VOLE DAMAGE TO COVER-CROPPED SOYBEANS: EXPLORING OPTIONS OF BIOLOGICAL AND CULTURAL CONTROL

by

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To my parents, who told me I could do anything and encouraged me to try. Thank you.

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ABSTRACT

Cover cropping, the practice of planting a non-commodity crop between rotations of commodity crops, is an emerging conservation practice in row-crop agriculture. Cover crops are used to improve soil health and reduce the need for chemical inputs. Cover crops also provide habitat for wildlife in fields that typically are not utilized by most wild occupants of highly fragmented agroecosystems. Though increasing wildlife habitat generally is viewed as a benefit, presence of some species may conflict with economic goals of producers. Voles (*Microtus*), a genus of rodent typically found in grassland habitats, have been reported by producers to consume the commodity soybean (*Glycine max*) crop, however, few evidence-based strategies exist to prevent vole use of fields and subsequent damage. I examined how voles perceive cover crops as a source of habitat and how fields may be monitored and manipulated to prevent damage by voles.

I conducted captive feeding trials to identify common cover crops selected as forage by 10 meadow (*M. pennsylvanicus*) and 15 prairie voles (*M. ochrogaster*). I also gathered data on landscape features, weather conditions, and farming techniques for 66 cover-cropped fields and identified factors most important to predicting vole damage to soybeans. Lastly, I surveyed 38 cover-cropped fields for vole sign and explored other covariates, including cover-crop density, that contributed to vole damage to young soybean plants.

Both meadow and prairie voles commonly preferred clover (*Trifolium*), alfalfa (*Medicago sativa*), and hairy vetch (*Vicia villosa*) cover crops as forage, whereas canola (*Brassica napus*) was avoided by both vole species. Cover crops that were highly (or minimally) preferred were selected (avoided) more consistently than plants that were moderately preferred. Selection of cover crops by voles was affected by diversity of available forage, nutritional characteristics of the plants, and individual vole personalities.

Probability of vole damage to cover-cropped fields was most strongly tied to soil type, days of snow, and permanent grassland habitat available. Fields that had been cover cropped for $\geq$3 years, had not been tilled, contained high proportions of well-drained soils, and 5-7% grassland habitat within 50 m were at greater risk for vole damage, especially if winter snow cover was minimal. Increased levels of vole damage also were found in fields containing a greater number of vole burrows and denser plant cover during spring surveys. Farmers may survey fields for vole sign and evaluate field attributes and weather conditions to identify where and when vole damage

is likely to be greatest. They may reduce in-field vegetative cover, expand permanent grassland habitat at field edges to cover >7% of land area within 50 m of the field, plant cover crops that do not provide ideal forage, or apply conservation tillage to reduce habitat suitability of cover-cropped fields for voles before planting the commodity soybean crop.

CHAPTER 1. INTRODUCTION

Conversion of land to agriculture has accounted for great loss in biodiversity and ecosystem simplification (McLaughlin and Mineau 1995, Benton et al. 2002, Tscharntke et al. 2005). For this reason, farm management practices that enable wildlife to use land within agroecosystems are considered valuable and are often encouraged (Ribaudo et al. 1990, McLaughlin and Mineau 1995). Cover cropping is one such emerging practice that has potential to increase availability of wildlife habitat during parts of the year when conventionally farmed row-crop fields are left bare or only contain crop stubble. Since 2010, area of cover-cropped fields has expanded quickly across the Midwest (White 2014). Growth has been especially notable in Indiana, where producers planted over 378,000 hectares of cover crops in 2017 (United States Department of Agriculture [USDA] 2019).

Cover cropping is the practice of planting a non-commodity crop immediately following the harvest of commodity crops and leaving it to grow until it is terminated shortly before or just after the next crop is sown. Farmers use cover crops to retain soil, improve soil health, and reduce chemical inputs (White 2014). The species or mix of species planted depends on a farmer's soil health objectives. Cover crops may remedy soil compaction, add essential nutrients to the soil by fixing nitrogen, suppress weeds, or improve soil structure by adding organic material resulting from decomposition after the crop is terminated and left on the field (Fageria 2007, White 2014). Though not an intentional benefit of cover crops, they also provide structure and forage needed by some wildlife species to use agricultural fields and likely increase diversity of the small mammal community (Getz et al. 2001, Wiman et al. 2009, Berl et al. 2018, Wilcoxen et al. 2018). Though increased biodiversity within agroecosystems is often beneficial (Altieri 1999), some species can cause conflict when populations grow to large numbers within fields (Dolbeer et al. 1994, Witmer et al. 2007, Wiman et al. 2009).

Voles (*Microtus*) are rodents known to depredate crops in a variety of agricultural systems (Witmer et al. 2007, Wiman et al. 2009, Motro 2011, Heroldová et al. 2018), although they are rarely found in conventional corn-soybean (*Zea mays*; *Glycine max*) rotational agriculture (Berl et al. 2018). However, cover crops likely improve habitat for voles because they provide cover and an over-winter food source within field boundaries. Meadow (*M. pennsylvanicus*) and prairie voles (*M. ochrogaster*) are found in grass habitats where overhead cover provides protection from predators (Reich 1981, Klatt and Getz 1987, Stalling 1990) and are primarily herbivores that consume a variety of fresh vegetation (Reich 1981, Stalling 1990, DeJaco and Batzli 2013). Voles produce large litters in short intervals (Reich 1981, Stalling 1990), and when food and cover quality are ideal, they can breed year-round and quickly become overabundant (Cole and Batzli 1978, Getz et al. 2007, Goswami et al. 2011). Though reproduction and survival rates slow over winter months, populations typically spike in the spring (Getz et al. 2007). This increase in population size coincides with cover-crop termination and soybean planting. Cover crops may allow voles to move into and reproduce within fields, but the loss of the cover crops as forage in the spring likely forces voles remaining in fields to eat newly planted soybeans, thus causing damage to the commodity crop.

In 2016, voles in Indiana caused sufficient damage to cover-cropped soybeans to cause concern (Fisher et al. 2014; J. Rorick, Agronomist, Conservation Cropping Systems Initiative, pers comm.). Unfortunately, farmers lacked evidence-based tools to anticipate and mitigate vole damage to their crops. My research explored how native meadow and prairie voles use resources provided by cover-cropped fields. My goal was to provide farmers with tools to predict and reduce vole depredation of cover-cropped soybeans.

I first explored the selection of cover-crop species as forage by meadow and prairie voles (Chapter 2). Some species used as cover crops, such as alfalfa and clovers, are known to be palatable (DeJaco and Batzli 2013), however, many species employed as cover crops have not been tested for their attractiveness to voles. I also explored how other factors, such as diversity of forage available to voles and vole individuality may influence selection of a given plant species. Identifying cover crops that are avoided by voles provides producers with options for planting cover crops of low value, which may discourage immigration and recruitment in fields and thus reduce potential for damage to young soybean plants.

In Chapter 3, I explored how physical attributes of fields, measured by GIS, and farming practices, reported by respondents to a producer survey, may alter habitat available to voles and affect probability of vole damage to individual fields. Identifying conditions that are most suitable for voles, such as soil type or yearly weather patterns, allows farmers to employ long-term planning and focus mitigation efforts on fields that are most likely to incur damage. Farming practices associated with reduced damage risk can then be employed to make fields less attractive for voles.

Lastly, I evaluated the relationship between amount of vole sign found in fields prior to soybean planting and severity of damage to the soybean crop, with the intent of providing a short-term tool to evaluate the need for vole population management (Chapter 4). Vole populations cycle in the Midwest (Getz et al. 2001), meaning damage levels will be negligible in some years and thus render mitigation efforts unnecessary. Short-acting vole population management strategies and alternative baiting efforts are effective but can be time consuming and expensive (Hygnstrom et al. 2000). A method to evaluate the status of the vole population each year will allow farmers to gauge whether treatment is necessary. In addition to evaluating short-term forecasting methods, I also examined how habitat quality provided by the cover crop and predator habitat provided by artificial raptor perches influenced severity of vole damage.

Any single mitigation strategy is unlikely to completely rid fields of voles. However, use of several strategies may moderate the level of soybean damage, enabling farmers to reconcile the benefits of using cover crops with the drawback of damage incurred by voles. Refining tools to predict and prevent vole damage to cover-cropped soybeans will hopefully encourage continued use and adoption of cover-cropping, a valuable conservation practice.

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CHAPTER 2. SELECTION OF COMMON COVER CROPS BY VOLES (*MICROTUS*)

Abstract

Use of cover crops in intensive row-crop agriculture has dramatically increased over the last decade. Cover crops provide vegetative cover and forage that may support more diverse and abundant rodent communities than those found in conventional row-crop agroecosystems. However, increasing vole populations can lead to depredation of the soybean (*Glycine max*) commodity crop. We tested for selection of 13 commonly planted cover crops by meadow (*Microtus pennsylvanicus*) and prairie (*M. ochrogaster*) voles using cafeteria-style feeding trials. Red clover (*Trifolium pratense*), alfalfa (*Medicago sativa*), and hairy vetch (*Vicia villosa*) were commonly preferred among vole species, and canola (*Brassica napus*) was avoided. Meadow and prairie voles consistently chose or avoided highly and minimally palatable species, respectively, but were more variable in choosing moderately palatable species. Consumption scores were negatively associated with the number of plants offered in a trial, and the relationship was stronger for males than females. The interaction of protein and fiber content of plants, and vole identity included as a random effect, were also important in predicting score probability for both vole species. Identifying minimally preferred plants and factors that influence selection may allow farmers to manage cover-cropped soybean fields to discourage immigration of small mammals into fields, thus reducing negative consequences that might otherwise limit future adoption of a valuable soil conservation practice.

Introduction

Use of cover crops in conventional row-crop agriculture has increased greatly over the last decade (White, 2014). In corn-soybean rotations of the Midwestern U.S., producers plant cover crops after harvesting the commodity crop in fall and terminate in spring before the next commodity crop germinates. Cover crops are used to improve soil health by retaining topsoil, providing essential nutrients, and maintaining soil moisture (Fageria, 2007).

In addition to improving soil health, cover crops provide forage and vegetative structure in fields that, under conventional tillage practices, contain only bare soil or crop stubble from late fall to early spring. Improved overhead cover likely increases diversity of the small mammal community in row-crop fields (Berl et al., 2018; Getz et al., 2007; Jug et al., 2008) and could enable population growth of herbivorous small mammals that can incorporate the cover crops into their diets. Although increased biodiversity can benefit farm management (Altieri, 1999), some species, such as voles (*Microtus*), may depredate the commodity crop when their populations grow too large (Wiman et al., 2009; Witmer et al., 2007). When appropriate cover and food is available, voles reproduce year-round, and populations can quickly grow to large numbers (Cole and Batzli, 1978; Getz et al., 2007; Goswami et al., 2011).

Vole depredation of crops in row-crop fields has been reported previously (Witmer et al., 2007), and complaints of vole damage to soybeans (*Glycine max*) in cover-cropped fields are numerous (Fisher et al. 2014; Joe Rorick, [Conservation Cropping Systems Initiative, West Lafayette, IN] personal communication, [August, 2017]). However, we are unaware of research designed to evaluate which cover crops used in corn-soybean rotations may, by virtue of their relative palatability, encourage vole use of fields and hence increase risk of damage to soybeans. Our objective was to rate commonly used overwinter cover crops for selection by meadow (*M. pennsylvanicus*) and prairie (*M. ochrogaster*) voles. The geographic ranges of these two vole species encompass the bulk of the Midwestern U.S., where row-crop agriculture dominated by soybean and corn (*Zea mays*) is prevalent. Identifying cover crops that are avoided by voles provides producers with options for planting cover crops of lower value to voles, which may discourage immigration and recruitment in fields and thus reduce potential for damage to young soybean plants. Alternatively, knowledge of differential selection would allow producers to anticipate damage in fields planted with highly preferred cover crops and act preemptively to minimize damage in these fields.

We expected clovers (*Trifolium*) and alfalfa (*Medicago sativa*) to be preferred relative to other species tested, as they ranked high in previous vole diet studies comparing plants from permanent vole habitats (DeJaco and Batzli, 2013; Lindroth and Batzli, 1984). We anticipated that vetches, specifically hairy vetch (*Vicia villosa*) and cicer milk vetch (*Astragalus cicer*), would be avoided, as *Vicia* was suggested by Sullivan (2006) to be the most likely group of cover crops avoided by voles, and *A. cicer* was reported to deter voles from entering fields (Lisa Holscher, [Conservation Cropping Systems Initiative, West Lafayette, Indiana], personal communication, [August, 2017]).

In addition to rankings of relative preference, we evaluated factors hypothesized to influence variation in selection and avoidance of each species by voles. These objectives were operationally motivated; plant species that consistently are avoided by voles are less likely to yield variable results when used by producers compared to plant species for which avoidance varies with factors such as vole sex, age, or availability of alternative foods. Swihart (1990) found that woodchucks (*Marmota monax*) more consistently selected and avoided highly and minimally preferred species of orchard ground cover, respectively; whereas, moderately preferred species exhibited greater variation among feeding trials. Hence, we predicted a similar unimodal relationship between relative preference and variation in choice of cover crops for our vole species.

Meadow and prairie voles are generalist herbivores (Reich, 1981; Stalling, 1990) that can adjust diets to account for changes in plant availability (Haken and Batzli, 1996). Thus, we also tested for trends in relative preference as a function of availability. We hypothesized that voles would become increasingly willing to consume a plant as available plant diversity and quality, determined as a function of protein and acid detergent fiber content, declined (Haken and Batzli, 1996), resulting in greater relative preference. To control for possible effects of plant diversity, we also tested whether voles consumed less when presented with an equally diverse offering of plants rated as avoided versus preferred based on prior trials.

Materials and Methods

Study site

We captured voles and performed captive feeding trials at the Purdue University Wildlife Area (PWA) located 11 km west of West Lafayette, Indiana. PWA encompasses 1.17 km^2 of restored tallgrass prairie, savanna, and wetland habitat and is surrounded by row-crop agriculture. We captured five female and five male meadow voles and two male prairie voles within restored prairie at the site and at a nearby Purdue property. Low population levels during the study prevented us from capturing sufficient prairie voles for our trials, so we acquired an additional eight female and five male captive-bred prairie voles from Miami University, Ohio.

We placed outdoor enclosures used to house voles on a mown lawn at PWA. The vegetation within enclosures consisted primarily of Kentucky bluegrass (*Poa pratensis*) and fescue (*Festuca arundinace*), and we removed any broadleaf plants found within enclosures.

Feeding trials

To assess selection of common cover crops, we conducted a series of six feeding trials on meadow and prairie voles from July to August 2018. We placed a single vole into one of 15 1.5 m x 1.5 m outdoor enclosures built to specifications outlined in Dejaco and Batzli (2013). To protect study animals from exposure, we supplied dried hay and nest boxes within enclosures and placed a sheet of metal above each enclosure to provide shade. Voles had access to unlimited water and were provided rat chow (Laboratory Autoclavable Rodent Diet 5010, LabDiet) as supplemental food when trials were not taking place.

We allowed voles at least 3 days to acclimate to enclosures before beginning trials. During acclimation, we supplied one of each plant species to be tested to ensure equal exposure to plant types that do not occur naturally in Indiana.

We tested 17 total plant species for meadow voles (Table 2.1) and 18 for prairie voles (Table 2.2). Yellow clover (*Melilotus officinalis*) was not included for meadow voles due to difficulty growing sufficient plants to the appropriate growth stage. We included 12 winter cover crops and a summer crop, sorghum sudangrass (*Sorghum bicolor x S. bicolor var. sudanese*), that are most commonly used in United States commodity agriculture (CTIC & SARE, 2016). Additionally, we included three benchmark species that Dejaco and Batzli (2013) identified as highly, moderately, and minimally palatable, respectively, in nonnative grasslands that serve as the primary permanent habitat for these voles: alfalfa, orchardgrass (*Dactylis glomerata*), and giant ironweed (*Vernonia gigantea*). We also included cicer milk vetch, which reportedly deters voles (L. Holscher, Director, Conservation Cropping Systems Initiative, in litt.). Finally, we included soybean to enable comparison with the commodity crop for which depredation was a concern. We grew all plants from seed in a greenhouse and presented them to voles at approximately the same growing stage within each species (Hess et al., 1997). Whenever possible, we offered plants in growth stages 1-2, before they produced shoots or fruiting bodies.

To initiate a trial, we removed supplemental food and placed one of each plant species to be tested into each enclosure. We placed potted plants flush with the soil surface in the center of the enclosure to simulate a vole's natural encounter with forage. Each test period began between 1900h and 2100h and lasted 12 hours, after which test plants were removed and supplemental food was once again provided. Trials took place under ambient environmental conditions.

Before we placed plants in the enclosures, we recorded number of leaves or stems, as appropriate, for each plant and noted marks or tears that might mistakenly be attributed to voles. After the test period, we removed plants from enclosures and again observed the number of leaves or stems and damage to each plant. Following Dejaco and Batzli (2013), we then assigned a score of 0-4, which represented five categories: plant not sampled (0), < 25% of the plant missing (1), 25-49% missing (2), 50-74% missing (3), and ≥75% missing (4).

