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Hogs and Hazelnuts: adaptively managing pest spillover in the agricultural-wildland matrix

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Abstract:	Pest spillover from wildlands to farms can create conflict between wildland conservation and agricultural production. For example, the key economic pest of hazelnuts in Oregon's Willamette Valley is the filbertworm (Cydia latiferreana), a moth hosted by the native Oregon white oak (Quercus garryana). Oak stands near hazelnut orchards can sustain source populations that compound pest pressure in hazelnuts throughout the growing season. This dynamic is of conservational concern as historical oak habitat has been greatly reduced and what remains is almost entirely on private land, often in proximity to hazelnut orchards. Here, we present of a novel strategy to reconcile this conflict by using hogs to reduce pest pressure through prescribed grazing. From 2018 to 2020 we prescribed hog-grazing in early fall to glean filbertworm-infested acorns from an oak woodland floor. Hogs were both highly successful at reducing the total number of infested acorns and the ratio of infested acorns the following year. Despite an oak masting year in 2019, grazing reduced both the emerging and adult mating population of filbertworms the following year. We did not measure significant changes in woodland understory vegetation, suggesting hog-grazing may not entail tradeoffs for understory vegetation. Our results demonstrate that prescribed grazing in oak patches can be an effective strategy to reduce filbertworm source populations. By benefiting both conservation and farmers, this novel pest management approach provides a model for similar challenges and conflicts across the agricultural-wildland interface.

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Abstract

Pest spillover from wildlands to farms can create conflict between wildland conservation and agricultural production. For example, the key economic pest of hazelnuts in Oregon's Willamette Valley is the filbertworm (*Cydia latiferreana*), a moth hosted by the native Oregon white oak (*Quercus garryana*). Oak stands near hazelnut orchards can sustain source populations that compound pest pressure in hazelnuts throughout the growing season. This dynamic is of conservational concern as historical oak habitat has been greatly reduced and what remains is almost entirely on private land, often in proximity to hazelnut orchards. Here, we present of a novel strategy to reconcile this conflict by using hogs to reduce pest pressure through prescribed grazing. From 2018 to 2020 we prescribed hog-grazing in early fall to glean filbertworm-infested acorns from an oak woodland floor. Hogs were both highly successful at reducing the total number of infested acorns and the ratio of infested acorns the following year. Despite an oak masting year in 2019, grazing reduced both the emerging and adult mating population of filbertworms the following year. We did not measure significant changes in woodland understory vegetation, suggesting hog-grazing may not entail tradeoffs for understory vegetation. Our results demonstrate that prescribed grazing in oak patches can be an effective strategy to reduce filbertworm source populations. By benefiting both conservation and farmers, this novel pest management approach provides a model for similar challenges and conflicts across the agricultural-wildland interface.

Keywords: Oaks; Silvopasture; Source-Sink Dynamics; Grazing; Filbertworm; Non-timber Forest Product

Declarations

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Conflicts of interest/Competing interests

Not applicable

Ethics approval

Not applicable

Consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and material

The datasets generated and analyzed during this study are available on Github: https://github.com/HallettLab/hogsandhazelnuts

Code availability

The code developed during this study is available on Github: https://github.com/HallettLab/hogsandhazelnuts

Figure Captions

Fig. 1 Historical (circa 1850; Christy & Alverson 2011) and 2016 remnant Oregon white oak habitat (Kagan et al 2018) in the Willamette Valley (ODFW 2016), Oregon (BLM 2001, DLG 1970). Crops that have direct economic conflict with these remaining stands due to the spillover of pests, such as hazelnuts (USDA 2016), have been the most at odds with conservation and restoration goals.

Fig. 2 Density of infested acorns on the woodland floor in grazed (dashed line) and control (solid line) sections before and after hog-grazing. Grazing significantly reduced infested acorns by 73.03% on average during **(a)** 2018 and **(b)** 2019.This resulted in a significant divergence from the un-grazed control during the same time during both years, respectfully.

Fig. 3 Baseline (2018) filbertworm moth populations in the hazelnut orchard and adjacent oak woodland with **(a)** emergence from ground traps (n = 40) and **(b)** aerial abundance from canopy sticky traps (n = 16). A lack of emergence but aerial presence in hazelnuts suggested source populations from oak habitat spill over into hazelnuts, increasing pest pressure.

Fig. 4 Filbertworm populations in the oak woodland from **(a)** ground emergence traps and **(b)** aerial abundance sticky traps in the canopy from 2018-2020 with grazed (dashed line) and un-grazed control (solid line) sections. The control saw a significant increase in filbertworm emergence in 2018 compared to 2019 and between grazed and control in

2019. Although filbertworm emergence significantly decreased in the control from 2019 to 2020, there was an overall increase in aerial abundance since 2018.

Fig. 5 Percent cover of vegetation classes in grazed (dashed line) and control (solid line) sections of the oak woodland before grazing in 2018 and 2020. After grazing, there was no significant change in percent cover of vegetation when compared to the un-grazed control.

Online Resource 1 Half-meter by half-meter ground emergence traps were constructed with wooden dowels, window screening, automotive funnels, and plastic food containers. These traps were staked to the ground underneath oak trees halfway between the trunk and canopy edge, and a pheromone lure was placed in the top with a wooden clothes-pin.

Online Resource 2 Acorn density in grazed (dashed line) and control (solid line) sections during early fall 2018 – 2020, prior to hog-grazing. Acorn density increased in 2019 but significantly decreased in 2020, capturing a boom-and-bust of acorn masting.

Introduction

Agricultural lands are often embedded in a landscape matrix that includes unmanaged or economically unproductive wildlands (Rusch et al. 2010). A common problem in these mosaic landscapes is pest spillover, where wildlands can sustain source populations of agricultural pests (Damon 2000, Tonina et al. 2018, Wilby & Thomas 2002). This is the case in Oregon, where a booming hazelnut industry is threatened by the filbertworm (FBW; *Cydia latiferreana*), a native moth that can destroy over half of potential production (Rusch et al. 2010, AliNiazee 1998, Miller et al. 2019) and whose native host is the Oregon white oak (*Quercus garryana*). Furthermore, hazelnut orchards exist in close proximity to oak patches in their shared landscape (Mehlenbacher & Olsen, 1997, Miller et al. 2019). Our overarching question is whether FBW source populations can be controlled in their wildland habitat through prescribed grazing, reducing the potential of spillover into farms.

