EVALUATING THE USE OF BARN OWL NEST BOXES FOR RODENT PEST CONTROL IN WINEGRAPE VINEYARDS IN NAPA VALLEY

By

Ashley N. Hansen

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Committee Membership

Dr. Matthew Johnson, Committee Chair

Dr. Daniel Barton, Committee Member

Dr. Barbara Clucas, Committee Member

Dr. Erin Kelly, Program Graduate Coordinator

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ABSTRACT

EVALUATING THE USE OF BARN OWL NEST BOXES FOR
RODENT PEST CONTROL IN WINEGRAPE VINEYARDS IN NAPA VALLEY

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Attracting natural enemies to farms to reduce pests has long been a part of integrated pest management for insects, but knowledge of the impact of raptors on rodent and other vertebrate pests is comparatively sparse. In this study, I compared rodent prey on winegrape vineyards in Napa California with and without occupied barn owl nest boxes. We collected data before the breeding season, when hunting pressure should be light, and again when adult owls were hunting actively to feed their chicks. I used the open-hole method to quantify an index of gopher activity, and Sherman live traps to estimate the abundance (minimum number alive) of other rodents. I found that gopher activity declined from before to peak hunting pressure on the vineyard with barn owl nest boxes, whereas it slightly increased on the vineyard without nest boxes. Live trapping revealed that the abundance of mice declined from before to during peak hunting pressure, but this decline was not significantly affected by the presence of nest boxes. Results were inconclusive for voles because they were not well-sampled by our live trapping method, even though analysis of owl pellets confirmed they are an important source of prey for barn owls. This is among the first work in the United States to confirm that barn owl nest

boxes can reduce activity of gopher pests in agriculture. Future work should replicate this study after adding nest boxes to the vineyard that lacks them and employ another method to assess vole abundance or activity.

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INTRODUCTION

Through expansion and intensification, the growth of global agriculture poses one of largest threats to biodiversity (Green et al. 2005, McLaughlin 2011, Tscharntke et al. 2012). Rising population growth, per capita consumption, and the resulting conversion of uncultivated lands into agriculture (Tillman et al. 2011) continues to not only pose threats by degrading natural systems, but also through agrochemical inputs (Matson et al. 1997, Coeurdassier et al. 2014). As a result, environmentally friendly strategies such as utilizing natural predators as part of an integrated pest management (IPM) plan are becoming more common in agricultural settings (Green et al. 2005, Gómez-Baggethun et al. 2010, Paz et al. 2013, Sekercioglu et al. 2016).

Rodents are economically damaging pests in agriculture worldwide (Stenseth et al. 2003, Gebhardt et al. 2011). Rodents impact agriculture by directly consuming annual crops and reducing harvests by cutting roots or gnawing bark, which diminishes crop output or quality and in some cases kills adult crop plants (Baldwin et al. 2014). Though the economic impact can vary considerably across crop types and regions, damage caused by pests for California crops has been estimated to cost an average $95.9 million per year (Hueth et al. 1998). A meta-analysis done by Gebhardt et al. (2011) examined bird and rodent damage of 19 economically important crops within California, including winegrapes. By compiling published studies with unpublished reports, surveys, and interviews with agricultural extension experts, they were able to provide damage estimates for each crop using Monte Carlo simulations. Based on an expected 10.7% loss per acre and an expected 67.5% acres damaged, winegrapes were calculated to have the second greatest losses in the state, with an estimated 7.2% yield reduction per year (Gebhardt et al. 2011). Their results indicate that damage to winegrapes by vertebrates remains substantial despite the use of a variety of pest control methods. With such significant losses, a benefit is to be had by establishing and implementing more effective pest control methods.

The use of rodenticides is widely used as the dominant rodent pest control measure (Tickes et al. 1982, Stenseth et al. 2003, Wood and Fee 2003), but killing rodents with rodenticide is costly, may have decreasing efficacy as rodents become resistant to certain compounds, can pose health risks to workers, and can have negative effects on the environment, such as secondary poisoning of non-target species (Erickson and Urban 2004, Berny 2007, Browning et al. 2016). Trapping is less damaging ecologically, but is very laborious and costly. Consequently, more ecologically safe measures to control rodent pest populations, such as utilizing biological control agents as a form of IPM, are essential for future management (Johnson et al. 2018).

High-value crops such as winegrapes are experiencing an increase in public demand for sustainable agriculture and pest management solutions (Barber et al. 2010). The ongoing need to control rodent pest populations has led to the increased awareness of using IPM in agroecosystems (Evenden 1995, Kan et al. 2014, Kross et al. 2016, Labuschagne et al. 2016), including within vineyards in Napa Valley, California (Brodt et al. 2006). One of the main issues concerning vineyard owners is how to control rodent pests, which can cause millions of dollars in winegrape crop damage annually (McGourty et al. 2011, Baldwin et al. 2014). As a result, growers in California have been installing nest boxes to attract American barn owls (*Tyto furcata*) as a form of natural pest control (Kross and Baldwin 2016, Labuschagne et al. 2016). Through the installation of nest boxes, farmers can attract barn owls, which may be able to act as a natural predator and reduce populations of voles (*Microtus* spp.), mice (*Peromyscus* spp. and *Mus.* spp.), and pocket gophers (*Thomomys bottae*) – key pests in winegrape vineyards (Ross 2009, Tillmann 2012, Murray and DeFranesco 2016).

Given the economic importance of vineyards and the consequences of using rodenticide, there is incentive to research how effective barn owls are as an alternative to conventional rodent control practices. Theoretical modeling suggests barn owls could help control background levels of rodents, but even the highest barn owl densities may be unable to control abundant and quickly reproducing pocket gopher populations (Kross and Baldwin 2016, Hiroyasu et al. 2020). In Spain, Luna et al. (2020) documented a clear reduction in two vole species (*Microtus arvalis* and *M. duodecimcostatus*) after installing nest boxes for common barn owls (*Tyto alba*) and common kestrels (*Falco tinnunculus*) in both fruit-tree plantations and alfalfa crops. And in Malaysia, Abidin et al. (2021) found that installing nest boxes for Javan barn owls (*Tyto javanica*) reduced damage to oil palm fruits by house rats (*Rattus rattus*) to a level achieved when applying rodenticides (chlorophacinone, a first-generation anticoagulant). Meanwhile, recent empirical research on the use of barn owls in California has focused on patterns of nest box occupancy (Wendt and Johnson 2017), hunting habitat selection (Castañeda et al. 2021, Huysman and Johnson 2021), and prey removal rates (Johnson et al. 2018, Johnson and St. George 2020). Browning et al. (2016) documented substantial gopher predation on a vineyard in California, and gopher mound surveys suggested the practice of installing barn owl boxes has the potential to reduce gopher activity. Thus, while it is widely postulated that barn owls can benefit California farmers by hunting rodent pests, empirical data on the topic are very scarce.

