

ABSTRACT

Title of Thesis: ENHANCING BIOLOGICAL CONTROL BY
GROUND BEETLES (COLEOPTERA:
CARABIDAE) THROUGH AGRICULTURAL
DRAINAGE DITCH MANAGEMENT
PRACTICES

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Entomology

The establishment of semi-natural habitats on crop field margins is an increasingly popular integrated pest management (IPM) tool for conservation biological control of crop pests, decreasing reliance on harmful chemical pesticides. Agricultural drainage ditches are uncropped areas built to mitigate flooding on farms, but they may also provide suitable habitats for beneficial arthropods such as ground beetles, which are generalist predators of many common plant and invertebrate pests. In this study, I aimed to evaluate the potential of drainage ditches as natural habitats that promote biological control by ground beetles. To do this, my objectives were (1) to assess the impact of altered ditch management practices on ground beetle communities within a ditch and (2) to investigate ground beetle community composition and dynamics between ditch and adjacent crop field habitats across the Delmarva peninsula. Addition of straw to ditch banks in the fall increased ground beetle numbers by 97% in subsequent years, and ground beetle activity-density in drainage ditches was proportional to activity-density in adjacent fields for most genera. Results of this study suggest that altering drainage ditch management practices may provide additional ecological benefits by enhancing populations of ground beetles, thus reducing pest damage in adjacent crop fields.

ENHANCING BIOLOGICAL CONTROL BY GROUND BEETLES (COLEOPTERA:
CARABIDAE) THROUGH AGRICULTURAL DRAINAGE DITCH MANAGEMENT
PRACTICES

by

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
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Table of Contents

Acknowledgements	ii
Table of Contents.....	iii
List of Tables	iv
List of Figures	vi
Chapter 1: Effect of delayed mowing and straw application practices on ground beetle communities in agricultural drainage ditches	1
Abstract	1
Introduction.....	2
Methods	5
<i>Study site</i>	5
<i>Sampling</i>	8
<i>Treatments</i>	10
<i>Statistical analysis</i>	11
Results	12
<i>Ground beetle diversity</i>	12
<i>Treatment effects</i>	17
Discussion.....	25
Chapter 2: Ground beetle assemblages in agricultural drainage ditches and their relationship with adjacent field crops.....	29
Abstract	29
Introduction.....	30
Methods	33
<i>Study sites</i>	33
<i>Sampling</i>	39
<i>Statistical analysis</i>	40
Results	40
<i>Ground beetle diversity</i>	40
<i>Activity-density across ditch and field</i>	48
Discussion.....	51
Bibliography	56

List of Tables

Table 1.1 Ground beetle genera identified from the drainage ditch at the Wye Research and Education Center from 2020 – 2022, as well their diet (Larochele, 1990), life history category (Bousquet, 2010), and adult and larval presence in the ditch as observed in this study. Species are given where known. Diet categories include omnivorous (OM), primarily predaceous (PR), and primarily phytophagous (PH). Feeding groups marked with an asterisk were determined using the overall proportion in diet reported of the wider genus due to insufficient (fewer than 5) reports given for the species.

Table 1.2 Table of two-way ANOVA results for analyses on linear mixed effects models using treatments as fixed effects and sampling block and month as random effects.

Table 2.1 Characteristics of farms on which study sites were located. An opposing ditch layout indicates that the two ditch segments sampled were located along two separate drainage ditches on opposite sides of the field, while a parallel ditch layout indicates that both ditch segments were located along the same drainage ditch.

Table 2.2 Plant families identified from each drainage ditch at the five farms sampled during this study.

Table 2.3 List of ground beetle genera collected from all sites throughout the study period from 2021 – 2023 along with adult & larval presence and their life history category: autumn breeding (AB), spring breeding (SB), or unknown (?) (Bousquet, 2010). Species are given where known but may not include all species present within a genus.

Table 2.4 Adult ground beetle presence-absence matrix. An “X” marks that an adult specimen of the given genus was observed in pitfall traps from a given month and farm across years 2021 – 2023. Farm E was not sampled in June any year due to later soybean planting, and September sampling was conducted only in 2023.

Table 2.5 Results of generalized linear mixed models representing the number of ground beetles captured via pitfall traps from two distances into crop fields as a function of the number of ground beetles captured from the adjacent drainage ditch along the same transect. Results are shown for the six most frequently captured genera. Overdispersed sets of data (dispersion > 1.2) were modeled using a negative binomial

distribution, while others were modeled using a Poisson distribution. P-values indicating significant or marginally significant results at $\alpha = 0.05$ are marked with an asterisk.

List of Figures

Figure 1.1 The drainage ditch sampled at the Wye Research and Education Center in Queen Anne's County, MD and adjacent crop fields. GPS coordinates: N38.9161°, W76.1455°. Image modified from Google Maps.

Figure 1.2 Mean number of adult ground beetles of each genus captured from the drainage ditch at the Wye Research and Education Center across all sampling rounds from 2020 – 2022 by year.

Figure 1.3 Mean number of larval ground beetles of each genus captured from the drainage ditch at the Wye Research and Education Center by year from 2020 – 2022.

Figure 1.4 Shannon Diversity Index \pm SE calculated for adult ground beetles for each sampling year.

Figure 1.5 Principal component analysis (PCA) biplot demonstrating similarities between communities and effects of experimental treatments, shown as vectors, as compared to control treatments set at the origin.

Figure 1.6 Principal response curve (PRC) illustrating trends in deviation from the control across each treatment over time. Genus scores, plotted on the right, provide relative weight values for each genus based on how much they contribute to the given trends.

Figure 1.7 Mean adult ground beetle count \pm SE captured in pitfall traps in 2022 across each plot treatment.

Figure 1.8 Mean adult *Harpalus* count \pm SE captured in pitfall traps in 2022 across each plot treatment.

Figure 1.9 Mean adult *Pterostichus* count \pm SE captured in pitfall traps in 2022 across each plot treatment.

Figure 2.1 Map of the Delmarva peninsula with locations of the five farms used for sampling marked. Image courtesy of Google Earth.

Figure 2.2 Drainage ditch segments (white) and transects (yellow) sampled on each farm. Images adapted from Google Earth.

Figure 2.3 Mean number of adult ground beetles of each genus captured in pitfall traps across all sampling sites and periods.

Figure 2.4 Mean number of larval ground beetles of each genus captured in pitfall traps across all sampling sites and periods. Different shades represent the row each larva was captured in: (1) edge of drainage ditch, (2) 1.5 meters into the crop field, (3) 9.1 meters into the crop field.

Figure 2.5 Total number of larval ground beetles captured from 2021 – 2023 by month and row.

Figure 2.6 Preference factors of the most frequently collected adult ground beetle genera, obtained as a ratio of the pitfall trap capture rate in drainage ditches to the mean capture rate in samples from adjacent crop fields. Preference factors are plotted on a logarithmic scale such that 0 indicates no habitat preference while a greater or lesser value indicates apparent preference for the ditch or field respectively.

Chapter 1: Effect of delayed mowing and straw application practices on ground beetle communities in agricultural drainage ditches

Abstract

Conservation biological control seeks to mitigate pest damage by enhancing natural enemy populations. Agricultural drainage ditches are underutilized field margin habitats that hold high plant and arthropod biodiversity that may support beneficial insects. For example, ground beetles (Coleoptera: Carabidae) are widespread generalist predators that feed on economically important plant and invertebrate pests. My objectives were (1) to quantify the diversity and abundance of ground beetles in an agricultural drainage ditch, and (2) to compare the effects of ditch management practices, including delaying mowing until spring and applying straw along ditch banks in fall, on ground beetle communities. To do this, epigeal ground beetle activity-density was measured using pitfall traps along a drainage ditch in summer 2020 as a control. The ditch was divided lengthwise into 16 plots, each assigned one of four treatments in a randomized block design. Treatments were applied in the fall and spring over the following two years, and ground beetle activity-density measurements were repeated in summers 2021 and 2022. I observed a diverse community of ground beetles within the ditch, including adults of 15 genera and larvae of 5 genera, likely indicating use of the

drainage ditch as a reproductive site. In 2022, total carabid activity-density was 97% greater in plots treated with straw. This trend was dominated by two of three collected species of autumn-breeding ground beetles which overwinter as larvae, implying that these treatments may aid larval survival. Results of this study can be used to provide farmers with novel management practices for increasing the activity of natural enemies and reducing pest damage.

Introduction

Insecticide use remains among the most common methods to manage invertebrate pests but is a financial burden for farmers and poses numerous complications to human and environmental health (Pimentel *et al.*, 1993). Insecticides may also harm beneficial arthropods including pollinators, natural enemies, and decomposers, leading to other negative effects on farms (Ndakidemi *et al.*, 2016; Siviter & Muth, 2020). The creation of semi-natural field margin habitats is seeing increased recognition for conservation biological control, which involves increasing beneficial insect populations by providing enhanced food and shelter resources to control invertebrate pests, thereby reducing reliance on harmful chemical controls (Landis *et al.*, 2000; Holland *et al.*, 2016; Gontijo, 2019; Middleton & MacRae, 2021). However, existing non-crop field margins such as drainage ditches are understudied in this context. In this study, I investigated the potential of management practices aimed at increasing the natural properties of drainage ditches to enhance pest predation by ground beetles (family Carabidae) in adjacent fields.

Similar goals are accomplished in habitats such as beetle banks, which typically consist of stretches of native perennial grasses that provide shelter to overwintering predatory beetles (Thomas *et al.*, 1991; Collins *et al.*, 2002; MacLeod *et al.*, 2004). Ground beetles comprise a widespread, abundant, and ecologically diverse family of insects that have been extensively studied in agricultural contexts as beneficial ground-running generalists (Lövei & Sunderland, 1996). Although they are most often known to be generalist predators, most ground beetle species are opportunistic and polyphagous, ranging from entirely predaceous to almost entirely granivorous (Laroche, 1990). Many ground beetles are natural enemies of highly injurious invertebrate pests, including slugs, aphids, and caterpillars (Kromp, 1999; Mugala *et al.*, 2023). Primarily granivorous ground beetles are rarely pests of crop seeds, likely in part due to complex seed choice mechanisms involving seed burial, lipid content, and surface hydrocarbons, and are desired in crop fields for their ability to manage undesired plants by feeding on weed seeds, reducing the need for herbicide application (Bohan *et al.*, 2011; Kulkarni *et al.*, 2015; Gaba *et al.*, 2019; Saska *et al.*, 2019; Ali *et al.*, 2022).

The vast majority of ground beetles live for several years and may be placed into one of two categories according to their life history: spring breeders and autumn breeders. Spring breeders demonstrate two major periods of activity throughout the year, with the first, dedicated to mating, taking place in the spring and early summer, while the second activity period, dedicated to feeding, takes place in the autumn. Larvae in this category develop throughout the summer and autumn, overwintering only as adults. In contrast, autumn breeders demonstrate a single activity period throughout the summer,

mating in the fall and overwintering as both larvae and as adults (Bousquet, 2010), and are generally longer-lived than spring-breeding ground beetles (Lövei & Sunderland, 1996).

In addition to beetle banks, ground beetle populations benefit from semi-natural field margin habitats that may serve as valuable overwinter habitats (Pfiffner & Luka, 2000; Collins *et al.*, 2003; Knapp & Saska, 2012; Ganser *et al.*, 2019; Hoffmann *et al.*, 2021). Specifically, greater vegetative cover may provide more suitable hibernation sites by giving rise to favorable microclimates which increase the overwintering survival of ground beetles (Dennis *et al.*, 1994; Gallé *et al.*, 2018). Thus, management practices aimed at increasing vegetative structure in drainage ditches during the winter months may result in enhanced ground beetle populations during the following growing season.

Agricultural drainage ditches are structures built adjacent to croplands to manage water levels in these fields, particularly in areas with high water tables that are at high risk of flooding such as the Eastern Shore of Maryland (Needelman *et al.*, 2007). Drainage ditches vary greatly in both their physical and biological characteristics but tend to be lightly managed areas with high plant and arthropod diversity relative to adjacent crops. Based on discussions with farmers involved in this study, ditches on the Eastern Shore are often mowed just once a year in the fall for aesthetic purposes and to prevent weeds and woody growth from growing out of control. This is in stark contrast to the majority of land use within agroecosystems which may be extensively managed through frequent tillage, mowing, spraying of pesticides, and planting of monocultures. The relatively light management of drainage ditches may lead to their provision of ecological benefits in

addition to their hydrological functions (Herzon & Helenius, 2008; Dollinger *et al.*, 2015). Altering management practices in these areas to provide additional resources to attract and enhance beneficial arthropod communities may lead to the enhancement of ecosystem services provided by arthropods in crop fields.

To investigate how farmers can manage drainage ditches to enhance biological pest control by ground beetles, a study was conducted at the Wye Research and Education Center on the Eastern Shore of Maryland with two primary objectives. I aimed to (1) analyze the diversity of ground beetles in an agricultural drainage ditch habitat during the growing season and (2) compare the effects of different ditch management practices, specifically delayed mowing and spreading of straw along ditch banks, on ground beetle communities. I hypothesized that diverse communities of ground beetles live and reproduce in drainage ditches and that actions taken to increase vegetative structure during the winter, including postponing mowing until the spring and the addition of straw in the fall, would result in increased numbers of ground beetles.

Methods

Study site

This experiment took place at the Wye Research and Education Center (WyeREC), a University of Maryland research farm on the Eastern Shore of Maryland. The study site featured an agricultural drainage ditch located between two fields where rotations of soybeans and corn were cultivated (Figure 1.1). Along its length, the ditch was on average 1.8 meters deep, 5.2 meters wide measured from the top edges of the

slope, and 0.9 meters wide measured from the bottom edges of its slope. The ditch vegetation extended 0.8 meters out from the top edge of the slope. A 3-meter-wide grass strip separated the drainage ditch from the adjacent crops, and this strip underwent regular mowing every few months.



