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Research

Pest Management

Arthropod Granivory of Lime-Coated Cover Crop Seeds

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Abstract

Diversifying cropland plant communities is prerequisite to restoring ecosystem functions in agricultural habitats. Cover crops are one such way to improve biodiversity, and broadcasting calcium carbonate-coated (lime) seeds can be a viable method for plant establishment. In addition to improving seed-to-soil contact, calcium carbonate may also reduce arthropod granivory. Here we examine the effect of this seed-coating technology on arthropod granivory for seven cover crop species under field conditions. Carabidae, Gryllidae, and Staphylinidae were the three most frequently collected granivorous taxa in pitfall samples, and *Pterostichus permundus* and *Gryllus pennsylvanicus* represented 60.8% of all individual granivores. Cover crop seed damaged was variable among plant species. Among all plant species, the presence of a seed coating significantly reduced granivory by nearly 40% in the 7-d field exposure. Individually, hairy vetch and sorghum × sudan seeds were especially protected by calcium carbonate. No positive correlations were observed between invertebrate groups and the number of seeds consumed. Alternative methods for assessing the functionality of granivorous arthropod communities should be pursued, as activity-density measured from pitfall traps failed to reveal important cover crop seed consumers. Protection of cover crop seeds from granivory through a calcium carbonate coating may allow producers to adjust seeding rates and save on costs, increasing the rate of adoption for this conservation practice.

Key words: cover crop, seed coating, granivory, insect, seed establishment

A growing number of agricultural producers are planting noncrop vegetation, or cover crops, at some point during their crop rotation (CTIC 2017). Cover crops are typically grown during a period outside of annual crop growth (i.e., pre-planting, post-harvest, or over winter), but some producers establish cover crops while the cash crop is actively growing (Curran et al. 2018). Regardless of when cover crops are implemented, they are used by farmers to improve farmland performance by restoring or enhancing agroecosystem functions, which are lacking or have been lost after a long period of monocultures, simple rotations, and frequent disturbances such as tillage and agrichemical use (Blanco-Canqui et al. 2015). Cover crops can have a significant positive effect on the physical properties of soil by reducing compaction (Chen and Weil 2010), bulk density (Reeves 2017), and erosion (De Baets et al. 2011, Alliaume et al. 2014), while increasing a soil's water holding capacity (Basche et al. 2016), organic matter content (Plaza-Bonilla et al. 2016), and water infiltration rates (Kahimba et al. 2008). Cover crops can also influence a soil's chemical properties by altering pH (Fernandez et al. 2016), detoxifying pesticides (Edwards 1975), ameliorating salinity and sodicity issues (Gabriel et al. 2012), and scavenging for or making critical plant nutrients available (Grove and Pena-Yewtukhiw 2017). Concurrently, cover crops can be an important resource for animal conservation on agricultural land. Cover crop-derived refuge and nutrition allows animals including large vertebrate grazers, birds, and members of arthropod guilds to persist in cropland (Landis et al. 2000).

Pest management is one primary reason that producers use cover crops in their rotation (CTIC 2017). For example, cover crops can suppress weeds by utilizing excess nutrients (Blanco-Canqui et al. 2015), through allelopathic action (Kunz et al. 2016), and by physically restricting weed germination and growth (Teasdale and Mohler 1993). Additionally, providing nonprey nutrition and favorable abiotic conditions to arthropod biological control agents can improve the management of production-limiting herbivores (Gurr et al. 2017) and weeds (Blubaugh et al. 2016, Davis and Liebman 2003) without the use of synthetic pesticides. Blubaugh et al. (2016) observed this phenomenon in cover crop plots bearing clover (*Trifolium pratense*), where predation of weed seeds (*Chenopodium album*) by ground beetles (Carabidae) was significantly increased in comparison to plots lacking vegetative cover.

The perceived benefits of cover crops on farms have resulted in increasing adoption rates. Between 2012 and 2017, respondents of the annual Conservation Technology Information Center cover crop survey who were cover cropping on their farms increased the average number of acres where this tool was implemented by nearly 85% (CTIC 2017). Since the inauguration of the survey, in 2012, cover cropped land has invariably increased annually. Another metric that demonstrates this expansion is the increased seed sales. Between the years 2009 and 2018, the amount of seed sold by Greencover Seed has increased from enough to cover 400 ha, to approximately 344,000 ha (personal communication with Keith Berns, owner of Green Cover Seed, Bladen NE).

Broadcasting cover crop seeds onto the soil's surface has both benefits and challenges. Deploying seeds like this can be done rather quickly and with relatively inexpensive equipment. Broadcasting seed also opens opportunities for cover crop establishment during the growth of another crop without the risk of physically damaging growing plants. Though a simpler method of seeding, broadcasting can result in poorer germination from a lack of seed-to-soil contact (Evert et al. 2009), desiccation of small, shallowly rooted seedlings (Heckman et al. 2002), and loss of viable seed due to animal granivory (Decker et al. 1990, White et al. 2007). Advancements in seed-coating technology are continually being developed to ameliorate the negative issues associated with surface-scattering seeds.