Oregon hazelnut farming is a multi-million-dollar industry, making up 99% of domestic hazelnut production and covering over 50,000 acres in 2020, the majority of which is found in the Willamette Valley (USDA 2019, INC 2018). Accordingly, hazelnut orchards are intensively managed for FBW (Olsen 2002, Akbaba et al. 2011, AliNiazee 1998). Unfortunately, spillover from infested oaks adjacent to hazelnut orchards can lead to cyclical re-infestation throughout the growing season (AliNiazee 1998, Coblentz 1980, Miller et al. 2019, Rohlfs, 1999). This makes oak habitat a potential burden to hazelnut growers and incentivizes the removal of the remaining privately-owned oak patches (Fischer & Bliss 2008, ODFW 2016, Hagar & Stern 2001).

Today, conserving and restoring oak habitat is a major concern throughout the Pacific Northwest (Fischer & Bliss 2008, ODFW 2016, Vesely & Rosenberg 2010). Oak habitat was once a dominant vegetation type in the Willamette Valley (Christy & Alverson 2011, Kimmerer & Lake 2001), yet today less than 5% of oak habitat remains, primarily on rocky or seasonally saturated soils (Vesely & Rosenberg, 2010). Oak habitats support levels of diversity rivaling old-growth Douglas-fir forests, including numerous endemic species, of which at least 45 are at-risk for extinction (Altman 2011, Hagar & Stern 2001, Ulrich 2010). Since *Q. garryana* is an extremely slow growing species (Devine & Harrington 2013, Jimerson & Carothers 2002, Stein 1990, Vesely & Rosenberg 2010), conservation groups and government agencies are prioritizing the conservation of remaining mature oak habitat in Oregon. These patches, over 95% of which are on private land, are dispersed throughout an otherwise-developed landscape (Fig. 1), and are increasingly under threat from shifting cultural practices and continued land-use change (Altman 2011, Vesely & Rosenberg 2010).

Here, we prescribed domesticated pig (hog) grazing in oak patches to reduce FBW spillover into hazelnut orchards. Livestock grazing is a common practice for managing pest populations within agricultural systems (Wilson & Hardestry 2006). For example: free-range chickens have been used to control pests in squash and blueberry fields (Clark & Gage 1996, Wenig & Farm 2013), sheep have been used in grain and alfalfa systems (Hatfield 2011), and hogs have been used in apple orchards (Nunn et al. 2007). In all of these cases, grazers remove material that can harbor pest insects or disease. While this can be effective within farms, pest populations can re-invade agricultural land from wildland habitat. Hog grazing in oak woodlands (silvopastures) has the potential to impact source populations directly, reducing FBW spillover while creating additional revenue, and incentivizing oak habitat conservation.

Infested nuts abort and drop early, providing a window for their selective removal. Removing infested nuts during this time could reduce FBW populations (Chambers et al. 2010, Dohanian 1940, Olsen 2002). When the nuts first fall, the FBW larva inside are vulnerable to predation and a well-timed intervention has potential to reduce pest pressure by interrupting the FBW life cycle. This fact is well-understood by hazelnut farmers, who run multiple early passes with harvesters to keep hazelnuts from sitting on the ground for too long (AliNiazee 1998, Mehlenbacher & Olsen 1997, Olsen 2002). The same principle could be applied in nearby oak patches, where infested acorn removal could reduce FBW source populations. Hogs have a strong preference for acorns, which can make up a majority of their diet (Díaz-Caro et al. 2019), and are competent woodland grazers (Dagar & Tewari 2016, Nunn et al. 2007). While mechanically removing acorns is not practical, a carefully managed hog silvopasture program has the potential to be an ideal pest management tool.

The disturbance-adapted nature of Oregon oak woodlands may mean that the system is particularly well suited for hog-grazing as a management practice. Oak habitat in the Willamette Valley evolved with prescribed burning by indigenous cultures over millennia – and require some level of disturbance to persist (Christy & Alverson 2011, Kimmerer & Lake 2001, Ulrich 2010, Stein 1990). Use of prescribed fire for disturbance is generally restricted, but controlled grazing may offer an alternative tool for habitat management. While grazing and burning are different, they have similar impacts of removing biomass, recycling nutrients and opening up the soil surface for colonization. Grazing has been shown to have similar effects as fire on grassland (D'Antonio & Chambers 2006, Harrison et al. 2003, Hernandez et al. in review), and woodland (McGregor 1996, Vesely & Tucker 2004) vegetation. Introducing an omnivore to a complex natural system is a major intervention, however, and hogs uproot areas of soil to eat foliage, seeds and roots (Ickes 2001, Wang 2017). This behavior may negatively impact understory vegetation by removing native herbs or tree seedlings, or allowing for the invasion of undesirable species (Anderson et al. 2016, Bevins et al. 2014, Lewis et al. 2019, Snow et al. 2017, Sytsma et al.

2007). Assessing the effects of hog-grazing on understory vegetation will be important to weigh potential co-benefits or tradeoffs of this management strategy.

To test the effectiveness of hog-grazing on controlling FBW, we conducted a three-year experiment in an oak woodland and adjacent hazelnut orchard. Our expectation was that hogs would be effective at reducing FBW populations, while controlled rotation would minimize grazing disturbance. Specifically, we hypothesized that grazing in the oak woodland would effectively reduce the number of infested acorns relative to an ungrazed control. This reduction in infested acorns should be reflected in a reduction of both emerging FBW moths the following spring and in the mating population of adults over the summer. We hypothesized that grazing would also reduce the percent cover of herbaceous vegetation on the woodland floor and increase bare ground. If successful, this approach could help reconcile the conflict between conservation and hazelnut production, decreasing the burden of oak habitat to farmers and incentivizing conservation within the agricultural-wildland matrix.

Methods

Study Site

Our study was conducted at My Brothers' Farm in Creswell, Oregon. This 320-acre farm in the southern Willamette Valley experiences a Mediterranean climate, with cool-wet winters and warm-dry summers (Taylor & Bartlett 1993). The twenty-acre hazelnut orchard at My Brothers' Farm was planted in 2014 and consists of over 2000 trees. The orchard is managed organically, with an integrated pest management strategy for controlling FBW and other pests. The approximately twenty-acre oak patch used for this study is an intermittent woody-wetland with silty clay-loam soil branching off the Coast Fork Willamette River (USGS 2020). This oak woodland is approximately 500 meters from the hazelnut orchard. Aerial photography indicated that it has had a consistent mixed-oak canopy during the last century (Knight Library Aerial Photography Collection 2019). Currently, the canopy includes *Q. garryana*, *Fraxinus latifolia*, *Acer macrophyllum*, and *Aluns rubra,* and the understory is dominated by non-native Himalayan blackberry (*Rubus armeniacus*) with various native and non-native grasses and forbs in the herbaceous layer.