My research aimed to advance our understanding of using barn owl nest boxes for rodent pest control and to help assess whether barn owls attracted to nest boxes in winegrape vineyards can meaningfully suppress the number of rodent pests. Specifically, my study assessed changes in rodent activity over time between two vineyards, one with and one without barn owl nest boxes. Rodent surveys were conducted at two sampling periods: before barn owl chicks hatched and again during the nesting season when chicks were growing and adult prey delivery rates were among their highest. I hypothesized that rodent abundance and activity will be negatively associated with the presence of and hunting pressure by barn owls on vineyards. Results from this study can help determine if barn owls can benefit farmers by significantly reducing rodent numbers and activity within vineyards via predation. Such results can direct future research and application regarding rodent control in winegrape vineyards.

MATERIALS AND METHODS

Study Area

This project was conducted on vineyards in Napa Valley, California, where Cal Poly Humboldt researchers have been collecting data since 2015. Ongoing research started by Wendt and Johnson (2017) established affiliations with vineyard owners and provided contacts for 65 collaborating vineyards and access to approximately 300 barn owl nest boxes throughout Napa Valley. Napa Valley is a 50 km stretch of land located 100 km north of San Francisco, California that is characterized by a Mediterranean climate ideal for growing grapes and renown for creating a wine industry valued at $3.7 billion (Stonebridge 2012). Surrounding habitats include mixed oak woodlands and oak savannas with more grasslands in the south and more mixed oak scrub and conifer forests in the north (Napa County 2010, Wendt and Johnson 2017).

Study Site

Two large vineyard operations were used as study sites, each with multiple fields near Soscol Creek just south of the city of Napa (Figure 1). Cakebread Vineyard (approximately 250 ha) had no nest boxes at the time of study, and Soscol Vineyard (approximately 345 ha) had 13 operational nest boxes. These vineyards were selected because they had similar row cropping, vine spacing (approximately 3 m between vines), and other farming practices that could affect rodent abundance, and they were in the same drainage and general landscape which minimized confounding environmental variables (though Cakebread was more upslope than Soscol) and eased travel logistics. Neither vineyard used rodenticides which would otherwise compromise rodent sampling. Both vineyards used a cover crop in between vine rows, comprised of a standard mixture of annual grasses such oats (*Avena sp*.) and barley (*Hordeum sp*.) as well as legumes, including common vetch (*Vicia sativa*), fava beans (*Vicia faba*), daikon radish (*Raphanus sativus*), field mustard (*Brassica rapa*) and Persian clover (*Trifolium resupinatum*). Cover crops were planted in the fall, and then mowed and/or tilled into the soil in the spring, typically timed when the cover crop was flowering, and sometimes alternating rows among weeks. No grids were mowed/tilled during the time of the study. Multiple sampling grids were established on each vineyard, as detailed below.

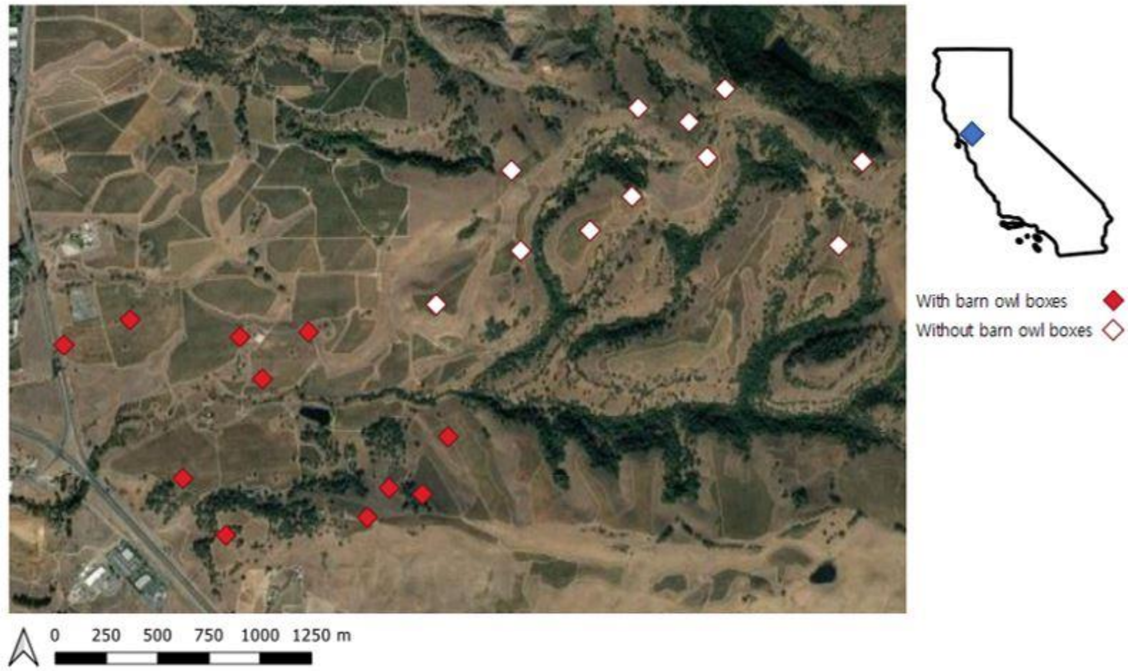

Figure 1. Map of study grids across two vineyards in Napa Valley, Soscol Vineyard (with barn owl nest boxes) and Cakebread Vineyard (without barn owl nest boxes). Service layer credits: QGIS, USGS, and the QGIS User Community

Study Species

Barn owls have a worldwide distribution that encompasses a range of habitats, from savannas in Africa to rainforests in Australia, as well as agricultural landscapes across Europe, North America, Central America, Africa, and the Middle East (Taylor 1994). The use of barn owls as a means of rodent control are appealing to farmers because the installation and maintenance of artificial boxes is relatively inexpensive (Kross and Baldwin 2016), and behaviorally they are not territorial, allowing them to reach high densities (Smith et al. 1974, Labuschagne et al. 2016). As natural cavity nesters, they can also be readily attracted to vineyards through the installation of artificial nest boxes (Labuschagne et al. 2016). They are effective hunters, a single nest requires many prey items (Taylor 1994, Durant and Handrich 1998), and in agricultural settings rodent pests compose a majority of their diets (Taylor 1994, Van Vuren et al. 1998, Kross et al. 2016). Within this study system, it was found that a single breeding pair with an average of three to four chicks removes 1,001 rodents (± 290) within a single breeding season (St. George and Johnson 2021).