After plant assessment, we averaged the number of voles that sampled a given species and the total damage scores for that plant species together. We then used these averages to assign a preliminary consumption score to plants and eliminate from the next trial's offerings for all voles the plant species that on average were most preferred. Because we were most interested in the least preferred species, we eliminated at least two species between each trial. The number of species eliminated was determined by searching for natural breaks in scores for the most palatable species and the remaining plants.

We conducted a series of six trials for each vole species, with 1-2 nights between each trial. The first five trials consisted of sequential reductions of the most palatable species. For trial 6, we offered voles a set of the most preferred plants, as determined in the first two trials. The number of plant species we offered for trial 6 equaled the number offered in trial 4, thus permitting comparison of feeding behavior for assemblages of equal diversity but differing preference. We performed trials and selected plants for elimination separately for each vole species. Methods were consistent with guidelines specified by the American Society of Mammalogists (Sikes et al., 2016) and were approved by the Purdue University Animal Care and Use Committee (protocol number 1710001635).

Analysis

Because meadow and prairie voles were presented with different sets of plant species across their respective trials, separate analyses were run for each vole species. To assess relative preference and variation in choice for each plant species, we calculated the mean and standard deviation for each plant species in trials 1-5. We then compared observed means for each trial to corresponding null distributions generated via 1,000 simulated trials in which mean scores were assigned randomly to plant species offered in the trial. Observed means were then compared to the null distribution to generate quasi-*P* values. We used one-tailed tests for plants expected to be palatable or unpalatable to voles based on prior research (references in Introduction) and two-tailed tests for all other species. Within each trial, we adjusted quasi-*P* values with Holm's procedure (Holm, 1979) and used an alpha value of 0.1 to assess significance.

To examine the effect that preference had on the consistency with which voles chose a plant species, we calculated the standard deviation of scores between trials (Swihart, 1990) for each vole. Because we eliminated the most preferred set of plants after the first trial, we lacked data from subsequent titration trials to calculate a mean and standard deviation for them. Instead, we combined data from trial 6, in which only the most preferred species were offered, with data from trial 1 to calculate a mean and standard deviation for the most palatable species. We tested the relationship between average consumption score and standard deviation across trials for each vole and plant species combination and tested for consistent differences among individuals by incorporating vole identity as a random effect in R package lme4 (Bates et al., 2019). We used AICc (Burnham and Anderson, 2002) to compare the evidence for intercept-only, linear, and quadratic models. For assessing evidence of random effects, we used conditional AIC (Saefken et al., 2014) and R^2 (Nakagawa and Schielzeth, 2013) as implemented in R packages cAIC4 (Saefken and Ruegamer, 2018) and MuMIn (Bartoń, 2019). Variation explained by random effects was calculated using adjusted repeatability in package rptR (Stoffel et al., 2019). Fitted values were then computed for AICc- or cAIC-best models.

We used a binomial test conducted on signed differences in consumption scores for successive pairs of trials to test the hypothesis that scores would exhibit positive trends in preference as food choices became more limited. To more formally account for the semi-quantitative nature of our response variable, we also performed ordinal (proportional odds) regression on results from all six trials to model the probability of consumption falling in score class k (k = 0-4) as a function of plant diversity, vole characteristics, and plant nutritional factors as reported in the literature (see references in Appendices A & B). Specifically, we fitted cumulative probability with logistic or probit links to the number of plants offered in a trial, vole sex, crude protein, acid detergent fiber fitted as second-order polynomials with the poly function in R package stats (R Core Team, 2018), and all two-way interactions. To account for variation due to differences among individual voles, we incorporated vole identity as a random effect. The interactive model and its proper subsets were compared using AICc and likelihood ratio tests. Random-effects ordinal regression was implemented in R package ordinal (Christensen, 2019).

Following Bonnot et al. (2018), we replicated ordinal models by treating consumption score as a continuous response in linear mixed effects models, which enabled us to report adjusted repeatability estimates using R package rptR (Stoffel et al., 2019) and conditional R^2 (Nakagawa and Schielzeth, 2013) for best models.

To separately test if relative preference affected the average score for voles when offered plants of equal diversity but differing quality, we compared the means of differences in scores for each individual vole in trial 4 (*n*=5 [meadow voles] or 6 [prairie voles] plants) and trial 6 (*n*=5 [meadow voles] or 6 [prairie voles] plants). Observed mean differences were compared to distributions of null mean differences derived from scores in trials 4 and 6 in which pairs of scores were assigned at random, and quasi-*P* values were computed by tabulating the fraction of the null distribution greater than the observed mean difference. All analyses were conducted in R (R Core Team, 2018).

Results

Relative preference

No plant species was wholly avoided, as both meadow and prairie voles sampled all plant species at least once. However, canola (*Brassica napus*) ranked lower than most plant types for both vole species and was chosen less than expected by meadow voles in trials 1, 2, and 4 (Table 2.1). Meadow voles also ate turnip (*B. rapa*) less than expected in trials 1 and 3.

Of the 17 plant species presented to both vole species, red clover (*T. pratense*), alfalfa, and hairy vetch were consistently selected more than expected, though only selection by meadow voles differed significantly from the null distribution in trial 1 (Table 2.1). Of the most-consumed species, prairie voles ate only hairy vetch more than expected in trial 2 (Table 2.2). Both vole species also highly preferred soybean, with meadow voles choosing it more than expected in trial 2 and prairie voles in trial 3. In general, meadow voles demonstrated greater levels of discrimination among plant species than prairie voles. Meadow voles preferred red clover, alfalfa, crimson clover (*T. incarnatum*), hairy vetch, soybean, winter wheat (*Triticum aestivum*), cereal rye (*Secale cereale*), barley (*Hordeum vulgare*), and radish (*Raphanus sativa*) and avoided canola, turnip, barley, and radish in at least one trial (Table 2.1). Interestingly, two species avoided in early trials, barley and radish, were consumed more than expected in later trials from which highly preferred species had been omitted (Table 2.1). In contrast, prairie voles demonstrated strong preference only for hairy vetch and soybean (Table 2.2) and avoided none of the species, with the possible exception of barley ($P = 0.11$).

Variation in preference across trials

When testing the relationship of intertrial standard deviation and mean consumption score with vole identity included as a random effect, the quadratic model exhibited overwhelming support for meadow voles (ΔAICc = 132.6 and 133.7 for linear and intercept-only models, respectively) and prairie voles (ΔAICc = 218.7 and 260.0; Fig. 2.1). Fitted models demonstrated important quadratic effects for both meadow ($t = -15.0$, $P << 0.001$) and prairie voles ($t = -20.94$, $P << 0.001$). For meadow voles, the model containing a quadratic term without vole identity as a random effect was superior ($X^2 = 0.01$, $P = 0.920$) indicating no consistent differences among individual voles in their responses. However, for prairie voles the quadratic random-effects model was substantially superior ($X^2 = 11.71$, $P < 0.001$). Repeatability for prairie vole identity was slight, but significant ($r = 0.14$, [0.02, 0.30], $P < 0.001$).

Correlates of consumption level

Meadow voles yielded 30 sequences of trials for which differences in mean consumption scores could be computed. Of these, 24 (80%) resulted in increased consumption scores as the offered set of plants declined in overall diversity and quality, a greater fraction than expected by chance (binomial test $P = 0.0007$; Fig. 2.2). For prairie voles the fraction of sequential trials exhibiting an increase in mean consumption score was less dramatic, with 22 increases out of 34 (65%) tests (binomial test $P = 0.061$; Fig. 2.2).

When plant diversity was constant, but quality differed in trials 4 (most avoided) versus 6 (most preferred), both meadow and prairie voles ate more of the preferred set of plants. Meadow voles exhibited a 1.4-unit increase (quasi-$P = 0.008$) in consumption score in trial 6 ($\bar{x} = 3.69$ [3.21, 4.16]) compared to trial 4 ($\bar{x} = 2.29$ [1.10, 3.47]). The mean score for prairie voles increased by 0.9 units (quasi-$P \leq 0.001$) in trial 6 ($\bar{x} = 1.75$ [0.97, 2.53]) compared to trial 4 ($\bar{x} = 0.83$ [0.01, 1.65]).

For meadow voles, the ordinal regression model containing all additive effects and interactions was AIC-best (second-best model ΔAIC = 28.2). Models fit with probit and logistic links received similar support (ΔAICc = 0.8), so we present results from the logistic link model (Table 2.3). The interaction of fiber and protein was important (z = 5.83, P << 0.001) and resulted in a high probability of low consumption scores for plants with maximum fiber and minimum protein and for plants with minimum fiber and maximum protein (see supplementary data SD1). The interaction of sex and number of plants was also important (z = -1.93, P = 0.053). Male voles produced higher consumption scores in any given trial and showed a stronger negative response to reduction in plant diversity than females (see supplementary data SD2). Both sexes exhibited an increased chance for lower scores as diversity increased. The random intercept for variation captured by differences among individual voles improved model fit (X^2 = 34.30, ΔAICc = 32.2, df = 1, P << 0.001). Repeatability of the random effect was low (r = 0.16), but different from zero (95% CI: [0.03, 0.33], P << 0.001). Improvement due to the random effect was best demonstrated by comparing marginal (0.22) to conditional r-squared (0.35).

For prairie voles the best ordinal model (second-best model ΔAICc = 3.6) was the model including all additive effects and appropriate interactions (Table 2.3). The model fit with a probit link was best, compared to a logistic link model (ΔAICc = 6.21), so we present results from the probit model. Both the interactions of protein and fiber (z = 4.19, P << 0.001) and sex and plant diversity (z = -2.26, P = 0.024) were important to predicting the probability of a given consumption score and had the same effect as for meadow voles. The random factor included to account for prairie vole identity improved model fit (X^2 = 74.72, ΔAIC = 72.6, df = 1, P << 0.001) and though the repeatability was small (r = 0.18), it differed from zero (95% CI: [0.05, 0.33], P << 0.0001). Marginal r-squared was lower than for meadow voles (marginal R^2 = 0.04) but also was greatly improved by the inclusion of the random effect (conditional R^2 = 0.21).

Discussion

We found pronounced differences in selection of commonly used cover crop species. As expected, alfalfa and clovers were preferred by both meadow and prairie voles. However, voles also preferred hairy and cicer milk vetch, in contrast to predictions. Though Sullivan (2006) suggested that *Vicia*, which includes hairy vetch, was likely to be avoided by voles, his assessment was generalized across vole species and across species of *Vicia*. Vole species are known to differ in preference for the same plant species (DeJaco and Batzli, 2013), and plant species within the same genus may vary widely in nutritional and chemical composition (Duke and Atchley, 1986); both factors presumably affected the consumption scores we observed. Cicer milk vetch is planted by farmers to deter voles due to putative toxicity of its roots. Our study did not assess selection of roots, but our results indicate that above-ground biomass of cicer milk vetch is selected by voles.

Interestingly, we found that young soybean plants, the commodity crop of concern, were also selected by voles. Soybean plants are available in conventional agriculture and no-till fields but reports of vole damage are concentrated in cover-cropped fields. Our original hypothesis was that cover crops serve as a forage resource for voles. Soybean depredation thus occurs once cover crops are terminated and soybeans are left as the only source of vegetative forage in the field. In this scenario, farmers may successfully deter voles by planting unpalatable cover crops. However, our finding that soybeans are selected by voles, coupled with the limited damage to soybeans observed in conventional and no-till systems, suggests two additional scenarios that may explain damage observed by farmers that use cover crops.

First, cover crops may facilitate soybean damage primarily by providing overhead cover necessary for voles to access soybeans. In this case, cover crops that are planted at low densities or have growth forms that provide minimal overhead cover will best deter meadow voles. Prairie voles, which can thrive in areas of comparatively sparse cover (Getz et al., 2001), may be more difficult to manage in this fashion. Another possible scenario is that cover crops attract voles by providing both forage and cover, in which case unpalatable cover crop species that provide poor cover would be best for limiting vole damage to soybeans. This solution is likely to limit damage by meadow voles more effectively than prairie voles.

Some species, such as canola, were avoided by both meadow and prairie voles, but all plant species except barley were sampled in each trial. Other studies have reported complete avoidance of several plant species during feeding trials (DeJaco and Batzli, 2013; Marquis and Batzli, 1989), but they did not systematically restrict diversity or quality of available plants. Our results indicated that limiting plant diversity increased the odds of voles consuming a species. Thus, failure of voles to completely avoid some plant species throughout our study likely resulted because more desirable food was unavailable during some trials.

Despite lack of complete avoidance, unpalatable plants may still be used to discourage vole use of agricultural fields if our original forage-driven hypothesis is correct. Vole populations can quickly colonize and reproduce in fields containing preferred habitat, with lower growth potential in areas where preferred habitat or food is lacking (Cole and Batzli, 1979, 1978; Getz et al., 2001). If voles use cover crops solely because of their forage quality, plants such as canola and barley, which are of limited attractiveness when other forage is available, may encourage voles to use areas with more desirable and diverse forage. Alternatively, if cover density is a mechanism that enables voles to depredate soybeans, the cover quality provided by these plants must also be considered.

Prairie voles exhibited more muted trends of preference and avoidance compared to meadow voles, presumably as a consequence of lower overall consumption of plants offered in trials (Fig. 2.2). Thirteen of 15 prairie voles used in our study were bred in captivity. Other studies (Batzli and Jung, 1980; Marquis and Batzli, 1989) reported similar selection of plants in laboratory feeding experiments using captive-reared and wild-caught voles compared to results of plants selected in the field but did not compare amounts of forage eaten. Captive-bred animals not habituated to prolonged food stress may expect rat chow to be available at regular intervals and thus wait for a familiar food source, rather than feed extensively on relatively novel plant resources.

Consumption score was influenced by the interaction of plant protein and acid detergent fiber. The increased chance of a low score for high fiber and low protein plants was expected (Batzli, 1985; Bergeron and Jodoin, 1987; Marquis and Batzli, 1989), as plants with these qualities are hard to digest and provide minimal nutrition. Other results of the interaction, such as the high probability of a low score for high protein, low fiber plants are counterintuitive and may be explained better by the presence of compounds such as phenolics and alkaloids that are important in predicting plant consumption by voles (Dearing et al., 2005). However, we did not conduct assays to test for the presence of chemicals important to deterring rodent herbivory in the plants included in our trials.

Consumption score was predicted by plant characteristics and by the context in which a plant was offered. Restricting the diversity of available forage increased the chance of plant consumption, especially by male voles. Even if use of cover crop fields is based solely on forage quality of cover crops, vole use of fields is likely to persist if there is insufficient preferred forage elsewhere on the landscape. However, voles ate less of low-quality forage compared to equally diverse offerings of preferred plants. Thus, voles are likely to eat less in fields planted to cover crops they view as less preferred, with population densities limited by forage quality (Cole and Batzli, 1979, 1978).

Highly and minimally preferred plants were chosen and avoided more consistently than plants of intermediate preference (Fig. 2.1). Swihart (1990) observed a similar pattern for woodchucks (*Marmota monax*) and cautioned against quantitative comparisons of food habits for generalist herbivores from studies with differing vegetative composition. Our results suggest that there are limits to the flexibility of voles at either extreme of forage quality. In contrast, plants of intermediate quality appear to offer voles the option of tradeoffs among plants that are viewed as roughly equivalent, or for which consistent individual differences in choice exist. Our data supported the latter explanation only for prairie voles. Future discrete choice experiments could improve our understanding of how voles perceive tradeoffs among traits for plants exhibiting intermediate preference (Sundaram et al., 2018).

Consistent behavioral differences among individual voles may affect a local population's ability to use cover crops as forage. Intraspecific variation in behavior too often is ignored (Jenkins, 1997), despite its implications for ecosystem services and management (Brehm et al., 2019; Feldman et al., 2019). Our results suggest that individual variation in vole behavior may impact how vole populations interact with cover-cropped fields, as model fit was improved by including vole identity as a random effect in all AIC-best ordinal models. Although repeatability estimates were low, they were comparable to other studies that detected individual variation in the context of foraging behavior (Dochtermann et al., 2015). The applied implications are clear: some voles will consistently be more willing than conspecifics to consume any cover crop, regardless of palatability. As such, it is unlikely that farmers will eliminate vole damage solely by altering composition of cover crops planted in a soybean field.

From an ecological perspective, intraspecific behavioral variation may enable voles to repopulate in areas of row crops that previously had not provided habitat. Row-crop fields without cover crops tend to receive little use by voles (Berl et al., 2017). However, if some vole phenotypes regularly incorporate cover crops into their diet, survive, and reproduce amidst cover-cropping operations, vole populations may avail themselves of significantly more habitat than in the previous decades of intensive row-crop agriculture with little use of cover crops.

Conclusion

Common cover crop species range in attractiveness to meadow and prairie voles. Red clover, alfalfa, and hairy vetch were commonly preferred, and canola was avoided. Highly and minimally preferred species were selected or avoided, respectively, more consistently than moderately palatable species. Farmers can plant minimally palatable cover crops to deter voles, however, the effectiveness of this strategy depends on availability of additional preferred forage on the landscape and personality of voles that make use of cover-cropped fields. Alternatively, farmers can anticipate greater risk of damage to soybeans in fields where highly preferred species are planted, and act to manage vole populations in other ways.