Hog Grazing

Using a Before-After-Control-Impact (BACI) experimental design, we divided the oak woodland into grazed and ungrazed sections in 2018. Within the grazed section, we established five approximately two ($\pm$ 0.3) acre paddocks with electric fencing, which were used to rotate hogs through the paddocks in October of 2018 (20 hogs) and 2019 (26 hogs). The increased number of hogs used in 2019 was in part due to commercial demand and compensated for the higher than average acorn production. The grazing treatment was timed for when infected acorns were dropping but the majority of intact nuts had yet to fall (this was slightly earlier in 2019 than 2018 and 2020). To minimize disturbance, hogs spent only four to five days in each paddock, with more time allowed in the slightly larger paddocks. In one instance, the hogs escaped the study area for several hours and were given an additional day to graze when returned to their paddock. Additionally, when four hogs were removed from the study due to a scheduled slaughter in 2019, an additional day of grazing was added for the remaining paddocks.

To count the number of infested and intact acorns, we selected five mature, productive oak trees (DBH > 6”) in both the grazed and ungrazed sections. We measured the farthest distance from the center of each tree to the outermost edge of the canopy, and cleared all tall vegetation in a 4 m^2 plot at the midpoint. This process was repeated on the opposite side of the tree. To assess the success of hog-grazing at removing acorns, we counted all acorns in situ before and after grazing took place in 2018 and 2019. Acorns were visually inspected for physical integrity, bore holes, and/or insect frass as evidence of infestation (Perry & Mangini 1997, Rohlfs 1999). We considered the proportion of infested acorns before grazing each year as a baseline infestation rate. We repeated infestation monitoring in 2020 to evaluate the 2019 grazing effect.

We monitored FBW baseline populations in 2018 and evaluated the effect of previous year grazing in 2019 and 2020. We used two types of traps to monitor FBW populations: aerial sticky traps placed in trees to capture mating adults (Miller et al. 2019), and a ground-based emergence trap to capture adult FBW moths in the spring as they emerge from pupa in the leaf litter (Chambers et al. 2010, Dohanian 1940). For the aerial sticky traps, we used commercially available Pherocon VI traps manufactured by Trécé Inc. with pheromone lures to attract FBW. Four aerial sticky traps were installed 15 – 20 meters up in the oak canopy of both the grazed and ungrazed sections (Aliniazee 1983, Miller et al. 2019). We replaced the sticky bottoms and installed a new lure every four weeks during the FBW flight season, from June through September (AliNiazee 1998, Olsen 2002). Concurrently, we installed and sampled from ten ground emergence traps in each section. These half-meter by half-meter traps were constructed economically, using wooden dowels, window screening, automotive funnels, and plastic food containers

(Online Resource 1). Emergence traps were staked to the ground underneath oak trees halfway between the trunk and canopy edge. We placed a Trécé FBW pheromone lure at the top of each emergence trap and replaced it every six weeks. During all three years, we also monitored 20 emergence and 8 sticky traps in the adjacent hazelnut orchard using the same methods. All traps were removed prior to introduction of hogs in the fall.

Vegetation Monitoring

To determine the effects of hog-grazing on the understory vegetation, we measured vegetative cover using 24 plots along six transects. We estimated total percent cover of the following categories: bare ground, litter and herbaceous layer, native shrubs, and introduced shrubs. Each group's cover was estimated independently, leading to cover estimates over 100 percent. The grazed and ungrazed woodland sections each had three 50 meter transects, spaced 30 meters apart. We visually estimated percent cover in four 4 m^2 quadrats along each transect at 5, 20, 35, and 50 meters. Baseline cover was collected in September of 2018, prior to the introduction of hogs two weeks later. To see how two years of hog-grazing affected vegetation, we re-surveyed the same transects in September of 2020.

Analysis

All analyses were conducted in R (Version 3.6). Grazing effects on acorns and FBW were evaluated with two-way ANOVAs, paralleling our BACI design with timing (before vs. after grazing) and grazing treatment as independent variables with a Tukey post-hoc analysis. Effects on vegetation were evaluated with mixed models, using transect as a random factor and grazing treatment and year as interacting fixed factors. To test whether FBW had a resident population in the hazelnut orchard, we tested whether emergence was significantly different from zero, aggregating counts from 2018-2020. To test whether hogs effectively removed infected acorns, we aggregated 2018 and 2019 counts based on whether they were taken before or after grazing implementation (our timing variable). To test the effect of grazing on the baseline proportion of infested acorns, we compared counts taken before grazing took place each year to capture the ratio of infested to intact acorns produced early in the masting season. Additionally, we ran parallel analyses to see if grazing affected FBW emergence and abundance in the oak woodlands; in which we used each trap's count throughout the season as a replicate, grouped within years (our timing variable) and looked for an interaction with grazing. Finally, we compared 2018 and 2020 vegetation cover by type and grazing status to see if grazing modified cover. We considered a p-value less than 0.05 to be significant, and less than 0.1 to be marginally significant.

Results

Acorns

There was high variability in the total number of acorns produced each year, with moderate production in 2018 (7.9 per acorns m^2), a high-production masting event in 2019 (19.7 acorns per m^2) and very low production in 2020 (0.4 acorns per m^2, Online Resource 2). In 2018 and 2019, the number of infested acorns on the woodland floor decreased significantly following grazing but not in the control. The average infested acorn density in the grazed section decreased following grazing from 4.6 to 1.9/m^2 ($P = 0.046$) in 2018, and from 5.8 to 0.1 per m^2 ($P < 0.001$) in 2019 (Fig. 2). This represents a 73.03%

reduction in the density of infested acorns averaged across both years immediately following grazing. In contrast, density in the un-grazed control increased on average by 67.02%. Grazing significantly reduced the baseline proportion of infested acorns from 51.4% to 29.7% between 2018 and 2019 ($P = 0.066$), whereas the baseline proportion of infested acorns in the ungrazed section did not change significantly between these years. Across both treatments, the baseline proportion of infestation was very high in 2020 (90% and near 100% in grazed and ungrazed, respectively) but the sample size was very low this year due to limited acorn production (Online Resource 2). Although acorn sampling plots were cleared of vegetation, potentially allowing easier access to acorns, we qualitatively observed similar reductions of acorn density throughout the woodland.