Barn owls are central place foragers when nesting, hunting primarily near their nests to minimize travel costs associated with bringing back frequent and heavy prey to their growing chicks (Roulin 2020). After collecting over 10,000 GPS telemetry locations of barn owls hunting in Napa Valley, Castañeda et al. (2021) found that 95% of them were located within 3 km of the occupied nest box, 80% of them were within 800 m, and 53% of them were within 500 m of the occupied box.

In Napa Valley, pocket gophers (*Thomomys* spp.) and voles (*Microtus* spp.) are considered the most damaging rodent pests to vineyards (Ross 2009, Salmon and Baldwin 2009, Salmon and Gorenzel 2010). Both threaten the health of vines by cutting roots and gnawing bark and pose threats year round (Ross 2009, Baldwin et al. 2014). Pocket gophers in particular are adaptable to conditions of disturbance caused by agriculture and logging activities (Marsh and Steele 1992) and are considered nuisances due to burrowing and underground foraging, which negatively affect crop yields and can damage irrigation lines (Baldwin et al. 2014). Additionally, mounds made by gophers create an uneven vineyard floor, leaving tripping hazards for agriculture workers and obstacles that can damage farm equipment (Baldwin 2015). Both voles and gophers are also problematic as their herbivory can undermine survival of young vines (Ross 2009). Though rodents are viewed solely as pests, especially in this system and for the purposes of this research, it is important to note they do have some ecological benefits such as seed dispersal and soil aeration (Davidson et al. 2012).

Pocket gophers have a litter size of 2-10 and may breed 1 to 3 times per year, while voles may produce 1-10 young 5 to 10 times per year. Voles mature rapidly, and typically their numbers peak every 6 to 8 years, reaching potentially hundreds of voles per acre (Baldwin 2015). Reproduction rates for *Peromyscu*s spp. are similar to pocket gophers, with some dependencies on local conditions (Reid 2006). Though all breed year-round, there is usually an increase in reproduction during the winter to spring and again in the fall season. Gophers may be active any time of the day or night, and remain active year-round (Reid 2006). Thus, sustained monitoring and control of these rodent pests are necessary to keep populations low.

Small mammal abundance and diversity in agricultural landscapes depends on several factors such as habitat disturbance (Men et al. 2015, Balčiauskas et al. 2019), application of rodenticides or other mechanical control methods such as frequent mowing or trapping (Baldwin et al. 2014), nonlethal methods that may affect pest behavior and reproductive success such as utilizing natural predators (Kross et al. 2012), and crop type (Hueth et al. 1998, Gebhardt et al. 2011).

IACUC

All methods were approved by the Humboldt State University Institutional Animal Care and Use Committee Protocol (IACUC No. 20/20 W.46-A).

Field Methods

Sampling design

To assess changes in rodent activity over time between the two vineyards, I conducted rodent surveys at two sampling periods: before barn owl chicks hatched (3 February – 13 March 2020) and again during the nesting season (4 May – 12 June 2020) when chicks were growing and adult prey delivery rates were among their highest. St. George and Johnson (2021) found peak prey delivery rates for chicks occurred at 4-7 weeks of age. I used a GoPro mounted on an extendable pole (Wendt and Johnson 2017) to non-invasively monitor occupied nest boxes at Soscol vineyard and timed the second sampling period accordingly. Hereafter these two sampling periods are called “before” and "during" peak hunting presence. By monitoring rodent abundance before and during peak hunting presence in areas both occupied and unoccupied by barn owls, I was able to examine the relative change in rodent abundance and activity hypothesized to be affected by owl hunting.

Spatially, rodents were monitored on 22 sampling grids, 11 on Cakebread and 11 on Suscol vineyard. The grids on Suscol vineyard were each positioned to be within 100 m of an owl nest box. Of the 13 operational nest boxes on Soscol vineyard (several older broken boxes were also present), two pairs of nest boxes were close enough (< 250 m apart) that one sampling grid was established between them. For both vineyards, each grid was placed directly within vineyard rows (Figure 1). The widespread use of barn owl nest boxes in Napa Valley and the relatively large hunting range used by owls makes it impossible to achieve a comparison of vineyards with and entirely without barn owl hunting. Nonetheless, the minimum distance between a grid with a barn owl box and one without a barn owl box was 700 m and the maximum was 4090 m, so I assumed that barn owl hunting and presence was low on the vineyard without boxes (Cakebread) whereas it was higher on the vineyard with boxes (Soscol Creek). However, I also explored variation in barn owl presence within the vineyard with boxes (Soscol Creek) to obtain a measure of "intermediate" barn owl presence; see analysis below for details.

Live-trapping

At each sampling grid, Sherman traps were evenly dispersed in an 8×8 arrangement (n = 64) at ~8×6 m spacing (0.24 ha), so that traps fell directly in line with vine stems to avoid disturbance by any farm workers or equipment traveling between rows. Each grid was run for 4 trap nights at each sampling period, before and during peak hunting pressure. Due to the time and assistance required to process animals across vineyards, a maximum of two pairs of grids were surveyed each week, requiring 6 weeks in total to survey all 11 pairs of grids within each sampling period. The order in which each grid was surveyed during the "before" sampling was replicated for the "during" sampling period. Each trap was baited with peanut butter and oats and provided with polyester batting to ensure any captured animals remained warm throughout the night. Traps were opened within one hour after sunset and checked within 1.5 hours after sunrise the following day, with all traps remaining closed throughout the day. All captured animals were visually inspected for prior marking, and all unmarked animals were marked with a Monel-style ear tag (National Tag & Band model 1005-1, Monel ~7 mm) before release. The animal's ear tag number, species, sex, age class, and weight were recorded for each capture. The total number of animals captured on a grid over the 4-night sampling effort, excluding recaptures, was used as a measure of rodent abundance for that sample grid and sample period and used to calculate changes in rodent abundance over time (Murano et al. 2019). This can be referred to as the minimum number alive (MNA); see analysis below for details.