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Table 2.1.—Average scores (± *SD*) showing consumption of common Indiana cover crops offered to meadow voles (*Microtus pennsylvanicus*) in cafeteria-style feeding trials, July to August 2018. Consumption scores range from 0-4, with higher scores corresponding to higher relative preference. Observed means were compared to a null distribution to generate quasi-*P* values, that were then adjusted using Holm's procedure. The most-preferred plants were removed from consideration in each subsequent trial.

Species name	Trial 1	*P*	Trial 2	*P*	Trial 3	*P*	Trial 4	*P*	Trial 5	*P*
Trifolium pretense	3.0 ± 1.4	0.005 [a]								
Medicago sativa	2.9 ± 1.7	0.008 [a]								
Vicia villosa	2.8 ± 1.6	0.016 [a]								
Trifolium incarnatum	2.4 ± 1.5	0.241								
Glycine max	2.5 ± 1.8	0.282	3.2 ± 1.6	0.025 [a]						
Triticum aestivum	1.9 ± 1.9	1	3.2 ±1.4	0.025 [a]						
Lolium multiflorum	1.8 ± 1.4	1	2.8 ± 1.6	0.511						
Avena sativa	2.4 ± 1.7	0.457	2.7 ± 1.7	0.623						
Hordeum vulgare	0.3 ± 0.9	0.018 [b]	2.0 ± 1.9	1	3.0 ± 1.7	0.072 [a]				
Astragalus cicer	1.6 ± 0.7	1	2.2 ± 1.6	0.953	2.8 ± 1.6	0.110				
Sorghum bicolor x S. bicolor	0.8 ± 1.3	0.516	2.2 ± 1.9	1	2.8 ± 1.6	0.227				
Dactylis glomerata	0.9 ± 1.0	0.709	1.7 ± 1.7	1	2.0 ± 1.4	1				
Secale cereale	1.0 ±0.8	0.878	1.1 ± 0.3	0.623	1.8 ± 1.5	1	3.3 ± 1.5	0.069 [a]		
Vernonia gigantea	1.3 ± 1.9	0.979	1.3 ± 1.8	0.623	1.8 ± 1.9	1	2.9 ± 2.0	0.248		
Raphanus sativus	0.3 ± 0.5	0.018 [b]	1.2 ± 1.6	0.630	1.1 ± 1.5	0.377	2.1 ± 2.0	1	2.6 ± 1.7	0.048 [a]
Brassica napus	0.4 ± 0.5	0.051 [b]	0.6 ± 1.3	0.020 [b]	1.0 ± 1.5	0.252	1.1 ± 1.5	0.042 [b]	1.6 ± 1.8	0.389
Brassica rapa	0.2 ± 0.6	0.008 [b]	1.0 ± 1.3	0.436	0.6 ± 1.3	0.020 [b]	2.0 ± 1.3	1	1.5 ± 1.9	0.335

[a] Indicates mean is greater than expected.
[b] Indicates mean is less than expected.

Table 2.2—Average scores (± *SD*) showing consumption of common Indiana cover crops offered to prairie voles (*Microtus ochrogaster*) in cafeteria-style feeding trials, July to August 2018. Consumption scores range from 0-4, with higher scores corresponding to higher relative preference. Observed means were compared to a null distribution to generate quasi-*P* values, that were then adjusted using Holm's procedure. The most-preferred plants were removed from consideration in each subsequent trial.

Species name	Trial 1	*P*	Trial 2	*P*	Trial 3	*P*	Trial 4	*P*	Trial 5	*P*
Trifolium pratense	1.3 ± 1.6	0.776								
Medicago sativa	1.3 ± 1.4	0.776								
Astragalus cicer	1.2 ± 1.1	1								
Vicia villosa	1.0 ± 1.2	1	2.1 + 1.4	0.025 [a]						
Lolium multiflorum	1.6 ± 1.7	0.212	1.6 + 1.7	1						
Melilotus officinalis	0.7 ±1.2	1	1.4 + 1.2	1						
Raphanus sativus	1.2 ± 1.5	1	1.3 + 1.2	1						
Trifolium incarnatum	1.1 ± 1.7	1	1.0 + 1.3	1						
Glycine max	1.6 ± 1.9	0.212	1.4 + 1.9	1	2.5 + 2.0	0.001 [a]				
Avena sativa	0.4 ± 1.2	1	0.8 + 1.5	1	1.9 + 2.0	0.180				
Brassica rapa	0.2 ± 0.4	0.852	0.3 + 0.9	0.902	1.5+ 1.4	1				
Triticum aestivum	0.8 ± 1.2	1	1.2 + 1.7	1	1.0 + 1.6	1				
Vernonia gigantea	0.3 ± 0.9	0.852	0.7 + 1.6	1	0.5 + 0.9	0.416	1.2 + 1.8	0.303		
Dactylis glomerata	0.2 ± 0.4	0.852	0.6 + 0.9	1	0.6 + 1.2	1	0.9 + 1.7	1		
Secale cereale	0.3 ± 0.9	1	0.7 + 1.4	1	1.0 + 1.5	1	0.8 + 1.5	1		
Sorghum bicolor x S. bicolor	0.4 ± 1.2	1	0.8 + 1.5	1	0.5 + 1.2	1	0.5 + 1.3	1	1.8 + 2.1	1
Hordeum vulgare	0.0 ± 0.0	0.314	0.4 + 1.2	1	0.3 + 0.6	0.416	0.0 + 0.0	0.108	1.3 + 1.5	1
Brassica napus	0.8 ± 1.5	1	0.7 + 0.9	1	0.6 + 1.4	1	0.9 + 1.5	1	1.2 + 1.9	1

[a] Indicates mean is greater than expected.
[b] Indicates mean is less than expected.

Table 2.3—Model summaries for AIC-best ordinal (proportional odds) regression models predicting cumulative odds of consumption score, *n*, where higher scores indicated higher consumption. Plant species were presented to meadow (*Microtus pennsylvanicus*) and prairie (*Microtus ochrogaster*) voles in a series of six cafeteria-style feeding trials, July to August 2018. The most-consumed plants were removed from consideration in each subsequent trial, except for trial 6 which consisted of only highly preferred plants.

Vole species	Effect	Coefficient	*SE*	*z*	*P*
Meadow	Plant Diversity	-0.14	0.20	-0.67	0.504
	Protein	0.08	0.13	0.61	0.539
	Fiber	10.58	2.99	3.53	<0.001
	$Fiber^2$	13.92	2.33	6.00	<<0.001
	Male	1.64	0.54	3.06	0.002
	Diversity*Male	-0.44	0.23	-1.93	0.053
	Protein*Fiber	1.07	0.18	5.83	<<0.001
Prairie	Plant Diversity	-0.05	0.06	-0.76	0.449
	Protein	0.03	0.07	0.48	0.631
	Fiber	2.78	1.77	1.57	0.115
	$Fiber^2$	2.65	1.36	1.94	0.052
	Male	-0.22	0.34	-0.66	0.507
	Diversity*Male	-0.23	0.10	-2.26	0.024
	Protein*Fiber	0.42	0.10	4.20	<<0.001

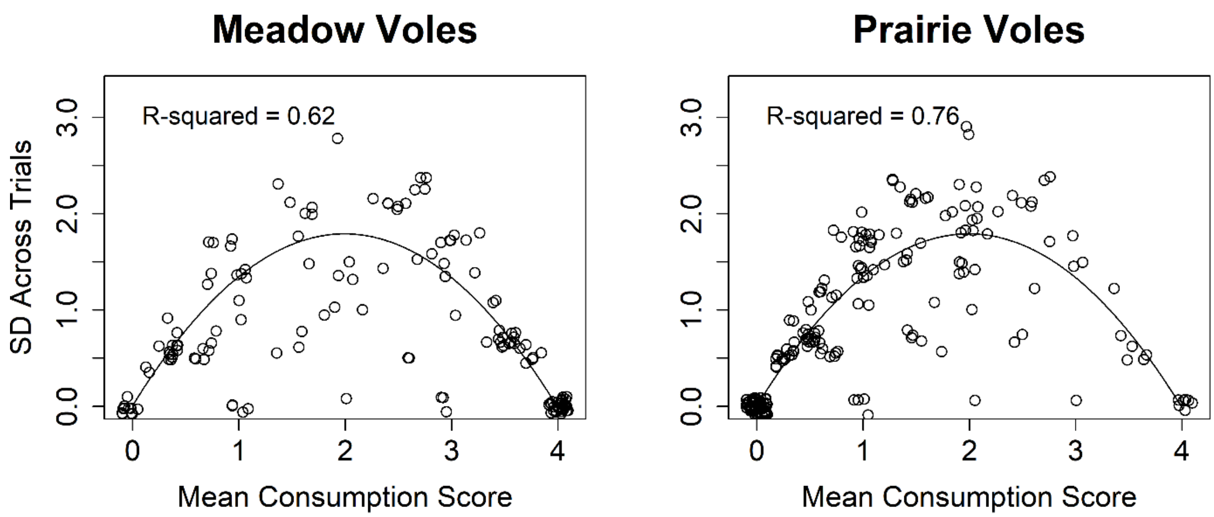


Figure 2.1—Relationship of mean consumption to intertrial standard deviation for 17 and 18 plant species presented to meadow (*Microtus pennsylvanicus*) and prairie (*Microtus ochrogaster*) voles, respectively, in a series of six cafeteria-style feeding trials, July to August 2018. The most preferred plants were removed from consideration in each subsequent trial, except for trial 6 which consisted of only highly preferred plants. Consumption scores range from 0-4, with higher scores corresponding to higher amounts consumed.

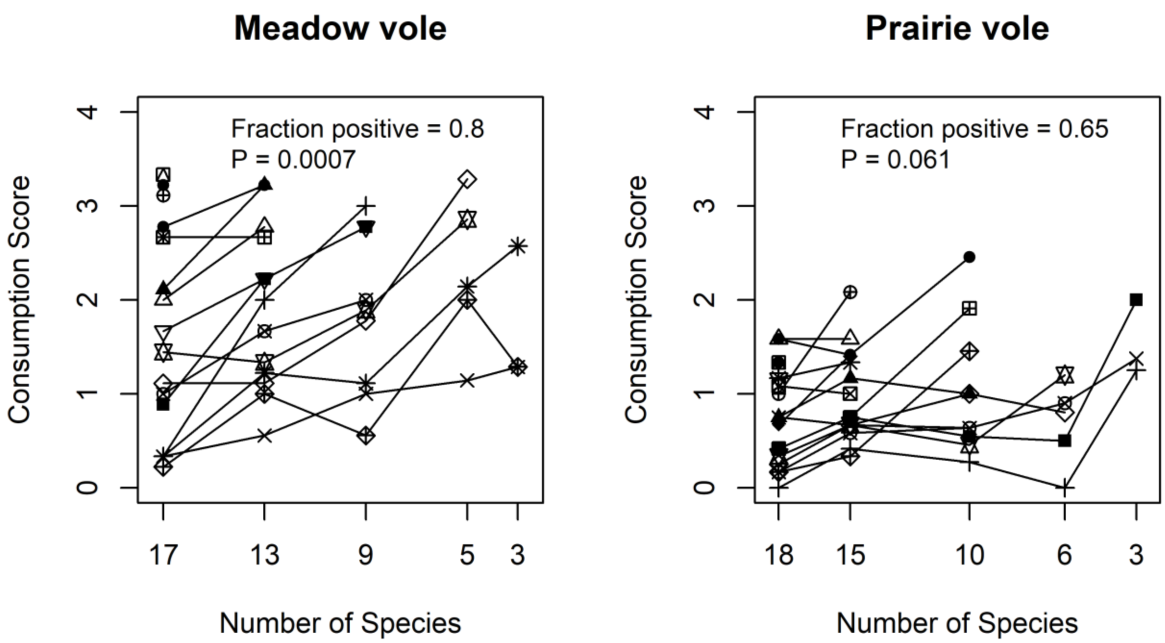
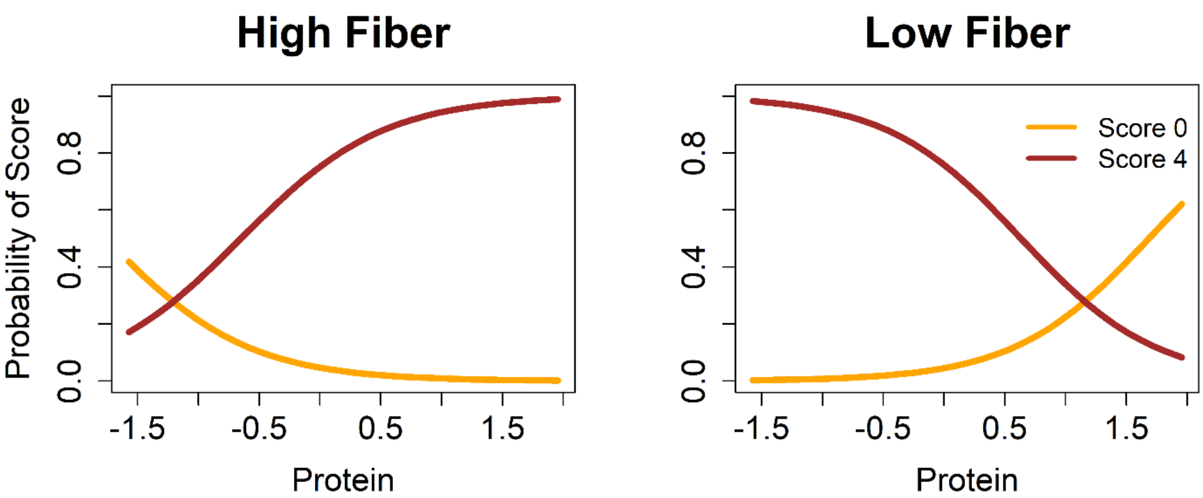
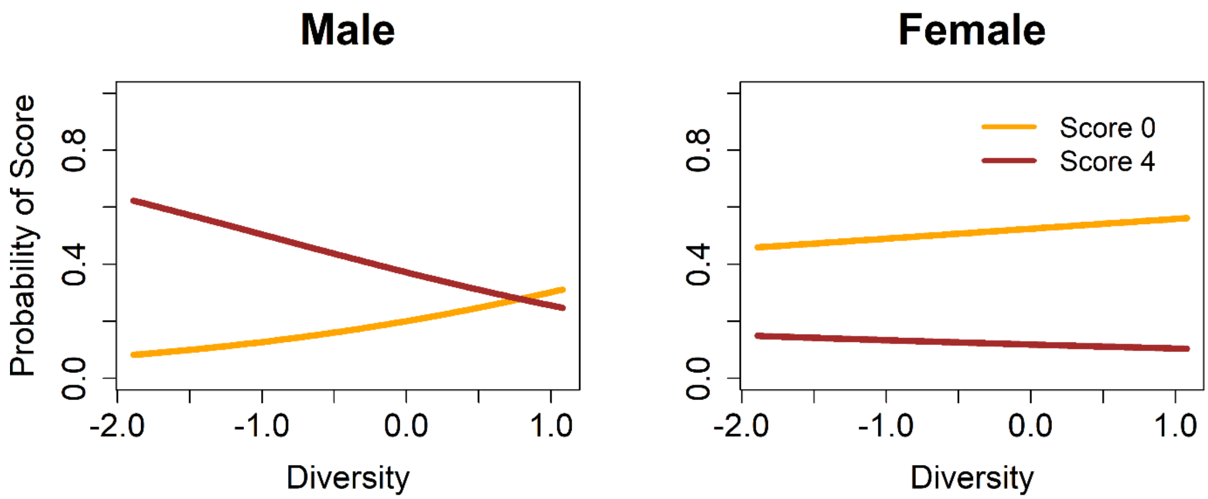


Figure 2.2—Trends in mean scores for 15 common cover crops and 3 benchmark plant species as diversity and relative preference of plants offered were reduced. Plants were presented to meadow (*Microtus pennsylvanicus*) and prairie (*Microtus ochrogaster*) voles in a series of five cafeteria-style feeding trials, July to August 2018. The most-consumed plants were removed from consideration in each subsequent trial. Consumption scores range from 0-4, with higher scores corresponding to higher consumption. Each symbol represents a different plant species.

Supplementary Data SD1—Interaction of acid detergent fiber and protein level of common cover crop plants offered to meadow (*Microtus pennsylvanicus*) voles in a series of six cafeteria-style feeding trials, July-August 2018. Proportional odds logistic regression was performed to predict probability of consumption scores 0-4, where 0 indicates a plant not consumed, and 4 indicates 75% or more of a plant consumed.



Supplementary Data SD2—Interaction of vole sex and number of common cover crop plants offered to meadow (*Microtus pennsylvanicus*) voles in a series of six cafeteria-style feeding trials, July-August 2018. Proportional odds logistic regression was performed to predict probability of ordinal consumption scores 0-4, where 0 indicates a plant not consumed, and 4 indicates 75% or more of a plant consumed.