Figure 1.1 The drainage ditch sampled at the Wye Research and Education Center in Queen Anne’s County, MD and adjacent crop fields. GPS coordinates: N38.9161°, W76.1455°. Image modified from Google Maps.

Based on informal surveys of ditch vegetation, the most prevalent genera by area covered included *Solidago*, *Asclepias*, *Apocynum*, *Cirsium*, *Convulvulus*, and *Hibiscus*. Soybeans were planted in the 24,281-m² field on the northwest side of the ditch during all three years of the study, with rye planted as winter cover crop in 2020 and winter wheat planted in 2021. The 18,211-m² field on the southeast side of the ditch contained soybean crops in 2020 and 2022 and field corn in 2021.

A 244-meter stretch along the drainage ditch was divided into four blocks, each containing four 12.2-meter plots. There was a 15.2-meter gap between the blocks, except for the third and fourth blocks, where a 3-meter gap was present due to an error during the application of the straw treatment in 2021. Each plot was further divided into two subplots, one located on the northwest (NW) ditch bank and the other on the southeast (SE) ditch bank. The ditch was 1.8 meters deep and the banks of each subplot were 2.8 meters wide on average, for a total surface area of 34.6 m² per subplot.

Sampling

To collect ground-running ground beetles, I employed a standard pitfall trapping protocol. To set up a pitfall trap, a hole 11 cm wide and 12 cm deep was dug using a golf hole digger, and two plastic Solo cups, each 10 cm wide and 11 cm tall, were placed within the hole. Any gaps between the cups and the walls of the hole were filled with soil, and the soil was molded to be flush with the lip of the top cup. Approximately 100 mL of propylene glycol was introduced into the top cup as a preservative liquid, with the bottom cup facilitating trap replacement. A square trap cover with 24 cm side lengths and constructed from a 1-mm-thick plastic sheet and bolts to secure the cover into the

ground was then positioned over the cup with a 3-cm gap to minimize vertebrate capture and interference while mitigating the risk of rain-induced flooding. The covers were spray painted white on their upper surface to mitigate sampling bias due to excessive heat absorption. The traps remained in the field for one week before retrieval. After collection, trap contents were sieved through a 500-micron mesh, and any material left after sieving was preserved in 100-mL snap-lock plastic jars filled with 80% ethanol.

Data collection spanned a three-year period, encompassing years 2020 to 2022. Each year, five sampling rounds were executed throughout the growing season, beginning in April after the planting of crops in the adjacent fields and concluding in September just before crop harvest. Each sampling round involved the placement of one pitfall trap in each subplot, with traps being retrieved one week after deployment. At least two weeks were left between each sampling period. Captured ground beetles were sorted and identified to genus, as variation in major functional groups (i.e. across diet and life history) within the family tends to be most prominent at this level (Larochelle, 1990; Bousquet, 2010). Although counts for each species were not recorded, common morphotypes encountered within select prominent genera were identified to species. Adult diets of each genus were loosely categorized as omnivorous (OM), primarily predaceous (PR), or primarily phytophagous (PH), with the latter two groups being defined as species where greater than 70% of reports according to Larochelle (1990) consisted of one food type or the other. Diet types for species with fewer than five reports were determined using the overall proportion in diet reported for all species within its genus.

Treatments

Initial sampling was conducted in 2020 to establish a baseline before any treatments were applied. The following four treatments, consisting of combinations of two straw and two mowing treatments, were assigned to plots in a randomized block design: (1) straw added in the fall, plot mowed in the fall, (2) no straw added, plot mowed in the fall (control), (3) straw added in the fall, plot mowed in the spring, and (4) no straw added, plot mowed in the spring. Both subplots within each plot received identical treatments. Plots were sampled using the same protocol in all three years. Thus, each plot had 2 subsamples and each of the four treatments was replicated four times, resulting in 32 subsamples per sampling date.

For plots assigned to treatments 1 and 3, a layer of straw was applied to the slopes of ditch banks in November 2020 and late October 2021. Each plot received one bale of straw, with half a bale applied to each side of the plot. The straw bales were 100 x 36 x 48 cm and weighed an average of 14.9 ± 1.0 kg. A subsample of straw was collected, dried, and weighed, revealing that the straw consisted of 52.8% dry matter. Thus, an average of 7.8 ± 0.5 kg of dry straw were applied to the banks of each plot, or 0.11 ± 0.01 kg/m². Plots assigned fall mowing treatments were mowed in October prior to straw application and plots assigned spring mowing treatments were mowed between April and May. Ditch bank vegetation was mowed down to three centimeters with a ditch bank mower.

Statistical analysis

All statistical analyses were performed in R version 2023.06.2 (R Core Team, 2022). Ground beetle activity-densities measured from individual subplots were averaged for each plot. Shannon diversity indices were calculated for each sample and compared across years.

A multivariate redundancy analysis (RDA) was performed to explore and visualize relationships between treatments and ground beetle activity-densities across sampling years. A principal response curve (PRC) was then generated to identify years and genera that presented the greatest response to straw and mowing treatments. The “vegan” package in R was used for Shannon diversity, RDA, and PRC analyses (Oksanen *et al.*, 2022). Activity-density measurements were log-transformed and fitted to a linear mixed effects model using the “lme4” R package (Bates *et al.*, 2015) with straw and mowing treatments as fixed effects and sampling block and month as random effects. Two-way analyses of deviance were used to identify significant differences in activity-density for these genera across treatments at $\alpha = 0.05$. Total activity-density of ground beetles as well as that of genera with the greatest response to treatments according to multivariate analyses were tested as response variables. Tukey’s HSD comparisons of treatment interactions were used for post hoc analysis of two-way ANOVA results.

Results

Ground beetle diversity

A total of 401 adult and 22 larval ground beetles, from 15 and 5 genera respectively, were collected from 2020-2022. The most frequently collected genus was *Harpalus*, followed by *Anisodactylus* and *Pterostichus* (Figure 1.2). The total number of ground beetles collected increased with each successive year, but perhaps in part due to low sample sizes, the only significant increase was a 98% increase in total ground beetle activity-density between 2021 and 2022, owing in large part to the almost sixfold increase in *Harpalus* activity-density in 2022. Larval ground beetle activity-densities were much lower, with *Chlaenius* being the most frequently collected genus, followed by *Harpalus* and *Amara* (Figure 1.3). Out of all genera identified from the ditch, seven were categorized as omnivorous, six were categorized as primarily predaceous, and one was categorized as primarily phytophagous (Table 1.1). Three autumn-breeding genera (*Harpalus*, *Pterostichus*, and *Patrobus*) were identified while all others were spring-breeders. Mean Shannon-Weiner diversity of adult ground beetles in samples was greatest in 2021 (Figure 1.4).

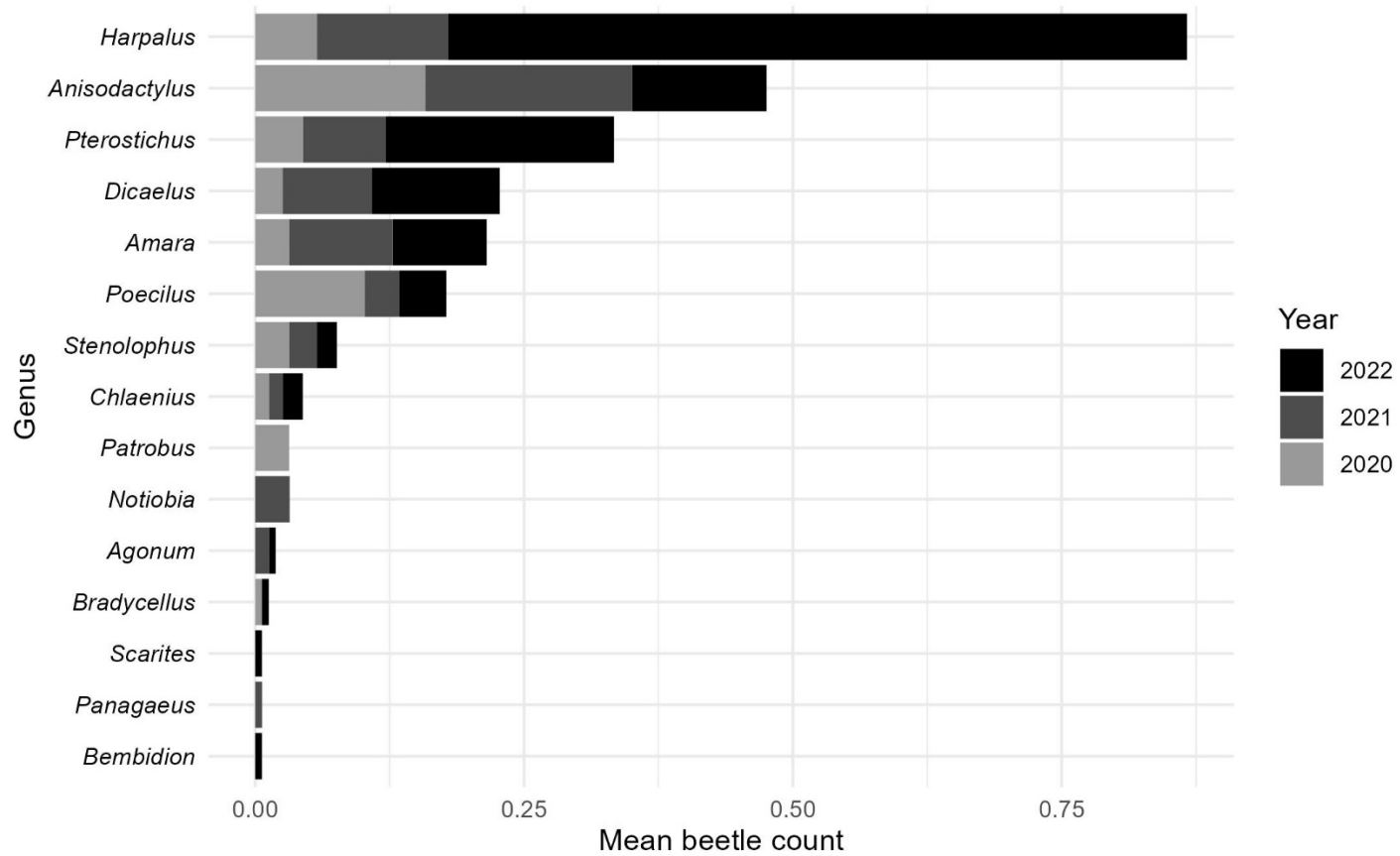


Figure 1.2 Mean number of adult ground beetles of each genus captured from the drainage ditch at the Wye Research and Education Center across all sampling rounds from 2020 – 2022 by year.

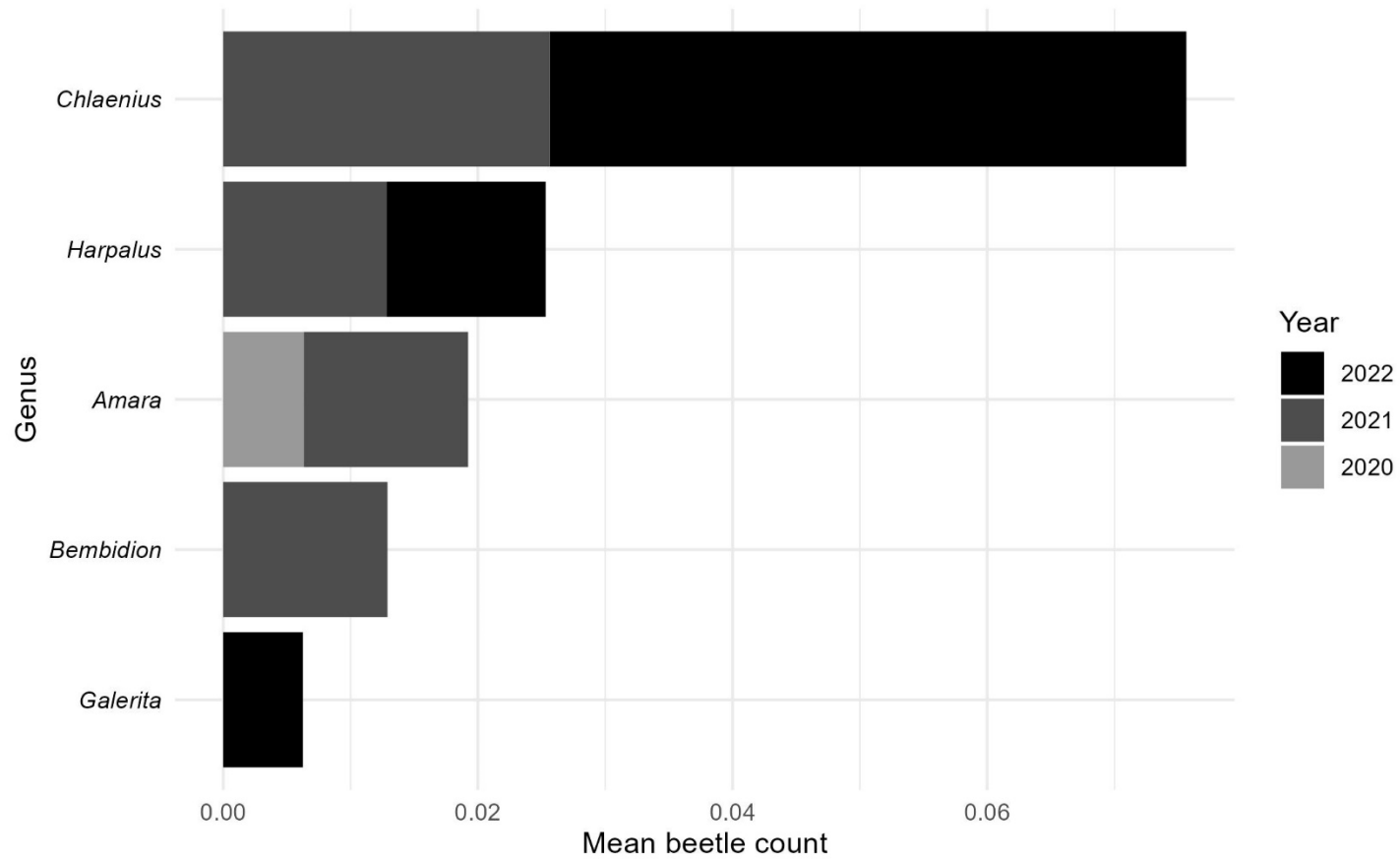


Figure 1.3 Mean number of larval ground beetles of each genus captured from the drainage ditch at the Wye Research and Education Center by year from 2020 – 2022.