FBW Populations

Out of 160 samples in 2018, only 1 FBW ever emerged in the hazelnut orchard. When averaged across samples throughout the season, this was not significantly different from zero (Fig. 3, $P=0.99$). By comparison, 33 FBW were captured in oak-woodland emergence traps over the duration of the experiment. At the same time, aerial FBW moths were consistently found in both oak and hazelnut canopies, suggesting spillover from the oak habitat (Fig. 3).

FBW population levels followed the pattern of acorn infestation rates (Fig. 4). Overall FBW emergence increased from 1.7/m^2 in 2018 to 3.2/m^2 in 2019, but this was driven by an increase of 138% in the control section ($P = 0.004$), with no significant increase in the grazed section (Fig. 4). In 2020, FBW emergence dropped in both grazed (0.16/m^2) and ungrazed (1.86/m^2) sections despite a heavy masting year in 2019. Over the three years, emergence in the grazed plot remained low and statistically unchanged ($P = 0.96$), while it varied significantly (2019, $P = 0.001$; 2020, $P < 0.001$) in the un-grazed control section. In 2019, emergence was significantly lower in the grazed section than in the ungrazed control ($P < 0.001$). FBW canopy abundance measured with sticky traps showed an overall increase in the ungrazed control from 2018 to 2020 ($P = 0.008$), with no overall change in the grazed section.

Vegetation Monitoring

Overall, grazing had no effect on vegetative cover from 2018 to 2020 (Fig. 5), as measured by the interaction between year and grazing treatment for bare ground ($P = 0.91$), herbaceous/litter ($P = 0.48$), native shrub ($P = 0.93$), and introduced shrub ($P = 0.91$). While there were occasionally significant differences in the main effect of grazing between sections like bare ground ($P = 0.03$), herbaceous/litter ($P = 0.083$), and introduced shrub ($P = 0.03$), these effects were present in 2018 before grazing began.

Discussion

Our results demonstrate that prescribed hog-grazing in oak patches can be effective at reducing FBW pest populations by removing infested acorns from the forest floor, while minimizing impact on vegetative cover. We observed a consistent effect in which grazing reduced the rate of acorn infestation and subsequent FBW emergence. Consequently, the aerial abundance of FBW was suppressed in the grazed section even as it climbed in the un-grazed control. The fact that grazing reduced infested but not intact acorns suggested that infested acorns drop earlier and that our prescribed grazing was well-timed to remove the majority of infested acorns without affecting the viability of oak populations. As such, our findings indicate a win-win solution for agriculture and conservation and provide a model for addressing similar challenges across the agricultural-wildlands interface.

Although we observed an immediate effect of grazing on acorn infestation rates and FBW emergence, we did not observe a significant effect on aerial abundances until the final year. This difference in response time between FBW emergence and aerial abundance can be accounted for by the same issues of scale and spillover that motivated our experiment. Adult FBW moths can migrate up to five acres throughout the landscape, especially when aided by wind (AliNiazee 1998). Our use of both ground emergence and aerial sticky-trap methods for monitoring FBW populations allowed us to begin to disentangle the effect grazing has at different scales. Emergence traps are a very localized method of capturing FBW that emerge from pupae from the woodland floor (Perry & Mangini 1997). By contrast, aerial traps are designed to attract and trap moths from up to two acres (Davis & Mcdonough 1981). While our emergence traps showed a reduction in the locally pupated FBW population, we expect that FBW emerging outside our grazed section migrated in and were caught in our aerial traps. This is not surprising given the proximity and relatively small size of our grazed and ungrazed sections, and indicates that for hog-grazing to be most effective it must be done at scale.

A masting event in 2019, where oaks produce acorns in a decade-long boom and bust cycle to control predator populations (Peter & Harrington 2009, Stein 1990), exaggerated the divergence between ground emergence and aerial abundance from 2019 to 2020. While we saw nearly 100% infestation rates in 2020; this was likely due to many

FBW competing over a small number available acorns. We expect it is likely that 2021 will be a corresponding bust year for FBW, as the next generation responds to the lack of resources provided in 2020. Our ability to control FBW populations despite the presence of a mast year suggests that adjusting stocking rates based on availability of acorns, as was done in this experiment, is an important consideration for a successful hog silvopasture program (Díaz-Caro et al. 2019, Fischer & Bliss 2008).

While our results suggest that hog-grazing has the potential to be an effective biological control method, this practice will only be implemented widely if hazelnut farmers are receptive to the economic benefits it can provide. Traditionally, hazelnut orchards use costly pesticides in an attempt to reactively control FBW (Mehlenbacher & Olsen 1997, Miller et al. 2019, Pscheidt et al. 2016) and applications need to be repeated multiple times per year as they re-invade (AliNiazee 1998, Miller et al. 2019). As such, focusing solely on the control of local populations in orchards will likely be insufficient to minimize infestation rates. Controlling pest populations at their woodland source can reduce farmers' dependence and expenditures on pesticides, potentially allowing them to take advantage of an increased organic market demand (Akbaba et al. 2011, Demiryurek & Ceyhan 2008, Julian et al. 2009, Mehlenbacher & Olsen 1997, Thompson 1998). The reduction of pesticides also benefits pollinators and other beneficial insects that support diverse farm systems (Demiryurek & Ceyhan 2008, Fischer 2018, Miller et al. 2019, Thompson 1998). Finally, there is growing market demand for ecologically-friendly farm practices (Hatfield 2011) and feed-varied pork (Dagar & Tewari 2016, Orefice et al. 2017, Rocadembosch et al. 2016), as demonstrated by gourmet acorn-finished pork from Spain and Germany (Danz et al. 2018, Díaz-Caro et al. 2019). In addition to creating a premium product, silvo-pasturing hogs reduces their feed costs up to 75% (Rocadembosch et al. 2016, Dagar & Tewari 2016, Orefice et al. 2017). These additional benefits may help make the extra work involved in hog silvopasture attractive to farmers.