On 3 July 1866, U.S. patent number 56,104 was issued to W. Blessing for his invention of the technique for coating cotton seeds with wheat flour paste to improve 'plantability' (Blessing 1866, Porter and Scott 2016). Since then, seed-coating technologies have been developed and used on a regular basis with various types of coating materials, and varying degrees of success (Scott 1975, Porter and Scott 2016). In his book, 'The One Straw Revolution', author and farmer Masanobu Fukuoka (1978) describes coating rice seeds in a homemade blend of clay and water to improve establishment of his hand-broadcasted seeds. In recent years, the use of lime (calcium carbonate, $CaCO_3$) for coating cover crop seeds has been explored to improve seed ballistics (to fly further and penetrate through a dense canopy of vegetation or residue when broadcasted) and to provide a pseudo seed-to-soil contact that aids water imbibition.

An additional benefit to lime coating, overlooked thus far in the literature, may be a reduction in cover crop seed loss due to granivory. Granivorous arthropods, birds, and small mammals can have a significant impact on surface-scattered seeds (Kelt et al. 2004, White et al. 2007), which comes as a benefit when weed seeds are those being consumed (Blubaugh et al. 2016, Kulkarni et al. 2017b), but possibly a detriment when desirable seeds are destroyed. Observations of damage to desirable surface-scattered seeds, not weeds, by arthropods are difficult to find, but examples exist for a few crops. For instance, under laboratory conditions, Lundgren and Rosentrater (2007) observed the destruction of seeds for several crop species, including alfalfa (*Medicago sativa*) and broccoli (*Brassica oleraceae*), by three commonly collected insect granivores in agricultural farmscapes, two Carabidae ground beetles (*Harpalus pensylvanicus* and *Anisodactylus sanctaecrucis*) and one species of cricket (*Gryllus pennsylvanicus*).

Coating seeds with substances to deter damage inflicted by animals has proven successful in certain applications. In a study of prairie restorations through reseeding native species, Pearson et al. (2018) examined the effect of coating seeds in powdered Bhut Jolokia peppers (*Capsicum chinese*) in hopes that capsaicin present in the coating would deter granivory by small mammals. In the laboratory, this seed coating resulted in significantly greater protection from deer mice (*Peromyscus maniculatus*), an important predator of native seeds.

The addition of a lime coating on cover crop seed holds promise for increasing the adoption of this conservation practice by producers because this benign compound improves water imbibition by surface-scattered seeds. We hypothesize a lime coating on cover crops seeds will provide the additional benefit of deterring arthropod granivory.

Materials and Methods

Study Sites

In 2016, field sites were approximately 10 km north of Bruce, SD (site coordinates: 44.405192, −96.886847). Crops grown during 2015 at the study site were cereal rye (*Secale cereale*), which was chopped for forage, followed by buckwheat (*Fagopyrum esculentum*), harvested for seed. In spring of 2016, corn (*Zea mays*) was no-till planted on 20 May into buckwheat residue at a population of 79,000 seeds/ha (Elk Mound Seed Company, Elk Mound, WI; variety: EMS 8100; maturity: 80 d) with 76-cm row spacing. Four plots measuring 32 × 32 m were established with a distance of 16 m between plots. Roundup (rate: 2338 ml/ha; active ingredient [a.i.]: glyphosate; Monsanto, St. Louis, MO) and Confidence (rate: 2,923 ml/ha; a.i.: acetochlor; WinField, Arden Hills, MN) were used as preplant herbicides in the field on 15 May, whereas Accent Q (rate: 66 ml/ha; a.i.: nicosulfuron; DuPont, Wilmington, DE) and Status (rate: 370 ml/ha; a.i.: sodium salt of diflufenzopyr and sodium salt of dicamba; BASF, Florham Park, NJ) were used as postemergent herbicides on 16 June. No fertilizer was applied to the study field during the 2016 growing season.

The same size and number of research plots were used during the 2018 season, but were located approximately 10 km east of Gary, SD (site coordinates: 44.916862, 96.397883). Soybeans (*Glycine max*) were grown during the 2017 season and harvested for grain. The field received tillage following soybean harvest and again in the spring prior to corn planting for seedbed preparation. Organic corn seed (Blue River Organic Seed, Ames, IA; variety: P1000684; maturity: 96 d) was planted on 26 May at a population of 79,000 seeds/ha with an interrow spacing of 76 cm. A pre-emergent herbicide application of SureStart II (rate: 2,923 ml/ha; a.i.: acetochlor, flumetsulam, and clopyralid; Dow AgroSciences, Indianapolis, IN) was conducted on 20 May. No postemergent herbicides were applied. Fertilizer was broadcasted into research area at a rate of 157 kg/ha nitrogen as urea, 56 kg/ha phosphorous as diammonium phosphate, and 56 kg/ha potassium as potash. Insecticides were not used during either study season.