Table 1.1 Ground beetle genera identified from the drainage ditch at the Wye Research and Education Center from 2020 – 2022, as well their diet (Larochele, 1990), life history category (Bousquet, 2010), and adult and larval presence in the ditch as observed in this study. Species are given where known. Diet categories include omnivorous (OM), primarily predaceous (PR), and primarily phytophagous (PH). Feeding groups marked with an asterisk were determined using the overall proportion in diet reported of the wider genus due to insufficient (fewer than 5) reports given for the species.

Genus	Species	Adult Diet	Life History	Adults?	Larvae?
<i>Agonum</i>	<i>octopunctatum</i>	OM*	SB	X	-
<i>Amara</i>	<i>aenea</i>	PH	SB	X	X
<i>Anisodactylus</i>	<i>rusticus</i>	OM	SB	X	-
	<i>sanctaecrucis</i>	OM	SB	X	-
	<i>nigerrimus</i>	OM*	SB	X	-
<i>Bembidion</i>	-	OM*	SB	X	X
<i>Bradycellus</i>	-	OM*	SB	X	-
<i>Chlaenius</i>	-	PR*	SB	X	X
<i>Dicaelus</i>	-	PR*	SB	X	-
<i>Galerita</i>	-	PR*	SB	-	X
<i>Harpalus</i>	<i>pennsylvanicus</i>	OM	AB	X	X
<i>Notiobia</i>	-	OM*	SB	X	-
<i>Panagaeus</i>	<i>fasciatus</i>	-	SB	X	-
<i>Patrobus</i>	<i>longicornis</i>	PR*	AB	X	-
<i>Poecilus</i>	<i>chalcites</i>	PR	SB	X	-
	<i>lucublandus</i>	PR	SB	X	-
<i>Pterostichus</i>	<i>permundus</i>	PR*	AB	X	-
<i>Scarites</i>	<i>subterraneus</i>	PR	SB	X	-
<i>Stenolophus</i>	-	OM*	SB	X	-

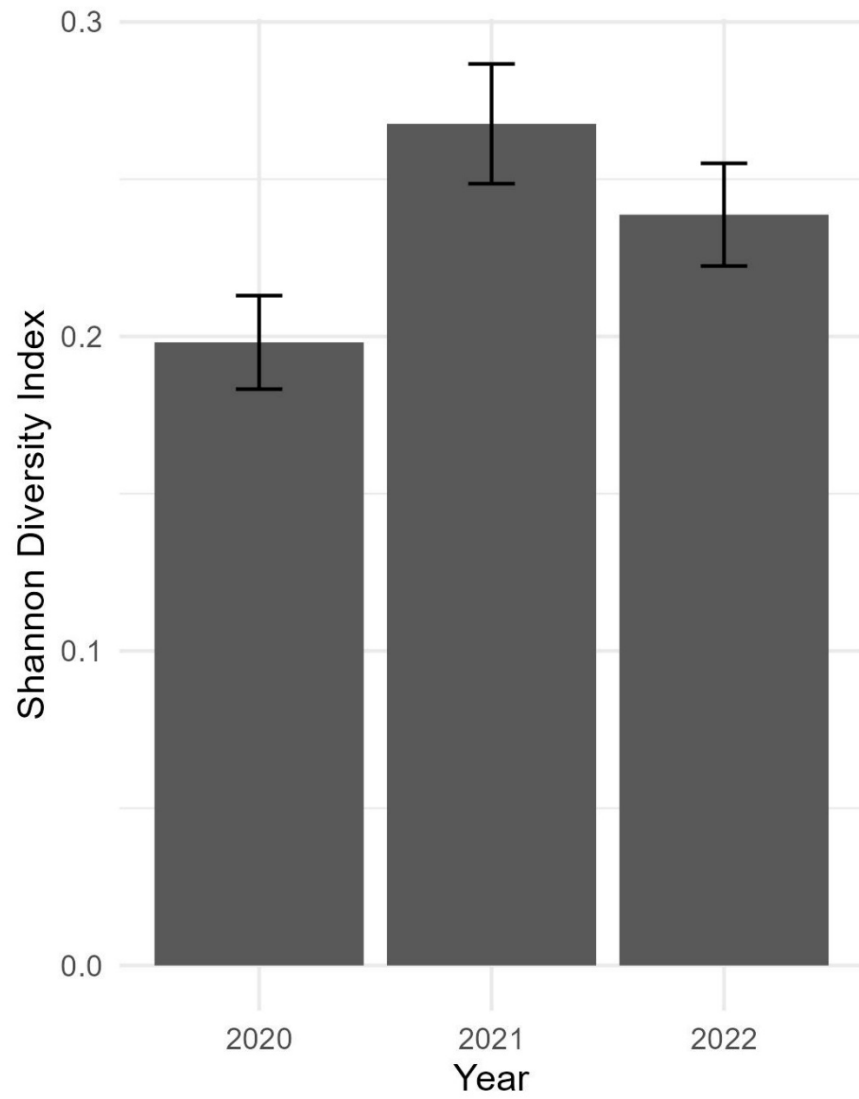


Figure 1.4 Shannon Diversity Index \pm SE calculated for adult ground beetles for each sampling year.

Treatment effects

An RDA plot of the community data using year, straw addition, and mowing season as explanatory variables revealed strong apparent trends on the principal axis related to straw addition in 2022, with these trends explaining 10% of the variance in the community data and the next highest axis explaining only 0.2% of variance (Figure 1.5). A PRC focusing on the principal axis within the RDA confirmed that the greatest response was seen in straw treatments in 2022, with genus weights revealing *Harpalus* and *Pterostichus* as being the two genera most contributing to these trends (Figure 1.6).

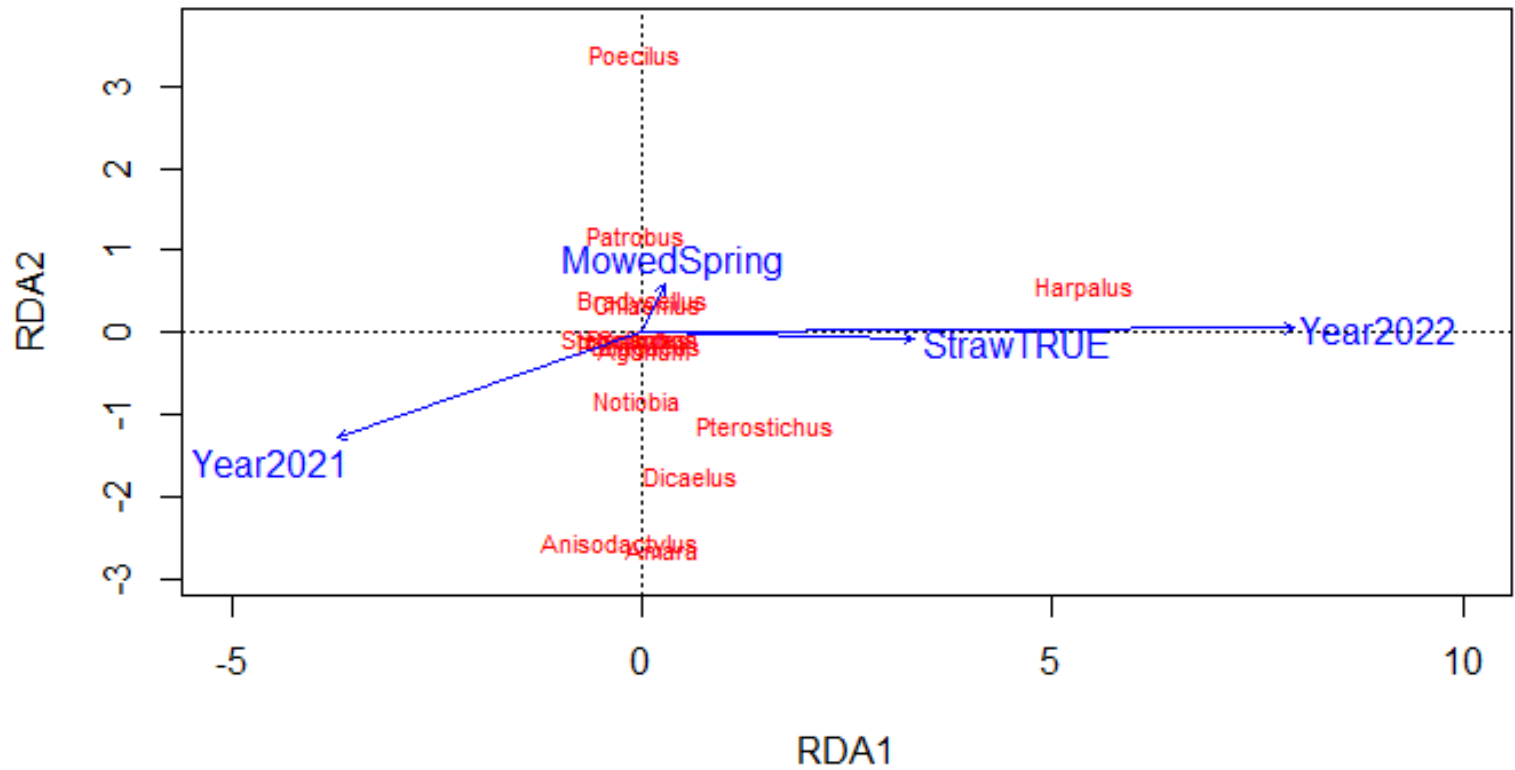


Figure 1.5 Principal component analysis (PCA) biplot demonstrating similarities between communities and effects of experimental treatments (plots mowed in the spring of that year, straw added to the banks of the drainage ditch during the previous fall), shown as vectors, as compared to control treatments (plots mowed in the previous fall and no straw added) set at the origin.

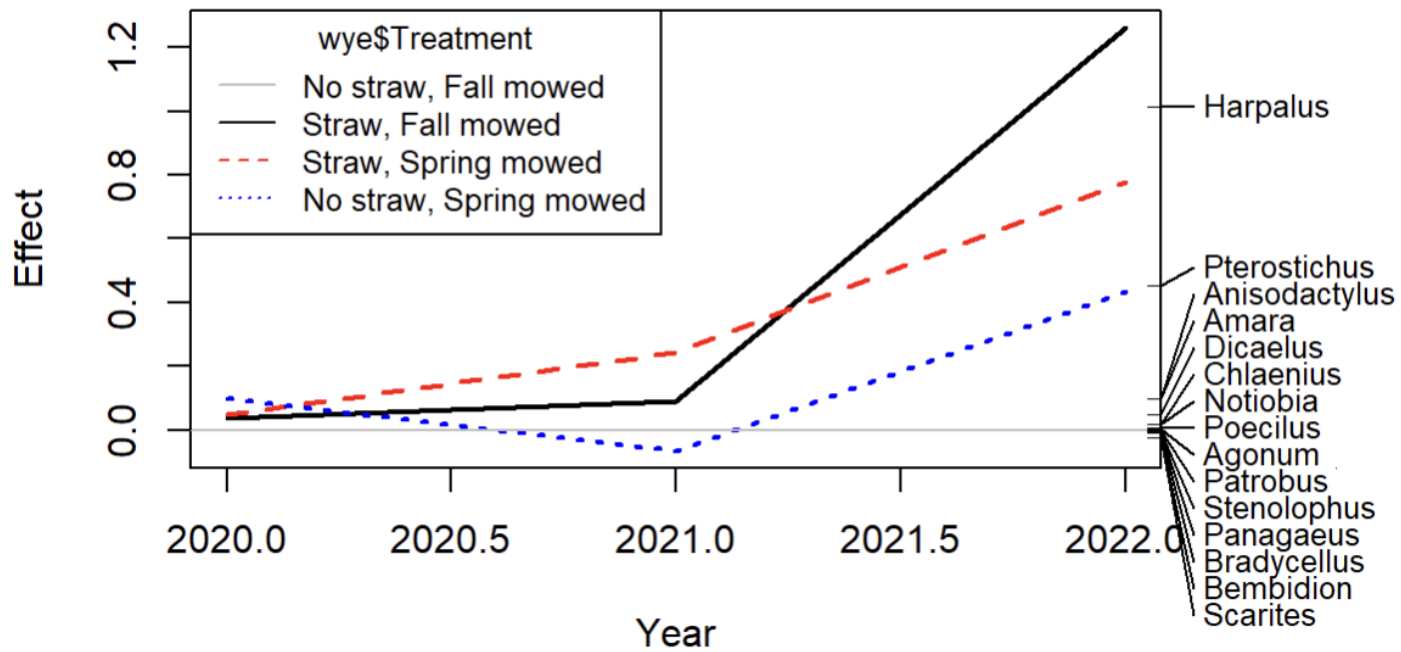


Figure 1.6 Principal response curve (PRC) illustrating trends in deviation from the control across each treatment over time. Genus scores, plotted on the right, provide relative weight values for each genus based on how much they contribute to the given trends.