CHAPTER 3. FIELD ATTRIBUTES AND FARMING PRACTICES MOST IMPORTANT TO PREDICTING VOLE (*MICROTUS*) DAMAGE IN COVER-CROPPED FIELDS

Abstract

Use of cover crops to promote soil health in high-intensity row crop agriculture has increased in the midwestern United States. With increased use of this agricultural conservation practice, reports of damage to the soybean (*Glycine max*) commodity crop have become more frequent. Meadow (*Microtus pennsylvanics*) and prairie voles (*M. ochrogaster*) may utilize overhead cover and forage provided by cover crops and feed upon the commodity crop after cover crops have been terminated. Because cover cropping is an emerging conservation practice, few methods have been evaluated for their relative effectiveness in preventing vole damage in cover-cropped fields. We used boosted regression tree models to assess how farming practices, physical and landscape attributes of fields, and seasonal weather conditions for cover-cropped soybeans fields located across the state of Indiana, USA, were associated with severity of damage by voles. We found that well-drained soils, number of days of snow cover, conservation tillage use, and number of years of cover-crop use in a field best predicted the odds of a field incurring vole damage. The practices we identified may be used by producers to identify fields and years where vole damage is most likely to occur and employ farming practices we determined to be most important to preventing vole damage to mitigate risk in those fields.

Introduction

Use of cover crops in corn-soybean (*Zea mays*, *Glycine max*) rotational agriculture has increased in the midwestern United States over the last decade (White, 2014). Cover crops are non-commodity plant species sown in the fall after harvest that die during the first frost or are terminated by mechanical or chemical means in the spring. Producers plant cover crops to aid in soil conservation, moisture retention, and weed suppression (White, 2014). Additionally, cover crops may provide wildlife habitat that does not exist in traditionally farmed row-crop agriculture fields (Berl et al., 2018; Jug et al., 2008; Wilcoxen, 2018). Though increasing wildlife habitat in highly fragmented agricultural ecosystems is generally viewed as a positive aspect of conservation agriculture (Altieri, 1999), some animals that use habitat provided by cover crops may cause conflict when they consume the commodity crop (Wiman et al., 2009; Witmer et al., 2007). In Indiana, USA, reports of damage by voles (*Microtus*) have occurred for several years and peaked in 2016 (Fisher et al., 2014; J. Rorick, Agronomist, Conservation Cropping Systems Initiative, pers comm.).

Meadow (*M. pennsylvanicus*) and prairie vole (*M. ochrogaster*) ranges span the state of Indiana (Reich, 1981; Stalling, 1990) and are associated with grassland habitat. Both species are found in areas of dense overhead cover, though prairie voles also persist in habitats that provide less protection from predators (Getz et al., 2001). In years when cover crops establish well in fields, they likely provide sufficient cover for both vole species. Cover crops also provide forage for voles (Chapter 2) that may allow them to persist in fields overwinter. However, when cover crops are terminated in the spring and are replaced by newly planted soybeans, voles may forage upon the commodity crop, which is the only source of vegetation after cover crop termination. Deer mice are also found in crop fields year-round, however, they typically persist on weed seeds and waste grain more so than on the commodity crop (Berl, 2017) and do not leave runway sign, which is an indicator of vole activity (Carrol and Getz, 1976) often associated with damaged crop areas in cover-cropped fields.

Because cover cropping is an emerging practice in large-scale corn-soybean agriculture, few methods have been evaluated for their relative effectiveness in preventing voles from using cover-cropped fields. We aimed to address this deficiency by comparing farming strategies and field attributes that may reduce risk of soybean damage incurred by voles. Soil disturbance caused by tillage reduced common vole (*Microtus arvalis*) abundance in European wheat fields compared to no-till fields (Heroldová et al., 2018). However, reduced or no-tilling practices are implemented as forms of soil conservation used in conjunction with cover cropping to improve soil health in agriculture fields. Farmers are unlikely to utilize full-width tillage to reduce vole populations, thereby sacrificing soil conservation efforts. Reduced tillage strategies, where a lesser portion of the soil area is disrupted, have been shown to reduce vole presence in agriculture fields (Roos et al., 2019), but it is not known if cover crops alter the negative effect of reduced tillage on vole abundance.

Methods used to plant cover crops and soybeans also have been suggested to reduce soybean depredation by voles (Fisher et al., 2014). Seed drills and planters intersect the soil surface, potentially disrupting burrows and may also protect seeds from predation by placing them beneath the soil surface or covering them over with soil. Other methods, such as broadcast spreading, leave seeds on the ground’s surface and do not disturb soil, thereby leaving soybeans open to predation and burrows and nests intact.

Managing quality of vole habitat in and adjacent to focal fields may also minimize risk of crop depredation. One strategy to deplete available habitat before soybeans are planted is to increase the time between cover crop termination and soybean planting (Fisher et al., 2014). Voles may feed upon soybeans as a consequence of the commodity crop being the only growing source of forage in a field after cover crops are terminated. Eliminating vole habitat provided by cover crops well before soybeans are planted may allow voles time to relocate to adjacent permanent habitats that provide more ideal cover and food or to be exposed to predation (Lin and Batzli, 2001; Smith and Batzli, 2006).

Lastly, the method used to terminate cover crops may influence vole survival, as some methods, such as roller-crimping, push cover crop plants flush with the ground and may create a barrier between predators and their vole prey (Klemola et al., 2000; Owen et al., 2019). Similarly, maintaining minimal vegetative cover by mowing, grazing, or chemically terminating the cover crop and adjacent permanent habitat may reduce vole populations by decreasing cover and opening the vegetative canopy to predators (Lin and Batzli, 2001; Peles and Barrett, 1996; Slade and Crain, 2006).

In addition to farming strategies that may be altered to reduce damage risk, we aimed to compare the relative importance of immutable features of the field, such as soil type, adjacent permanent habitat available to voles, and weather. Though farmers cannot manipulate these conditions to mitigate risk, identifying influential factors will allow farmers to identify fields or environmental conditions where damage risk is greatest and take preventative action to protect crops.

Soil texture and moisture retention affect voles' ability to burrow (Blank et al., 2011; Rhodes and Richmond, 1985), and well-drained soils support higher common vole populations in Europe (Santos et al., 2011). Suitable meadow and prairie vole habitat adjacent to cover-cropped fields, often provided by lands enrolled in the Conservation Reserve Program, grass waterways and road-side verges, can harbor vole populations in fragmented agroecosystems (de Redon et al., 2010; Rodriguez-Pastor et al., 2016; Santos et al., 2011). These permanent habitats enable voles to move into field interiors once cover and food are available (Lin and Batzli 2001; Smith and Batzli, 2006). Alternatively, adjacent forest landcover may be associated with reduced vole abundance. Many birds of prey, such as hawks, falcons, and owls are predators of small mammals and can help manage rodent populations in agricultural settings but often require perch sites from which to hunt (Kay et al., 1994; Machar et al., 2017; Motro, 2011).

Lastly, some weather conditions can affect vole survival and reproduction and may help farmers anticipate high risk for crop damage in years that have weather conditions favorable for voles. Sufficient snow cover provides protection from predators (Lindstrom and Hornfeldt, 1994) and insulation from extreme weather conditions during winter months (Esther et al. 2014; Tkadlec et al., 2006). However, ice may form below the snowpack and hinder movement and foraging activity (Korslund and Steen, 2006). Rainfall may also influence vole population fluctuations (Deitloff et al., 2010; Esther, 2014; Heisler et al., 2014), though effects may differ for prairie voles, which prefer drier sites, and meadow voles, which inhabit wetter sites (Findley, 1954; Getz, 1970).

Methods

Data Collection

We collected information for fields in the state of Indiana, located in the midwestern United States. Indiana is the third-ranked state in the USA for use of cover crops, with over 378,000 hectares of cropland planted to cover crops in 2017 (USDA NASS, 2019a). Indiana's geography and landcover composition becomes generally more topographically diverse, less agricultural, and more forested toward the unglaciated southern portion of the state. Weather also varies with latitude, with the northern and eastern parts of the state having generally colder temperatures across seasons than the southern and western areas (Arguez et al., 2010).

In 2017, we began contacting Indiana farmers using cover crops in corn-soybean rotations with the help of the USDA Natural Resources Conservation Service (NRCS). We asked willing participants to identify soybean fields from spring 2016 and 2018 that had been cover cropped the preceding fall. The National Aerial Imagery Program (NAIP) provided high-resolution imagery for 2016 and 2018 that allowed us to quantify vole damage and relate it to information provided by farmers.

For each qualified field, we mailed a 10-question survey (Appendix C; Purdue University IRB determined protocol #1710019818 did not meet the definition of human subjects research and did not require review) to the farmer who managed the field in the focal year. We inquired about the timing and method used for tillage, field edge management, and planting of cover crops and soybeans (Table 3.1). We also asked about the number of years cover crops had been grown in the field, and the species and height of the cover crops grown during study years. Lastly, we asked farmers which methods, if any, they used to control vole populations in the field. Collection of survey data continued through spring 2019.

To account for physical attributes of fields that may influence amount of vole damage incurred, we collected information on soils, habitat, and weather for individual fields (Table 3.1). We first calculated proportion of soils within fields that consisted of each of the seven soil hydrologic classes (USDA, 2009) reported by the Soil Survey Geographic database (USDA NRCS, 2019). We also quantified the proportion of land cover types within 50- and 100-meter buffers of each field. Each buffer polygon included the area of a field's interior to account for grass waterways or grassland strips that occurred within the field and could provide permanent habitat to voles. We consolidated landcover types reported in the Cropland Data Layer (CDL; USDA NASS, 2019b) to create variables for proportion of agriculture, forest, grassland, and water (Table 3.4).

Because roadside width is typically less than 30 m, the width of pixels displayed in the CDL layer, grassland habitat provided by roadsides is overshadowed by and classified as developed area (road surface) or agricultural land. To account for additional grassland habitat provided by roadsides, we measured the length of each road within the field buffer area that was parallel to agricultural landcover. We did not measure roads adjacent to other landcover types, such as grassland or forest, as we assumed that other landcover would be appropriately accounted for by the CDL layer. We multiplied the total roadside length for each field by 6 m, the average roadside width of local state and county roads. We then added roadside area to the grassland habitat variable and subtracted half of the roadside area from each of the landcover classifications that encompass roadside habitat, i.e., developed area and agricultural area. All GIS analysis was completed using ArcGIS Pro 2.3 (ESRI, 2018).

To partially account for factors that may affect vole survival and reproduction across years and latitudes, we included weather variables for each field (Table 3.1). We collected average daily temperature minima and total days of snow for cold-weather months (November to March) and average daily temperature maxima and total amount of rain for March to June. We recorded weather variables based on monthly summaries reported by the National Oceanic and Atmospheric Administration (NOAA) land-based weather stations (NOAA, 2019) closest to each field's location.

We measured total area of damage incurred by voles in each field using near infrared bands of NAIP imagery from 2016 and 2018 (USDA FSA, 2019). The 1-m resolution and infrared display of the images allowed us to sharply distinguish bare soil from growing vegetation within soybean fields. Vole damage appears as irregularly shaped patches of bare ground within soybean fields. The edges of vole damage patches are distinct, because detectable vole damage is the result of voles snipping young soybeans early in the growing season, which prevents regeneration and leaves a gap in the planting row (pers. obs.). Vole damage can be distinguished from mechanical damage because damage extends past a single planting row and does not typically occur at regular intervals (J. Rorick, Agronomist, Conservation Cropping Systems Initiative, pers. comm.). Flooding is also a common source of crop damage in Indiana. However, flood damage typically has less distinct edges due to gradual diminution in submersion effects on soybeans with increasing distance from the low points of flooded areas. All damage was identified and measured by a single observer (AAP), following the advice of an agronomist (J. Rorick) to ensure accuracy.

NAIP images were taken across the growing season, from approximately June to September. The size of damage patches shrinks as the season progresses and beans grow into the open space created by vole damage, which could result in underestimates of damage for late-season images. To quantify effects of plant growth on damage estimates, we tracked damage amount for a single test field using a series of RGB aerial photographs (provided by R. L. Nielsen and J. J. Camberato, Purdue University) taken biweekly across the 2016 growing season. All aerial imagery was viewed and measured in program ERDAS IMAGINE (Hexagon Geospatial, 2018).

Analysis

To adjust for variation in damage due to dates that photos were taken, we scaled damage for all fields to the same point relative to planting date. Using the test field for which we had bi-weekly photos, we fit a piecewise linear regression using R package ‘segmented’ (Muggeo, 2019) to the proportion of initial damage visible across time (Fig. 3.1). We specified time as the number of days between taking a photo and planting the field with soybeans. We then adjusted damage amounts for all study fields by using the piecewise regression to back-transform the proportion of damage visible at the time of the NAIP photo to 54 days post-planting, at which the maximum amount of damage was predicted to have been visible in the field. This adjustment allowed us to estimate damage visible at the same point in soybean growth for all study fields. We then transformed damage to the log-odds of damage, i.e., $\ln(p / 1 - p)$, where p is the proportion of the field damaged; this transformation removed effects due to field area and improved normality of the response variable.

We used boosted regression trees (BRT) (Elith et al., 2008; Hastie et al., 2001) to find covariates most influential in predicting the log-odds of vole damage to soybeans in a field. BRT uses machine learning to average results from a sequence of models built as regression trees (Hastie et al., 2001). By using BRT analysis, we were able to model non-linear relationships with the response variable and improve model accuracy (Hastie et al., 2001). We began by fitting models to predict damage as a function of farming practices, habitat, weather, and soils variables in R package ‘dismo’ (Hijmans et al., 2017). We used R package ‘caret’ (Kuhn, 2009) to select the learning rate (0.001) and interaction depth (1) that most reduced model deviance and used a bagging fraction of 0.6. After parameters were selected we used function gbm.simplify to detect variables that could be removed from analysis to help improve deviance and avoid overfitting. Finally, we refit a model with only variables deemed necessary by simplification and computed cross-validated model deviance to assess performance. We eliminated covariates until deviance ± 1SE increased above zero, resulting in a conservative model that only included variables that contributed to model performance. Due to high correlation between 50- and 100-m habitat variables, we chose to include only one set of buffer distances in our analysis. We compared via

AIC (Burnham and Anderson, 2002) a linear mixed model fit with all 50-m variables and farmer identity as a random effect to the same model except using 100-m variables to determine which distance had the strongest association with observed vole damage.

Results

We included 66 fields managed by 17 farmers in analysis. We received information for 92 fields, but NAIP photos for 26 fields were taken too early to show soybean growth, disqualifying those fields from analysis. Because we only sent surveys to farmers who agreed to participate and had previously identified field locations, we received answers for all distributed surveys, except one. The majority of fields were located in the northern half of the state, with 48.5% concentrated in the northwest quarter and 6.1% in the northeast. Field distribution in the south was uneven, with 39.4% of fields located in the southeastern quarter and 6.1% in the southwest.

For the test field used to adjust damage amounts to a common baseline, only 24% of the damage observed early in the growing season was still visible at the end of the season (Fig. 3.1). Moreover, piecewise regression revealed that the rate at which damage patches filled changed across the season. Prior to day 54, bean growth was not detectable using RGB aerial photography. From 54 to 86 days post-planting, damage patch size decreased at a rate of 0.025% per day. After day 86, damage decreased at a daily rate of only 0.0008% (Fig. 3.1).

After adjusting each field to reflect damage at 54 days after planting, damage ranged from 0 to 11.13%, with an average of 0.95%. Six fields did not exhibit any vole damage, and the greatest area of damage observed was 2.67 hectares in a 30.09-hectare field.

Habitat variables measured at 50 m better explained variation in the log-odds of damage compared to 100-meter variables (ΔAIC = 6.50) and thus were used for BRT analysis. Farmer reports of cover-crop termination methods, use of preferred vole forage as a cover crop, edge management methods, and vole control methods were all nearly invariant and thus were excluded from analysis. With few exceptions, farmers used herbicides to terminate cover crops, used grass and brassica cover crop types, which are not highly preferred forage for voles (Chapter 2), used mowing to manage permanent grass habitat at field edges, and did not employ any form of vole control for the years included in our study.

After simplification, the BRT model included 14 variables, explained 57.92% of total variation in log odds of vole damage to fields, and had a mean-squared error of 2.77. Cross-validated deviance explained was 25.12% (SE = 5.57%). Ten variables were determined to be unimportant in predicting vole damage and were removed from the final model: schedule, cover crop planting method, soybean planting method, cover crop diversity, A soils, C soils, D soils, AD soils, water, and spring high. Of the total variation explained by the model, snow days contributed the most to explaining vole damage risk (partial deviance = 16.66%), followed by percent BD soils (15.5%) and B soils (9.17%; Table 3.2). Percent grassland at 50 m was the top-ranked habitat variable (8.8%), and tillage (8.6%) and years planted (7.7%) were the top-contributing farm management strategies (Table 3.2).

Predicted odds of vole damage declined sharply as number of snow days increased (Fig. 3.2). Presence of BD and B soils increased the risk of vole damage, although only higher levels of BD soils resulted in greater-than-average levels of damage (Fig. 3.2). Small proportions of BD soils resulted in increasing levels of risk, but risk did not exceed the average damage level until approximately 60% were classified as BD. Fields with no B soils present exhibited a below-average risk of vole damage. However, any amount of B soils increased relative risk and quickly plateaued at average damage level. The top-ranking habitat variable, percentage of grassland, was positively associated with damage risk between 5 and 7% grassland within 50 m, but otherwise resulted in below-average levels of vole damage. Use of conservation tillage resulted in a reduced chance of vole damage, whereas no tillage resulted in an increased risk (Fig. 3.2). Lastly, the number of years cover crops had been used in a field was positively related to predicted odds of vole damage, with an asymptote of slightly above average damage for fields in cover crops ≥3 years. The contribution and effects of variables explaining minor amounts of variation in the data are shown in Table 3.2.