Seed Cards

Cards bearing seeds coated in lime (1:1 seed to $CaCO_3$ ratio by weight; seed coating performed by Smith Seed Services, Halsey, OR) and cards with bare seeds were deployed in research plots to assess granivory. For every seed card, 30 seeds each of cereal rye (*Secale cereale*), flax (*Linum usitatissimum*), Japanese millet (*Echinochloa esculenta*), sorghum × sudan (*Sorghum × drummondii*), hairy vetch (*Vicia villosa*), lentil (*Lens culinaris*), and field pea (*Pisum sativum*) were affixed (in a 3 × 10 orientation) to plastic sheets (12 × 14 cm) cut from three-ring binder separators (Avery table of contents dividers; product: 11842; Avery, Brea, CA) using double-sided tape (Scotch double-sided tape; model number: 237; Scotch, St. Paul, MN). Dry silica sand was sprinkled over seed cards, so that arthropods could walk freely without becoming entrapped by tape. Five of each seed card type (coated and bare) were arranged in an 'X' pattern in each plot. For each seed card type, four cards were placed 5 m diagonally inward toward the center from four plot corners and one seed card centrally located. To prevent vertebrate granivory, wire mesh cages (square openings measuring 1.25 × 1.25 cm; Fig. 1) were placed over

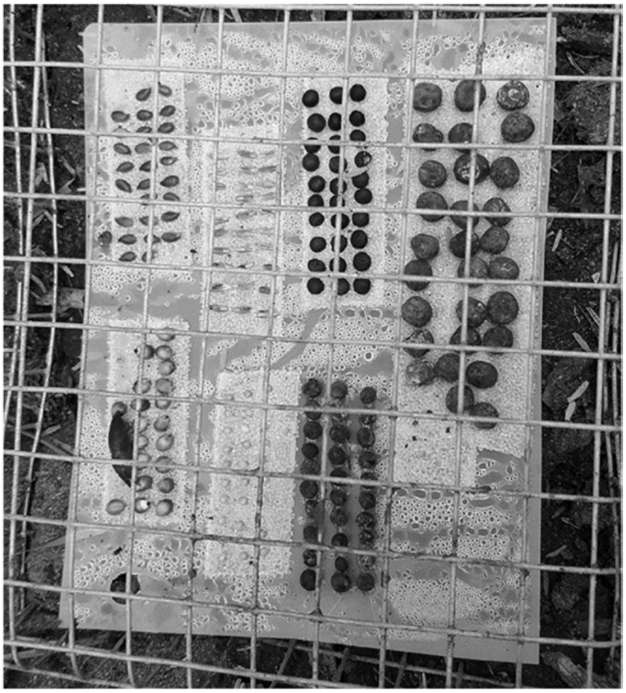

Fig. 1. Field-deployed seed card possessing uncoated cover crop seeds. A metal mesh cage (15-cm-long, 13-cm-wide, and 5-cm-deep square openings of 1.25 × 1.25 cm) protects seeds from granivory by birds and small mammals. There was 3 cm between cage top and seed card surface. In the lower-left quadrant of the seed card a slug can be observed feeding on sorghum × sudan (*Sorghum × drummondii*) seeds.

seed cards and held in place with a small marking flag through the cage. Cage dimensions were 15 cm long, 13 cm wide, and 5 cm deep. Metal cages were pressed into the soil until the distance between the cage top and seed card was approximately 3 cm. Seed cards remained in the field for 7 d beginning on 7 July and 26 June during 2016 and 2018, respectively. This period during the growing season typically presents corn at stages where farmers broadcast cover crop seeds (corn stage: V6). After collection from the field, each seed was microscopically inspected to determine whether arthropod granivory had taken place. A seed was considered to be eaten if there was obvious damage from invertebrate mouthparts.

Insect Sampling

In 2016, three sets of barrier-linked cup-in-cup pitfall traps were established in each study plot (Lundgren and Harwood 2012). Two were located in opposite corners and one located centrally. During the 2018 season, five pitfall traps were established in each plot in the same 'X' pattern as seed cards. Two plastic cups (473 ml, SOLO, Lake Forest, IL) stacked together were buried at a depth where their upper edges were flush with the soil's surface. A 15 × 90 cm piece of sheet metal standing erect and placed lengthwise was pressed into the soil approximately 2 cm and affixed using a stake so that one end of the metal sheet terminated adjacent to the buried cups. Two more stacked cups were buried until flush with the soil's surface at the alternate end of the erect metal slat. Wooden boards were placed over pitfall traps and leaned at approximately 45° against the metal slat to reduce rainfall from entering traps. To preserve trapped arthropods and prevent carnivory amongst captives, 50 ml of ethylene glycol antifreeze were poured into each collection cup. Pitfall traps remained activated during the same period as seed cards. Contents of collection cups were then transported to the laboratory where arthropods were placed in 70% ethanol for storage until identification and tabulation of known granivores.