Despite our concerns, two years of prescribed grazing did not affect vegetative cover. Specifically, we did not see increases in bare ground or shrubs like *R. armeniacus*. While this is promising, our study site began with an already highly invaded understory. This is a common condition throughout remnant woodlands, but further research is needed on the effects of hog grazing on high-quality or restored understories. Technical options for abating escapement, such as training and standard operating procedures, should be considered for prevention and response (Lewis et al. 2019, Mack et al. 2000, Sytsma et al. 2007, ODFW 2016) as the Willamette Valley is similar to other areas with problematic feral hogs, suggesting that their absence is likely from lack of introduction rather than unsuitable habitat (Barrios-Garcia & Ballari 2012, Bevins et al. 2014, Mack et al. 2000). Greater effects may also be seen in wetter years or sites where hog have more destructive impacts (Barrios-Garcia & Ballari 2012). We did not look explicitly at the effects of grazing on oak recruitment and seedlings, but care should be taken to allow for natural regeneration.

Conclusion

In a nutshell, this study demonstrates that prescribed grazing of hogs can be a practical and effective tool for controlling FBW source populations in remnant Oregon oak habitat. Agriculture and wildlands are interwoven, and conflicts between production and conservation in these landscapes are more and more common. Without landowner buy-in, pressure on conservation will increase as the global population rises and more land is required for farming. Our study provides a model for working with rural landowners to solve challenges that develop at the interface of agriculture and wildlands for the mutual benefit of their livelihood and regional conservation goals. While specific local conflicts may vary, considering production and conservation goals is general across the agricultural-wildland matrix and is necessary to create future win-win scenarios.