<u>Open-hole method for gopher surveys</u>

The "open hole" method is a validated method used for assessing the abundance of gophers (Engeman et al. 1993), which are notoriously difficult to live-trap. I used this method at each of the 22 grids at each sampling period. To reduce the chances of double-counting the activity of individual gophers, each grid was evenly subdivided into 64 8×6 m subplots. Within each subplot, if signs of gopher-caused soil disturbance were present, two holes into the tunnel systems were excavated with a hori hori knife (12-inch double-edged trowel), flagged, and inspected 48 hours later to determine if they were plugged by current gopher activity (Engeman et al. 1999). Each excavated hole was recorded as positive for activity if it was plugged within a 48-hour period. The proportion of all opened holes that were plugged was used as an index of gopher activity (e.g. if 40 holes were excavated on 20 of the 64 subplots, and 12 of those holes became plugged, the index of activity for that grid would be 0.3 [12/40]). The proportion of subplots with at least one hole plugged is an alternative measure of activity, but preliminary analysis indicated this was nearly identical to the total proportion of holes plugged, so I chose to just use the latter; see analysis below for details.

Owl pellet collection

To document the prey composition for owls nesting in boxes on the Suscol Vineyard (with barn owl boxes), owl pellets were collected during the second sampling period, during peak hunting activity. Since I was only concerned with the diet composition of owls included during my study, pellets were only collected if they appeared to be fresh. Each night, adult owls typically hunt for themselves before hunting and returning prey items to the nest for chicks, and the pellet from the prey consumed by adults is likely not deposited in the nest box (Roulin 2020). All pellets ejected by the young remain in the next box, except when the chicks are near fledging and begin to explore the exterior of the box. Therefore, the pellets collected from the box represent the vast majority of prey captured by adults. Pellets from each box were stored in plastic bags and labeled with the collection date, the number of pellets collected, and the owl box location. Volunteers assisted in dissecting and identifying prey items to genus (*Thomomys*, *Microtus*, *Peromyscus*, or other); each volunteer (n = 19) was sent pellets (n ≥ 3) in the mail, along with access to a video tutorial, identification guides, and personal datasheets. After pellets were returned and reviewed for accuracy, data were entered into a master sheet for the analysis. The minimum number of each prey type was primarily calculated using lower mandibles and skulls. One skull represented one individual, and left and right mandibles were used to count individuals (e.g. 5 left and 6 right vole jaw bones indicated a minimum of 6 individual voles were consumed). The proportion of each rodent genus in the pellets was used as a measure of prey composition during the breeding season, and summarized in a table. For descriptive purposes, the percent composition of voles, mice, and gophers in the pellets was calculated based on the estimated numbers of individual rodents, as well as weighted by their corresponding biomass. California voles weigh 36 to 55 g (Verts and Carraway 1998), mice weigh 15 to 52 g (lower range *M. musculus*, Huminski 1969; upper range *P. californicus*, Merrit 1978), and Botta's pocket gophers weigh 89 to 172 g (Vaughn 1967). I used the midpoint of each of these (45.5 g, 33.5, and 130.5 g, respectively) to estimate the percent composition of pellet remains by live biomass.

Analysis Methods

Live-trapping for mice and voles

I used generalized linear mixed effects models (GLMM, *glmr* from the *lme4* package in RStudio version 4.02 as described by Zuur et al. 2009) to test the prediction that the number of rodents captured declines more (from before to during peak hunting presence) on the vineyard with than without barn owl boxes. Using the minimum number alive (MNA) as my response variable, I built my candidate models using sample period (before and during peak hunting presence) and vineyard (with and without owl nest boxes) as factors. Since my grids were spatially correlated and nested within each vineyard, grid was specified as a random effect (RE). Initial fits to a GLMM with a Poisson distribution showed some overdispersion (φ =5.4), so I chose to use a negative binomial distribution. Theta was done using *glm.nb* function in the *MASS* package (θ=2.098). I built the full interactive model (MNA ~ vineyard * sampling period, RE = grid) as well as simpler candidate models with additive effects, with each predictor variable singly, and a constant only model. Candidate models were compared through ΔAICc, which I calculated using the *AICc* function from the *MuMIn* package in program R.

I ran a second analysis to test whether effects were different if the occupancy of nest boxes on the vineyard with boxes (Soscol) was recognized. Not all owl nest boxes are typically occupied each year, and the sampling grids were necessarily established before it was known which boxes would be occupied by nesting owls. Because owls are central place foragers and hunt mainly near the nest box, as described above, I effectively sampled rodents on grids under three levels of spatial barn owl presence: on a vineyard without any nest boxes present (Cakebread, at least 700 m from on occupied box, low owl presence), on a vineyard with boxes within 100 m of an unoccupied nest box (Soscol, intermediate owl presence, 345 m minimum distance to an occupied nest box), and on a vineyard with boxes within 100 m of an occupied nest box (Soscol, high owl presence). I re-ran the models as described above, replacing vineyard (two levels) with "owl presence" (three levels). I again built a full interactive model (MNA ~ owl presence * sampling period, RE = grid) as well as simpler candidate models, using ΔAICc to arrive at a top model.

Open-hole for gophers

To test the hypothesis that gopher activity declines more (from before to during peak hunting pressure) on the vineyard with than without barn owl boxes, I used a GLMM with a binomial distribution (*glmr* from the *lme4* package in RStudio version 4.02 as described by Zuur et al. 2009). Using the proportion of holes plugged to opened as my response variable, my full model included: proportion of holes plugged ~ vineyard * sampling period, RE = grid, weights = total number of subplots surveyed across each grid (n = 64). I again built the full interactive model as well as simpler candidate models with additive effects, with each predictor variable singly, and a constant only model. Candidate models were compared through ΔAICc, which I calculated using the *AICc* function from the *MuMIn* package in program R. As with the analysis for trapping, I also chose to test whether the effects for the open-hole data were different if the occupancy of nest boxes on the vineyard with boxes (Soscol) was recognized. I re-ran the models as described above, but again replacing vineyard (two levels) with “owl presence” (three levels).