Data Analysis

The mean ± SEM number of damaged seeds per seed card per plot was determined for each species in both coated and uncoated treatments. A two-way analysis of variance (ANOVA; α = 0.05) was conducted to examine within-treatment (plant species) and between-treatment (coated or bare seeds) differences in rates of seed damage per plot across both field seasons, and if interactive effects existed. Statistically different means were separated using Tukey's HSD. A factorial ANOVA with seed species and site years were factors, and the number of damaged seeds per plot as a dependent variable was used to determine whether seed damage varied between seed coatings and site years. Mean ± SEM granivorous arthropods per pitfall (excluding Collembola) were determined for each plot across both field seasons. Granivorous arthropods collected at a rate of ≥0.5 individuals per pitfall are included in the results section. A one-way ANOVA paired with Tukey's HSD all-pairwise comparison was used to determine differences among abundant granivorous taxa. One-way ANOVAs were used to examine variability in abundance of pitfall-collected arthropods between site years. Pearson's correlations (α = 0.05) were conducted to test relationships between common granivore groups and rates of seed consumption per seed card, per plot. Statistical analyses were conducted using Statistix 10 software (Analytical Software, Tallahassee, FL).

Results

Pitfall-Collected Arthropods

In total, 3,685 arthropods (excluding Collembola) were collected, with an average of 115.16 ± 13.68 individuals per trap. Three insect families possessing granivorous individuals were commonly collected from pitfalls within research plots (Table 1). Species belonging to Carabidae (ground beetles) were most abundant with an average of 27.16 ± 7.00 individuals per trap, followed by Gryllidae (crickets, 17.35 ± 6.00) and Staphylinidae (rove beetles, 11.79 ± 8.36).

Table 1. Mean ± SEM arthropod granivores collected per pitfall in plots possessing cover crop seed cards

Common taxa, grouped	Insect abundance
Total Carabidae	27.16 ± 7.00
Total Gryllidae	17.35 ± 6.00
Total Staphylinidae	11.79 ± 8.36
Common taxa, individuals	**Arthropod abundance**
Carabidae—*Bembidium* sp.	7.12 ± 2.89 AB
Carabidae—*Pterostichus permundus*	13.98 ± 6.18 A
Carabidae—*Stenolophus* sp.	1.77 ± 0.78 AB
Cucujidae—*Pediacus* sp.	1.25 ± 0.49 B
Gryllidae—*Allonemobius* sp.	5.14 ± 2.34 AB
Gryllidae—*Gryllus pensylvanicus*	12.16 ± 3.40 AB
Julida (millipede order)	0.96 ± 0.60 B
Porcellionidae—*Trachelipus rathkii*	0.61 ± 0.34 B

Common taxa were included if present at ≥0.5 individuals per pitfall (*n* = 32 slatted, double pitfall traps, total) in research plots (*n* = 8). Letters written after values represent the Tukey's HSD all-pairwise comparison groupings between individual taxa (α = 0.05).

Significant differences were observed among abundant granivore taxa ($F_{7,63}$ = 3.44, P < 0.01; Tukey's HSD post hoc groupings are noted in Table 1). Two granivorous species, *Pterostichus permundus* (Coleoptera: Carabidae) and *Gryllus pennsylvanicus* (Orthoptera: Gryllidae), were collected at 13.98 ± 6.18 and 12.16 ± 3.40 individuals per pitfall, respectively. Of commonly collected granivores (≥0.5 per pitfall), these two species represented 60.8% of the entire community abundance and likely have an important impact on granivory of surface-scattered seeds. The remaining frequently collected arthropods comprised two Carabidae (Coleoptera: *Bembidium* sp. [7.12 ± 2.89] and *Stenolophus* sp. [1.77 ± 0.78]), one Cucujidae (Coleoptera: *Pediacus* sp. [1.25 ± 0.49]), one Gryllidae (Orthoptera: *Allonemobius* sp. [5.14 ± 2.34]), one Julida (unidentified millipede specimen [0.96 ± 0.60]), and one Porcellionidae (Isopoda: *Trachelipus rathkii* [0.61 ± 0.34]; Table 1).

Average abundance of all granivorous invertebrate taxa collected per pitfall did not differ between site years ($F_{1,7}$ = 1.42, P = 0.27). However, the abundances of certain granivore groups differed. Gryllidae were more frequently collected in 2018 ($F_{1,7}$ = 8.60, P = 0.03), with collections of Carabidae also being marginally significantly higher during that year ($F_{1,7}$ = 5.42, P = 0.06).

Cover Crop Seed Granivory

Across all cover crop species, a lime coating on cover crop seeds reduced the frequency of damage inflicted by arthropods in comparison to bare seeds ($F_{1,111}$ = 6.27, P = 0.01). Plant species also had a significant overall effect on the rate of granivory, with some species being more frequently damaged than others ($F_{1,111}$ = 9.71, P < 0.01). Lime coating seeds reduced granivory for two of the species tested: hairy vetch ($F_{1,15}$ = 6.81, P = 0.02) and sorghum × sudan ($F_{1,15}$ = 7.54, P = 0.02; Fig. 2, Supp Table 1 [online only]). Cereal rye was the sole plant species whose mean seed damage tended to be higher for coated seeds in comparison to bare seeds (3.83 ± 0.92 and 2.88 ± 0.68 per seed card, respectively), but the difference was not significant ($F_{1,15}$ = 0.70, P = 0.42).