Analyses of deviance for total adult ground beetle counts in 2022 revealed significant differences due to one main effect (fall straw addition) and marginal interactions between these main effects (Table 1.2). Total adult ground beetle activity-density was 97.22% greater in plots treated with straw than that in plots without straw (Figure 1.7).

Two-way analyses of deviance focusing on activity-density of *Harpalus* and *Pterostichus* as response variables found similar results for both genera, with activity-density of adult *Harpalus* being 133% greater (Figure 1.8) and that of *Pterostichus* being 225% greater (Figure 1.9) in 2022 in plots where straw had been added than those where it had not. Post-hoc pairwise comparisons of least square means between treatments were performed using the Tukey's HSD adjustments for total adult ground beetle numbers and those of *Harpalus* and *Pterostichus* (Lenth *et al.*, 2023). For both groups, activity-density was significantly different between plots where straw was added and plots where straw was not added except among spring-mowed plots exclusively, in which case straw addition was not significant.

Table 1.2 Table of two-way analysis of deviance results for analyses on linear mixed effects models of 2022 pitfall trap captures from a drainage ditch using treatments as fixed effects and sampling block and month as random effects.

Response	Treatment	Chi-sq.	df	p-value	Significance
Ground beetle activity-density	Straw	9.63	1	0.002	**
	Mowing	0.06	1	0.805	
	Straw*Mowing	3.80	1	0.051	-
<i>Harpalus</i> activity-density	Straw	6.91	1	0.008	**
	Mowing	0.11	1	0.739	
	Straw*Mowing	2.09	1	0.149	
<i>Pterostichus</i> activity-density	Straw	5.99	1	0.014	*
	Mowing	0.36	1	0.545	
	Straw*Mowing	2.16	1	0.142	

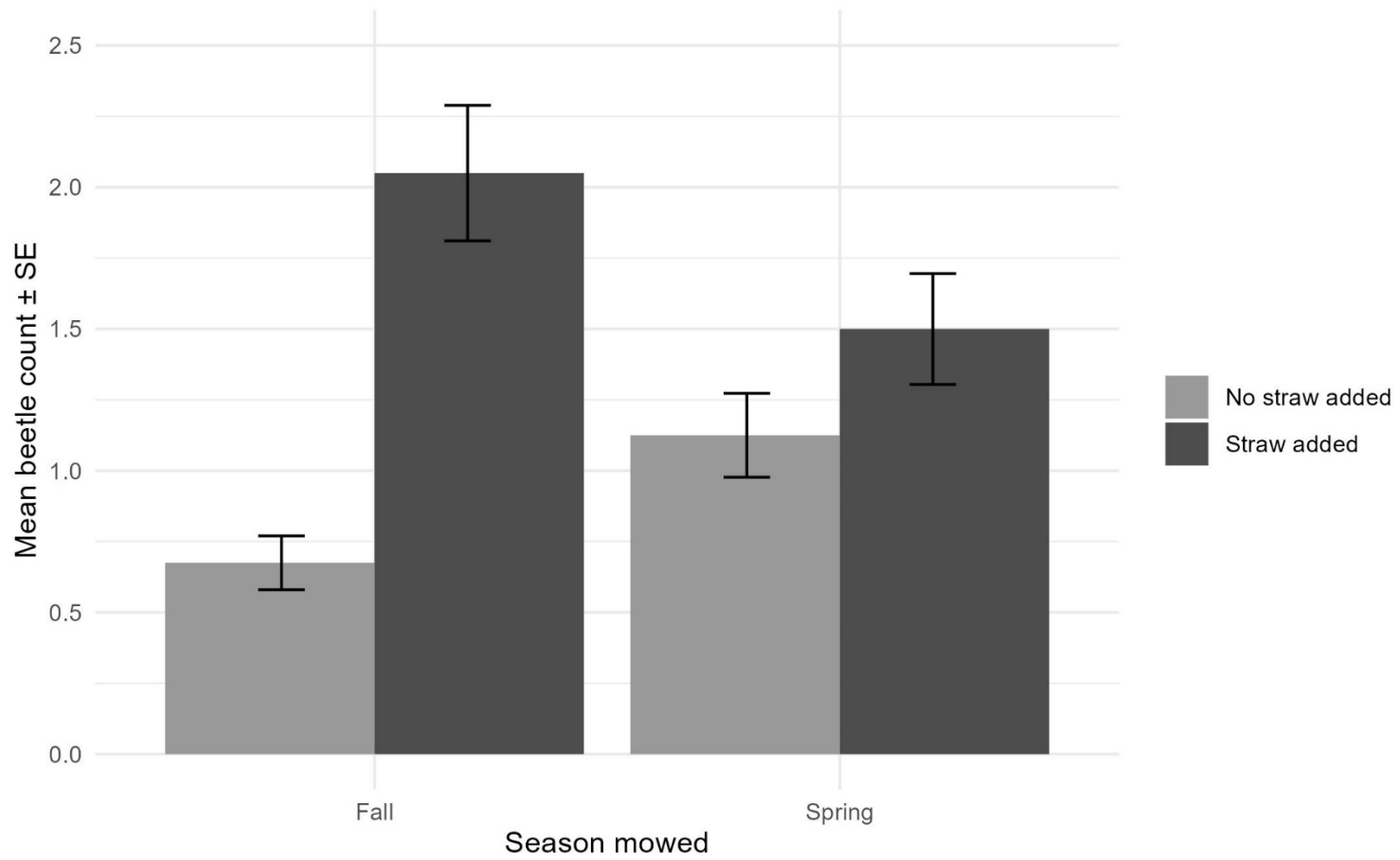


Figure 1.7 Mean adult ground beetle count \pm SE captured in pitfall traps in 2022 across each plot treatment.

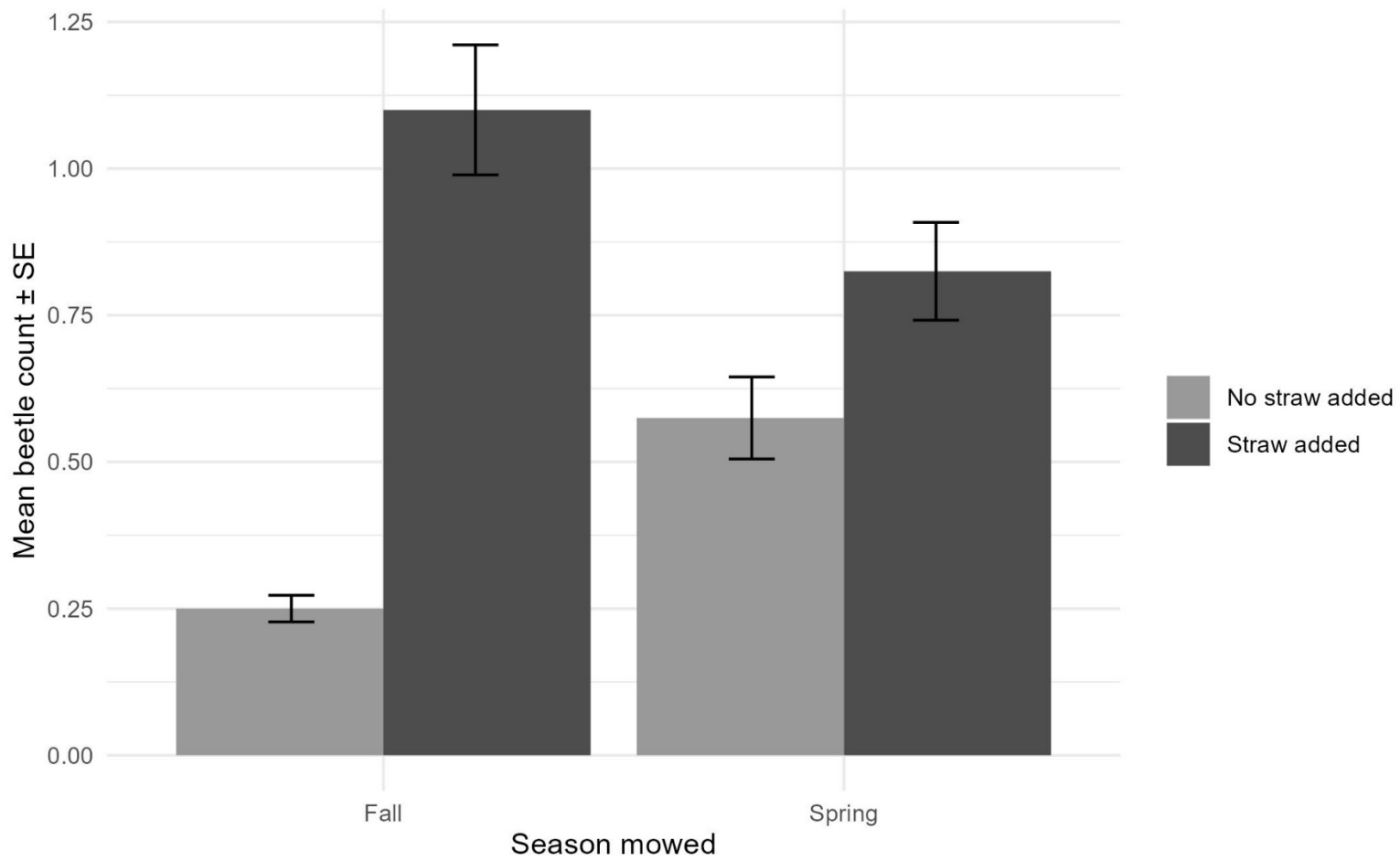


Figure 1.8 Mean adult *Harpalus* count \pm SE captured in pitfall traps in 2022 across each plot treatment.

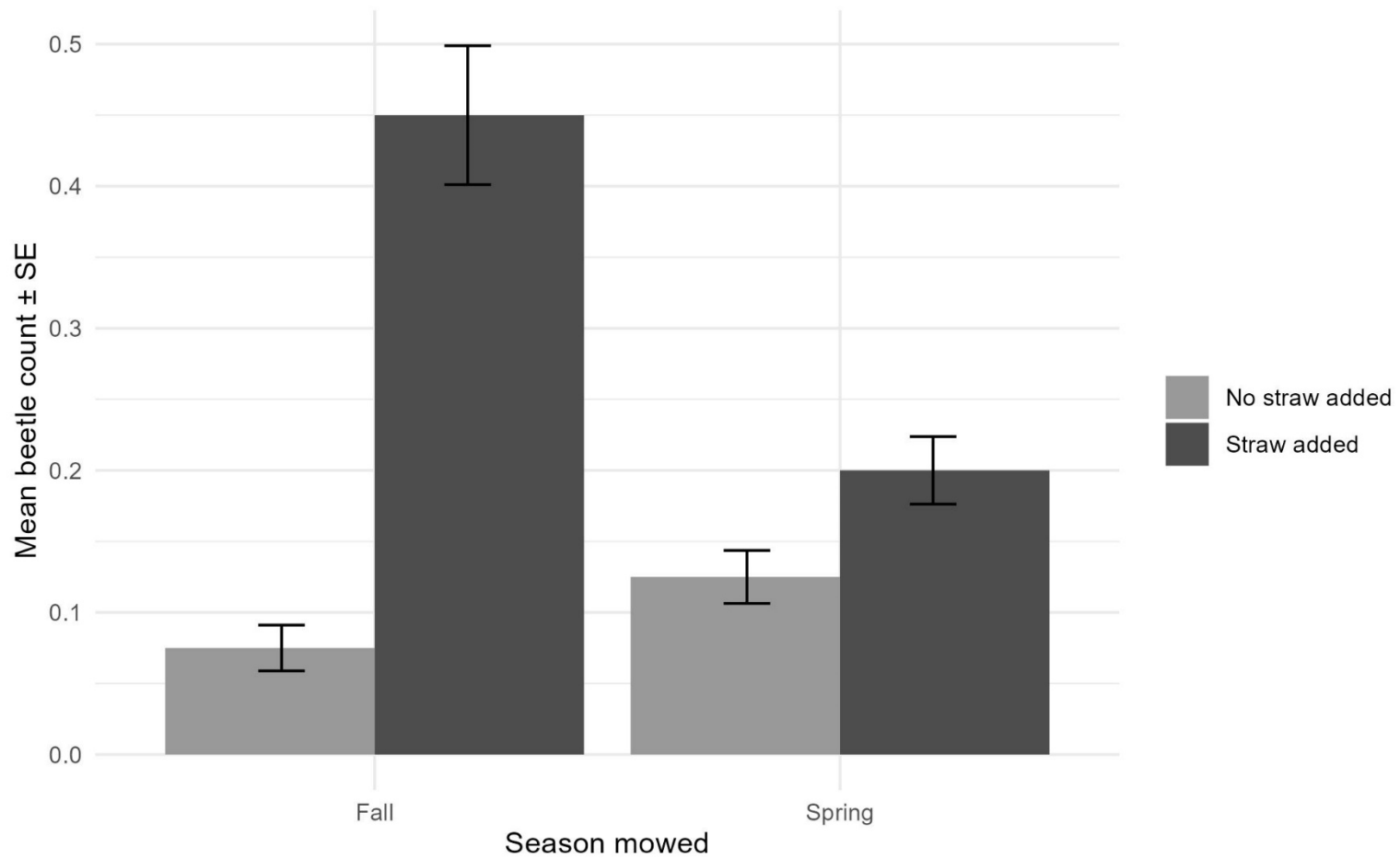


Figure 1.9 Mean adult *Pterostichus* count \pm SE captured in pitfall traps in 2022 across each plot treatment.

Discussion

The goal of this chapter was to assess the impact of management practices aimed at increasing vegetative structure within agricultural drainage ditches on ground beetle populations. Here, I have shown that treatments increasing vegetative ground cover over the winter can bolster communities of some ground beetle species, namely *Harpalus* and *Pterostichus*, in these ditches. In particular, the addition of a layer of straw on ditch banks in the fall significantly increased the activity-density of both genera.