RESULTS

Live-trapping

A total of 11,264 trap nights were recorded over the two sampling periods, yielding 203 animals captured on Soscol Vineyard and 270 on Cakebread Vineyard. No voles were caught on either vineyard, and the majority of captures were *Peromyscus* spp: deer mouse *Peromyscus maniculatus* (n = 400), brush mouse *Peromyscus boylii* (n = 58), pinyon mouse *Peromyscus truei* (n = 7), and house mouse *Mus musculus* (n = 8). Due to this, I was only able to analyze owl effects on the abundance of mice. For one grid on the Soscol Vineyard, no animals were caught during either sampling (nor during the pilot study conducted in the summer of 2019). Initial models yielded similar results whether or not this grid was excluded from analysis, so, I decided to retain it in my final analysis.

Modeling results indicated that the number of mice declined from before to during peak hunting presence, but it did so fairly similarly on both vineyards, regardless of the presence of barn owl boxes (Figure 2). The top model included only an effect of sampling period on mouse abundance, carrying 62% of the model weight in the candidate set (

Table 1). However, the model with a main effect of vineyard and sampling period was also competitive (ΔAICc = 1.72, wt = 0.26), with marginally higher mouse abundance on the vineyard without owl nest boxes. The interaction between sampling period and vineyard, which was predicted to be significant if MNA declined more rapidly on the vineyard with owl nest boxes, was not significant and this model was not competitive (ΔAICc = 3.61, wt = 0.10). If anything, the number of mice declined more on the vineyard without than with owl nest boxes, but there was considerable variation among grids, and this was not a significant difference.

Owl presence on the MNA

Of the 13 boxes on Soscol Vineyard, 8 were occupied and 5 were unoccupied. This resulted in 6 grids being classified as "high owl presence," 5 grids as "intermediate owl presence" and the 11 grids on Cakebread Vineyard as "low owl presence." The top model included additive effects of owl presence and sampling period, which carried 89% of the model weight in the candidate set (Table 2). The MNA of mice was lower on the grids classified as intermediate owl presence than on the other grids, and overall the MNA declined from before to peak hunting presence, but it did so fairly similarly on all three levels of owl presence (Figure 3).

Open-hole for Gophers

Gopher activity was widespread on the vineyards. Out of a total of 2,816 subplots examined for potential gopher activity, a total of 868 holes were dug, of which 550 (63%) were plugged by gophers within 48 hrs, 289 on Suscol Creek Vineyard and 261 on

Cakebread. Modeling results suggested that gopher activity declined on the vineyard with owl nest boxes (Soscol), whereas it increased slightly on the vineyard without (Cakebread; Figure 4). The top model for explaining gopher activity, the proportion of holes plugged, included the interaction between sampling period and vineyard, and no other model was competitive (

Table 3).

<u>Owl presence on gopher activity</u>

Like the results above, the top model for the effect of owl presence on gopher activity included owl presence and its interaction with sampling period. This model carried 99% of the weight in the candidate set, thus there was no other competitive model (Table 4). Grids classified as having “low owl presence” (the vineyard with no barn owl boxes, n = 11) experienced a significant increase in gopher activity across the two sampling periods, whereas the opposite was found for those classified as having “high owl presence” (p = 0.02, Figure 5). Those classified as intermediate owl presence had a gopher response intermediate between high and low owl presence, with relatively stable gopher activity.

Owl Pellet Composition

A total of 67 pellets was collected across the Soscol Vineyard, with a total of 148 prey items identified (8.38 ± 7.87 of 18.5 ± 20.68 items per pellet). Prey items found included voles (n = 72), mice (n = 16), gophers (n = 38), and shrews (n = 1). There were 20 instances of invertebrates and one other. Numerically, the vertebrate prey composition for Soscol Vineyard was therefore comprised primarily of voles (49%), followed by gophers (25%), then mice (10%). Using the biomass for gophers, mice, and voles, the prey composition for Soscol Vineyard was mostly gopher (57%), followed by voles (37%) and mice (6%).

Table 1. Candidate model set for predicting the minimum number alive (MNA) of mice in relation to the presence of occupied barn owl nest boxes across both sampling periods (SP). The model set was tested using generalized linear mixed effects models (GLMM). The top model (ΔAICc = 0) is bolded and significant coefficients (p-value < 0.05) for the top model (if any) are also indicated in bold.

Candidate Models	Intercept	Vineyard*	Sampling Period (SP)	Vineyard*SP	k	AICc	ΔAICc	wAICc
MNA~vineyard*SP	2.79	-0.47	-1.02	0.42	6	299.41	3.61	0.10
MNA~vineyard+SP	2.71	-0.27	-0.80	-	5	297.52	1.72	0.26
MNA~vineyard	2.44	-0.32	-	-	4	306.51	10.71	0
MNA~SP	**2.58**	-	**-0.82**	-	4	295.80	0	0.62
MNA~intercept only	2.28	-	-	-	3	305.44	9.64	0.01

*Coefficent refers to the vineyard with barn owl boxes.

Table 2. Candidate model set for predicting the minimum number alive (MNA) of mice in relation to barn owl hunting presence across both sampling periods (SP). The model set was tested using generalized linear mixed effects models (GLMM). The top model (ΔAICc = 0) is bolded and significant coefficients (p-value < 0.05) for the top model are also indicated in bold.

Candidate Models	Intercept	Low Presence	Medium Presence	Sampling Period (SP)	Low Presence * SP	Intermediate Presence * SP	k	AICc	ΔAICc	wAICc
MNA~presence*SP	2.84	-0.05	-1.40	-0.61	-0.39	0.05	8	289.17	4.76	0.08
MNA~presence+SP	**2.94**	-0.22	**-1.37**	**-0.81**	-	-	6	284.41	0	0.89
MNA~presence	2.59	-0.16	-1.34	-	-	-	5	298.37	13.96	0
MNA~SP	2.53	-	-	-0.84	-	-	4	291.82	7.41	0.02
MNA~intercept only	2.20	-	-	-	-	-	3	307.56	23.15	0

Table 3. Model selection table for predicting pocket gopher activity based on the proportion of gopher holes plugged to open across both sampling periods (SP). The model set was tested using generalized linear mixed effects models (GLMM). The top model (ΔAICc = 0) is bolded and significant coefficients (p-value < 0.05) for the top model (if any) are also indicated in bold.