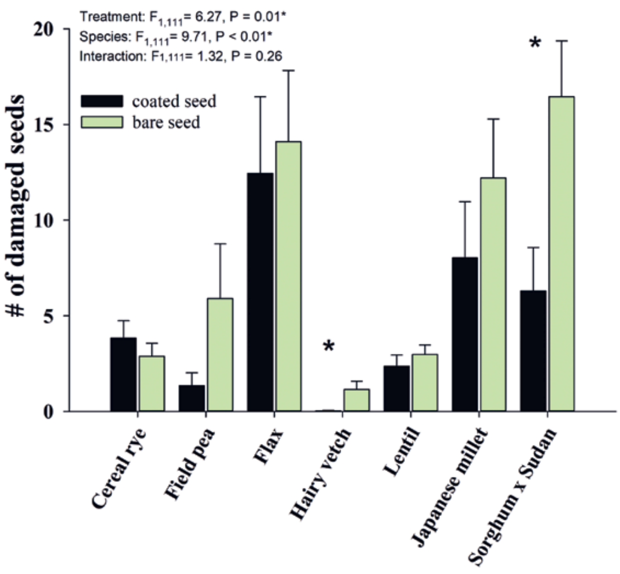

Fig. 2. Cover crop seeds per species (mean ± SEM) damaged by arthropods after seeds were exposed to field conditions for 7 d. Bars represent across-plot (n = 8) average coated and bare seeds damaged by invertebrates (five coated and five bare seed cards per plot, each possessing 30 seeds of each species). Asterisks demarcate significant differences (α = 0.05) between coated and bare seed treatments for a given plant species.

When comparing the consumption of coated and uncoated seeds separately, damage to cover crop seeds differed among plant species ($F_{6,111}$ = 9.71, P < 0.01), with no interaction effect observed between seed treatment and plant species ($F_{6,111}$ = 1.32, P = 0.26; Supp Table 1 [online only]). Among all plant species and treatments, the number of seeds damaged per card varied between site years ($F_{6,111}$ = 35.61, P < 0.01), with average granivory rates much greater in 2016 (9.68 ± 1.28) than 2018 (3.18 ± 0.52).

No positive correlations were found between abundant arthropod groups and rates of seed damage. However, there were four occurrences where arthropod abundance was negatively correlated with the number of damaged seeds per seed card. These correlations were between lime-coated sorghum × sudan and Gryllidae (r = −0.78, P = 0.02), bare field pea and Carabidae (r = −0.73, P = 0.04), bare hairy vetch and Carabidae (r = −0.80, P = 0.02), and bare hairy vetch and Gryllidae (r = −0.82, P = 0.01). These negative correlations are likely a result of larger Carabidae and Gryllidae captures and overall decreased seed consumption rates in 2016. When these correlations were assessed via per individual field season the only pairing which remained negatively correlated was between bare hairy vetch and Gryllidae during 2016 (r = −0.97, P = 0.03).

Discussion

Many researchers have examined the effects of arthropod granivores on damage and removal of undesirable seeds within agricultural situations (Lundgren 2005, Westerman et al. 2008, Davis et al. 2013, Kulkarni et al. 2017b). However, few studies have described the effect of otherwise beneficial insects on intentionally surface-scattered seeds such as cover crops. As they have for more than one 150 y (Blessing 1866), novel seed-coating technologies will probably continue to play a role in improving plant establishment, in part by protecting cover crop seeds from predation. Conservation practices within agriculture boost invertebrate populations capable of granivory (LaCanne 2017), and thus methods of seed protection conducive for habitats hosting beneficial granivores are worth consideration, as these organisms have the potential to affect plant establishment (Honek et al. 2009). As was observed in this study, different cover crop seeds are damaged variably depending on species and, in certain cases, a lime seed coating can reduce granivory by common cornfield invertebrates.

Numerous omnivore arthropods consume seeds as an important source of nutrition (Lundgren 2009, Lundgren and Lehman 2010, Saska et al. 2014). For instance, ground beetles (Carabidae), crickets (Gryllidae), and rove beetles (Staphylinidae), three of the most abundant arthropods collected in this study (Table 1), are well-known seed removers and are commonly collected in cornfields (Saska 2004, Lundgren and Fergen 2014, LaCanne 2017). In one study, 22% of *Pterostichus permundus*, the ground beetle most frequently captured in pitfall traps here, had consumed dandelion seeds (*Taraxacum officinale*) in an agricultural shelterbelt (Lundgren et al. 2013). In the same study, Lundgren et al. observed that >37% of *Gryllus pennsylvanicus* and >3% of all Staphylinidae (both abundant in the present study; Table 1) had also consumed marked seeds. It is likely that these omnivorous insect populations, recruited by farmers for the ecosystem functions of pest biological control and weed predation, may also have the possible confounding effect of restricting the establishment of intentionally broadcasted cover crops. Though this may imply that these invertebrates are potential pests to cover crop-producing farmers, an attempt to eliminate these organisms would probably result in a loss of important ecosystem functions such as weed seed granivory (White et al. 2007, Kulkarni et al. 2017a), predation of crop pests (Douglas et al. 2015, Lundgren et al. 2015), and bioturbation of soil (Garcia and Niell 1991), to name a few.