Discussion

Fields with high percentages of BD- and B-class soils were at highest risk for vole damage in years with minimal snow cover. Voles prefer loam-textured soils with moderate moisture content (Rhodes and Richmond, 1985; Santos et al., 2011). Loam soils contain minimal rock and gravel material, which allows for easy digging, but are also well drained which prevents flooding of burrow systems. B-class soils are loamy sand or sandy loam soils that are moderately well drained (USDA, 2009) and therefore provide ideal habitat for voles to burrow. BD soils have the same textural components as B soils but are associated with water tables present at or closer than

60 cm below the ground's surface (USDA, 2009). High water tables are negatively associated with burrowing mammal presence (Bertolino et al., 2015; Ingles, 1949), but agricultural fields in Indiana often are drained using subsurface tile-drainage systems. Removing saturation from BD soils would effectively allow them to function as B-class soils and thereby allow vole burrowing activity.

Snow cover provides protection from predators and extreme ambient temperatures (Heisler et al., 2014; Lindstrom and Hornfeldt, 1994). However, in Indiana presence of snow negatively impacted vole damage to soybeans. This may be due to limited access to forage when snow is on the ground and, consequently, reduced survival (Korslund and Steen, 2006), as well as unrealized benefits due to shallow and fluctuating snow cover. Indiana receives 35 to 190 cm (approximately 8.75 to 47.5 cm per winter month) of snow cover on average, but only the northern-most counties receive maximal snowfall due to proximity to Lake Michigan (Arguez et al., 2010). Other regions of the state receive more modest amounts of snow that typically do not remain on the ground for extended periods during winter. Benefits to voles, such as insulation from extreme ambient temperatures and protection from predators, may not be realized when snow depth is minimal or when snow cover is not continuous. Johnson et al. (2017) showed that voles at high altitudes benefitted from continuous snowpack, whereas voles had decreased survival at lower elevations where snow cover fluctuated. Additionally, insulation from extreme ambient temperatures only occurs once the snowpack exceeds 20 cm (Pruitt, 1957). In Indiana, where snow fall events rarely accumulate to 20 cm, voles are left vulnerable to extreme temperatures and remain susceptible to predation between snow events.

Although we found a negative relationship with snow, we do suggest caution, as our data encompassed only 2 winters. Exceptional years with large amounts of long-lasting snow cover may improve vole survival compared to years with fluctuating snowfall (Johnson et al., 2017) and result in increased crop damage.

Producers may reduce probability of vole damage in high-risk fields, despite weather and soil conditions, by implementing conservation tillage and managing grassland habitat adjacent to fields. Of the farm-management practices we tested, strip or vertical tillage had the most influence on vole damage. Tilling before planting in the spring, rather than in fall, may more effectively reduce vole populations (Heroldová et al., 2018). Soil disruption rapidly reduces vole populations and lasts long enough to allow soybeans time to grow while vole populations are low (Jacob, 2003;

Roos et al., 2019). However, the time between fall tillage and soybean planting in spring may be sufficient for voles to repopulate fields before soybeans are sown (Getz et al., 2001). Though strip and vertical tillage are associated with reduced damage risk, farmers should weight possible negative effects of reduced tillage on soil health (Overstreet and Hoyt, 2008) with benefits of vole management. Tilling areas of known vole activity, rather than the entire field, may be one option to balance vole management with soil conservation. However, further study is needed to evaluate effectiveness of targeted tillage in preventing damage incurred by voles.

Grasslands adjacent to high-risk fields can be managed during years that are most likely to incur vole damage, as we found that fields with the lowest proportion of grasslands had the lowest risk of receiving vole damage. Adjacent grass habitats harbor voles in agricultural landscapes (de Redon et al., 2010; Rodriguez-Pastor et al., 2016; Santos et al., 2011; Witmer et al., 2007), but maintaining short vegetative cover through mowing, grazing, or burning in these areas can be effective at preventing high populations (Clark and Kauffman, 1989; DeGolier et al., 2015; Lagendijk et al., 2019; Lemen and Clausen, 1984; Slade and Crain, 2006). Though keeping vegetation short will reduce presence of voles, farmers should optimize timing of grassland management strategies to balance vole population reduction efforts with maintaining benefits of having grassland habitat on the landscape. Some grassland management strategies negatively impact other wildlife, such as grassland birds, when improperly implemented (Bryan and Best, 1991; Dale et al., 1997; Gruebler et al., 2008). Reducing vegetative cover in adjacent grassland habitat only in winters preceding a soybean crop and retaining dense cover in other years may be one strategy to balance vole management with negative impacts on other wildlife.

An increase in nearby grassland habitat between 5 and 7% caused a spike in odds of vole damage, followed by a decline to below-average damage levels. This may be indicative of a threshold level of grassland habitat that provides enough resources for voles to persist long term but does not contain sufficient resources to support large populations in years of peak vole abundance, forcing voles to find additional habitat in nearby agriculture fields (Desy et al., 1990; Getz et al., 2005). Additionally, small areas of grassland habitat may harbor voles, but not attract some predators that prefer to optimize hunting efforts (Meunier et al., 2000). Predation pressure dampens effects of rodent population fluctuations, extends trough stages of vole population cycles (Erlinge, 1983; Hanski, 1991), and also reduces movement distances (Desy et al., 1990), all of which may prevent or delay voles from moving into agricultural fields. Our results suggest that as an alternative to reducing amount of grassland habitat, which nullify benefits of having grasslands near fields (Altieri, 1999), farmers can increase grassland area to encourage use by predators and reduce risk of vole damage.

Lastly, we found that number of years that a field has been planted with cover crops is positively associated with vole damage. Long-term use of cover crops reduces soil compaction and increases organic material (White, 2014), creating more friable and moisture retentive soils, conditions ideal for vole burrowing behavior. The number of years a field has been planted to cover crops can be altered by farmers. However, benefits of cover crops, which likely outweigh the costs incurred by vole damage (Chapter 5), could eventually be degraded. An alternative to abandoning use of cover crops may be to acknowledge long-term cover crop fields as higher risk, as with fields containing high proportions of B and BD soils, and create focused management plans for these fields which include tillage and grassland habitat management.

Two caveats merit mention. First, with our limited sample size, we were unable to test the importance of several farm management strategies, including method of cover-crop termination, species of cover crops planted, and methods of vole control. Nonetheless, we suspect that some variables not tested may play a role in enabling or mitigating vole damage. We suggest that farmers consider additional strategies to reduce vole presence in and around cover-cropped fields and attempt to monitor responses of vole populations using an adaptive management framework. Second, many farmers who participated in our study provided information for multiple fields, which likely introduced correlation structure among fields. Unfortunately, boosted regression trees do not allow for incorporation of random effects. Although inclusion of weather and soils variables likely accounted for some spatial correlation, future work conducted over a longer period with a larger number of independently selected fields is needed to assess the generality of our results.

Conclusions

We identified field attributes and farming practices most important to mitigating vole damage to cover-cropped fields. Damage was variable across fields, but average damage levels were minimal. Fields that have been cover cropped for $\geq$3 years and contain high proportions of well-drained soils and 5-7% grassland habitat within 50 m will be at most risk for vole damage. Damage levels will be higher in years when snow cover is minimal. In years and fields where high damage levels are anticipated, farmers can implement a form of conservation tillage to reduce vole abundance shortly before planting the commodity crop. Additionally, producers can minimize quality of vole habitat near high-risk fields by maintaining short, less dense vegetative cover in nearby grasslands to prevent vole populations from growing too large. Alternatively, they can increase availability of grassland habitat on the landscape to encourage use by vole predators. Because our research did not evaluate all possible field management strategies, we recommend additional research that evaluates other management techniques that can be used for mitigating vole damage to cover-cropped agricultural fields.

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Table 3.1—Variables evaluated for importance to predicting risk of vole (*Microtus*) damage to cover-cropped fields in Indiana, USA.

Variable	Source	Description
Farming Methods		
Years Planted	Farmer Survey	Total number of years overwinter cover crops were planted in the field.
Schedule	Farmer Survey	Whether cover crops were planted in continuous or alternate years.
Rest Period	Farmer Survey	Amount of time between when cover crops were terminated and soybeans were planted.
Cover Crop Planting	Farmer Survey	Whether cover-crop seeds were planted using a method that disturbed the soils surface, including drilling or planting, or were broadcast or aerially spread.
Soybean Planting	Farmer Survey	Method of soybean planting. Includes planting or drilling.
Cover-Crop Height	Farmer Survey	Maximum height of cover crop determined by height of non-winter killed species present at termination in the spring.
Tillage	Farmer Survey	Whether or not a reduced-tillage method was used.
Cover-Crop Diversity	Farmer Survey	Number of cover-crop species planted in fall.
Landscape Attributes		
A Soils (%)	SUURGO Database	Well-drained soils consisting mostly of sand or gravel.
B Soils (%)	SUURGO Database	Moderately well-drained soils consisting mostly of sand, but with higher clay content than A soils.
C Soils (%)	SUURGO Database	Somewhat poorly drained soils consisting of up to 40% clay and less than 50% sand.
D Soils (%)	SUURGO Database	Poorly drained soils with more than 40% clay and less than 50% sand.

Table 3.1 continued

Dual Soil Groups (e.g. AD) (%)	SUURGO Database	Presence of a water table within 60 cm of soil surface, making the area prone to flooding and reduced drainage. The first letter in the class describes soils class when the area is drained.
Agriculture (%)	Cropland Data Layer	Percent landcover dedicated to row-crop agriculture within the field and buffered area.
Grassland (%)	Cropland Data Layer	Percent landcover composed of natural grassland area, fallow field, or pastureland within field and buffered area. Also includes estimate of grass habitat provided by roadsides.
Forest (%)	Cropland Data Layer	Percent landcover composed of deciduous or evergreen forests and shrubland.
Water (%)	Cropland Data Layer	Percent landcover composed of standing water, including herbaceous and wooded wetlands.
Weather		
Snow Days	NOAA Weather Station	Count of days between November and March when snow ground cover was above 7.62 cm. If snow was present during a warming period at or above 32 ºF aerial temperature, snowpack on that and the following days were counted as Ice Days.
Ice Days	NOAA Weather Station	Count of days between November and March of ice ground cover determined by rainfall and subsequent freezing temperatures, melting and re-freezing of the snowpack, or snowpack less than 7.62 cm.
Winter Low (ºF)	NOAA Weather Station	Average low temperature from November to March.
Spring Rain	NOAA Weather Station	Total rainfall from March to June.
Spring High (ºF)	NOAA Weather Station	Average high temperature from March to June.

Table 3.2—Contribution of habitat, farming practices, and soil hydrologic classes to explaining variance in risk of vole (*Microtus*) damage to cover-cropped soybean fields. Farming practices and physical attributes pertaining to the 2016 and 2018 soybean growing season were collected for 66 fields located across the state of Indiana, USA.

Factor	Relative Influence (%)
Snow days	16.66
BD soils	15.50
B soils	9.17
Grassland	8.80
Tillage practices	8.57
Years planted	7.70
Agriculture	7.57
Forest	5.69
CD Soils	4.85
Spring rain	4.42
Ice days	4.22
Winter low	2.68
Cover crop height	2.65
Rest period	1.52

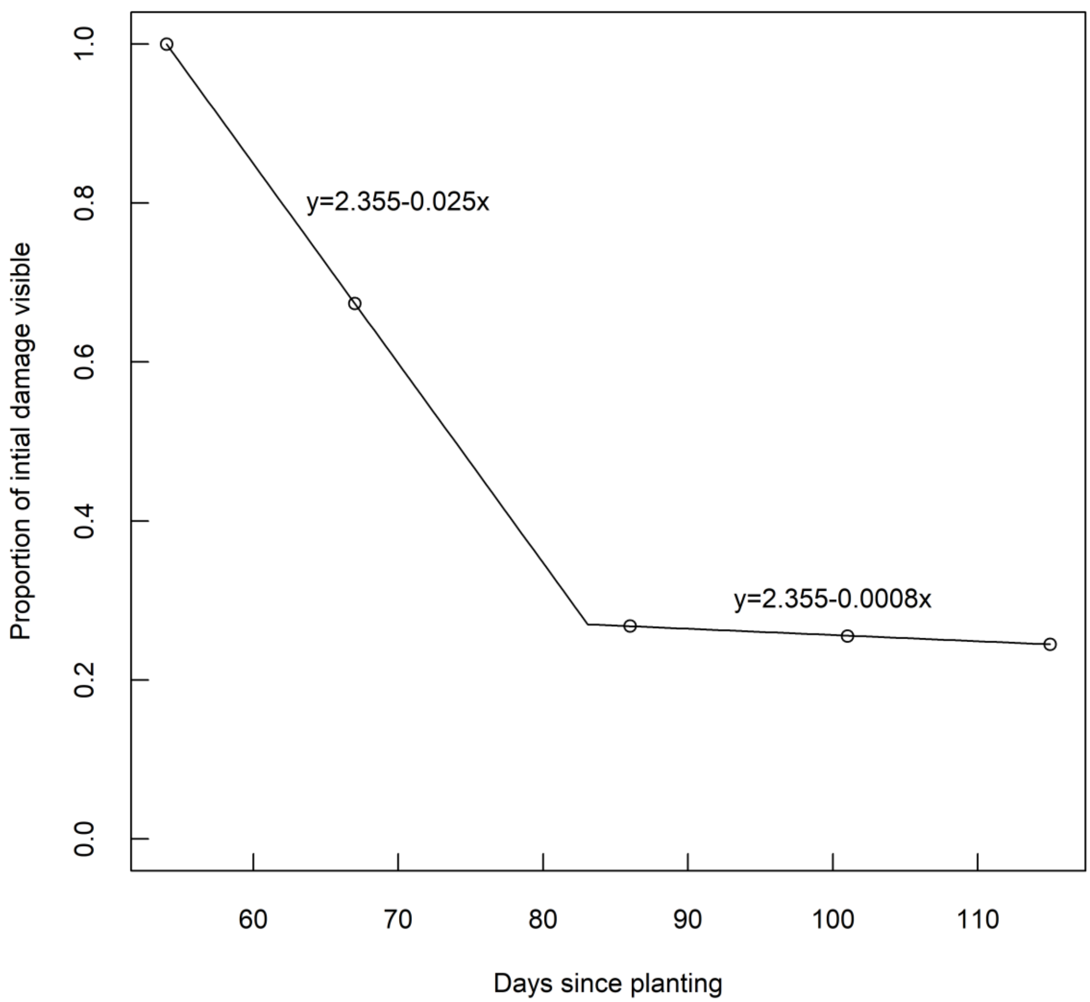

Figure 3.1—Appearance of damaged crop area incurred by voles (*Microtus*) in a cover-cropped soybean field as a function of time. Data were fit with piecewise linear regression to reflect the threshold at which beans are at maximal growth and have covered damaged area as much as possible. Damaged area was measured approximately biweekly from June to September 2016 for a field located at the Southeast Purdue Agricultural Center, Indiana, USA.

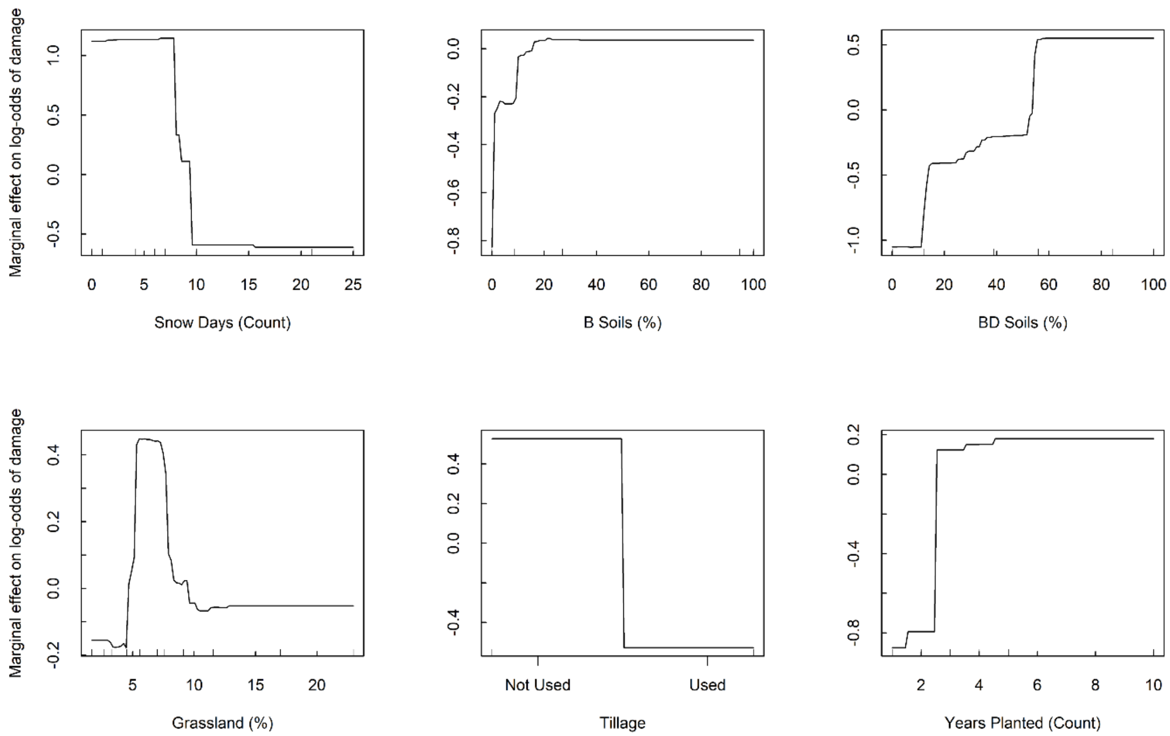

Figure 3.2— Partial dependence plots and percent variation explained for the six most important variables of 24 tested for predicting risk of vole (*Microtus*) damage in cover-cropped soybean fields in Indiana, USA. Practices and physical field attributes pertaining to the 2016 and 2018 soybean growing season were collected for 66 fields located across the state.