Marginal interaction effects indicate that the efficacy of each of these treatments may depend on the other. Straw addition was most impactful across fall-mowed plots but did not have a significant effect among spring-mowed plots. Similarly, spring mowing significantly increased activity-density only when compared to the control treatment (fall mowing and no straw addition), but not when compared to fall-mowed plots with and without straw added. Fall mowing with straw addition had the greatest positive effect on activity-density, followed by spring mowing, but performing both treatments (spring mowing with straw addition) does not appear to have significant benefits over just spring mowing. Both straw addition and spring mowing resulted in greater numbers of autumn-breeding ground beetles than the control. The low impact of straw on spring-mowed plots may be due to some quantity of straw resting on top of existing ditch vegetation rather than settling to the bottom and creating a continuous blanket as in plots that are mowed before straw application, limiting the capacity of the vegetative cover to create sheltered microclimates that benefit ground beetle overwintering.

The two species that were notably impacted by these practices, *Harpalus pennsylvanicus* and *Pterostichus permundus*, are both autumn-breeding ground beetles, in contrast to the other genera collected in the ditch which were almost all spring-breeders (Kirk, 1973; Bousquet, 2010). Because autumn-breeders overwinter as both larvae and as adults while spring-breeders overwinter only as adults, these results may indicate that larval ground beetles benefit more greatly from shelter provided by the straw prior to the winter. There is a lack of other studies reporting a strong disparity in response between spring and autumn-breeding ground beetles, although this may be due to a broader scarcity of knowledge regarding larvae, which likely stems from the inherent challenges associated with larval sampling and identification.

Given the more limited mobility and dispersal potential of larval ground beetles, the presence of ground beetle larvae in the drainage ditch indicates that at least some ground beetles use the ditch as a reproductive site (Lövei & Sunderland, 1996). Furthermore, the increase in larval activity-density observed after the first year of treatments suggests that there may be increased ground beetle reproduction occurring in the ditch as a result of increased vegetative cover. However, these results should be taken with caution, as limited larval mobility makes assessment of true larval densities using pitfall traps difficult due to small resulting sample sizes. Additionally, other environmental factors such as temperatures and rainfall may have major impacts on ground beetle populations year-to-year, making interpretations of results based on changes observed only across a few years unreliable. Similar challenges may explain the overall low level of response in 2021. Alternatively, it is possible that the ground beetle

response to these treatments was present in 2021, but the effect was not large enough to show up as significant in my data until this enhanced population of ground beetle reproduced, resulting in an exponentially greater ground beetle abundance in 2022. More research into the mechanisms behind these effects is necessary to better understand these results.

Monetary and perceived aesthetic costs of the drainage ditch management practices proposed in this study may pose obstacles to their implementation. A cost-benefit analysis of the monetary and labor costs associated with straw addition as well as the savings associated with a potential increase in biological control services would be valuable for assessing the economic practicality of straw addition for enhanced pest management. While the financial expenses associated with delayed ditch mowing are small, private farmers involved with this study have expressed hesitation in avoiding cutting ditch vegetation to the ground before the winter for aesthetic reasons.

A major limitation of this study is the lack of insight as to whether or not these enhanced ground beetle densities translate to enhanced biological control in adjacent fields. Although related studies focused on beetle banks have demonstrated enhanced pest control in areas of fields located closer to semi-natural habitats, it is possible that in some cases, these habitats are not serving as sources of predatory beetles but rather as ecological sinks that draw natural enemies away from fields. For enhanced natural enemy communities in ditches to have an impact on pest control in field crops, dispersal into the field is necessary. For my second chapter, I investigated ground beetles in both drainage ditches and adjacent crop fields to assess the relationship between these

communities. Future research combining these studies to demonstrate the effects of altered ditch management on ground beetle populations and predation seen in crop fields would be valuable as a more direct investigation of potential increases in biological control.

Chapter 2: Ground beetle assemblages in agricultural drainage ditches and their relationship with adjacent field crops

Abstract

The establishment of biodiverse semi-natural field margin habitats has seen increasing use for enhancing conservation biological control of pests in field crops. Agricultural drainage ditches are existing structures on farmscapes that share these characteristics and may be managed to increase abundances of beneficial ground beetles (Coleoptera: Carabidae). To investigate the potential of drainage ditches as ecological sources of natural enemies for biocontrol, I aimed to (1) characterize ground beetle communities across a broad range of ditches and adjacent crops on the Delmarva peninsula, and (2) compare the prevalence of ground beetles across these habitats and determine whether activity-densities in drainage ditches are correlated with those in adjacent fields. Epigeal ground beetle activity-density was measured using pitfall traps at 10 drainage ditches and 1.5 and 9.1 meters into their adjacent crop fields on 5 farms across the Delmarva peninsula monthly from June – August of 2021 – 2023. Ground beetle activity-density in drainage ditches was directly correlated to activity-density in adjacent fields for most genera, implying that there is regular movement between the two habitats. The results of this study suggest that ecological management of drainage ditches may present a potential path to increasing biological control of plant and invertebrate pests in crop fields.

Introduction

Conservation biological control aims to enhance naturally occurring populations of natural enemies to manage pests (Eilenberg *et al.*, 2001). The establishment of semi-natural field margin habitats such as prairie strips and beetle banks has been increasingly studied as an integrated pest management (IPM) tactic for increasing conservation biological control on farms, thus decreasing reliance on chemical pesticides which exhibit numerous health, environmental, and economic drawbacks (Jonsson *et al.*, 2008; Begg *et al.*, 2017; Shields *et al.*, 2019). Semi-natural habitats typically contain higher plant diversity and experience less frequent disturbance compared to crop fields, thus providing enhanced resources such as food and shelter for beneficial arthropods (Landis *et al.*, 2000). Agricultural drainage ditches are existing semi-natural habitats within agroecosystems that share these characteristics and may confer similar ecological benefits in addition to their primary function.

Agricultural drainage ditches are channels built for hydrological management and are common in areas with a high water table that are prone to flooding such as the Delmarva peninsula. They are diverse in their physical and biological characteristics, including their shape and dimensions, as well as the plants and other organisms inhabiting them. They also vary in how they are managed, which depends on the local climate and the time, labor, and resources devoted to them by farmers based on need, ability, and preference (Dollinger *et al.*, 2015). Common management methods include cutting with a ditch mower or spot treatment of undesired weeds and woody plants with herbicides, as well as “clean-outs” in which soil is removed and ditches are reformed.

However, they tend to be lightly managed in comparison to the majority of agricultural land and are often mowed once a year in the fall to prevent overgrowth of weeds and woody plants. In contrast to crop fields, which are disturbed frequently for soil tillage, crop planting, pesticide spraying, and crop harvest, drainage ditches may provide a more stable habitat for the establishment of diverse plant and arthropod communities. Diverse plant communities may then give way to further enhanced abundance and diversity of the arthropods that inhabit these areas, which may include natural enemies that can then move into adjacent fields and feed on crop pests (Hendrickx *et al.*, 2007; Herzon & Helenius, 2008). However, community dynamics and connectivity between distinct habitats are often complex and depend on numerous factors (Donald & Evans, 2006; Schellhorn *et al.*, 2014). Previous research has shown that drainage ditches contain diverse spider assemblages, with the occurrence of certain spider species shifting from drainage ditches to crop fields over the course of the field season (Kutz, 2020). Generalist predators have been shown to be valuable biological control agents (Symondson *et al.*, 2002). Here, I explore the community dynamics of another group of generalist predators in the form of ground beetles, which can be diverse and plentiful in ditches and other semi-natural habitats (Bennewicz & Barczak, 2020). Specifically, I investigated the relationship between ground beetle assemblages within agricultural drainage ditches and those in adjacent crop fields across the Delmarva peninsula.

Ground beetles (Coleoptera: Carabidae) are a highly diverse group, exhibiting a broad range of physical and ecological characteristics across different species and genera. For instance, ground beetle diet breadth ranges from primarily granivorous species that

feed on weed seeds in agricultural systems to opportunistic omnivores to entirely predaceous species that specialize on mollusks, caterpillars, or aphids (Kromp, 1999). For this reason, it is important to consider ground beetle identities at a level that separates functional groups. Nevertheless, ground beetles are rarely injurious to agricultural operations and are generally valued for their ability to manage plant and invertebrate pests through consumption of injurious invertebrates and weed seeds, making them effective biocontrol agents (Lövei & Sunderland, 1996; Lundgren, 2005; Kulkarni *et al.*, 2015).

In the first chapter of my thesis, I showed that management practices aimed at increasing vegetative ground cover in an agricultural drainage ditch during winter months can increase the activity-density of certain autumn-breeding ground beetle species in the ditch. For these increases to be meaningful to biological control in field crops, it is essential that ground beetles readily move from the ditch into the field. If this is the case, I predicted that I would see greater numbers of ground beetles in fields where we see greater numbers of ground beetles in adjacent ditches. Due to the diverse habitat preferences between ground beetle genera, it is also possible that different groups would exhibit different behaviors in relation to these two distinct habitats. In this chapter, I aimed to describe the relationship between ground beetle communities within the ditch and those in adjacent crop fields. Specifically, my objectives were (1) to characterize ground beetle communities across a broad range of drainage ditches and adjacent crop fields on the Delmarva peninsula, and (2) to identify whether there is a significant

correlation between ground beetle activity-density in ditches and in adjacent fields and how this differs between genera.

Methods

Study sites

Five farms located across the Delmarva peninsula containing soybean and corn rotation crop fields bordering drainage ditches were selected as sites for this study and sampled each year from 2021 to 2023. These included four farms on the Eastern Shore of Maryland and one farm in Delaware (Figure 2.1). Farm D was a university-affiliated research farm while all others were private farms. All farms were conventionally managed aside from farm E which practiced organic crop management techniques (Table 2.1).

For each farm, one field that bordered at least 91 meters of drainage ditch was chosen and two ditch segments were defined for sampling. Within the chosen fields, farm A planted corn all three years while farm E planted soybean all three years. The other three farms alternated between the two crops each year, with farms B and D beginning with corn in 2021 while farm C began with soybean in 2021. The ditch segments at farms A and B were located on opposite sides of the same field, and three transects 30.4 meters apart were defined starting from the ditch and extending into the field. The ditch segments at farms C, D, and E were located along the same ditch, with transects extending in the same direction into the field. Transects at farm C and E were located 30.4 meters apart with another 30.4 meters between the two ditch segments,

while those at farm D were located 15.2 meters apart with 30.4 meters between the ditch segments (Figure 2.2).

Prominent ditch vegetation was collected from each ditch in June of 2022 and identified to family (Table 2.2). Pitfall trap samples were collected from three points (rows) along each transect, with row 1 located at the top edge of the slope of the ditch segment (henceforth referred to as a ditch), row 2 located at 1.5 meters from the edge of the crop, and row 3 located 9.1 meters from the edge of the crop.

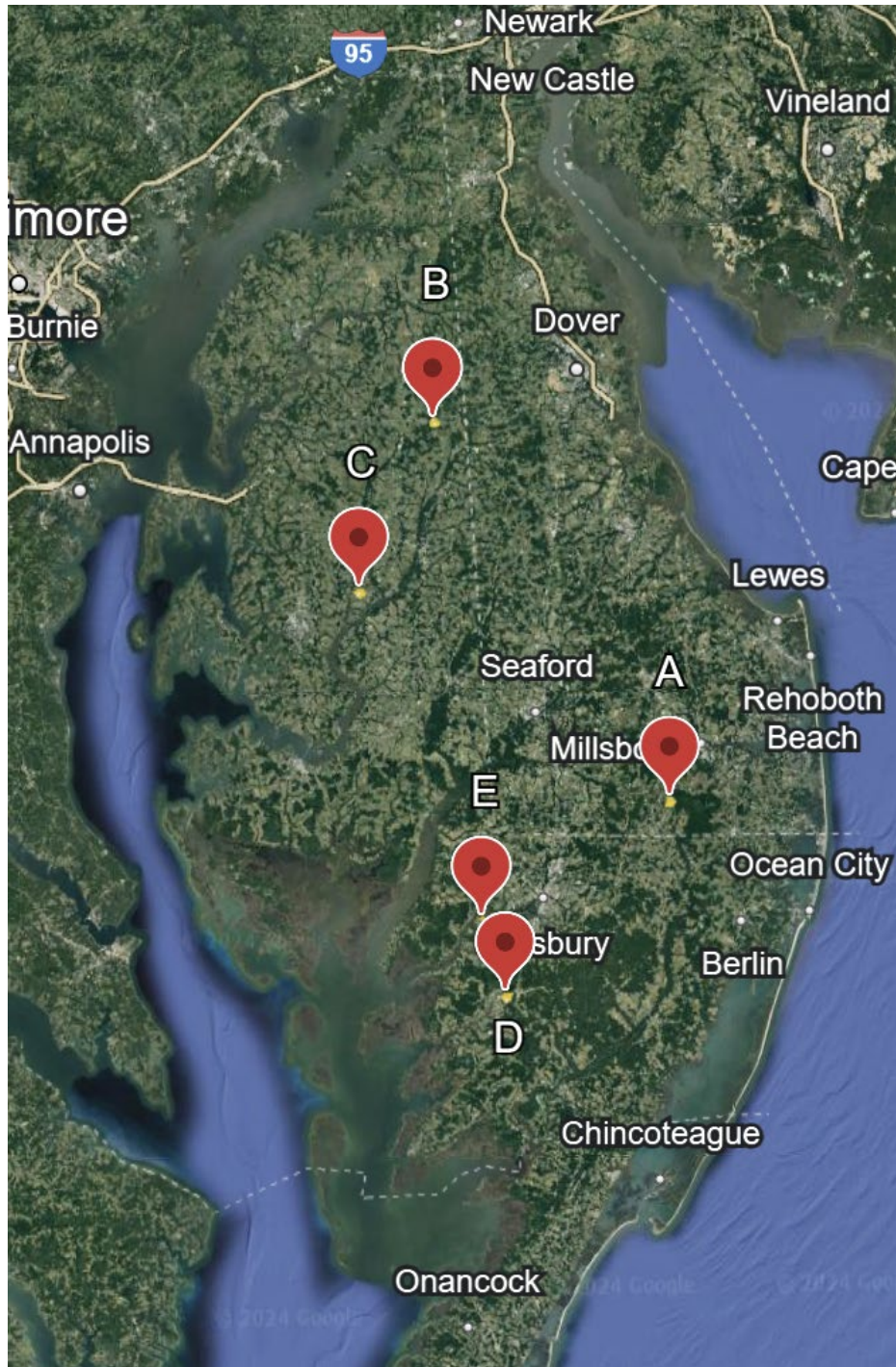


Figure 2.1 Map of the Delmarva peninsula with locations of the five farms used for sampling marked. Image courtesy of Google Earth.