As described here (Fig. 2, Supp Table 1 [online only]), seed species were differentially damaged. Coated cover crop seed consumption ranged from as high as 12.45 ± 4.00 per seed card for flax, to a low of 0.03 ± 0.03 per card for hairy vetch, with a comparable range for bare seeds (14.10 ± 3.72 [flax], 1.15 ± 0.43 [hairy vetch]). Average seed consumption rates for other tested cover crop species fell within this range at varying levels (Fig. 2). This same phenomenon has been observed when granivorous arthropods are given a choice between multiple seed types (Honek et al. 2007). For example, in laboratory microcosms, White et al. (2007) measured velvetleaf (*Abutilon theophrasti*), redroot pigweed (*Amaranthus retroflexus*), and giant foxtail (*Setaria faberi*) seed consumption by a variety of granivorous invertebrates. Two Carabidae species (*Anisodactylus sanctaecrucis* and *H. pensylvanicus*), and the cricket, *G. pennsylvanicus*, preferred consuming pigweed seeds, then giant foxtail and velvetleaf, in decreasing order. Explanations for variability in seed consumption rates may be due to differences between plant species in terms of seed nutritive value (Lundgren 2009), seed size (Honek et al. 2007, Brust and House 2009), or physical (Rogers and Kreitner 1983), or phytochemical deterrents (Hudaib et al. 2017). Such factors might explain why there were significant differences between species within coated seed and bare seed treatments (Supp Table 1 [online only]).

There were few correlations among granivore abundances and seed removal rates, which may have been an artifact of our methodological approach. Crickets (Gryllidae) and ground beetles (Carabidae) are proven granivores (Lundgren et al. 2013), so it was unexpected that seed consumption decreased as their abundance increased in the cornfields. This result appears to be an artifact of year-specific patterns in the data, rather than some deeper biological pattern. Other work suggests that pitfall sampling may not always be well correlated with seed removal rates (Kulkarni et al. 2017b). This result supports the idea that multiple sampling methods would be appropriate. A combination of variability in site years and pitfalls being a questionable method for granivore collection makes it difficult to draw conclusions on the ties between arthropod activity-density and cover crop seed damage in this study. Future attempts to correlate the ecosystem function of seed damage through invertebrate granivory in the field could rely on alternate methods such as molecular marking (Lundgren et al. 2013, Hagler and Machtley 2016) or video recording (Harrison and Gallandt 2012, Brown et al. 2016) to improve this area of research.

Across all cover crop species, the addition of a lime seed coating reduced arthropod granivory. Though the reduction in granivory was statistically significant for only two of the seven species examined, hairy vetch and sorghum × sudan, nearly all other cover crops (except for cereal rye), had nonsignificant reductions in seed removal when a lime coating was present (Fig. 2). Though the loss in established plant density as a result of granivory has not been observed under field conditions for cover crops, other work with weed communities may clarify the potential impact granivores have on desired plants in agricultural fields (White et al. 2007). For example, Honek et al. (2009) measured dandelion emergence under field conditions in arenas, which were either open to arthropods or totally protected from predation. Allowing access to dandelion seeds by arthropods resulted in a significant reduction in seedling emergence of up to 40%. Proven plant density reductions due to invertebrate granivory, combined with in-field observations of surface-available cover crop seed damage here, suggests that arthropod communities may be an important factor in contributing to reduced broadcasted cover crop seed germination. Protecting seeds and improving germination by coating them in calcium carbonate have potential to allow farmers to reduce their seeding rates to achieve adequate plant stands and save money on seed costs. However, further field research addressing the effect of invertebrates on broadcasted cover crop stand establishment is needed to give producers accurate guidance for adjusting seeding rates depending on if they are or are not using seed-coating technology.

Supplementary Data

Supplementary data are available at *Environmental Entomology* online.

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References Cited

Alliaume, F., W. A. H. Rossing, P. Tittonell, G. Jorge, and S. Dogliotti. 2014. Reduced tillage and cover crops improve water capture and reduce erosion of fine textured soils in raised bed tomato systems. Agric. Ecosyst. Environ. 183: 127–137.

Basche, A. D., T. C. Kaspar, S. V. Archontoulis, D. B. Jaynes, T. J. Sauer, T. B. Parkin, and F. E. Miguez. 2016. Soil water improvements with the long-term use of a winter rye cover crop. Agric. Water Manag. 172: 40–50.

Blanco-Canqui, H., T. M. Shaver, J. L. Lindquist, C. A. Shapiro, R. W. Elmore, C. A. Francis, and G. W. Hergert. 2015. Cover crops and ecosystem services: insights from studies in temperate soils. Agron. J. 107: 2449–2474.

Blessing, W. 1866. Improved method of preparing cotton seed for planting. US Patent 56,140.

Blubaugh, C. K., J. R. Hagler, S. A. Machtley, and I. Kaplan. 2016. Cover crops increase foraging activity of omnivorous predators in seed patches and facilitate weed biological control. Agric. Ecosyst. Environ. 231: 264–270.

