library. (http://www.ksre.ksu.edu/wdl/).

Kogan, M., and S. G. Turnipseed. 1987. Ecology and management of soybean arthropods. Annu. Rev. Entomol. 32: 507–38.

Koul, O., G. S. Dhaliwal, and G. W. Cuperus. 2004. Integrated pest management: potential, constraints and challenges, pp. 21–22. *In* W. I. Bajwa and M. Kogan (eds.), Technology and engineering, cultural practices: springboard to IPM. CABI Publishing, Cambridge, MA.

Lavy, D., M. J. Van Rijn, H. R. Zoomer, and H. A. Verhoef. 2001. Dietary effects on growth, reproduction, body composition and stress resistance in the terrestrial isopods *Oniscus asellus* and *Porcellio scaber.* Physiol. Entomol. 26: 18–25.

Marriott, E. E., and M. M. Wander. 2006. Total and labile soil organic matter in organic and conventional farming systems. Soil Sci. Soc. Am. J. 70: 950–959.

Mastronardi, F. 2006. Control químico de isópodos y babosas en un cultivo de girasol bajo siembra directa. Grade Thesis, Facultad de Ciencias Agrarias, Universidad Nacional de Mar del Plata.

McCullough, D. G., R. A. Werner, and D. Neumann. 1998. Fire and insects in northern and boreal forest ecosystems of North America. Annu. Rev. Entomol. 43: 107–127.

Miller, W. 1979. Fire as insect management tool. Bulletin of the ESA 25: 137–140.

Moretti, M., M. K. Obrist, and K. Duelli. 2004. Arthropod biodiversity after forest fires: winners and losers in the winter fire regime of the Southern Alps. Ecography 27: 176–186.

Morisawa, J., C. Kim, T. Kashiwagi, S. Tebayashi, and M. Horiike. 2002. Repellents in the Japanese Cedar, *Cryptomeria japonica*, against the pill-bug, *Armadillidium vulgare*. Biosci. Biotechnol. Biochem. 66: 2424–2428.

NeSmith, D. S., W. L. Hargrove, D. E. Radcliffe, E. W. Tollner, and H. H. Arioglu. 1986. Tillage and residue management effects on properties of an ultisol and double-cropped soybean production. Agron. J. 79: 570–576.

Paoletti, M. G., A. Tsitsilasb, L. J. Thomsonb, S. Taitic, and P. A. Uminab. 2008. The flood bug, *Australiodillo bifrons* (Isopoda: Armadillidae): a potential pest of cereals in Australia? Appl. Soil Ecol. 39: 76–83.

Paris, O. H. 1963. The ecology of *Armadillidium vulgare* (Isopoda: Oniscoidea) in California grassland: food, enemies and weather. Ecol. Monogr. 33: 1–22.

Paris, O. H., and F. A. Pitelka. 1962. Population characteristics of the terrestrial isopod *Armadillidium vulgare* in California grassland. Ecology 43: 229–248.

Rapp, W. F. 2001. The terrestrial isopods of Nebraska (Crustacea: Isopoda). Trans. Nebr. Acad. Sci. 27: 9–11.

Refinetti, R. 1984. Behavioral temperature regulation in the pill bug, *Armadillidium vulgare* (Isopoda). Crustaceana 47: 29–43.

Rushton, S. P. 1981. The effects of food quality on the population dynamics of *Armadillidium vulgare* (Latreille). Ph.D. thesis, University of East Anglia, England.

Rushton, S. P., and M. Hassall. 1983. Food and feeding rates of the terrestrial isopod *Armadillidium vulgare* (Latreille). Oecologia 57: 415–419.

Rushton, S. P., and M. Hassall. 1987. Effects of food quality on isopod population dynamics. Funct. Ecol. 1: 359–367.

Saluso, A. 2004. Determinación del nivel de daño económico y plan de decisión secuencial para el manejo de *Armadillidium vulgare* (Latreille, 1804) (Crustacea: Isopoda) en soja. Master Thesis, Departamento Académico de Ciencias Aplicadas a la Producción al Ambiente y el Urbanismo, Universidad de La Rioja.

SAS Institute. 2012. SAS/STAT software release 9.3. SAS Institute, Cary, NC.

Saska, P. 2008. Granivory in terrestrial isopods. Ecol. Entomol. 33: 742–747.

Saxton, K., D. Chandler, and W. Schillinger. 2001. Wind erosion and air quality research in the northwest US, pp. 766–770. Proceedings of the Columbia Plateau: organization and progress. Purdue University and the U.S. Dep. Agric.-ARS National Soil Erosion Research Laboratory.

Schreiner, O. and H. S. Reed. 1908. The toxic action of certain organic plant constituents. Bot. Gaz. 45.

Siemann, E., J. Haarstad, and D. Tilman. 1997. Short-term and long-term effects of burning on oak savanna arthropods. Am. Midl. Nat. 137: 349–361.

Stinner, B. R., and G. J. House. 1990. Arthropods and other invertebrates in conservation-tillage agriculture. Annu. Rev. Entomol. 35: 299.

Teasdale, J. R. 2007. Strategies for soil conservation in no-tillage and organic farming systems. The Journal of Soil and Water Conservation (http://www.ars.usda.gov/sp2UserFiles/Place/12650400/JSWC200762-6-144.147.pdf).

Tebruegge, F., and R. A. Duering. 1999. Reducing tillage intensity: a review of results from a long-term study in Germany. Soil Till. Res. 53: 15–28.

Vincent, C., G. Hallman, B. Panneton, and F. Fleurat-Lessard. 2003. Management of agricultural insects with physical control methods. Ann. Rev. Entomol. 48: 261–281.

Wallner, W. E. 1987. Factors affecting insect population dynamics: differences between outbreak and non-outbreak species. Annu. Rev. Entomol. 32: 317–40.

Warburg, M. R. 1993. Evolutionary biology of land isopods. Springer Berlin Heidelberg, Germany.

Whitworth, R. J., P. Sloderbeck, and H. Davis. 2008. Pillbugs. Kansas State University, Extension Publication MF-2855, Manhattan, KS.

Wolters, V., and K. Ekschmitt. 1997. Gastropods, isopods, diplopos, chilopods: neglected groups of the decomposer food web, pp. 265–306. *In* G. Benckiser (ed.), Fauna in soil ecosystems. Recycling processes, nutrient fluxes, and agricultural production. Marcel Dekker Inc., New York.

Young, W. C., G. A. Gingrich, T. B. Silberstein, and B. M. Quebbeman. 1998. Post-harvest residue management of creeping red and chewings fescue feed crops. Agron. J. 90: 69–73.

Zimmer, M. 2004. The role of woodlice (Isopoda: Oniscidea) in mediating the decomposition of leaf litter, pp. 285–311. *In* S. H. Shakir-Hanna and W.Z.A. Mikhaïl (eds.), Soil zoology for sustainable development in the 21st century. Eigenverlag, Cairo, Egypt.