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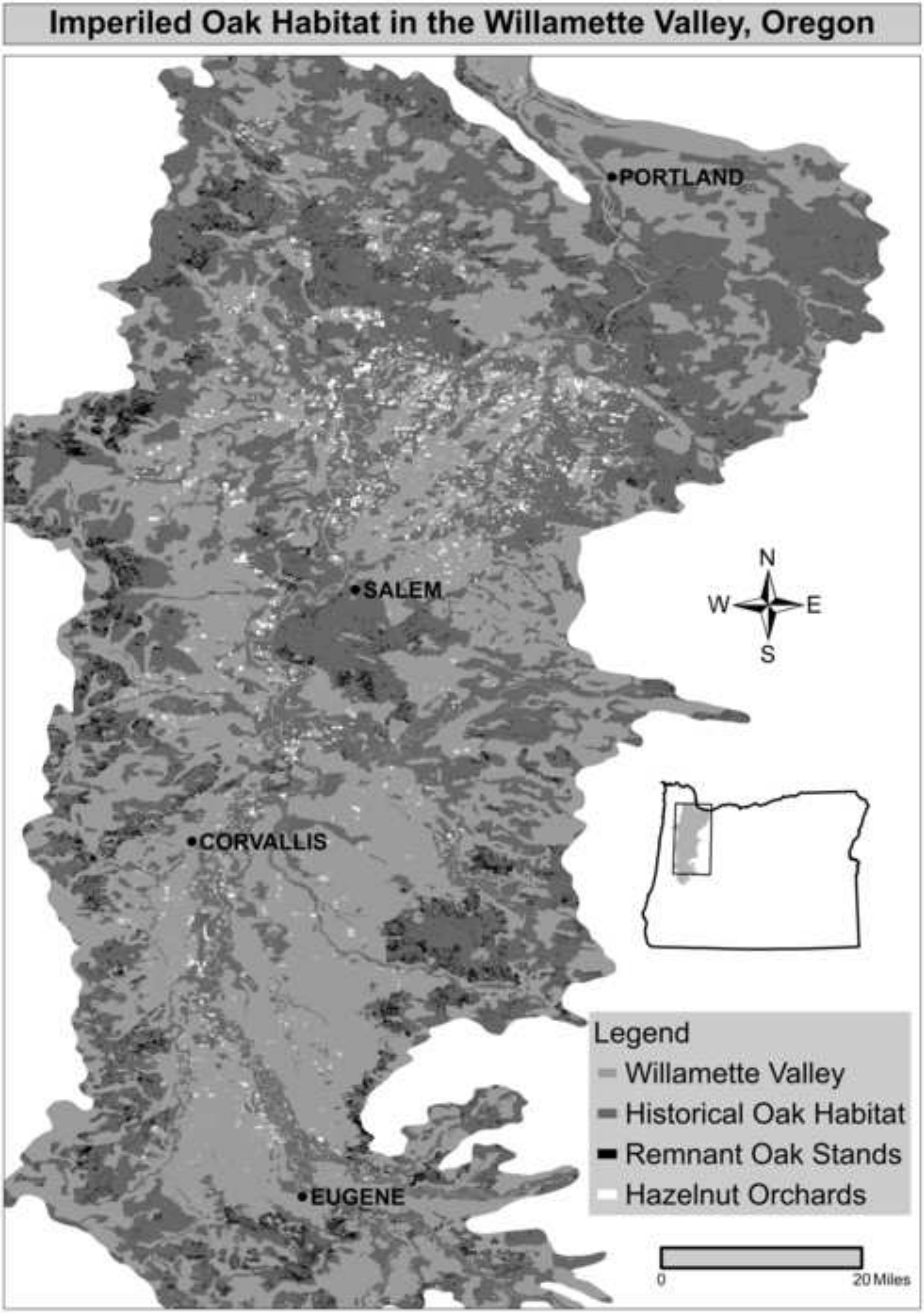
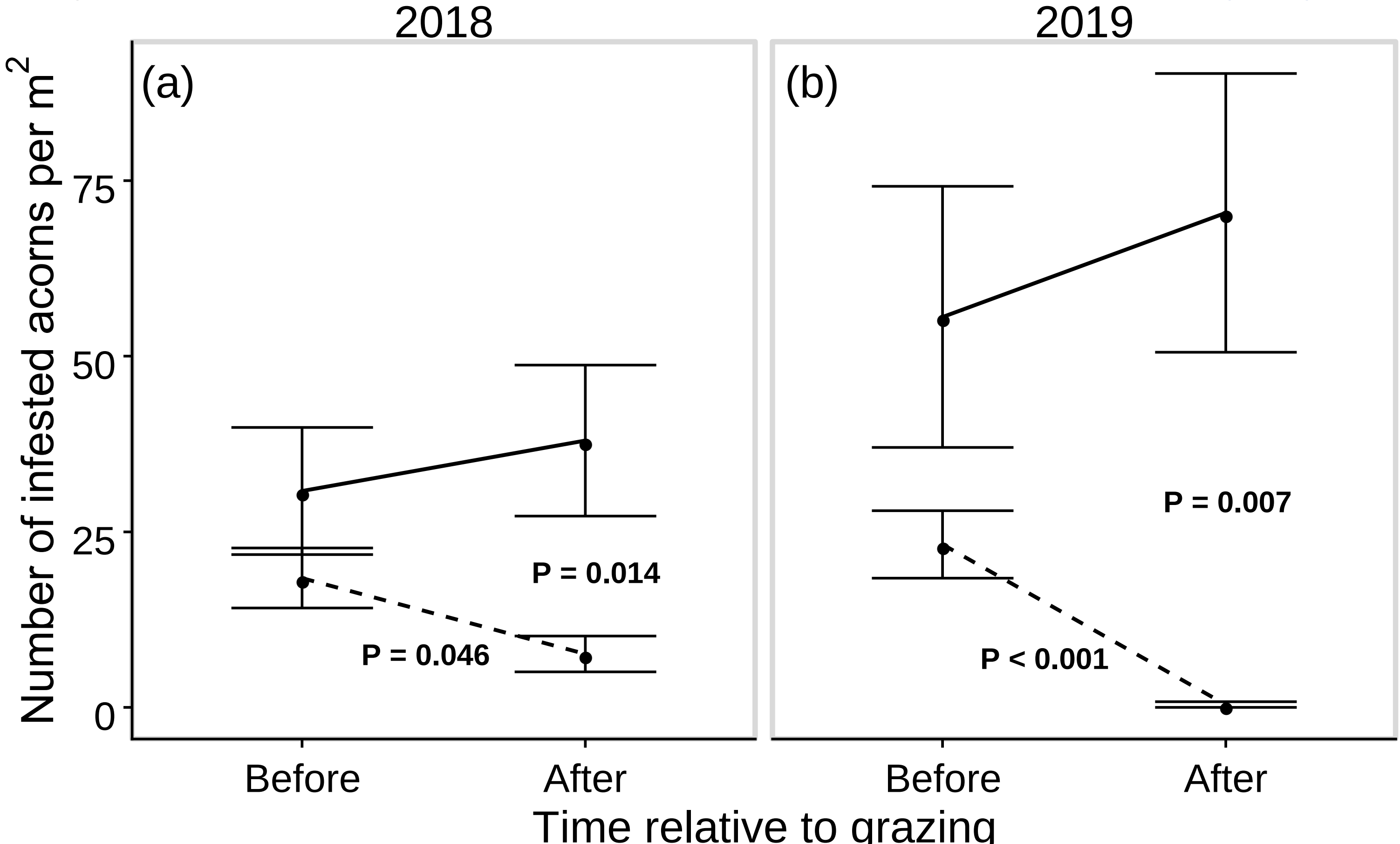