Brown, A. J., D. H. Deutschman, J. Braswell, and D. McLaughlin. 2016. Remote cameras reveal experimental artifact in a study of seed predation in a semi-arid shrubland. PLoS One 11: e0165024.

Brust, G. E., and G. J. House. 2009. Weed seed destruction by arthropods and rodents in low-input soybean agroecosystems. Am. J. Alter. Agric. 3: 19–25.

Chen, G., and R. R. Weil. 2010. Penetration of cover crop roots through compacted soils. Plant Soil 331: 31–43.

CTIC. 2017. Report of the 2016–17 National Cover Crop Survey. Joint publication of the Conservation Technology Information Center, the North Central Region Sustainable Agriculture Research and Education Program, and the American Seed Trade Association, West Lafayette, IN.

Curran, W. S., R. J. Hoover, G. W. Roth, J. M. Wallace, M. A. Dempsey, S. B. Mirsky, V. J. Ackroyd, M. R. Ryan, and C. J. Pelzer. 2018. Evaluation of cover crops drill-interseeded into corn across the Mid-Atlantic. Crops Soils 51: 18–60.

Davis, A. S., and M. Liebman. 2003. Cropping system effects on giant foxtail (*Setaria faberi*) demography: I. Green manure and tillage timing. Weed Sci. 51: 919–929.

Davis, A. S., E. C. Taylor, E. R. Haramoto, and K. A. Renner. 2013. Annual postdispersal weed seed predation in contrasting field environments. Weed Sci. 61: 296–302.

De Baets, S., J. Poesen, J. Meersmans, and L. Serlet. 2011. Cover crops and their erosion-reducing effects during concentrated flow erosion. CATENA 85: 237–244.

Decker, D. G., M. L. Avery, and M. Way. 1990. Reducing blackbird damage to newly planted rice with a nontoxic clay-based seed coating. *In* Proceedings of the Fourteenth Vertebrate Pest Conference 1990.

Douglas, M. R., J. R. Rohr, and J. F. Tooker. 2015. EDITOR'S CHOICE: Neonicotinoid insecticide travels through a soil food chain, disrupting biological control of non-target pests and decreasing soya bean yield. J. Appl. Ecol. 52: 250–260.

Edwards, C. A. 1975. Factors that affect the persistence of pesticides in plants and soils. Pesticide Chem. 3: 39–56.

Evert, S., S. Staggenborg, and B. L. S. Olson. 2009. Soil temperature and planting depth effects on Tef emergence. J. Agron. Crop Sci. 195: 232–236.

Fernandez, A. L., C. C. Sheaffer, D. L. Wyse, C. Staley, T. J. Gould, and M. J. Sadowsky. 2016. Associations between soil bacterial community structure and nutrient cycling functions in long-term organic farm soils following cover crop and organic fertilizer amendment. Sci. Total Environ. 566–567: 949–959.

Fukuoka, M. 1978. The one-straw revolution: an introduction to natural farming. Rodale Press, Emmaus, PA.

Gabriel, J. L., P. Almendros, C. Hontoria, and M. Quemada. 2012. The role of cover crops in irrigated systems: soil salinity and salt leaching. Agric. Ecosyst. Environ. 158: 200–207.

Garcia, C. M., and F. X. Niell. 1991. Burrowing beetles of the genus *Bledius* (Staphylinidae) as agents of bioturbation in the emergent areas and shores of an athalassic inland lake (Fuente de Piedra, southern of Spain). Hydrobiologia 215: 163–173.

Grove, J. H., and E. M. Pena-Yewtukhiw. 2017. Guiding cover crop establishment to scavenge residual soil nitrate nitrogen using site-specific approaches. Adv. Anim. Biosci. 8: 293–298.

Gurr, G. M., S. D. Wratten, D. A. Landis, and M. You. 2017. Habitat management to suppress pest populations: progress and prospects. Annu. Rev. Entomol. 62: 91–109.

Hagler, J. R., and S. A. Machtley. 2016. Administering and detecting protein marks on arthropods for dispersal research. J. Vis. Exp. 107: e53693–e53693.

Harrison, S., and E. R. Gallandt. 2012. Behavioural studies of *Harpalus rufipes* De Geer: an important weed seed predator in northeastern US agroecosystems. Int. J. Ecol. 2012. Article ID: 846546.

Heckman, N. L., G. L. Horst, and R. E. Gaussoin. 2002. Planting depth effect on emergence and morphology of buffalograss seedlings. Hortscience 37: 506–507.

Honek, A., Z. Martinkova, P. Saska, and S. Pekar. 2007. Size and taxonomic constraints determine the seed preferences of Carabidae (Coleoptera). Basic Appl. Ecol. 8: 343–353.

Honek, A., Z. Martinkova, P. Saska, and S. Koprdova. 2009. Role of post-dispersal seed and seedling predation in establishment of dandelion (*Taraxacum* agg.) plants. Agric. Ecosyst. Environ. 134: 126–135.

Hudaib, T., W. Hayes, S. Brown, and P. E. Eady. 2017. Seed coat phytochemistry of both resistant and susceptible seeds affords some protection against the granivorous beetle *Callosobruchus maculatus*. J. Stored Prod. Res. 74: 27–32.