CHAPTER 4. USING VOLE ACTIVITY SURVEYS TO PREDICT DAMAGE TO COVER-CROPPED SOYBEANS

Abstract

Across the Midwestern United States, farmers have increasingly used winter cover crops in corn-soybean rotations to improve soil health. Though this practice has many benefits, it also can provide habitat for potential pest species, such as voles (*Microtus pennsylvanicus* and *M. ochrogaster*). Voles have been reported by farmers to damage soybean plants in cover-cropped fields, but little has been done to quantify levels of damage related to their abundance. We evaluated the relationship between vole sign and soybean damage to help farmers manage this unintended consequence of using cover crops. We counted frequency of vole sign along transects in cover-cropped fields. In addition to vole sign, we considered influence of cover-crop density, distance to field edge, and presence of artificial raptor perches when fitting negative binomial models to predict amount of soybean damage. An additive model including all explanatory factors best explained variation in vole damage. Encounter rates with burrow entrances were positively associated with soybean damage, as were raptor perches and cover-crop density. Insufficient numbers of vole runways were detected to evaluate a relationship with damage. Farmers may use frequency of burrow clusters to predict relative amounts of damage incurred; conditions in a field should be considered when deciding to manage for reduced vole populations before planting of soybeans.

Introduction

Cover crops are non-commodity plant species sown in agricultural fields after the commodity crop has been harvested. Cover crops increasingly have been used in intensive row-crop agriculture over the last decade to improve soil health and retention and reduce chemical inputs (White, 2014). In addition to providing agricultural benefits, cover crops furnish wildlife habitat during parts of the year when traditionally managed fields only contain crop stubble or bare ground (Berl et al., 2018; Jug et al., 2008; Wilcoxen et al., 2018). Increasing availability of wildlife habitat in highly fragmented agricultural ecosystems is generally viewed as positive (Altieri, 1999). However, creating habitat for wildlife in crop fields increases potential for human-wildlife conflict when species that use the fields consume the commodity crop (Wiman et al., 2009; Witmer et al., 2007).

Meadow voles (*Microtus pennsylvanicus*) and prairie voles (*M. ochrogaster*), two species associated with grassland habitat in Indiana (Reich, 1981; Stalling, 1990), are suspected to inhabit cover-cropped fields and cause damage to soybean plants (Fisher et al., 2014; J. Rorick, Agronomist, Conservation Cropping Systems Initiative, pers comm.). Cover crops provide overhead cover and forage needed by both vole species to persist in fields (Chapter 2; Carroll and Getz, 1976; Mackin-Rogalska et al., 1986), but after the cover crop is terminated in preparation for soybean planting, little fresh forage is available. For voles that remain in fields after termination of cover crops, soybean seedlings are likely an important source of fresh forage.

Because cover cropping is an emerging practice in row-crop agriculture, few scientific studies are available to help farmers predict vole damage to cover-cropped soybeans. Additionally, meadow and prairie vole populations are cyclical (Getz et al., 2001) which results in variation in damage severity between years and makes the need for vole management in all years unnecessary. Damage in individual fields also can vary according to weather patterns, physical features of fields, and farming practices used (Chapter 3). To enable farmers to identify fields that may require vole management prior to planting soybeans, our primary objective was to calibrate indices of vole abundance, previously tested in other ecosystems, for use in cover-cropped soybean fields and expand upon them by identifying associations with amount of soybean damage. Formulation of an accurate index of vole damage would allow farmers to focus vole reduction efforts in fields that are likely to have the most damage.

Previous research has identified encounter rates of fecal material (Quere et al., 2000), runways (Carroll and Getz, 1976; Krohne, 1982; Lidicker and Anderson, 1962), reopened burrows (Blank et al., 2011; Liro, 1974), and burrow clusters (Mackin-Rogalska et al., 1986) as accurate methods to detect vole presence and predict fluctuations in density. We evaluated the relationship between counts of vole runways and burrow entrances to the amounts of soybean damage, because these indicators are easy to detect and require little to no equipment to measure. These methods, therefore, are more practical for farmers who manage large amounts of land or have limited time and resources for detecting voles with more direct methods like trapping.

In addition to evaluating ways to predict vole damage, we assessed possible strategies to mitigate risk. One approach to limit rodent populations in agricultural systems is to encourage raptor hunting by installing artificial perches within fields (Hall et al., 2006; Kay et al., 1994; Machar et al., 2017; Sheffield et al., 2001). Predators can reduce damage directly by killing voles and indirectly by inhibiting vole movements (Desy et al., 1990), which may limit access to crop plants.

Perches provide an increased number of aerial predators access to in-field vole populations. However, quality of the cover-crop stand may mitigate the influence of predators. Tall cover-crop growth may obscure prey movements from predators, enabling higher survival rates (Getz et al., 2005; Lin and Batzli, 2001; Slade and Crain, 2006). Cover quality also may affect movement of voles into the interior of fields. Voles persist year-round in permanent grassland habitat on the edge of fields (de Redon et al., 2010; Rodriguez-Pastor et al., 2016), and may move into field interiors when cover grows to sufficient heights. We tested whether vole damage is likely to be greater near the field edge, where voles that live in permanent habitat and voles living within fields have access to soybeans. We also explored whether density of the cover crop affects damage levels.

Our last objective was to identify the date and vegetation density at which the greatest number of burrows could be detected to help better advise farmers on when to scout fields for vole sign. Vole survival and reproduction often spike in spring (Getz et al., 2001), when farmers are terminating cover crops and planting soybeans. Later survey dates, which typically accompany warm weather that promotes plant growth and increased vole foraging opportunity, should be associated with higher encounter rates of vole sign and enable a more accurate prediction of whether damage will occur. Conversely, denser vegetation also is characteristic of later survey dates and may obscure vole sign (Heroldová et al., 2018), making it harder for farmers to detect.

Our objective was to investigate tradeoffs of date and vegetation density that might allow us to recommend timing and conditions for farmers to scout fields for vole sign.

Methods

Data Collection

We surveyed 38 cover-cropped soybean fields located within 100 km of Lafayette, Indiana. Indiana ranks third in the United States in total area of cover-cropped agricultural land, and cereal rye (*Secale cereale*) is the most commonly planted overwinter cover crop in the United States (CTIC & SARE, 2016). We chose study fields that were planted to a cereal rye cover crop to reduce variation among fields due to type of cover crop.

In spring 2018 and 2019, we surveyed fields for sign of voles. We walked 45-m transects while looking for runway tracks that intersected the transect (Lidicker and Anderson, 1962) and searched for burrow entrances ≤5 m from the transect line. Vole runways are 2.5-5 cm-wide tracks that are cleared of vegetation and associated with plant clippings and feces when active (Dolbeer et al., 1994). For each burrow hole located, we marked the location using a GPS and subsequently attributed a burrow entrance to voles if it was located ≤5 m from another burrow (Davis and Kalisz, 1992). In Indiana, deer mice (*Peromyscus maniculatus*) are permanent residents in agricultural fields but are more frequently associated with single burrow holes (Berl et al., 2017a; Davis and Kalisz, 1992; Houtcooper, 1972). Burrows were counted unless notably inactive, as indicated by cave-ins or the burrow having been dug out by predators. Additional to surveying for vole sign, we measured the density of cover crops every 5 m along the transect with a Robel pole (Robel et al., 1970), and subsequently computed mean cover crop density for each transect.

We organized transects in groups of three to provide coverage across grid-trapping sites. The intent of this arrangement was to derive independent estimates of vole abundance and evaluate the relationships between vole abundance, vole sign, and amount of soybean damage. However, we failed to capture voles within 13 fields trapped in both years of the study (Appendix D), despite detecting sign, and thus were unable to answer questions related to vole abundance. Grouped transects were spaced 30 m apart and were placed perpendicular to the field edge at 50 or 200 m from the edge. As part of a companion study, 16 fields contained artificial perches installed to evaluate raptor use of cover-cropped fields (Zagorski, 2019). In these fields, we also included transects at 50- and 200-m perch sites.

In the summer when soybeans were in vegetative growth stages VC to V7 (Licht, 2014), we surveyed for vole damage. When possible, we aligned damage transects with those we searched in the spring. To accurately count the number of soybean plants surveyed, we aligned damage transects with the direction of planting rows, which were not always parallel to the field edge. Therefore, damage transects and transects surveyed for sign did not always perfectly coincide. We looked for soybean depredation within two soybean rows on either side of each damage transect. Plants that were missing were only attributed to vole damage if there was vole sign near the missing plant, or if the pattern of damage was consistent with large-scale vole damage. Sign of vole damage in a field often manifested in irregularly shaped bare patches that spanned several planting rows and often was associated with burrow holes and runways within the bare area (Chapter 3). When plants were damaged but not missing, rodent foraging sign was easily distinguished from deer clipping, in which a tendril of vegetation is left from the deer stripping instead of cleanly nipping vegetation due to lack of upper incisors (Dolbeer et al., 1994). Rodents use top and bottom teeth to cut vegetation cleanly, typically at an angle (Dolbeer et al., 1994). Deer mice are the only other rodent commonly found in agricultural fields (Berl et al., 2017a, 2018), however, they rarely eat the soybean crop (Berl et al., 2017b). Therefore, we attributed all rodent damage found in our surveys to voles.

Concurrent with damage surveys, we counted the number of soybeans in a 1-meter segment every 10 m along the transect. Occasionally, we would encounter an area of damage in which the soybean stalks were no longer present, prohibiting a precise count of damaged soybeans. For these areas, we measured the length of the planting rows included in the damaged area and multiplied that length by the average soybeans per meter for the transect. Additionally, we used mean soybean density to estimate the total number of plants surveyed for each transect.

Analysis

Because each transect within a group was spatially proximal to its other group members, we evaluated the degree of damage similarity between grouped transects to determine if data should be pooled. To derive a null distribution, we randomly selected with replacement three transects from across all fields, conditional upon distance from edge, and calculated variance in the fraction of damage for each triplet thus selected. We then computed for each triplet the variance in fraction of soybeans damaged. We compared the null and observed distributions of variances using a Kolmogorov-Smirnov test (Conover, 1980) with 1000 replicates for the random triplets of transects (500 each at 50m and 200m).

We modeled counts of damaged soybean plants as a function of density of the cover crop, presence of artificial raptor perches, distance from field edge, and frequency of vole sign detected using negative binomial linear models with mixed effects in R package 'glmmTMB' (Magnussun et al., 2019). We included field identity as a random effect in all models to account for differences in farming strategies and environmental factors that differed between fields (Chapter 3). The number of soybeans surveyed also was included as a fixed effect to adjust for higher counts of damaged plants in fields where soybeans were more densely planted.

Because only 16 of 38 fields were provisioned with perch sites, we first applied models to the 16-field subset to evaluate the effect of perches on probability of vole damage in fields where perch and no-perch sites could be directly compared. We then compared these results to models fit to the full dataset, including perch fields and fields not containing perches, to assess which factors were important to predicting soybean damage.

We compared 18 intercept-only, additive, and interactive models using AICc (Burnham and Anderson, 2002) and determined model fit and importance of the random effect using conditional AIC (Saefken et al., 2014) and R^2 (Nakagawa and Schielzeth, 2013) in R packages 'cAIC4' (Saefken and Ruegamer, 2018) and 'MuMIn' (Bartoń, 2019).

To inform recommendations on conditions affecting survey efficacy, we modeled number of burrow entrances detected along a transect as a function of vegetation density, ordinal date, a second-order polynomial of ordinal date, and field identity included as a random effect using negative binomial linear mixed models in R package 'glmmTMB' (Magnussun et al., 2019). We confirmed lack of multicollinearity between fixed effects by computing variance inflation factors (VIF) in R package 'car' (Fox and Weisberg, 2019). A global model and 6 of its proper subsets were compared with an intercept-only model using AICc (Burnham and Anderson, 2002). All analyses were completed using program R (R Core Team, 2018).

Results

Damage severity ranged from 0 to 14.1% of soybeans damaged along transects. Of 315 transects sampled, 305 exhibited <2.5% damage, and 129 of these experienced no damage. When surveying for vole sign in spring, we detected only 10 runways intersecting the 314 transects. Therefore, we did not explore further the relationship between runway sign and vole damage. Number of burrow entrances ranged from 0 to 25, but there were only 3 instances of >10 entrances detected along a single transect, and 266 transects (84.4%) had no vole burrows.

Contrary to expectations, the mean variance for fraction of damage in transect triplets was 1.06 times larger than the mean variance for randomly selected triplets; the Kolmogorov-Smirnov test did not detect differences in the observed and null distributions of variances (D = 0.02, P = 0.92), although the P value was approximate because of a large fraction (0.26) of tied values (Fig. 4.1). Because we failed to detect any decline in variance for triplets, we treated transects as independent observations in subsequent analysis.

Comparison of models fit to data from the subset of fields with both perch and non-perch sites resulted in a best-fit additive model that included all fixed effects, though a model containing only number of soybeans surveyed and number of burrow entrances competed (ΔAICc = 1.68). For the top model, all factors except for the number of soybeans surveyed (X^2 = 1.42, P = 0.234) and vegetation density (X^2 = 0.19, P = 0.66), were important to the fit of the model; unexpectedly, the presence of perches was associated with increased damage to soybeans (z = 2.62, P = 0.008).

The global model containing all fixed effects and field identity modeled as a random intercept best explained variation in vole damage to soybeans for the full data set. All effects were important to model fit, although the contribution of distance from field edge was weak (Table 4.1). Transects 200m from the field edge were associated on average with 1 less soybean damaged than in transects 50m from the edge, assuming average values for all other covariates (Fig. 4.2). Number of soybeans surveyed, presence of perches, number of burrow clusters detected, and vegetation density resulted in an increase in expected damage (Table 4.1, Fig. 4.2). Number of burrow entrances had the greatest effect on predicted number of soybeans damaged compared to other factors included in analysis (Table 4.1, Fig. 4.2), with mean number of entrances ($\bar{x}$ = 0.87) resulting in 4 soybeans damaged, but maximal number of burrows (n = 25) resulting in 261 soybeans damaged. The global model predicted 4 damaged soybeans at mean vegetation density ($\bar{x}$ = 5.30 cm obstructed), and 6 plants damaged for a 1 SD increase (to 8.63 cm obstructed). Perch presence resulted in an average of 3 additional soybeans damaged compared to sites without perches. The random effect of field identity greatly improved model fit ($X^2 = 46.52$, $P < 0.001$) and explained a substantial proportion of the variation in vole damage (marginal R^2 due solely to fixed effects = 0.29, conditional R^2 incorporating field identity = 0.88).

Contribution of ordinal date and vegetation density to the probability of a burrow cluster being detected was insubstantial. Five models performed slightly better than the intercept-only model (ΔAICc<2.0), but all models tested were within 4 ΔAICc of the top model. The best model included ordinal date of burrow surveys, and later dates were positively associated with probability of detecting vole burrows ($z = 2.4$, $P = 0.017$). A 1-SD increase from the mean, i.e., from day 109 (April 19), to day 121 (May 1) resulted in an estimated 1.4 additional burrow entrances found. Multicollinearity of ordinal date and vegetation density was minimal (VIF = 1.22).

Discussion

Number of vole burrow entrances had the strongest effect of all factors tested (Table 4.1, Fig. 4.2). The confirmed relationship between burrow entrances and damage levels further supports the hypothesis that voles present in fields in the spring remain in fields after cover-crop termination and consume soybeans once fresh forage becomes limited, rather than moving into fields to selectively consume soybeans after they are planted. As expected, vole sign was not the only factor that was associated with vole damage. Increasing quality of the cover crop stand, as measured by vegetation density, also had a sizable effect on estimated odds of damage (Fig. 4.2). The highest mean density of vegetation we sampled was 23 cm visually obscured and was predicted to correspond to 33 soybeans damaged. Meadow and prairie voles prefer tall vegetation, and their populations can become large when cover is dense (Lemen and Clausen, 1984; Lin and Batzli, 2001; Slade and Crain, 2006; Smith and Batzli, 2006). Hence, as cover crops grow or are seeded at dense rates, they provide increasingly better habitat for voles. Dense cover-crop vegetation also provides continuous cover into the interior of fields, which may allow voles to travel further from the field edge where permanent habitat exists (Smith and Batzli, 2006), thereby allowing access to a larger number of soybean plants.