Table 2.1 Characteristics of farms on which study sites were located. An opposing ditch layout indicates that the two ditch segments sampled were located along two separate drainage ditches on opposite sides of the field, while a parallel ditch layout indicates that both ditch segments were located along the same drainage ditch.

Farm	Ditch layout	County	Affiliation	Management type	Distance between transects	Crop planted		
						2021	2022	2023
A	Opposing	Sussex Co., DE	Private	Conventional	30.4 m	Corn	Corn	Corn
B	Opposing	Caroline Co., MD	Private	Conventional	30.4 m	Corn	Soy*	Corn
C	Parallel	Talbot Co., MD	Private	Conventional	30.4 m	Soy	Corn	Soy
D	Parallel	Somerset Co., MD	University	Conventional	15.2 m	Corn	Soy	Corn
E	Parallel	Wicomico Co., MD	Private	Organic	30.4 m	Soy	Soy	Soy**

* A rye cover crop was planted at farm B in 2022 which was harvested between the June and July sampling dates.

** A wheat cover crop was planted at farm E in 2023 which was harvested before the July sampling date.

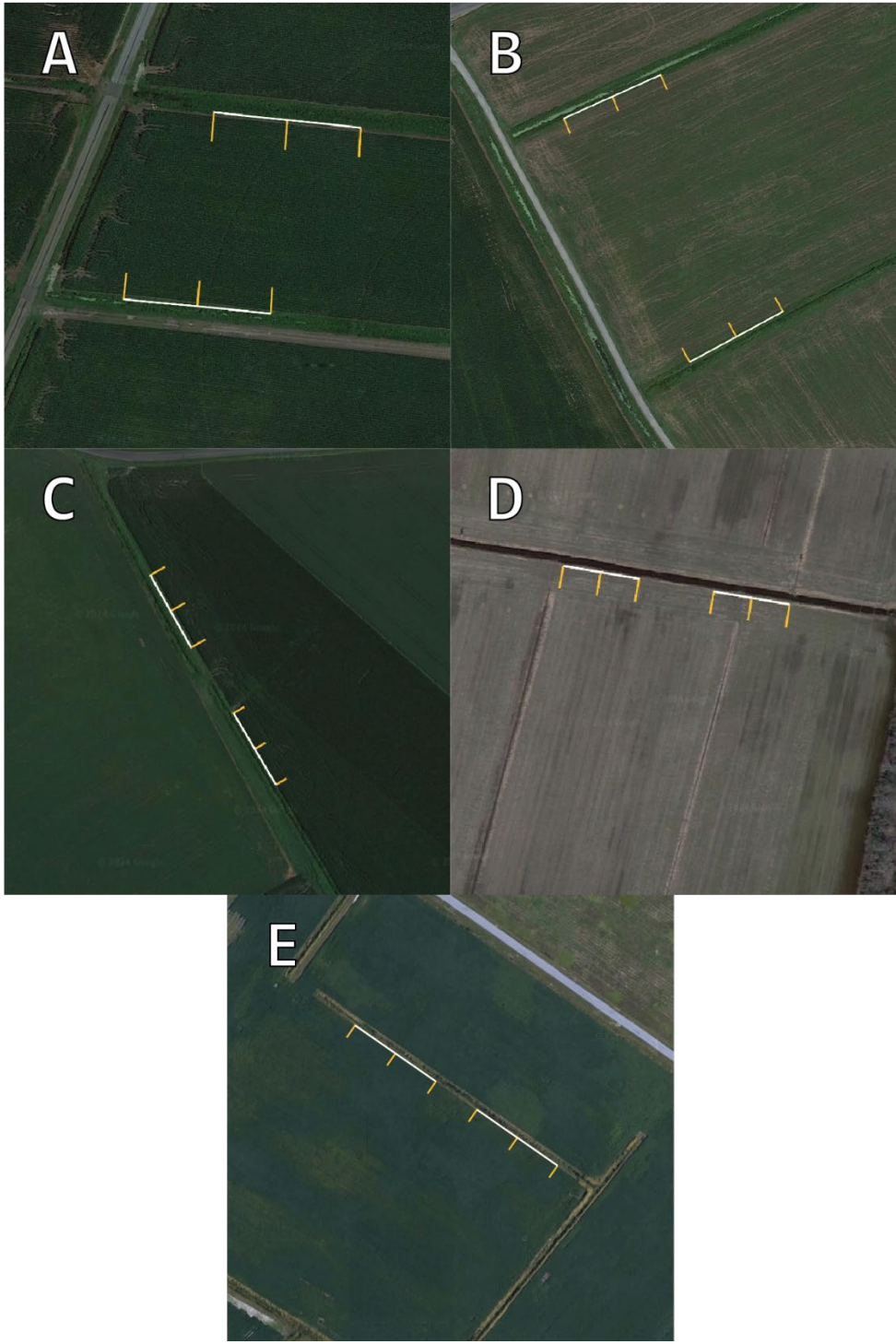


Figure 2.2 Drainage ditch segments (white) and transects (yellow) sampled on each farm (A – E). Images adapted from Google Earth.

Table 2.2 Plant families identified from each drainage ditch at the five farms sampled during this study.

Family	A		B		C		D		E	
	NO	SO	NO	SO	NW	SE	EA	WE	NW	SE
Adoxaceae	-	-	-	-	X	-	-	-	-	-
Amaryllidaceae	-	-	-	-	X	-	-	-	-	-
Apocynaceae	-	X		X	X	-	-	-	X	-
Asteraceae	-	X	X	X	X	-	X	X	X	X
Betulaceae	-	-	-	-	-	-	-	-	-	X
Bignoniaceae	-	-	-	-	-	-	-	-	X	-
Campanulaceae	X	-	-	-	-	-	-	-	-	-
Caprifoliaceae	-	-	-	-	X	-	-	-	-	-
Caryophyllaceae	-	-	-	-	-	-	X	-	-	-
Convolvulaceae	-	-	-	-	-	-	-	-	-	X
Cyperaceae	-	X	-	-	-	-	X	X	-	X
Ebenaceae	-	-	-	-	-	-	-	-	X	-
Fabaceae	-	-	-	-	-	-	-	-	X	-
Geraniaceae	-	-	-	-	X	-	-	-	-	-
Junaceae	-	X	-	X	-	-	-	-	X	-
Lamiaceae	-	-	-	-	-	-	-	X	-	-
Malvaceae	-	-	-	-	-	-	-	X	-	-
Melastomataceae	-	-	-	-	-	-	X	-	-	-
Oxalidaceae	X	-	-	-	-	-	-	-	-	-
Phyllanthaceae	-	-	-	-	-	-	-	-	-	X
Phytolaccaceae	X	-	-	-	-	-	-	-	-	X
Plantaginaceae	X	-	-	-	X	-	-	-	-	-
Poaceae	X	-	X	X	X	-	-	-	X	-
Polygonaceae	X	-	-	-	X	-	-	-	-	-
Rosaceae	X	X	-	X	-	-	-	-	X	X
Rubiaceae	-	X	-	-	-	-	-	-	-	-
Salicaceae	-	-	-	-	-	-	-	-	-	X
Sapindaceae	-	-	-	-	-	-	-	X	-	-
Solanaceae	-	-	X	-	X	-	X	X	-	-
Typhaceae	-	-	-	-	-	-	-	-	X	X
Urticaceae	-	X	-	-	-	-	-	-	X	-
Verbenaceae	-	X	-	-	-	-	-	-	-	-
Vitaceae	-	-	-	-	X	-	-	-	-	-

Sampling

Each sample consisted of the contents of a pitfall trap set up to passively collect ground beetles for one week before being collected. One pitfall trap was placed at each sampling location for each sampling round. For each pitfall trap, a golf hole digger was used to dig a hole 11 cm wide and 12 cm deep, and an 11-cm tall and a plastic Solo cup with a 10-cm diameter at its lip was placed inside with a hole punched out of the bottom to avoid flooding. The empty space around the cup was filled in using the dug soil, and another plastic Solo cup was placed inside the first cup and filled with 100 mL of propylene glycol. The soil surrounding the cup was molded to be flush with the lip of the cup, then a square plastic cover 1 mm thick and 30 cm across each side was placed over the cup with 3 cm of space between the ground and the cover to shield the trap from rain and interference from vertebrates while allowing arthropods to travel underneath. The upper surface of the trap cover was coated with white spray paint as a preventative measure against excessive heat absorption in the field.

Pitfall traps were collected one week after setup by pouring the contents of the top cup through a sieve with a 1 mm mesh. The solid contents were then transferred from the sieve to a 100-mL snap-lock plastic jar with 80% ethanol for preservation. Sampling was conducted once a month for three months (June, July, August) across years 2021 – 2023. Due to later soybean planting at farm E each year, sampling was not conducted in June, and an additional round of sampling was conducted in September of 2023. All captured ground beetles were separated into sample vials and identified to genus.

Statistical analysis

All statistical analyses were performed in R version 2023.06.2 (R Core Team, 2022), and all hypothesis tests were performed at $\alpha = 0.05$. To assess the habitat preferences of the ground beetle genera encountered in the study, preference factors were calculated for genera above a given sample size ($n = 15$) as a ratio between capture rate in drainage ditches and mean capture rate in adjacent crop fields (Lys *et al.*, 1994). To determine whether ground beetle abundance within ditches is proportional to ground beetle abundance in adjacent crop fields, paired counts of ground beetles captured in ditches and those captured in adjacent fields along the same transects were fitted to generalized linear mixed models for the six most frequently captured genera using the glmmTMB package in R (Brooks *et al.*, 2017). Genus-level ground beetle activity-density at the ditch was used as a fixed effect and year, month, farm, and ditch were used as random effects. Poisson distributions were used as a default to model count data, but for overdispersed generic datasets, a negative binomial distribution was used instead.

Results

Ground beetle diversity

Throughout this study, a total of 3,506 ground beetles from 23 genera were collected in pitfall traps. Of the 3,457 adult beetles collected, 22 genera were represented (Table 2.3, Figure 2.3), while the remaining 49 larval ground beetles represented 9 genera (Figure 2.4). The most frequently collected genus among adult beetles was *Anisodactylus*, followed by *Harpalus*, *Poecilus*, and *Amara* (Figure 2.3). Among larval captures, the most

frequently collected genus was *Calosoma*, followed by *Anisodactylus*, *Stenolophus*, and *Chlaenius* (Figure 2.4). Most larvae were collected from drainage ditches in June sampling dates, while more larvae were collected from ditch-adjacent crop fields from one sampling date in September at farm E (Figure 2.5).

Table 2.3 List of ground beetle genera collected from all sites throughout the study period from 2021 – 2023 along with adult & larval presence and their life history category: autumn breeding (AB), spring breeding (SB), or unknown (?) (Bousquet, 2010). Species are given where known but may not include all species present within a genus.