Candidate Models	Intercept	Vineyard*	Sampling Period (SP)	Vineyard*SP	k	AICc	ΔAICc	wAICc
proportion~vineyard*SP	-0.39	**1.41**	**0.62**	**-0.96**	5	392.74	0	0.99
proportion~vineyard+SP	-0.14	0.92	0.11	-	4	415.49	22.75	0.00001
proportion~vineyard	-0.08	0.92	-	-	3	414.35	21.61	0.00002
proportion~SP	0.32	-	0.11	-	3	415.37	22.63	0.00001
proportion~intercept only	0.38	-	-	-	2	414.39	21.65	0.00001

*Coefficient refers to the vineyard with barn owl boxes.

Table 4. Candidate model set for predicting pocket gopher activity based on the proportion of gopher holes plugged to open in relation to barn owl hunting presence across both sampling periods (SP). The model set was tested using generalized linear mixed effects models (GLMM). The top model (ΔAICc = 0) is bolded and significant coefficients (p-value < 0.05) for the top model are also indicated in bold.

Candidate Models	Intercept	Low Presence	Medium Presence	Sampling Period (SP)	Low Presence * SP	Intermediate Presence * SP	k	AICc	ΔAICc	wAICc
proportion~presence*SP	**1.26**	**-1.65**	-0.54	**-0.44**	**1.06**	0.21	7	397.83	0	0.99
proportion~presence+SP	0.98	-1.11	-0.43	0.11	-	-	5	417.91	20.08	0.00004
proportion~presence	1.03	-1.11	-0.43	-	-	-	4	416.61	18.78	0.00008
proportion~SP	0.32	-	-	0.11	-	-	3	415.37	17.54	0.0002
proportion~intercept only	0.38	-	-	-	-	-	2	414.39	16.56	0.0002

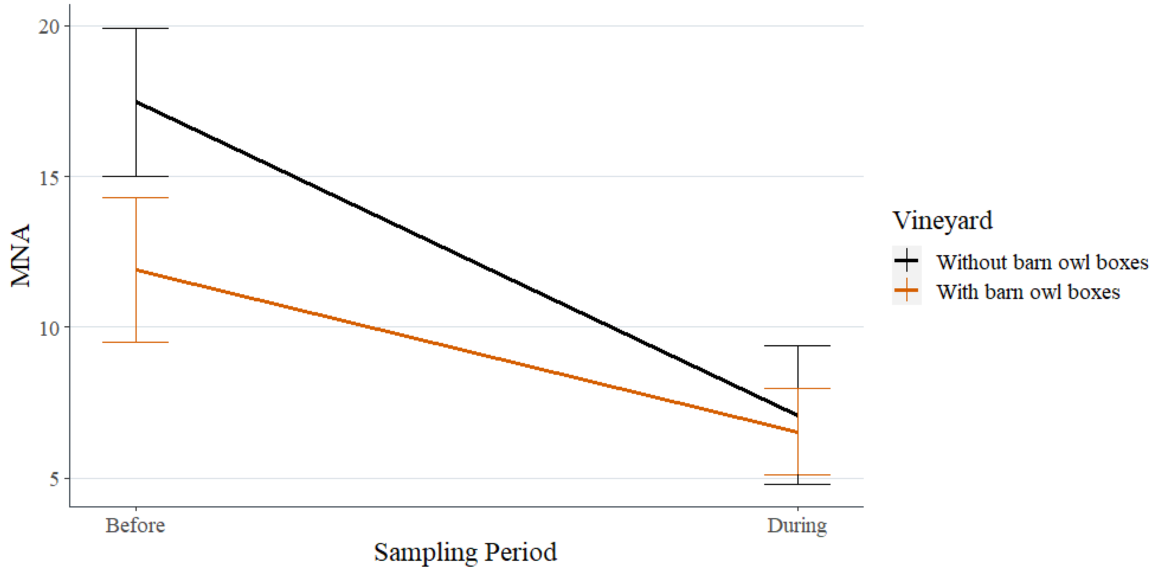

Figure 2. The minimum number alive (MNA) of mice caught across both vineyards and sampling periods (before and during peak owl hunting presence).

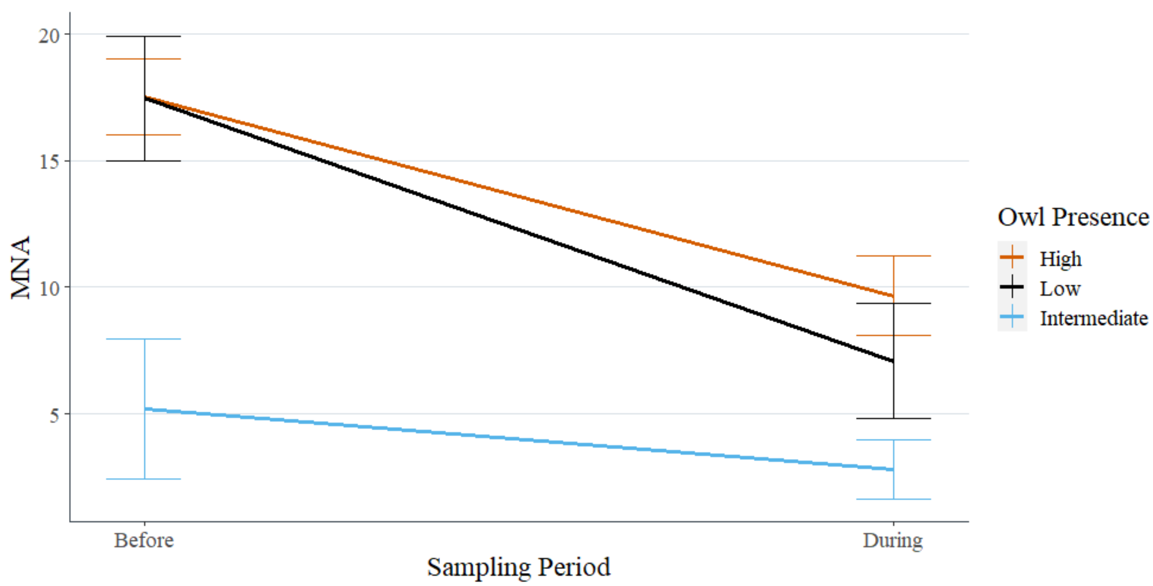

Figure 3. The minimum number alive (MNA) of mice caught across both vineyards and sampling periods (before and during peak owl hunting presence) with the associated classification of owl presence.