Finding greater damage near perch sites was unexpected, as enhancement of raptor predation with perches has proven effective at rodent management in other studies (Kay et al., 1994; Machar et al., 2017). However, reduction in rodent populations may not translate to reduction in crop depredation if prey populations are low. Kay et al. (1994) failed to detect a decrease in house mouse (*Mus musculus*) damage to soybeans at artificial raptor perch sites, which they attributed to low mouse densities during study years. Importantly, the magnitude of effect of perches was minimal compared to burrow entrances and cover crop density (Fig. 4.2). Rather than a positive effect of perches, we suspect that vole populations were not large enough for aerial predators to alter their normal habit of hunting field margins and focus their hunting efforts in fields. Although raptors used artificial perches in the study fields, use was infrequent (Zagorski, 2019). The timing of perch availability may also have affected the pattern we observed. Perches were present in fields from January to approximately the end April (Zagorski, 2019). Predation is most effective at stabilizing rodent populations if it occurs when vole populations are growing (Erlinge et al., 1983; Hanski et al., 1991), and vole reproduction often spikes in the spring in the Midwest (Getz et al., 2007). Spring, however, is also when farmers enter fields to terminate cover crops, which in our study necessitated removal of perches. Further study is needed to evaluate the benefit of replacing perches after cover crop termination or installing permanent perches.

Field identity was important in explaining variation in vole damage. Though more vole sign indicates higher levels of damage, the random field effect indicated that transects in some fields, due to factors not considered in this study, incurred more (or less) damage than others. Farming techniques used within fields and physical characteristics of fields, such as loamy soils and nearby grassland habitat, can account for variation in vole damage (Chapter 3). These factors differ between fields and may contribute to variation explained across fields. Monitoring may be most effective if farmers scout the same fields in continuous years and compare vole sign across years for individual fields, rather than comparing vole sign and damage between fields.

We were able correlate amount of soybean damage incurred by voles to the abundance of vole sign. However, due to lack of variation in vole sign detected and few samples of vole sign over 10 burrows per 45 m, we were not able to create a widely-applicable index that farmers can use to anticipate damage. The local vole population was likely in a trough phase during the years of our study (Getz et al., 2001), which resulted in little damage and, we assume, comparably infrequent vole sign at study sites. In 2016, the year before our study, farmers across Indiana reported widespread damage by voles (Fisher et al., 2014; J. Rorick, Agronomist, Conservation Cropping Systems Initiative, pers comm.). However, few problems were reported in 2018 and 2019 (S. Zezula, State Resource Conservationist, Indiana Natural Resources Conservation Service, pers comm.). Additionally, over 3,900 nights of live trapping for voles yielded no voles within field boundaries and 8 individuals in permanent habitats at field edges (Appendix D). To calibrate an accurate index that farmers can use to predict levels of damage in all years, we would require greater range in the number of burrow clusters found, and ideally would include data for a season when the vole population is at peak abundance (Lisicka et al., 2007; Village and Myhill, 1990).

We focused exclusively on fields planted with a cereal rye (*Secale cereale*) cover crop, as it was the most commonly used cover crop in Indiana. Carrol and Getz (1976) detected different relationships of vole sign and population abundance in alfalfa (*Medicago sativa*) and bluegrass (*Poa pratensis*) habitats. Consequently, the relationship of vole burrow entrances to damage found in our study only applies to cereal rye fields. Farmers could benefit from future work that considers how type of cover crop influences frequency of vole sign, variation in damage and their relation to the factors we considered. Other popular cover crop types, such as clovers or alfalfa (CTIC & SARE, 2016), are preferred forage for meadow and prairie voles (Chapter 2; DeJaco and Batzli, 2013) and provide different cover quality (Getz et al., 2001). Thus, they may result in different levels of soybean damage and treatment effects than fields planted to cereal rye.

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Table 4.1— Model summary for the AIC-best negative binomial regression model predicting damage to cover-cropped soybeans incurred by voles (*Microtus*). Sign of vole burrow clusters and cover crop vegetation density along linear transects was collected in spring 2018 and 2019 in fields in west-central Indiana. Damaged soybeans were counted at or near the same transects in summer 2018 and 2019. Perch site and distance from field edge are relative to baselines of non-perch sites and 50 m, respectively. X^2 and P values correspond to drop-in-deviance tests.

Effect	Coefficient	*SE*	X^2	*P*
Number of soybeans surveyed	0.35	0.16	4.74	0.029
Perch site	0.67	0.27	6.26	0.012
Number of burrow entrances	0.48	0.10	21.12	<0.001
Cover crop density	0.39	0.17	5.06	0.025
Distance from field edge, 200 m	-0.32	0.22	2.21	0.137

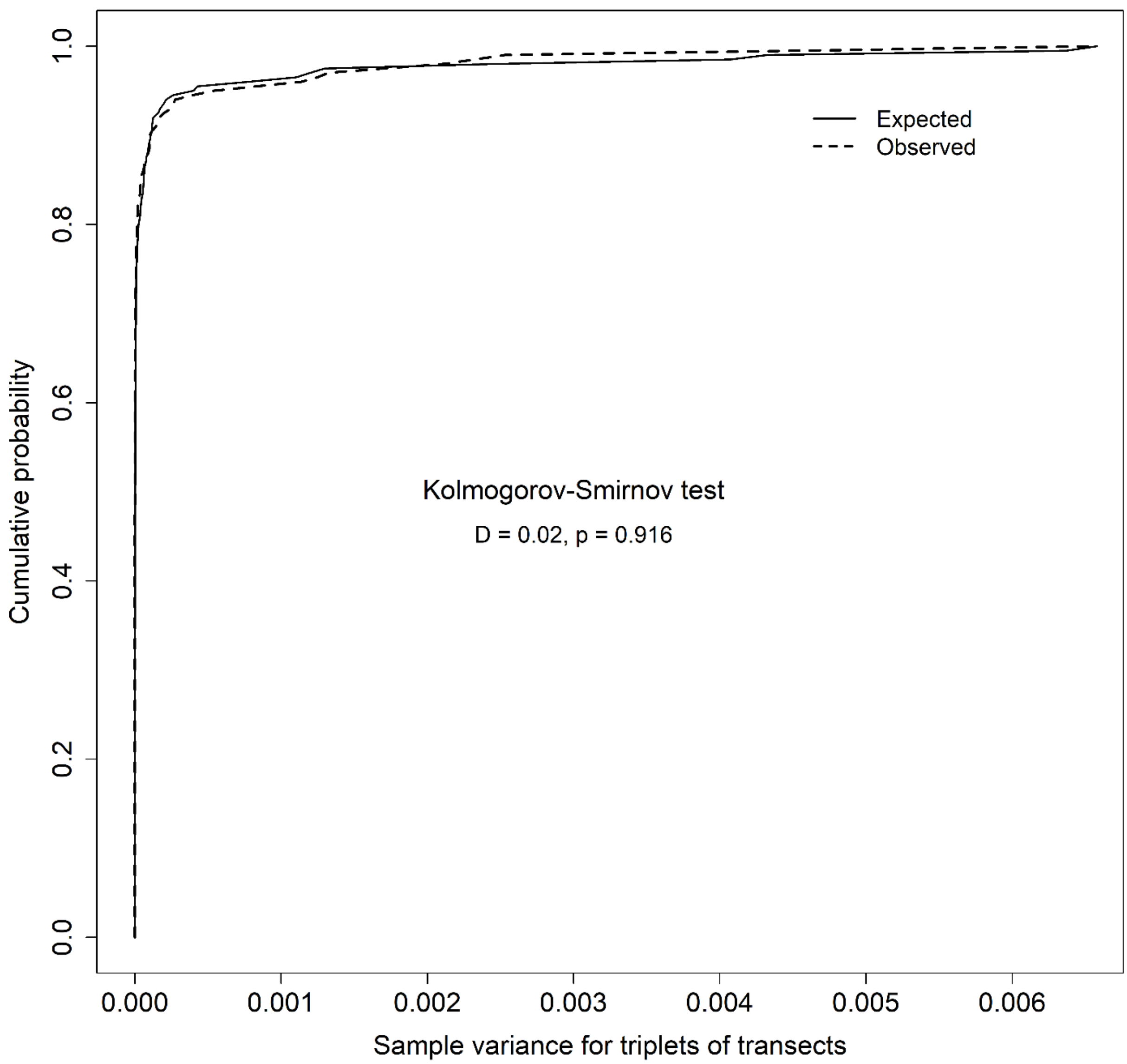

Figure 4.1—Comparison of expected and observed distributions of variance in soybean damage between randomly selected and spatially related triplet of survey transects. Vole damage to cover-cropped soybeans was surveyed for in fields in west-central Indiana in summer 2018 and 2019.

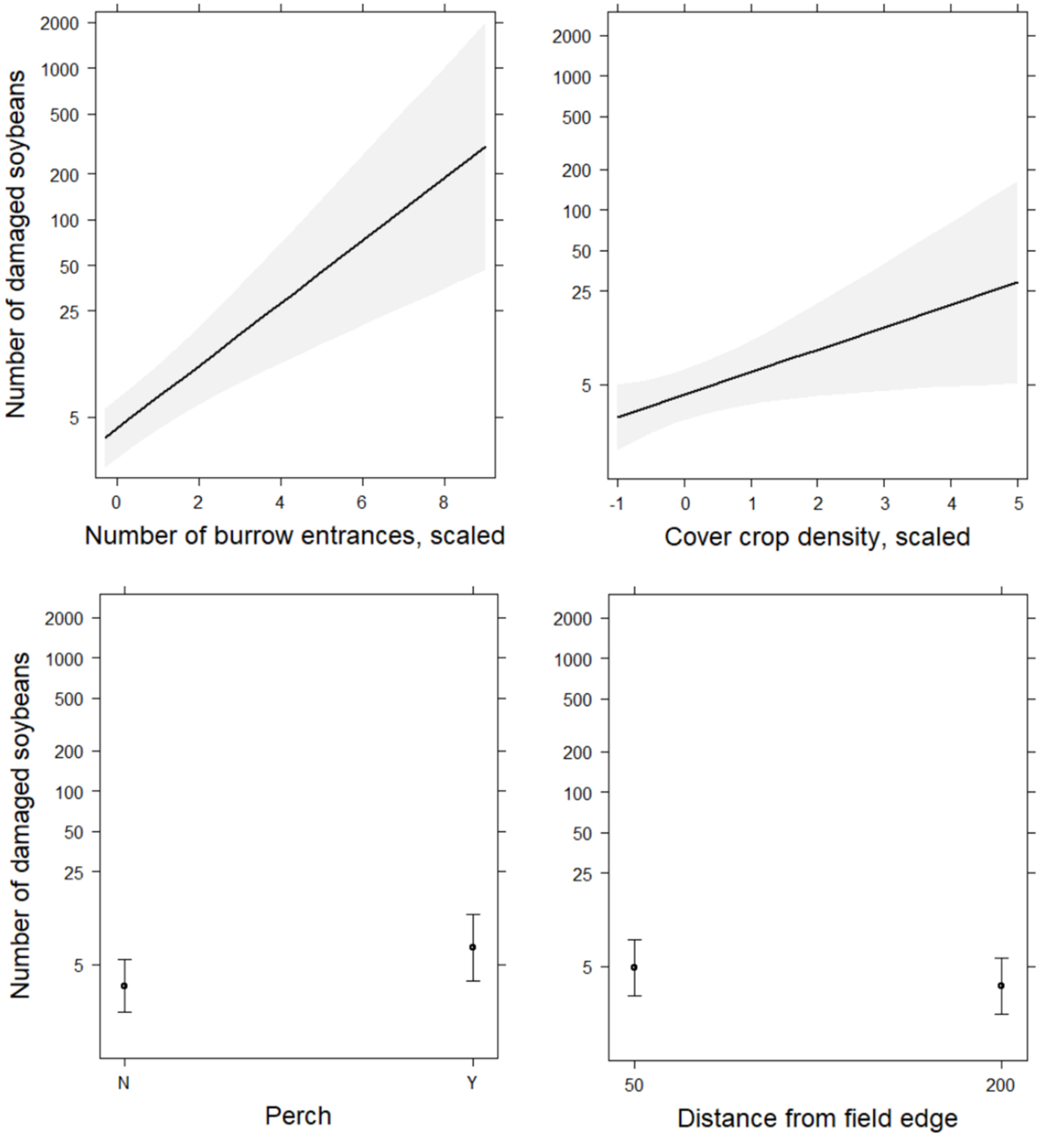

Figure 4.2—Marginal effects of factors associated with vole damage to cover-cropped soybeans. Damage was surveyed for during summer 2018 and 2019 in fields in west-central Indiana.

CHAPTER 5. CONCLUSION

I identified qualities of cover-cropped soybean fields that are preferred by voles and are linked with increased levels of damage to soybeans. Some features deemed important in predicting vole damage cannot be easily changed by farmers. For example, snow cover was associated with diminished vole damage risk, and fields that contain loamy soils are associated with higher risk of damage. Though these features are not within a farmer's power to change, they do allow for identification of years and individual fields where vole damage is likely to be greatest.

Other qualities of fields and cover crops, such as the species selected for planting, can be changed by farmers and thus be used as tools to manage against vole depredation. Many common cover crops are preferred forage for both meadow and prairie voles (Chapter 2). No species was found to be wholly unpalatable to voles when offered in cafeteria style feeding trials, as all species tested were selected at least once. Nitrogen-fixing species, such as clovers, alfalfa, and vetches were preferentially selected by both vole species, and thus may be more likely to encourage movement into fields (Cole and Batzli 1978, 1979, Getz et al. 2001). Though voles avoid some cover crop species, such as canola, they will consume even minimally desired forage when choices are limited. Farmers may plant cover crops that are not preferred by voles to make fields less attractive, though when little suitable forage is available in adjacent habitats or when populations are extremely high, this strategy may not be effective. Feeding trials also showed that voles prefer young soybean plants. Because vole damage to conventionally farmed soybeans is typically not an issue, cover quality provided by cover crops likely is required for voles to access soybean plants.

Dense cover crops are associated with increased potential for vole damage. In Chapter 4 increased vegetative cover contributed more dramatically to damage than either raptor perch availability or distance from field edge. By contrast, in Chapter 3 cover crop height contributed only minimally to probability of damage when compared to farm management strategies and other field attributes. Reduced predictive power of cover quality in Chapter 3 may have resulted from inclusion of fields containing any cover crop species or species mix, whereas in Chapter 4 I only collected data for cereal rye fields. Cover quality likely varies between cover crop types that have different growth forms such as grasses and clovers (Getz et al. 2001), and further study is needed to determine which popular cover crops provide minimal cover for voles. Cover provided by permanent grassland habitats also was important in predicting damage, though only 5-7% grassland habitat predicted above-average damage levels.

Reducing overhead cover provided by cover crops and surrounding grasslands is an effective management strategy to make voles more vulnerable to predation and reduce abundance (Lin and Batzli 2001, Smith and Batzli 2006). In addition to maintaining low amounts of cover, farmers may periodically employ a form of conservation tillage, which was the farming practice found to contribute most to reduction in vole damage in Chapter 3. Though farmers may till, mow, graze, or burn cover crops or adjacent grassland habitats (Birney et al. 1976, Lemen and Clausen 1984, Clark and Kaufman 1990, Slade and Crain 2006), the effect on other native wildlife and conservation goals should be carefully considered before taking such action. Reducing vegetative cover during inappropriate times of the year can harm other wildlife, such as grassland-nesting birds, that use permanent habitat (Bryan and Best 1991, Dale et al. 1997, Gruebler et al. 2008). Reducing biomass of cover crops may also limit the benefit and counteract the original intent of planting cover crops.

Managing against voles only in years when populations are high and in fields where high levels of damage are expected may reduce negative impacts on other farmland wildlife, save farmers valuable time and resources, and conserve long-term benefits of using cover crops. In the years 2016-2019 that spanned the three studies presented, the maximum amount of damage detected in a single field was 14.1% (Chapter 4). Though this level of damage likely exceeds a tolerable threshold, 97.1% of transects surveyed in the same project incurred less than 2.5% damage. Thus, reducing edge or in-field habitat and tilling all cover-cropped fields in fear of vole damage is not appropriate. In the test field from southeastern Indiana used to evaluate change in damage levels across the growing season in Chapter 3, 7.8% of the field was damaged (Fig. 5.1). Nonetheless, cover-cropped plots in the field exhibited no reduction in soybean yield at harvest compared to adjacent non-cover-cropped plots that did not incur vole damage (Kladivko et al., 2019).

Based on the results from this test field, farmers can conserve benefits provided by long-term use of cover crops and avoid direct costs associated with managing voles by choosing not to enact vole control measures in fields where less than 8% damage is predicted to occur. Of course, more work is needed to determine the generality of the results from the test field, and whether yield thresholds vary regionally or with other factors. Even so, costs of control merit consideration when vole control is contemplated. Applying tillage and disking, or continually mowing edge habitats, requires additional fuel, equipment maintenance, and labor, all of which are associated with a monetary cost. Additionally, farmers who abandon cover crops or no-tillage regimes in fear of yield loss incurred by voles may in turn experience yield reduction due to loss of benefits provided by cover crops including loss of topsoil, loss of essential nutrients introduced by cover crops, and reduced capacity for retaining moisture (White, 2014). In addition to loss of soil health and reversal of yield improvements provided by cover crops, farmers should incorporate direct costs associated with services previously provided by cover crops when considering the cost-benefit tradeoffs of managing for reduced vole populations. Costs may include additional herbicide application, need for fertilizers, and irrigation (White, 2014).