Kahimba, F., R. S. Ranjan, J. Froese, M. Entz, and R. Nason. 2008. Cover crop effects on infiltration, soil temperature, and soil moisture distribution in the Canadian Prairies. Appl. Eng. Agric. 24: 321–333.

Kelt, D. A., P. L. Meserve, and J. R. Gutiérrez. 2004. Seed removal by small mammals, birds and ants in semi-arid Chile, and comparison with other systems. J. Biogeogr. 31: 931–942.

Kulkarni, S. S., L. M. Dosdall, J. R. Spence, and C. J. Willenborg. 2017a. Brassicaceous weed seed predation by ground beetles (Coleoptera: Carabidae). Weed Sci. 64: 294–302.

Kulkarni, S. S., L. M. Dosdall, and C. J. Willenborg. 2017b. The role of ground beetles (Coleoptera: Carabidae) in weed seed consumption: a review. Weed Sci. 63: 355–376.

Kunz, C., D. Sturm, D. Varnholt, F. Walker, and R. Gerhards. 2016. Allelopathic effects and weed suppressive ability of cover crops. Plant Soil Environ. 62: 60–66.

LaCanne, C. 2017. Interactive effects of cover crops, invertebrate communities and soil health in corn production systems. Open Prairie Electr. Theses Diss. 1195: 37–59.

Landis, D. A., S. D. Wratten, and G. M. Gurr. 2000. Habitat management to conserve natural enemies of arthropod pests in agriculture. Annu. Rev. Entomol. 45: 175–201.

Lundgren, J. G. 2005. Ground beetles as weed control agents: effects of farm management on granivory. Am. Entomol. 51: 224–226.

Lundgren, J. G. 2009. Relationships of natural enemies and non-prey foods. Springer Science & Business Media, New York, NY.

Lundgren, J. G., and J. K. Fergen. 2014. Predator community structure and trophic linkage strength to a focal prey. Mol. Ecol. 23: 3790–3798.

Lundgren, J. G., and J. D. Harwood. 2012. Functional responses to food diversity: the effect of seed availability on the feeding behavior of facultative granivores. J. Entomol. Sci. 47: 160–176.

Lundgren, J. G., and R. M. Lehman. 2010. Bacterial gut symbionts contribute to seed digestion in an omnivorous beetle. PLoS One 5: e10831.

Lundgren, J. G., and K. A. Rosentrater. 2007. The strength of seeds and their destruction by granivorous insects. Arthropod-Plant Int. 1: 93–99.

Lundgren, J. G., P. Saska, and A. Honěk. 2013. Molecular approach to describing a seed-based food web: the post-dispersal granivore community of an invasive plant. Ecol. Evol. 3: 1642–1652.

Lundgren, J. G., T. McDonald, T. A. Rand, and S. W. Fausti. 2015. Spatial and numerical relationships of arthropod communities associated with key pests of maize. J. Appl. Entomol. 139: 446–456.

Pearson, D. E., M. Valliant, C. Carlson, G. C. Thelen, Y. K. Ortega, J. L. Orrock, and M. D. Madsen. 2018. Spicing up restoration: can chili peppers improve restoration seeding by reducing seed predation? Restor. Ecol. 27: 254–260.

Plaza-Bonilla, D., J. M. Nolot, S. Passot, D. Raffaillac, and E. Justes. 2016. Grain legume-based rotations managed under conventional tillage need cover crops to mitigate soil organic matter losses. Soil Till. Res. 156: 33–43.

Porter, F., and J. Scott. 2016. Seed coating methods and purposes: a status report. Mississippi State University Library Institutional Reciprocity, Mississippi State, MS.

Reeves, D. 2017. Cover crops and rotations, crops residue management, pp. 125–172. CRC Press, Boca Raton, FL.

Rogers, C. E., and G. L. Kreitner. 1983. Phytomelanin of sunflower achenes: a mechanism for pericarp resistance to abrasion by larvae of the sunflower moth (Lepidoptera: Pyralidae). Environ. Entomol. 12: 277–285.

Saska, P. 2004. Carabid larvae as predators of weed seeds: granivory in larvae of *Amara eurynota* (Coleoptera: Carabidae). Commun. Agric. Appl. Biol. Sci. 69: 27–33.

Saska, P., J. Němeček, S. Koprdová, J. Skuhrovec, and M. Káš. 2014. Weeds determine the composition of carabid assemblage in maize at a fine scale. Sci. Agric. Bohem. 45: 85–92.

Scott, D. 1975. Effects of seed coating on establishment. New Zeal. J. Agric. Res. 18: 59–67.

Teasdale, J., and C. Mohler. 1993. Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron. J. 85: 673–680.

Westerman, P. R., J. K. Borza, J. Andjelkovic, M. Liebman, and B. Danielson. 2008. Density-dependent predation of weed seeds in maize fields. J. Appl. Ecol. 45: 1612–1620.

White, S. S., K. A. Renner, F. D. Menalled, and D. A. Landis. 2007. Feeding preferences of weed seed predators and effect on weed emergence. Weed Sci. 55: 606–612.