Genus	Species	Life	Adults?	Larvae?
<i>Agonum</i>	<i>octopunctatum</i>	SB	Y	N
<i>Amara</i>	<i>aenea</i>	SB	Y	Y
<i>Amphasia</i>	-	SB	Y	N
<i>Anisodactylus</i>	<i>rusticus</i>	SB	Y	Y
	<i>sanctaecrucis</i>	SB	Y	
	<i>nigerrimus</i>	SB	Y	
<i>Bembidion</i>	-	SB	Y	N
<i>Brachinus</i>	-	SB	Y	N
<i>Bradycellus</i>	-	SB	Y	N
<i>Calosoma</i>	<i>sayi</i>	?	Y	Y
<i>Carabus</i>	<i>vinctus</i>	?	Y	N
<i>Chlaenius</i>	<i>aestivus</i>	SB	Y	Y
	<i>tomentosus</i>	SB	Y	
	<i>laticollis</i>	SB	Y	
<i>Cicindela</i>	<i>punctulata</i>	SB	Y	N
<i>Dicaelus</i>	<i>elongatus</i>	SB	Y	Y
<i>Discoderus</i>	-	SB	Y	N
<i>Galerita</i>	-	SB	Y	Y
<i>Harpalus</i>	<i>pennsylvanicus</i>	AB	Y	Y
	<i>compar</i>	SB	Y	
	<i>rubripes</i>	SB	Y	
<i>Notiobia</i>	-	SB	Y	N
<i>Poecilus</i>	<i>chalcites</i>	SB	Y	N
	<i>lucublandus</i>	SB	Y	N
<i>Pterostichus</i>	<i>permundus</i>	AB	Y	N
<i>Scarites</i>	<i>subterraneus</i>	SB	Y	N
<i>Selenophorus</i>	-	SB	Y	N
<i>Stenolophus</i>	-	SB	Y	Y
<i>Tetracha</i>	<i>virginica</i>	SB	Y	N
<i>Trichotichnus</i>	-	SB	N	Y

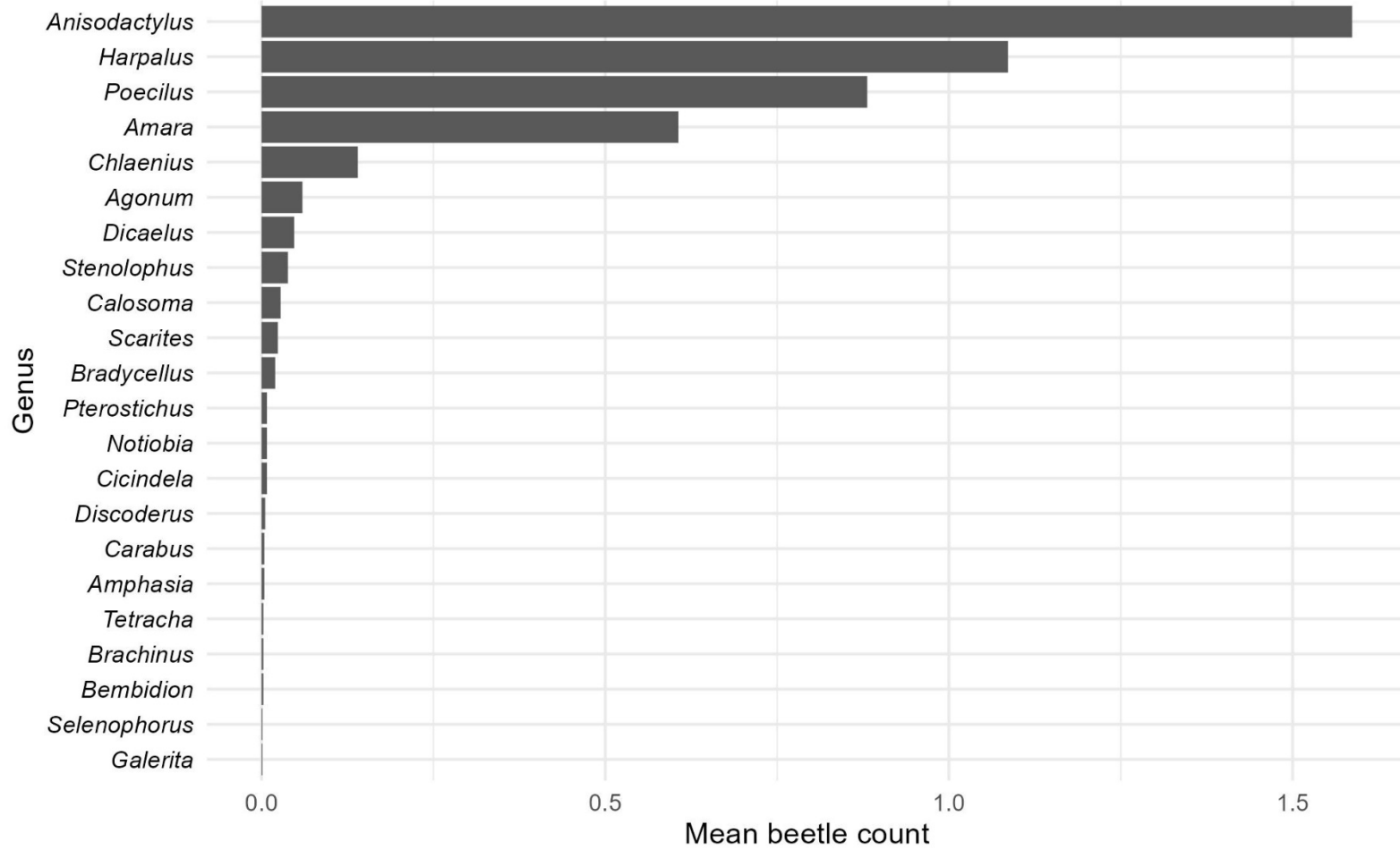


Figure 2.3 Mean number of adult ground beetles of each genus captured in pitfall traps across all sampling sites and periods.

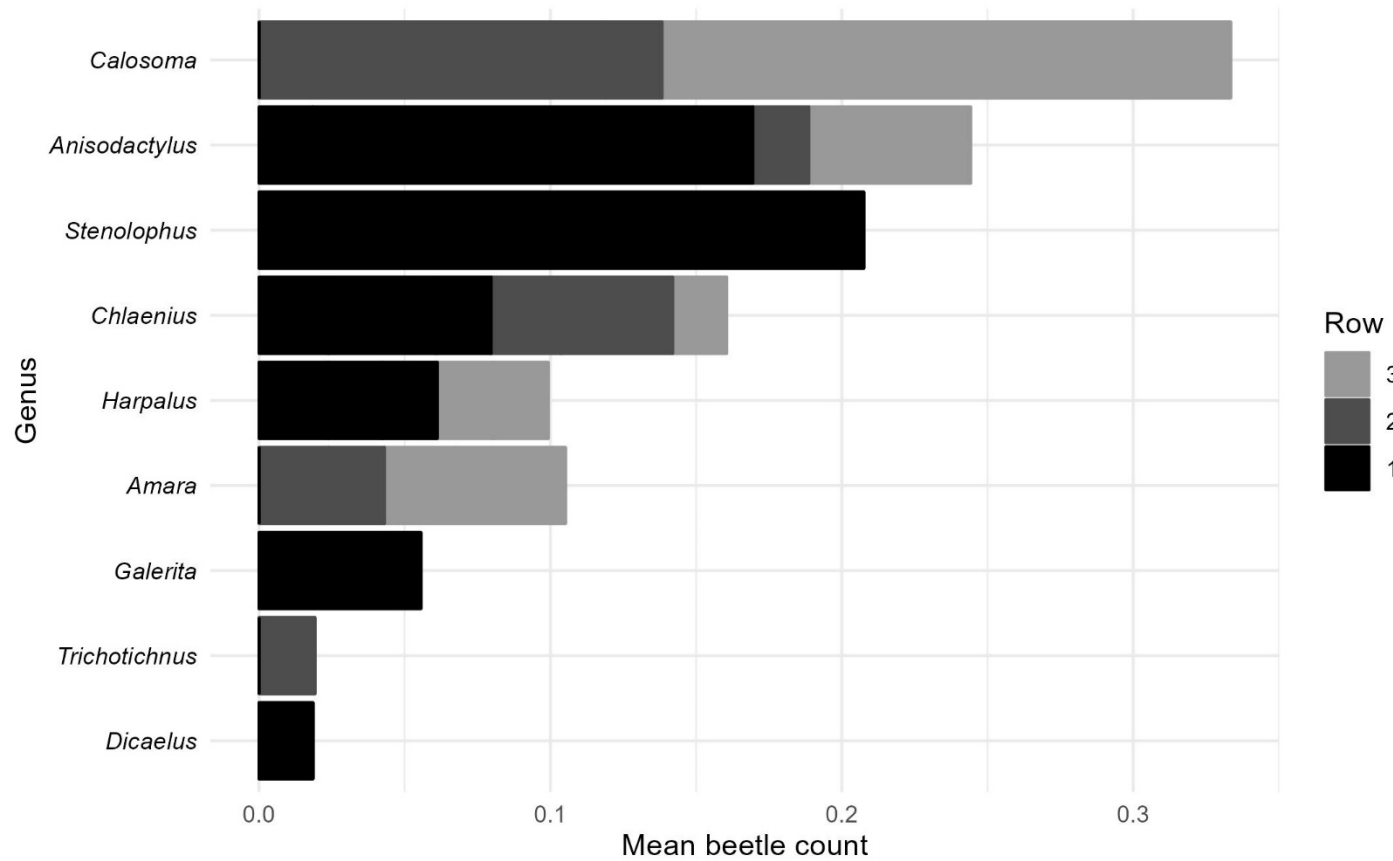


Figure 2.4 Mean number of larval ground beetles of each genus captured in pitfall traps across all sampling sites and periods. Different shades represent the row each larva was captured in: (1) edge of drainage ditch, (2) 1.5 meters into the crop field, (3) 9.1 meters into the crop field.

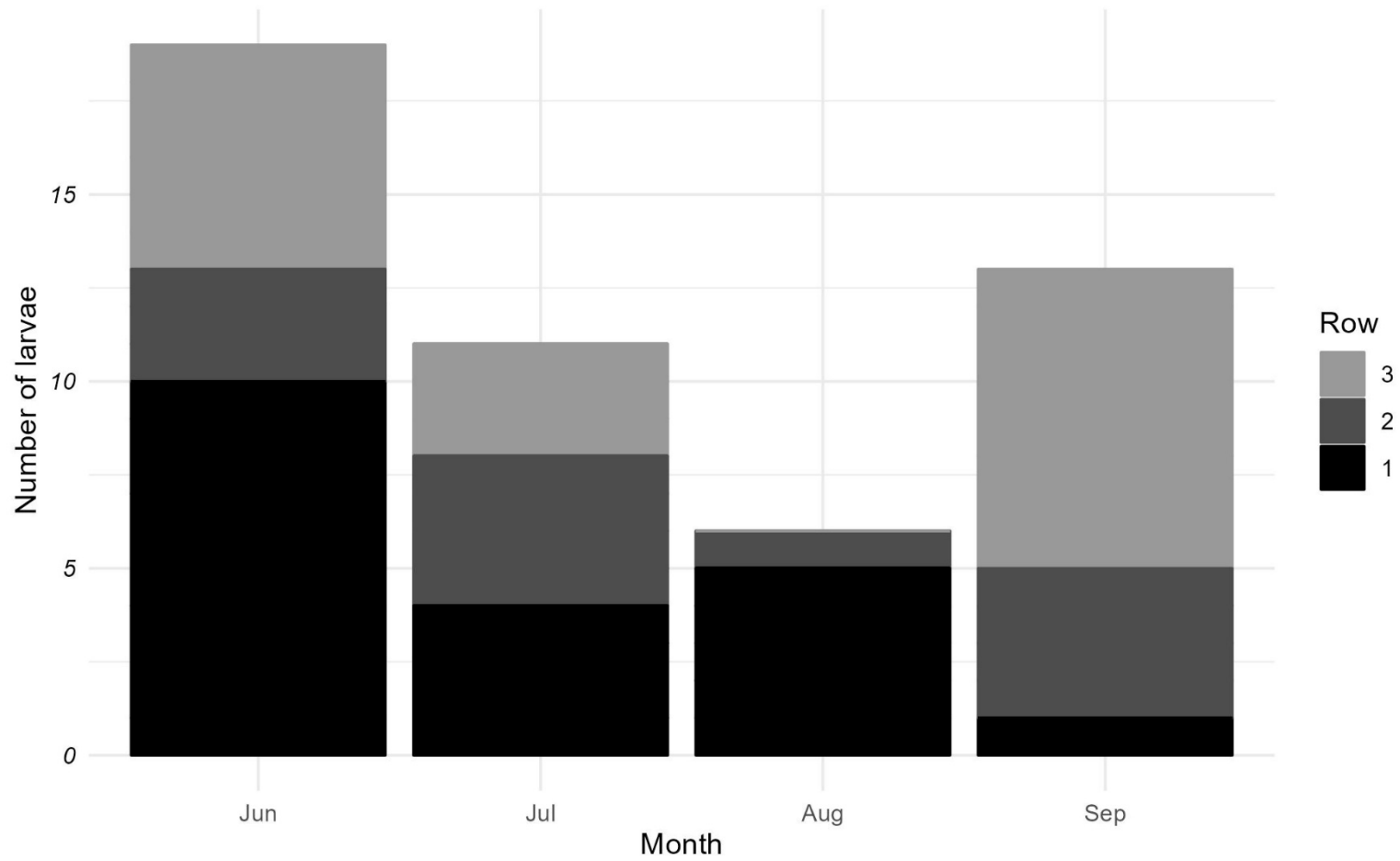


Figure 2.5 Total number of larval ground beetles captured from 2021 – 2023 by month and row.

Out of all adult ground beetles collected, *Harpalus* was present in samples from every sampling period at every farm, and *Chlaenius*, *Poecilus*, and *Dicaelus* were nearly as widespread. Other genera were collected far less broadly, such as *Brachinus* which was only collected at farm C. The presence of some genera was largely restricted to certain months, such as *Pterostichus* and *Scarites* which were only present in June samples apart from *Scarites* at farm E, which were found through July and August. *Stenolophus* and *Notiobia* were not found in any samples later than July. Many genera were only represented by a few captured specimens, including *Amphasia*, *Bembidion*, *Brachinus*, *Carabus*, *Galerita*, *Selenophorus*, and *Tetracha* which were only captured between 1-3 times each. There was a notable divide between the genera found at the two southernmost farms (D & E) and those at the other three farms. *Agonum* was only collected in July samples from the southernmost farms and *Carabus* and *Calosoma* were only collected in August and September samples from these farms, while *Bradycellus* was exclusively found in June samples across the other three farms (Table 2.4).

Table 2.4 Adult ground beetle presence-absence matrix. An “X” marks that an adult specimen of the given genus was observed in pitfall traps from a given month and farm across years 2021 – 2023. Farm E was not sampled in June any year due to later soybean planting, and September sampling was conducted only in 2023.