Producers concerned about vole damage to cover-cropped fields can work through the steps below, in order, to best predict and reduce risk of damage while extending the soil health and conservation benefits of using cover crops in years where vole management is not warranted.

1. Identify fields at high risk for vole damage, as determined by available grassland habitat, suitable soil types and weather (Chapter 3), and the relative palatability of cover crops planted in the field (Chapter 2). High-risk fields may be used as indicator sites where vole sign and resulting damage are monitored across years.
2. Look for vole sign in several areas of high-risk fields (Chapter 4), including areas that normally exhibit vole sign in spring and areas that do not. Record findings for reference in subsequent years. To best compare vole sign abundance across years, scouting should take place along the same transects, at approximately the same time of year or approximately the same cover crop density each year. If vole sign is low compared to previous years, or at levels that previously have not resulted in an intolerable yield loss, farmers should conserve resources and continue farming operations as usual. In years when comparatively high amounts of vole sign are found, farmers can proceed to step 3.
3. Extend scouting efforts to fields typically not at high risk for vole damage. In relation to vole sign detected in previous years and associated grain yield levels for the target field, determine if frequency of vole sign found in steps 1 and 2 is likely to lead to damage exceeding a tolerable level, in terms of yield loss. For fields in initial years of scouting, >21 burrow entrances per 45 m can be used as a threshold above which

vole management might be considered. Twenty-one entrances was the frequency of vole sign associated with 8% damage in Chapter 4, and approximately 8% damage did not lead to yield loss in the test field described previously. Use caution, as both of these cut-off values are associated with single data points from cereal rye fields. Thresholds for vole sign and associated damage may be much higher or lower, depending on the field and cover crop types, which further emphasizes the importance of multi-year monitoring.

4. If damage is expected to reach an intolerable level, consider haying or grazing cover crops as soon as possible and allow vole predators such as coyotes, foxes, and raptors, to access fields. Removing vegetation in the field and encouraging hunting by predators is likely to have less negative impact on soil conservation goals compared to tilling.
5. Apply strip or vertical tillage to areas of the field where frequent vole sign was detected. Recognize possible reversal of long-term soil health benefits accrued by using cover crops if this practice is applied. Disruption of possible future yield benefits also should be considered.

The process outlined above will allows farmers to identify years when voles are at peak abundance and to conserve resources and cover-crop benefits in years when vole abundance is tolerable (Getz et al. 2001).

For fields that do require vole management, my research provides a variety of options that farmers may use to reduce risk of vole damage to soybeans. However, no one strategy will completely rid fields of voles. Vole identity, modeled as a random effect, was important in predicting cover crop consumption in Chapter 2. Similarly, the random effect of field identity was retained in models fit to amount of soybean damage in Chapter 4. Therefore, some individual voles will consume more available forage, and some fields will receive greater amounts of damage regardless of manipulation of factors evaluated in my research. Additionally, the largest percentage of variation explained by fixed effects was 57.9% (Chapter 3), which indicates that there remains much variation in vole damage that needs to be addressed.

In addition to continued study of vole ecology in cover-cropped fields, there is a need for an examination of the economic tradeoffs of management to mitigate damage by voles. Identifying a threshold of economically intolerable vole damage that warrants management efforts and justifies loss of cover crop benefits would provide farmers with information that could save limited time and resources and preserve conservation and soil health benefits of cover crops in years when vole damage does not reach levels that adversely affect income derived from the crop.

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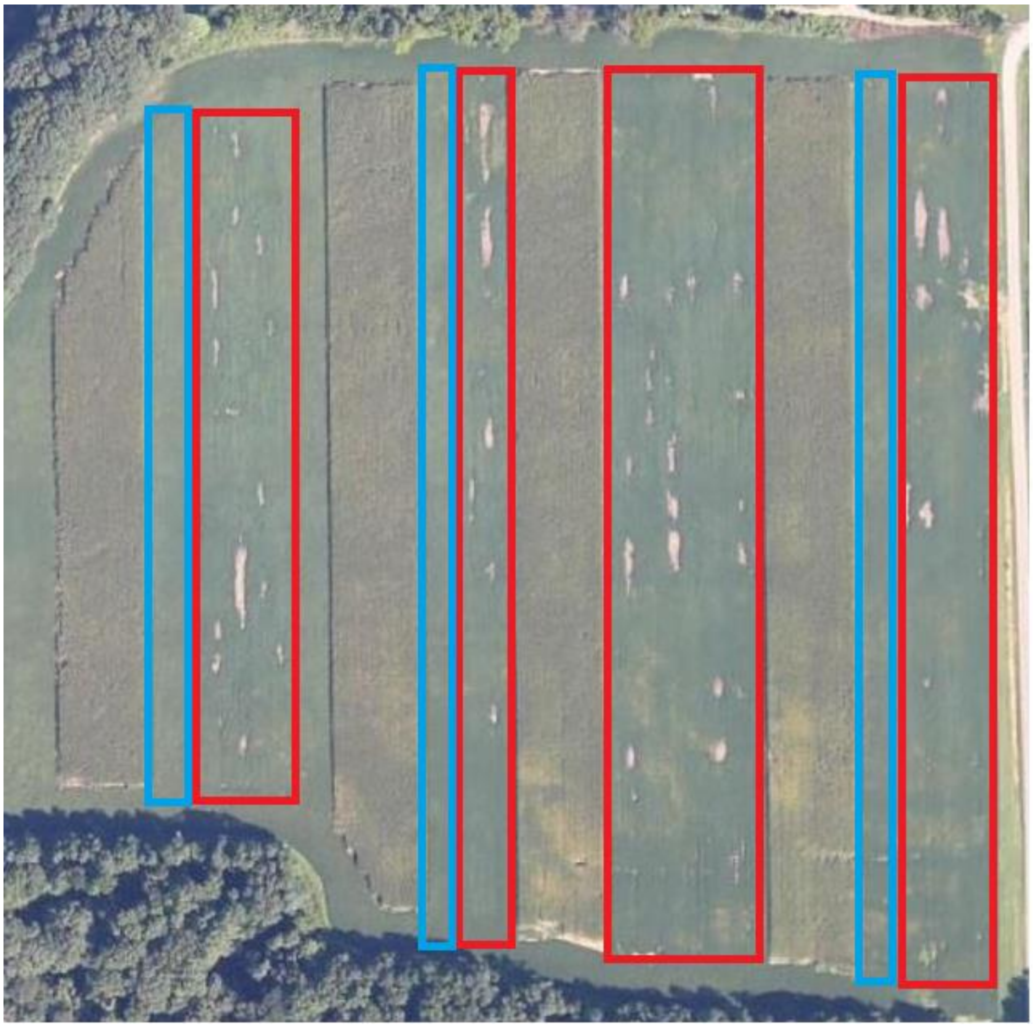

Figure 5.1—Soybean crop damage caused by voles (*Microtus*) in a field located in southeast Indiana. Red boxes indicated cover-cropped plots. Blue boxes indicate plots where no cover crop was used. Bare patches shown in red boxes are indicative of vole damage to soybeans.

Photo credit: R. Nielsen & J. Camberato, Purdue University, 2016. Image provided by Airscout, Inc., Monee, IL.

APPENDIX A. REFERENCES FOR PROTEIN VALUES

Protein values, represented as percent dry matter basis (DMB), for cover crops tested for palatability to voles (Chapter 2) as found in the literature. Unless noted, values were recorded only for fresh vegetative stage plants.

Plant species	Crude protein (% DMB)	Reference
Lolium multiflorum	14.5	National Research Council, 1982
	18.5[a]	Duke and Atchley, 1986
	23.2, 24.9	Han et al., 2018
Secale cereale	28.0	National Research Council, 1982
	21.4[a], 23.2[a]	Duke and Atchley, 1986
	30.1, 23.6	Edmisten et al., 1998
	21.4, 24.8	Han et al., 2018
Hordeum vulgare	22.7[a]	Duke and Atchley, 1986
	27.6, 20.4	Edmisten et al., 1998
Triticum aestivum	28.6	National Research Council, 1982
	18.1[a], 22.6[a]	Duke and Atchley, 1986
	26.0, 22.2	Edmisten et al., 1998
Sorghum bicolor x S. bicolor	16.8	National Research Council, 1982
Avena sativa	18.0[a]	Duke and Atchley, 1986
	18.2, 20.7	Edmisten et al., 1998
	15.9, 24.9	Han et al., 2018
Vicia villosa	30.5[a], 23.1[a]	Duke and Atchley, 1986
	14.8, 27.4	Han et al., 2018
Raphanus sativus	21.1, 25.8	Han et al., 2018

Trifolium pratense	17.2	Dougall, 1962
	23.0	National Research Council, 1982
	20.7[a]	Duke and Atchley, 1986
	18.9, 20.4	Brink and Fairbrother, 1988
	24.5	Hoffman et al., 1993
Trifolium incarnatum	18.8	Dougall, 1962
	17.0	National Research Council, 1982
	18.9[a], 16.7[a]	Duke and Atchley, 1986
	10.2, 24.5	Han et al., 2018
Melilotus officinalis	21.0	MSU Extension, 2019
Brassica rapa	30.2, 29.4, 26.0, 17.4, 30.9[b]	Duke and Atchley, 1986
Brassica napus	16.4	National Research Council, 1982
	16.0[a],17.4[b]	Duke and Atchley, 1986
Astragalus cicer	25, 21, 30, 17, 31, 20, 30, 25, 35, 30, 38, 23, 27, 21, 30, 23, 35, 21, 38	Loeppky et al., 1990
Glycine max	16.1[a], 16.6[a]	Duke and Atchley, 1986
Medicago sativa	20.0	National Research Council, 1982
	25.3[a], 19.3[a]	Duke and Atchley, 1986
	26.9	Hoffman et al., 1993
Vernonia gigantea	10.5, 12.5	Payne et al., 2010
	15.76	K. K. Payne, unpublished data

Dactylis glomerata	18.4	National Research Council, 1982
	12.6, 13.8	Duke and Atchley, 1986

[a] wet hay
[b] stage unknown

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APPENDIX B. REFERENCES FOR FIBER VALUES

Acid detergent fiber values, represented as percent dry matter basis (DBM), as found in the literature, for cover crops tested for palatability to voles (Chapter 2). Unless noted, values were recorded only for fresh, vegetative stage plants.

Plant species	Acid detergent fiber (%DMB)	Reference
Lolium multiflorum	26.1, 25.6	Han et al., 2018
	40.9[b]	Oliva et al., 2018
Secale cereale	17.8, 28.1, 20.1	Edmisten et al., 1998
	33.2[b]	Lema et al., 2004
	25.4 [b]	Otal et al., 2008
	21.6, 21.0	Han et al., 2018
Hordeum vulgare	22.5, 20.6, 18.7	Edmisten et al., 1998
	24.4 [b]	Otal et al., 2008
Triticum aestivum	30.0	National Research Council, 1982
	20.1, 21.9, 29.1	Edmisten et al., 1998
	33.6[b]	Lema et al., 2004
Sorghum bicolor x S. bicolor	29	National Research Council, 1982
	31.5 [a], 41.1 [a]	Gerhardt et al., 1994
Avena sativa	19.0, 20.0	Edmisten et al., 1998
	20.5 [b]	Otal et al., 2008
	22.9, 23.5	Han et al., 2018
Vicia villosa	22.3, 23.5	Han et al., 2018
Raphanus sativus	25.5, 21.7	Han et al., 2018

Trifolium pratense	19.8	Hoffman et al., 1993
Trifolium incarnatum	23.3, 22.6	Han et al., 2018
Melilotus officinalis	33.4[b]	Elgersma et al., 2013
Brassica rapa	23.5[b]	Francisco et al., 2011
Brassica napus	27.8[a]	Espinoza-Canales et al., 2017
Astragalus cicer	26.3[a], 24.5[a], 24.3[a], 33.9[a]	Acharya et al., 2006
Glycine max	28.2[a]	Hintz et al., 1992
	29.7[a], 38.8[a]	Desborough and Ayers, 1988
	32.8	Peiretti et al., 2018
Medicago sativa	29.0	National Research Council, 1982
	20.4	Hoffman et al., 1993
Vernonia gigantea	30.8[b]	K. K. Payne, unpublished data
Dactylis glomerata	31.0	National Research Council, 1982

[a] past vegetative stage
[b] stage unknown

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APPENDIX C. FARMER SURVEY

Cover letter and survey mailed to farmers to gather information about how cover-cropped fields located in the state of Indiana, USA that were planted to soybeans were managed in 2016 and 2018. Each survey was sent with a map identifying the focal field the survey corresponded to.

Dear Mr./Ms. [Name]:

Previously, you provided field boundaries to aid in Purdue University research of vole damage to cover cropped soybeans. With these boundaries and the information you provide in the enclosed questionnaire(s), we will attempt to identify factors that are most strongly associated with vole damage in cover-cropped fields. We hope that an understanding of these factors will yield information to help predict and manage vole issues in cover-cropped fields.

Enclosed is a map that indicates and labels each [2016/2018] soybean field where you used cover crops during winter [2015-2016/2017-2018] and questionnaires that are labeled with corresponding field numbers. Using your records of these fields, please fill out each questionnaire that corresponds with the numbered field on the map. Each questionnaire should take approximately 5 minutes to complete.

Please note that your participation is voluntary, and you are welcome to stop the questionnaire at any time. If you do participate, however, please enclose all materials in the pre-addressed, stamped envelope included in this packet and mail the letter by [DATE]. If we have not received your completed surveys after two weeks, we will send a reminder notification.

We greatly appreciate your participation in the project and hope that the information gained will help you and other Indiana producers in the future. Please do not hesitate to contact me with questions at aprieur@purdue.edu or [Phone Number].

Using your records, please answer the following questions to the best of your ability. Contact aprieur@purdue.edu with questions.

For this field:

1. Please list the years that winter cover crops have been planted (ex: 2011, 2014-2016)
 ____

2. For spring 2016, please label the time-period when the cover crop was terminated with a "T" and the time when soybeans were planted with a "P" in the chart below:

	Early (1^{st}-10^{th})	Mid (11^{th}-20^{th})	Late (21^{st}-31^{st})
March			
April			
May			
June			

3. Please mark the equipment you used to plant soybeans and cover crops in the chart below.

	Cover Crop (Fall 2015)	Soybeans (Spring 2016)
Drill		
Planter		
Airplane		

4. Please check the method you used to terminate the cover crop in Spring 2016.
   - ☐ Herbicide
   - ☐ Roller-crimper
   - ☐ Other________________________

5. Please check the box that best describes height of cover crop at termination:
   - ☐ Ankle high (1-6")
   - ☐ Knee high (6.1-18")
   - ☐ Waist high (18.1-36")
   - ☐ Above waist high (taller than 36")

6. Please check the tillage practice you used in Spring 2016.
   - ☐ No till (direct seeding)
   - ☐ Strip till (only a portion of the field disturbed)
   - ☐ Full-width or Vertical Till (entire area of field disturbed)
   - ☐ Other________________________

7. Please mark the cover crop species used in this field for each year indicated in the chart below (mark all that apply):

	Winter 2015-2016	Winter 2014-2015 (if applicable)	Winter 2013-2014 (if applicable)
Cereal Rye			
Radish			
Turnip			
Winter Wheat			
Annual Ryegrass			
Oats			
Rapeseed			
Crimson Clover			
Winter Pea			
Hairy vetch			
Red Clover			
Others (Please list):			

8. Please mark any practice you used *in grassy field edges or grass waterways* in the year indicated in the chart below:

Practices	2015	2016
Mow		
Till		
Burn		
Terminate with Herbicide		
Other (Please List):		

9. Please mark any practice you used *in the field* to control vole populations <u>in [2016/2018]</u>:
   - ☐ None
   - ☐ Broadcast soybean seed as alternate food source
   - ☐ Broadcast cracked corn as alternate food source
   - ☐ Installed raptor nest boxes or perches
   - ☐ Applied rodenticides before cover crop termination
   - ☐ Applied rodenticides after soybeans were planted
   - ☐ Applied rodenticides at a different time. Please describe:

   ____

   - ☐ Other. Please describe:

   ____

10. About what percentage of this field was damaged by voles (seedlings clipped and/or seeds eaten) <u>in [2016/2018]</u>? Please provide your best estimate, from 0 to 100: _______%

APPENDIX D. SMALL MAMMAL CAPTURES

Small mammal captures in cover-cropped soybean fields in west-central Indiana from April 30, 2018 to June 22, 2018 and March 28 to April 5, 2019. Sherman live traps were placed in a 10 x 3 grid with 15 m between each trap. Trap grids were located within field interiors, at 50 and 200 m from the field edge, and within permanent grassland habitat near field edges.

	Field Interior: 50 m		Field Interior: 200 m		Edge Habitat	
Species	Captures	Traps Nights	Captures	Trap Nights	Captures	Trap nights
Peromyscus spp.	67	2090	55	1821	18	959
Blarina brevicauda	0	2090	0	1821	10	959
Microtus pennsylvanicus	0	2090	0	1821	9	959
Zapus hudsonicus	1	2090	0	1821	8	959
Microtus ochrogaster	0	2090	0	1821	1	959