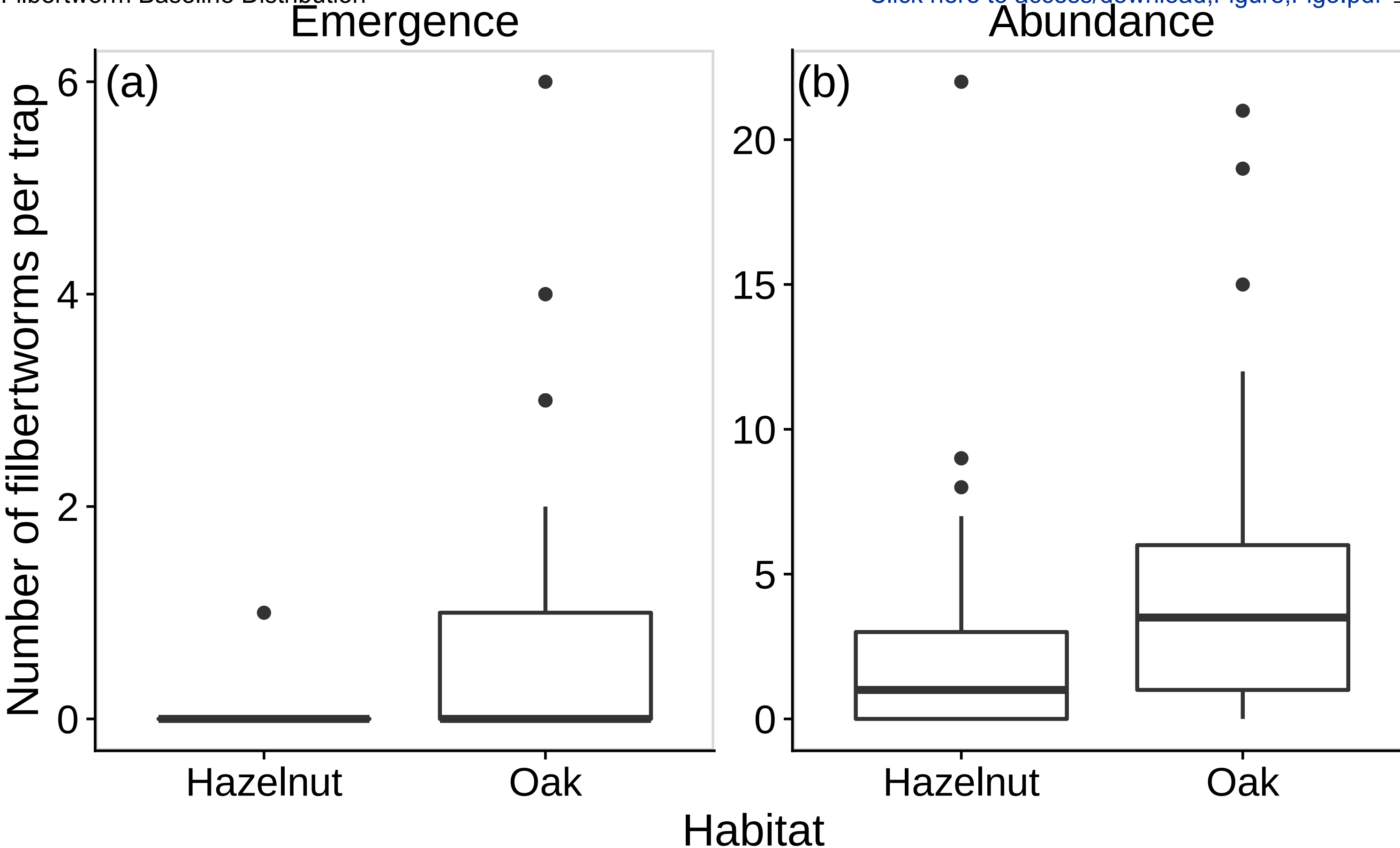
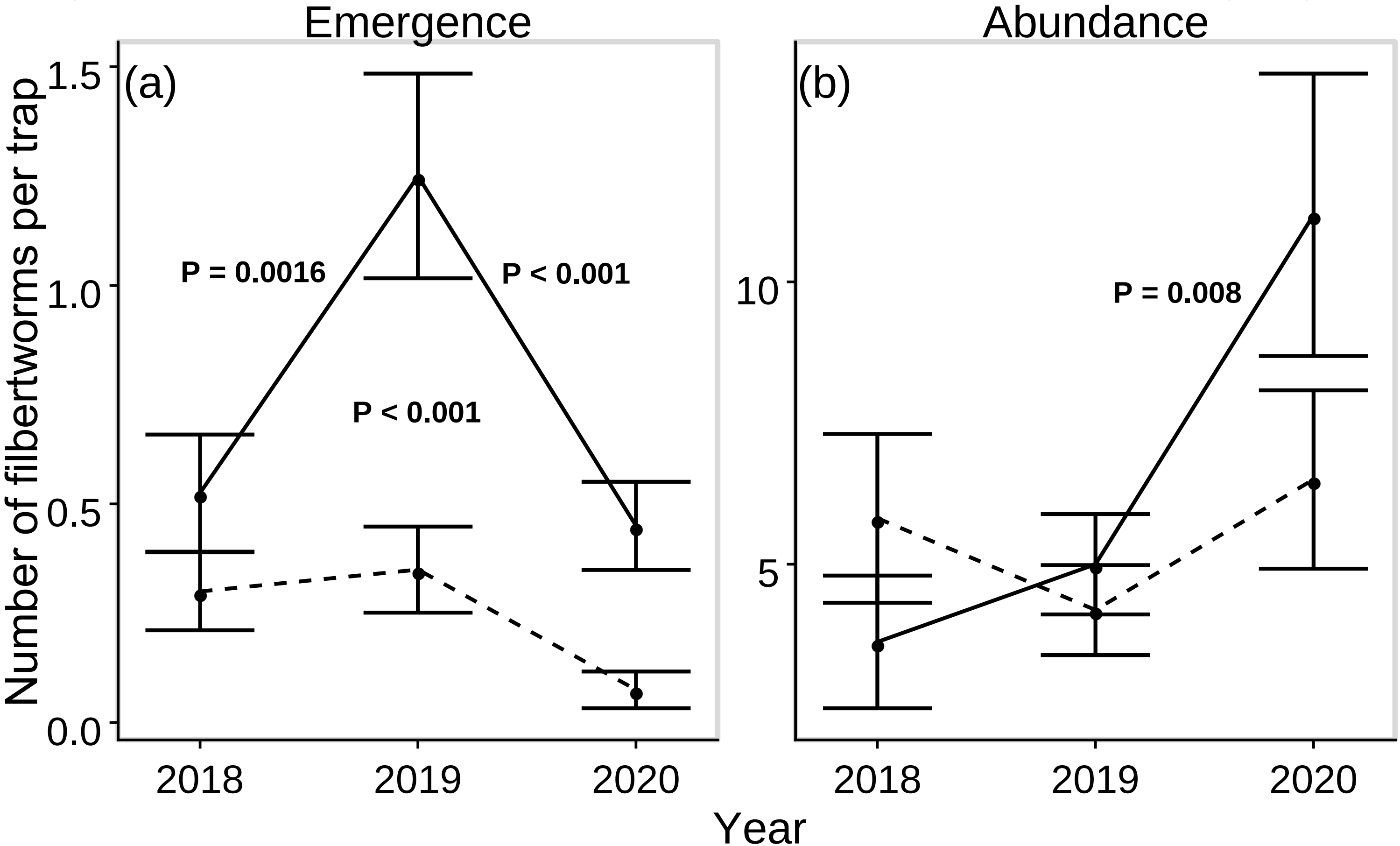
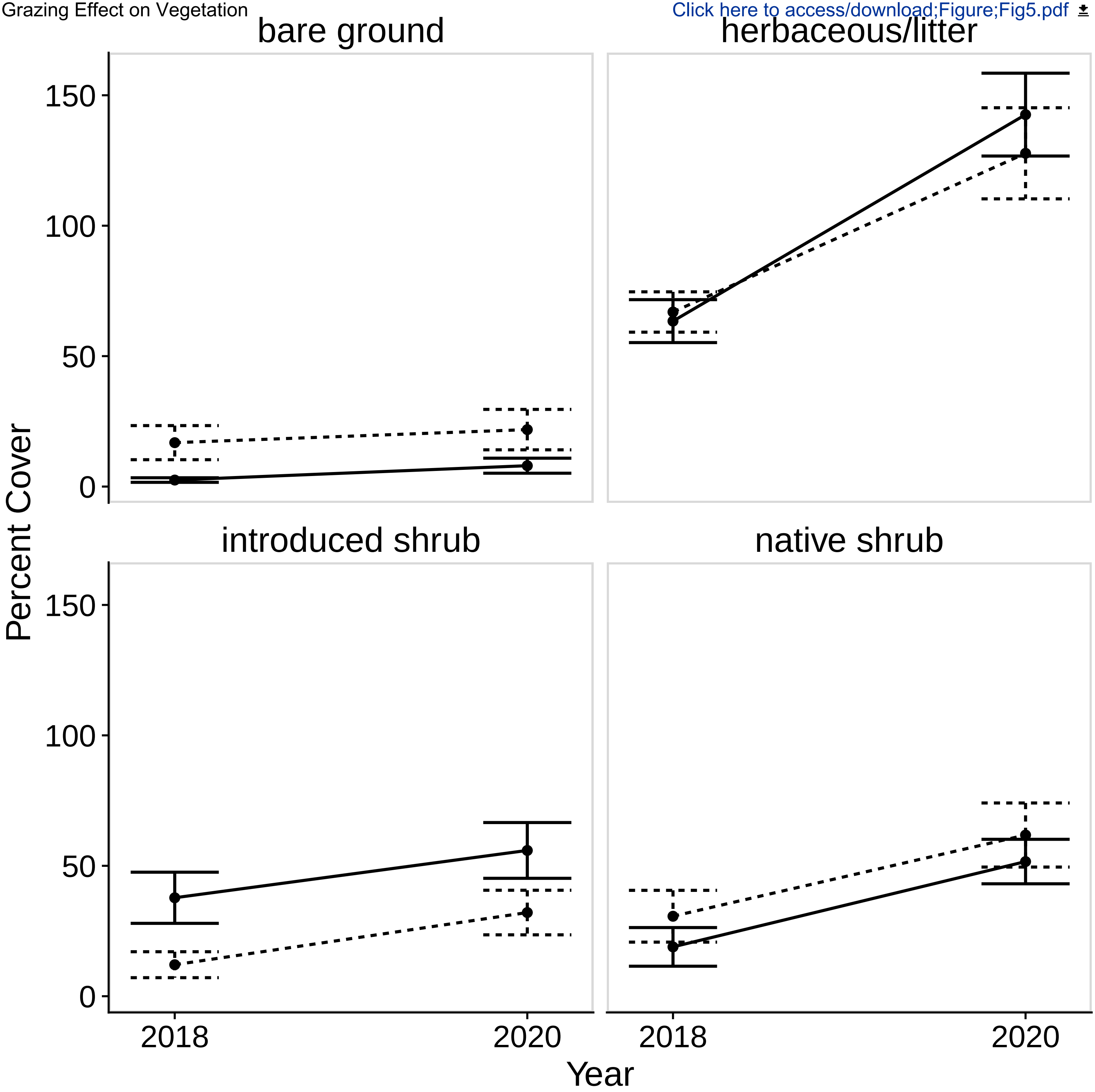