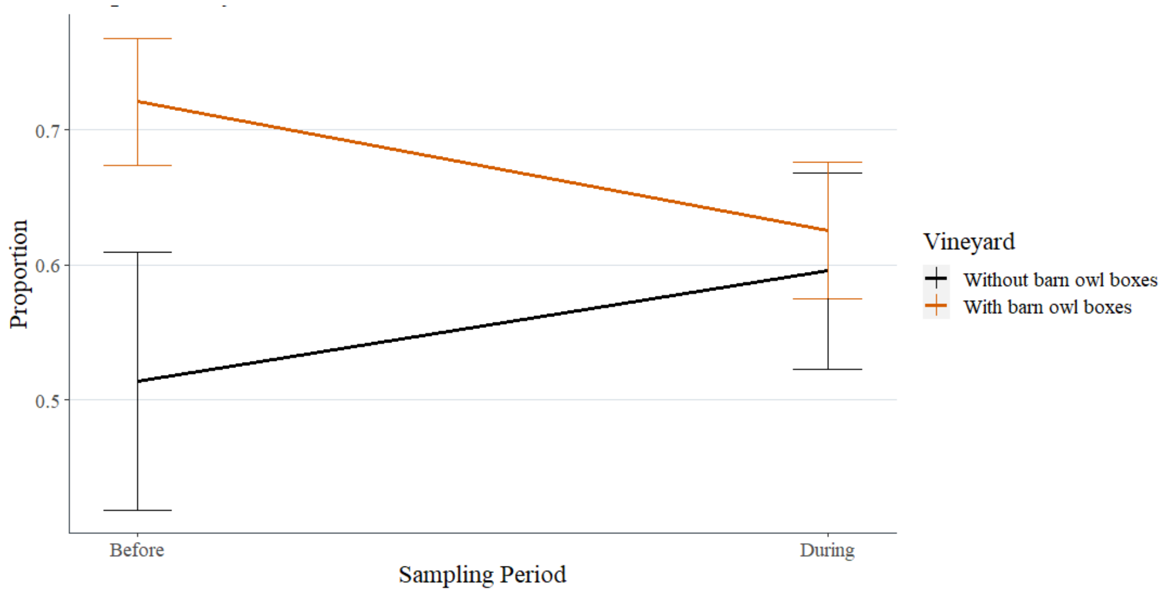

Figure 4. The proportion of holes plugged to opened (an index of gopher activity) across both vineyards and sampling periods (before and during peak owl hunting presence).

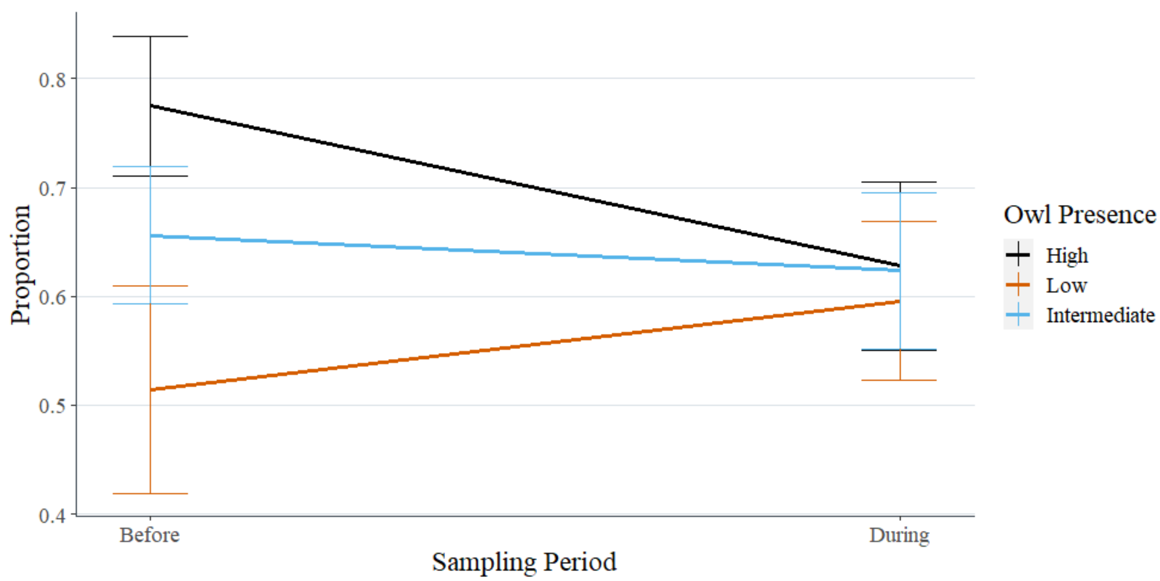

Figure 5. The proportion of holes plugged to opened (an index of gopher activity) across both vineyards and sampling periods (before and during peak owl hunting presence) with the associated classification of owl presence.

DISCUSSION

Though the practice of installing owl nest boxes for rodent control has been widespread over the past 20 years, these results are among the first in the United States to confirm an effect of owl boxes on gopher activity in the field. These findings join other studies in other regions showing effects on other prey species (Duckett and Karuppiah 1990, Hafidzi and Mohd 2003, Ojwang and Oguge 2003, Luna et al. 2020, Zainal Abidin et al. 2021). My analyses supported the hypothesis that pocket gopher abundance and activity is negatively associated with the presence of and hunting pressure by barn owls in Napa Valley vineyards. The vineyard with barn owl nest boxes experienced a decline in gopher activity from before to peak owl hunting presence, whereas the vineyard owl nest boxes experienced an increase in gopher activity (Figure 4). Moreover, within the vineyard that had owl boxes, gopher activity declined more on grids near occupied than on grids near unoccupied nest boxes (Figure 5).

In contrast to the strong results I found for gophers, I found that mouse abundance declined similarly on the vineyard with barn owl nest boxes than on the one without (Figure 2). Since a small proportion of mice was found in the prey analysis (discussed more below), the change in the number of mice may reflect background variation in rodent populations, which are known to experience considerable fluctuations within short periods (Whitford 1976). Weather and climate variation as well as agricultural practices can cause declines in rodent survival and activity (Tietje et al. 2018), and since these were likely to be operating similarly on my two study vineyards, the decline in mice numbers may be independent of owl hunting. Rodents are generally less abundant in farms more intensively cultivated (Balčiauskas et al. 2019) and activities such as mowing can cause a majority of rodents to temporarily emigrate out of the cut areas (Garratt et al. 2012). No mowing occurred during the time of my study, however herbicide was sprayed on both vineyards during the second session. Herbicides take several weeks to kill above ground vegetation, and I did not see any plants die during the study. Since there is no apparent literature showing immediate effects of herbicides on rodent abundance, and because both my results rest on comparisons of relative abundance of rodents on vineyards that were sprayed within one week of each other, I assume the herbicide application had minor if any effect on my results.