Genus	A			B			C			D			E*		
	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug	Jul	Aug	Sep
<i>Agonum</i>	-	-	-	-	-	-	-	-	-	-	X	-	X	-	-
<i>Amara</i>	X	-	X	X	-	X	X	-	-	X	X	-	X	X	X
<i>Amphasia</i>	-	-	-	X	-	-	-	-	-	-	X	-	-	-	-
<i>Anisodactylus</i>	-	X	-	X	-	X	-	X	X	X	X	X	X	X	-
<i>Bembidion</i>	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
<i>Brachinus</i>	-	-	-	-	-	-	X	-	X	-	-	-	-	-	-
<i>Bradycellus</i>	X	-	-	X	-	-	X	-	-	-	-	-	-	-	-
<i>Calosoma</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X
<i>Carabus</i>	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
<i>Cicindela</i>	-	-	X	-	-	-	-	-	-	-	-	-	X	-	-
<i>Chlaenius</i>	X	X	X	X	X	X	X	X	X	X	X	-	X	X	-
<i>Dicaelus</i>	X	X	X	X	X	X	-	X	X	X	-	-	X	X	-
<i>Discoderus</i>	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Galerita</i>	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-
<i>Harpalus</i>	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Notiobia</i>	X	-	-	-	-	-	X	-	-	X	X	-	-	-	-
<i>Poecilus</i>	-	X	X	X	-	X	X	X	-	X	X	X	X	X	X
<i>Pterostichus</i>	-	-	-	X	-	-	X	-	-	X	-	-	-	-	-
<i>Scarites</i>	X	-	-	-	-	-	X	-	-	X	-	-	X	X	-
<i>Selenophorus</i>	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-
<i>Stenolophus</i>	X	X	-	-	-	-	-	-	-	X	X	-	X	-	-
<i>Tetracha</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Total richness	9	6	7	9	3	6	10	5	5	10	9	4	11	9	4*

Activity-density across ditch and field

Ground beetle preference factors indicate an apparent variety in habitat preferences across genera. *Anisodactylus* and *Stenolophus* were most likely to be captured from pitfall traps located at drainage ditches relative to those in adjacent fields while *Bradycellus* and *Calosoma* were the only two genera that were caught more frequently in the field (Figure 2.6).

Results of generalized linear mixed models comparing ground beetle activity-density at the ditch against that in adjacent crop fields varied according to genus and distance into the crop field. For *Anisodactylus*, *Poecilus*, and *Amara*, the number of individuals captured from drainage ditches was a significant predictor of the number captured in fields along the same transect for both the nearer and further points (1.5 and 9.1 meters into the field). However, ditch activity-density was not significantly correlated with field activity-density for *Harpalus* at either distance. For *Chlaenius* and *Agonum*, the significance of this correlation depended on the distance, with ditch activity-density being a significant predictor of field activity-density for *Chlaenius* at the distance further from the ditch only and for *Agonum* at the nearer distance only (Table 2.5).

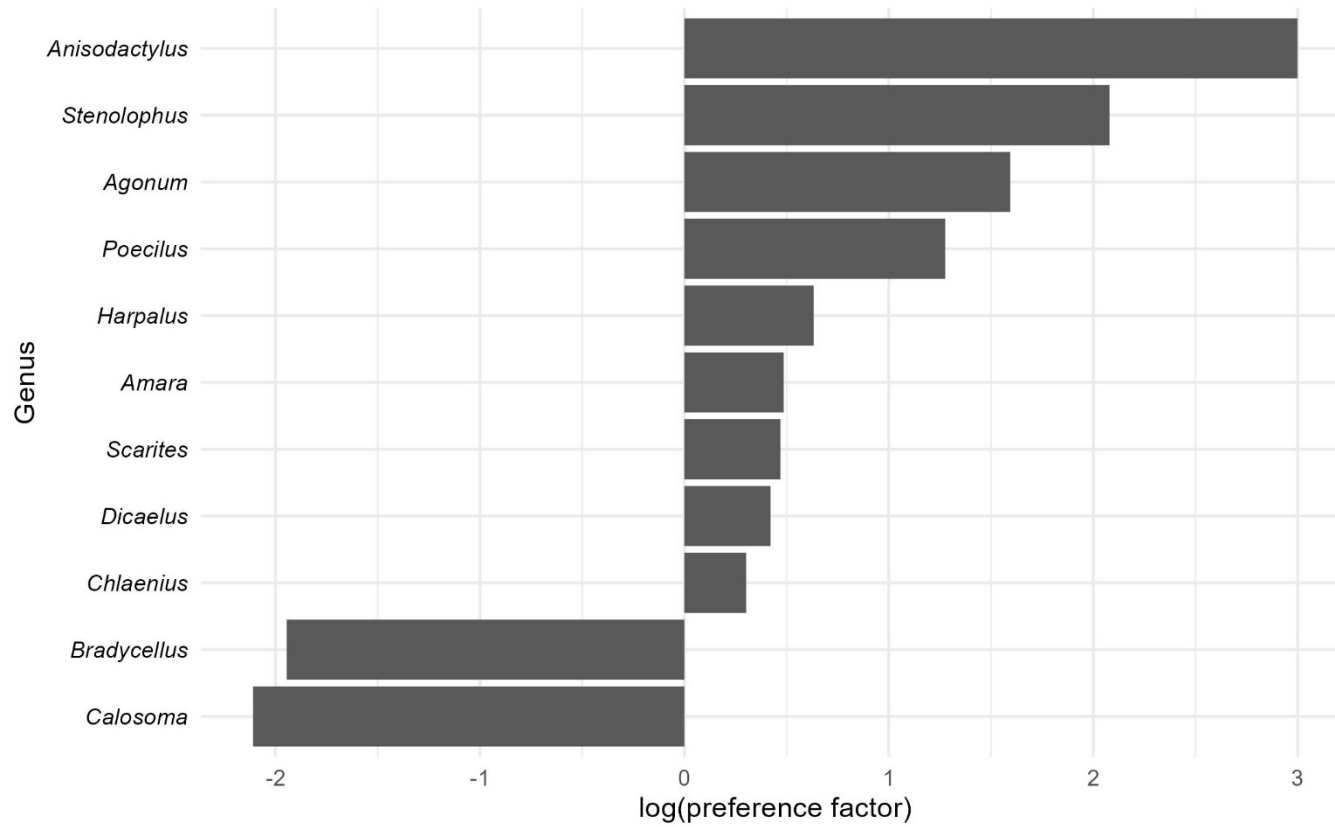


Figure 2.6 Preference factors of the most frequently collected adult ground beetle genera, obtained as a ratio of the pitfall trap capture rate in drainage ditches to the mean capture rate in samples from adjacent crop fields. Preference factors are plotted on a logarithmic scale such that 0 indicates no habitat preference while a greater or lesser value indicates apparent preference for the ditch or field respectively.

Table 2.5 Results of generalized linear mixed models representing the number of ground beetles captured via pitfall traps from two crop rows (distances into crop fields) as a function of the number of ground beetles captured from the adjacent drainage ditch along the same transect. Results are shown for the six most frequently captured genera. Overdispersed sets of data (dispersion > 1.2) were modeled using a negative binomial distribution, while others were modeled using a Poisson distribution. P-values indicating significant or marginally significant results at $\alpha = 0.05$ are marked with an asterisk.

Genus	Crop Row	Dispersion	Distribution	Coefficient Estimate	Standard Error of Mean	p-value
<i>Anisodactylus</i>	1.5 m	5.568	Negative binomial	1.022	1.008	0.008*
	9.1 m	3.920	Negative binomial	1.048	1.013	<0.001*
<i>Harpalus</i>	1.5 m	4.607	Negative binomial	1.007	1.061	0.899
	9.1 m	2.890	Negative binomial	1.071	1.044	0.109
<i>Poecilus</i>	1.5 m	4.717	Negative binomial	1.096	1.019	<0.001*
	9.1 m	3.339	Negative binomial	1.070	1.015	<0.001*
<i>Amara</i>	1.5 m	25.31	Negative binomial	1.220	1.096	0.030*
	9.1 m	34.68	Negative binomial	1.133	1.066	0.052*
<i>Chlaenius</i>	1.5 m	1.170	Poisson	0.228	2.911	0.167
	9.1 m	1.038	Poisson	0.208	2.167	0.042*
<i>Agonum</i>	1.5 m	1.545	Negative binomial	1.872	1.327	0.027*
	9.1 m	1.491	Negative binomial	0.662	1.464	0.279

Discussion

In this chapter, I aimed to characterize ground beetle communities in agricultural drainage ditches across the Delmarva peninsula and compare these communities with those in adjacent corn and soybean fields. In the first chapter of this study, I attempted to characterize the ground beetle community within a drainage ditch on the Delmarva peninsula and found that adding straw to the banks of the ditch in the fall could increase the activity-density of autumn-breeding ground beetles in following years. However, this community assessment was limited to a single ditch and no data was collected regarding whether these increases result in enhanced ground beetle populations in adjacent crop fields where demand for biological control is high. Here, I compared activity-densities of ground beetles in drainage ditches across five farms on the Delmarva peninsula with activity-densities at two distances into adjacent crop fields to determine whether ditch activity-density is significantly correlated to field activity-density.

While there are distinct differences in ground beetle communities in drainage ditches and adjacent fields across different farms, many of the most common genera are shared across these gradients. Overall, the most abundant genera were omnivorous or primarily granivorous, including *Harpalus*, *Anisodactylus*, and *Amara*. Predominantly predaceous ground beetles were less common, with some of the most frequently collected being *Poecilus*, *Chlaenius*, and *Dicaelus*. However, formal analyses involving functional feeding groups was challenging due to a lack of consensus in literature surrounding ground beetle diets in agricultural fields. This is in part due to the diverse and often strongly opportunistic diet breadth of ground beetles, but conflicting accounts

from various sources additionally make it difficult to categorize ground beetles into distinct feeding groups. For instance, *Anisodactylus rusticus*, the most abundant species of its genus in this study, is often cited as a weed seed predator but has been found to feed readily on slugs in laboratory assays (Menalled *et al.*, 2007; Vilorio, 2023).

Formal analyses on larval diversity and abundance based on pitfall trap captures were unreliable due to low sample sizes resulting from the low mobility of most ground beetle larvae. Additionally, measures of larval activity-density using pitfall traps are heavily biased towards larger, more mobile larvae such as those of *Chlaenius*, *Galerita*, and *Calosoma*. However, based on the larvae I sampled, there appeared to be a greater discrepancy in habitat preference among larvae as compared to adults, with all 14 *Calosoma* larvae having been caught in the crop field while all *Stenolophus* larvae were captured from a drainage ditch.

Preference factors of observed genera indicate that prevalence in each habitat is greatly dependent on genus identity. While these analyses are based solely on habitat use and do not reveal information regarding the mechanisms behind these preferences (Beyer *et al.*, 2010), they highlight the importance of considering community dynamics across this habitat gradient at a genus level. Groups that are much more likely to be found in the ditch, such as *Anisodactylus*, may not serve as effective biocontrol agents due to their weaker relative preference for moving into crop fields, while those that are found much more commonly in the field may not be strongly affected by ditch management practices. A more balanced preference factor is likely to be more desirable for purposes of conservation biological control.

Adult ground beetle activity-density was correlated between the two habitats for half of the six most frequently collected genera, including *Anisodactylus*, *Poecilus*, and *Amaru*, indicating that there is a significant amount of spillover between communities of these genera across these two habitats. This correlation implies that management practices that increase the abundance of these genera in drainage ditches may additionally enhance their abundance in adjacent crop fields. Results for *Chlaenius* and *Agonum* were more mixed, with ditch activity-density having been found to be a significant predictor of field activity-density at only one of the two measured distances into the field for each. This may have been caused by tendencies of each of these genera to travel more or less far into the crop, but as these were the two least commonly collected groups out of those analyzed, this may also have been a result of inadequate sample sizes for these genera.

Of the six genera analyzed, *Harpalus* was the only genus for which ditch and field activity-densities were not found to be correlated at any distance into the crop. Compared to other genera, this genus was more likely to be found in greater numbers either in the ditch or in the field at any given transect. This genus was also one of the two autumn-breeding genera that were heavily impacted by straw treatments in the previous chapter. *Pterostichus*, the other genus, was not captured in frequent enough numbers for analysis in this study.

These findings suggest that increased *Harpalus* abundances in the ditch would not necessarily translate to increased abundances in the field, although a lack of mechanistic understanding of these results makes prediction a challenge. It is possible that while this

genus appears to have a greater preference for one habitat over another at each given location, this preference is dependent on a factor that was not explored in this study, and thus conservation biocontrol through drainage ditch management may be conditionally effective in locations where *Harpalus* are more common in the field, though this assumes that individuals of this genus are affected by ditch management practices in these cases.

While the results of this study support the broad claim that semi-natural habitats have the potential to increase ground beetle activity in adjacent crop fields, they do not reject the possibility that creating or managing these habitats to provide greater shelter or other resources for ground beetles may only enhance their role as an ecological sink. While many studies have demonstrated meaningful increases in weed seed and pest predation as a result of conservation biological control by ground beetles (Hawthorne *et al.*, 1998; Varchola & Dunn, 2001; Collins *et al.*, 2002, 2003; MacLeod *et al.*, 2004), others have noted a failure to observe similar results (Carmona & Landis, 1999). Additionally, some studies have also shown that field margin strips may negatively impact biocontrol by presenting a physical barrier to natural enemy dispersal, impeding their ability to recolonize cropped areas following major habitat disturbances (Frampton *et al.*, 1995). However, drainage ditches are existing field margins that are present regardless of their ecological function, and this may in fact present a case for greater focus on enhancing the ecological functions of existing habitats prior to creating new habitats built solely for this purpose.

Future research in this area should focus on a combination of the experiments in both chapters of this thesis to directly observe potential changes in ground beetle

activity-density and predation rate in crop fields as a response to altered drainage ditch management practices. Such an experiment was not performed in this study because suitable drainage ditch sites on research farms were generally located adjacent to plots being utilized for other experiments, while private farms did not provide permission to apply treatments to drainage ditches.

Based on this study, agricultural drainage ditches are home to a high variety of ground beetle species that are additionally associated with adjacent crop fields, and it is likely that most ground beetles move readily between these habitats. Ecological management of drainage ditches presents a potential path to increasing biological control of plant and invertebrate pests in crop fields.

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