Imperiled Oak Habitat in the Willamette Valley, Oregon
PORTLAND
SALEM
CORVALLIS
EUGENE
N
W
E
S
Legend
Willamette Valley
Historical Oak Habitat
Remnant Oak Stands
Hazelnut Orchards
0
20 Miles


2018
2019
(a)
(b)
Number of infested acorns per m^2
0
25
50
75
P = 0.014
P = 0.046
P = 0.007
P < 0.001
Before
After
Before
After
Time relative to grazing


Emergence
Abundance
(a)
(b)
Number of filbertworms per trap
0
2
4
6
0
5
10
15
20
Hazelnut
Oak
Hazelnut
Oak
Habitat

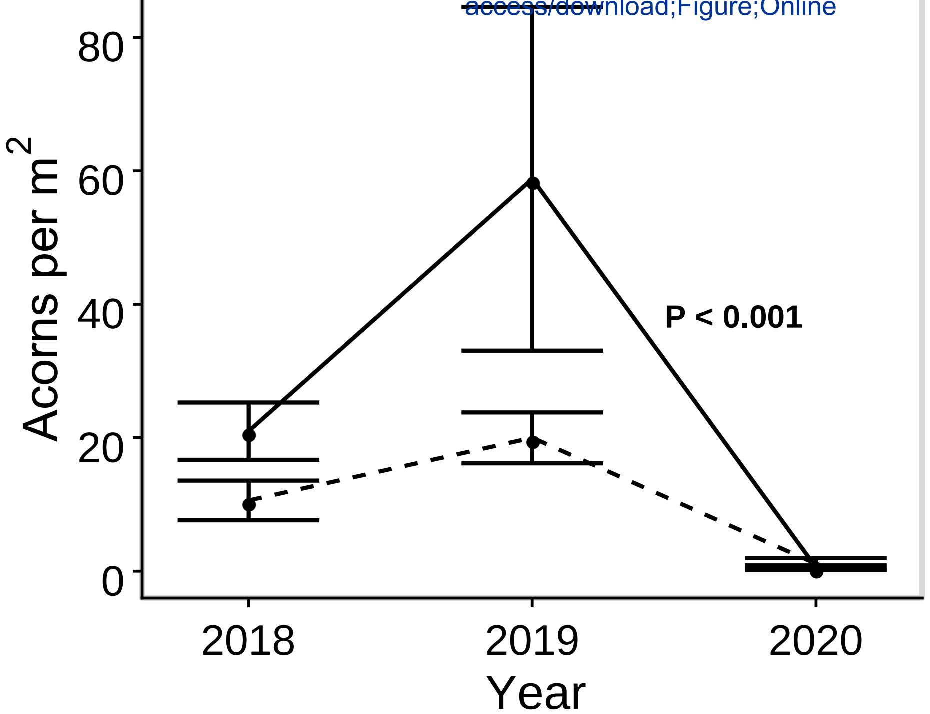

Emergence
Abundance
(a)
(b)
Number of filbertworms per trap
1.5
1.0
0.5
0.0
10
5
P = 0.0016
P < 0.001
P < 0.001
P = 0.008
2018
2019
2020
2018
2019
2020
Year


bare ground
herbaceous/litter
introduced shrub
native shrub
Percent Cover
0
50
100
150
2018
2020
Year

Filbertworm Ground Emergence Trap

Acorn Density Across Years

Click here to access/download;Figure;Online



UNIVERSITY OF OREGON | College of Arts and Sciences

November 30, 2020

Shibu Jose
Editor-in-Chief, Agroforestry Systems
University of Missouri, Columbia, MO, USA

Dear Dr. Jose,

We are pleased to submit the manuscript, "Hogs and Hazelnuts: adaptively managing pest spillover in the agricultural-wildland matrix" to be considered for publication as part of the *Agroforestry Systems* special issue, "Agroforestry for Sustainable Production and Resilient Landscapes".

The interface between agriculture and unmanaged land, or wildlands, brings about complex issues surrounding land-use change and economic incentivization. Conservation is often at odds with intensively managed crops, in particular habitat which maintains source populations of agricultural pests. This is the case in Oregon, where the key pest of hazelnuts spills over from imperiled oak habitat. Adaptive management strategies such as prescribed grazing have demonstrated to be an increasingly important tool for aligning economic and ecological processes. Here, we present a novel method of pest management using prescribed hog-grazing in remnant oak patches. We show that this practice can be effective at reducing infestation rates in oak habitat, decreasing its burden to landowners, while creating a valuable non-timber forest product that incentives conservation.

Our study provides a model for working with rural landowners to solve challenges that develop at the interface of agriculture and wildlands for the mutual benefit of their livelihood and regional conservation goals. We think this approach is of general interest to *Agroforestry Systems* readers, while our focal system is well-aligned with the special feature on Sustainable Production. We thank you in advance for taking the time to consider and review this manuscript.

Sincerely,

Calvin Penkauskas
Alejandro Brambila
Drew Donahue
Taylor Larson
Betsey Miller
Lauren M. Hallett

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