In this study, I did not capture any voles, so I cannot determine whether barn owl nest boxes had any effect on their abundance. This is unfortunate because voles are a significant portion of the owls' diet, and other researchers using very similar field methods successfully trapped voles (Wolff et al. 1999, Murano et al. 2019). Although no voles were caught in my study, previous studies on the prey composition of barn owls in the Napa Valley showed voles as being one of the most common prey items (49.6%), followed by mice (22%), and gophers (17.5%, Johnson and St. George 2020). Based on the collected owl pellets specific to this study and only considering the composition of identified rodents, the barn owls on the Soscol Vineyard primarily hunted voles (49%) and gophers (25%). Mice only made up 10% of their diet during the time of the study numerically, and even less based on biomass (6%) meaning that mice were not primary prey items for these owls. Additionally, if we only consider the biomass composition of rodents, Soscol Vineyard barn owl prey was primarily composed of gophers (57%) and voles (37%), with only 6% for mice. This may explain why I was unable to detect any significant differences in mice populations over the two sampling periods and vineyards.

Other sampling methods may be useful for examining vole responses to barn owl hunting. For example, Luna et al. (2020) was able to show, using an index of vole activity, a significant reduction in the abundance of two vole species after raptor nest boxes were installed; they counted active common vole burrows, which can be considered as a good estimator of vole abundance (Miñarro et al. 2012). The easiest way to identify vole burrows is to look for their runways (1–2 inch wide linear runways with cleared vegetation that voles use for travel) that extend back and forth between other burrow openings (Baldwin 2015). Other methods to detect vole presence, aside from pellet analyses, include using track plates, chew blocks, and camera-trapping (Whisson et al. 2005, McCleery et al. 2014, Gracanin et al. 2018). A primary reason for being unsuccessful in trapping voles is that densities are too low, suggesting that these owls were likely obtaining voles from surrounding habitats (Baldwin et al. 2015). Future research should consider alternative methods of detecting voles directly within vineyards if trapping proves to be unsuccessful.

Though I was not able to detect the effect of barn owl presence on voles in these two vineyards, the pellet analyses from this study and other diet composition work confirm that voles and gophers are a significant part of barn owl diets in California agriculture (Kross et al. 2016, St. George and Johnson 2021). This is good news for producers as these two rodent pests cause significant losses in agriculture. There is thus a benefit in researching ways to increase barn owl box occupancy, such as using north-facing wooden boxes that are positioned higher off the ground (Wendt and Johnson 2017, Carlino in prep). Additionally, future research conducted in areas outside of Napa, with different crop types, and outside of the breeding season can provide significant insight into integrating raptors into more IPM approaches. Lastly, Cakebread Vineyard now has plans on installing nest boxes on their property; utilizing such opportunities to carry out before-after research could help us further monitor and detect the benefits of having barn owls in vineyards.

Trophic webs are composed of complex relationships, including negative impacts of predators on the abundance of prey ("top-down" effects) as well as predators responding functionally or numerically to spatial and/or temporal variation in prey availability ("bottom-up" effects; Hunter and Price 1992, Power 1992). In my study, there is some evidence of both forces in operation between gophers and owls. Gopher activity as measured by the open-hole method is usually an index of gopher abundance (Engeman et al. 1993), in which case effects in my study reveal numerical responses. However, a decline in gopher activity could be a functional (behavioral) response due to the 'landscape of ear' imposed by hunting owls (Bleicher 2017). While there was clear evidence that barn owl hunting diminished gopher activity over the course of the owls' breeding season (a top-down effect, Figure 4), it also appears that owls chose to occupy nest boxes with higher gopher activity at the start of the nesting season. On the vineyard with barn owl boxes, the unoccupied boxes had lower gopher activity at the beginning of the nesting season (intermediate owl presence) than did the unoccupied boxes (high owl presence, Figure 5). This connection may be a result of bottom-up forces that are influencing barn owl box occupancy (Van Veen and Sanders 2013). Long-term rodent monitoring coupled with barn owl occupancy data may provide us with more information regarding any bottom-up or top-down forces that may be at play within this system. Trophic cascades results when top-down forces predominate, with predators diminishing the abundance or activity of their prey and triggering a release in herbivory, thereby indirectly benefiting plants (Terborgh and Estes 2013). Oft-cited examples of trophic cascades involve sea otter-urchin-kelp (Estes et al. 2011), wolves-elk-alder (Ripple et al. 2016), and fish-aquatic insects-macroalgae (Power et al. 2008). A cascade involving barn owls, their rodent prey, and agricultural crops is theoretically possible (Strong 1992, Schmitz et al. 2000, Fortin et al. 2005, Labuschagne et al. 2016), but to date relatively few have examined this system empirically (Abramsky et al. 1996, Tillmann 2012, Kross et al. 2016). This could be fruitful area of future research, especially since the owls' numbers and distribution are relatively easily manipulated with nest boxes.

SUMMARY

This study is the first to confirm an effect of owl boxes on gopher activity within a vineyard ecosystem. Gopher activity over this 19-week study decreased on the vineyard with barn owl boxes and increased on the vineyard without barn owl boxes. Rodent sampling grids classified as "low owl presence" experienced a significant increase in gopher activity across the two sampling periods, whereas the opposite was found for those classified as having "high owl presence." Those classified as intermediate owl presence had a gopher response intermediate between high and low owl presence, with relatively stable gopher activity. I was unable to detect any influence of barn owl presence on mice populations, however mice abundance decreased for both vineyards over the two sessions, with marginally higher mice abundance on the vineyard with owl boxes. Though voles were found to be a significant part of the owl's diet, I was unable to analyze any impact barn owls may have on their abundance since none were captured. Due to this and because voles are considered significant pests in agriculture, future research should incorporate other methods of detecting vole populations within winegrape vineyards.

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