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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 habitat 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 habitat near hazelnut orchards can sustain source populations that compound pest load 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 a novel strategy to reconcile this regional conflict by using hogs (*Sus domesticus*) to reduce pest populations through prescribed foraging. From 2018 to 2020 we prescribed hog-foraging in early fall to glean filbertworm-infested acorns from an oak woodland understory. 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, foraging reduced both the emerging and adult mating population of filbertworm the following year. We did not measure significant changes in the woodland understory, suggesting intermittent hog-foraging may not entail tradeoffs for understory vegetation. Our results demonstrate that prescribed foraging in oak patches can be an effective strategy to reduce filbertworm source populations. By benefiting both conservation and farmers, this adaptive pest management approach provides a model for similar challenges and conflicts across the agricultural-wildland matrix.

Keywords Oaks · Silvopasture · Source-sink dynamics · Foraging · Filbertworm · Non-timber forest product

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Introduction

Agricultural lands are often embedded in a landscape matrix that includes unmanaged or economically unproductive land (Rusch et al. 2010) that maintain wildlife populations – which we deem wildlands. A common problem in these mosaic landscapes is pest spillover, where wildlands sustain source populations of agricultural pests (Damon 2000; Tonina et al. 2018; Wilby and 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 (AliNiazee 1998; Miller et al. 2019; Rusch et al. 2010) and whose native host is the Oregon white oak (*Quercus garryana*). Hazelnut orchards in the region exist in close proximity to oak patches in the current landscape (Mehlenbacher and Olsen 1997) with their establishment continuing within historical oak habitat on higher quality farmland throughout the floodplains surrounding rivers, and oak habitat being restricted to less favorable land patches of rocky and seasonally saturated soils (Fischer and Bliss 2008; Vesely and Tucker 2004). Our overarching question is whether FBW source populations can be controlled in this wildland habitat through prescribed foraging, reducing the potential of spillover onto farms.

Oregon hazelnut farming is a multi-million-dollar industry, making up 99% of domestic hazelnut production and covering over 80,000 acres in 2020 (Webber et al. 2020), the majority of which is found in the Willamette Valley (Miller et al. 2019). As the hazelnut industry is recovering from the effects of eastern filbert blight (*Anisogramma anomala*), planted acreage is expected to double between 2018–2025 with help from blight-resistant variants and increasing market demand (Miller et al. 2019, Webber et al. 2020). Accordingly, hazelnut orchards are intensively managed for FBW (Akbaba et al. 2011; AliNiazee 1998; Miller et al. 2019; Olsen 2002). Unfortunately, spillover from infested oaks adjacent to hazelnut orchards can lead to cyclical re-infestation throughout the growing season (AliNiazee 1998; Coblentz 1980; Rohlfs 1999). This makes oak habitat problematic to hazelnut growers and incentivizes the removal of remaining privately-owned oak patches to minimize crop damage (Fischer and Bliss 2008, Hagar and Stern 2001, ODFW 2016). Since these wildlands in most cases are left marginalized in otherwise managed farms, their persistence is in part to their natural legacy for family farms (Fischer and Bliss 2008). As such, these remnant oak stands are highly fragmented and are dispersed throughout an otherwise-developed, mostly agricultural landscape (Fig. 1).

Today, conserving and restoring oak habitat is a major concern throughout the Pacific Northwest (ODFW 2016). Oaks in the Willamette Valley have historically shaped the landscape—consisting of 400,000 acres of continuous woodlands spreading out from riparian areas before European colonization (Christy and Alverson 2011; Kimmerer and Lake 2001), yet less than 5% of oak habitat remains today (Vesely and Rosenberg 2010). This landscape was regularly maintained by indigenous peoples and depended on the fire disturbance they once provided (Christy and Alverson 2011; Kimmerer and Lake 2001). Since colonization, fire exclusion, conifer planting and encroachment, and land-use change have been significant drivers of oak-habitat loss in the region (Kimmerer and Lake 2001, ODFW 2016, Vesely and Rosenberg 2010). Oak habitats support levels of diversity rivaling old-growth conifer forests and include numerous endemic species, of which, at least 45 are at-risk for extinction (Altman 2011; Hagar and Stern 2001; Ulrich 2010). Since *Q. garryana* is an extremely slow growing species (Devine and Harrington 2013; Jimerson and Carothers 2002; Stein 1990), conservation groups and government agencies are prioritizing the conservation of the remaining mature oak habitat in Oregon. However, less than 1% of this habitat is protected and its survival depends heavily on individual landowners (ODFW 2016, Vesely and Rosenberg 2010). Although there are a few large conserved patches, most oaks persist in small scattered patches of approximately 10 acres within productive farmland (Vesely and Rosenberg 2010). These patches represent the majority of total oak stands in the Willamette Valley and are not closely monitored due the large number of relatively small private land holdings (ODFW 2016, Vesely and Tucker 2004), which makes traditional conservation difficult.

Here, we present the use of domesticated pig (hog; *Sus domesticus*) foraging in oak patches to reduce the potential of FBW spillover into hazelnut orchards. Livestock grazing and foraging are common practices for managing pest populations within agricultural systems (Wilson and Hardestry 2006). For example: free-range chickens have been used to control pests in

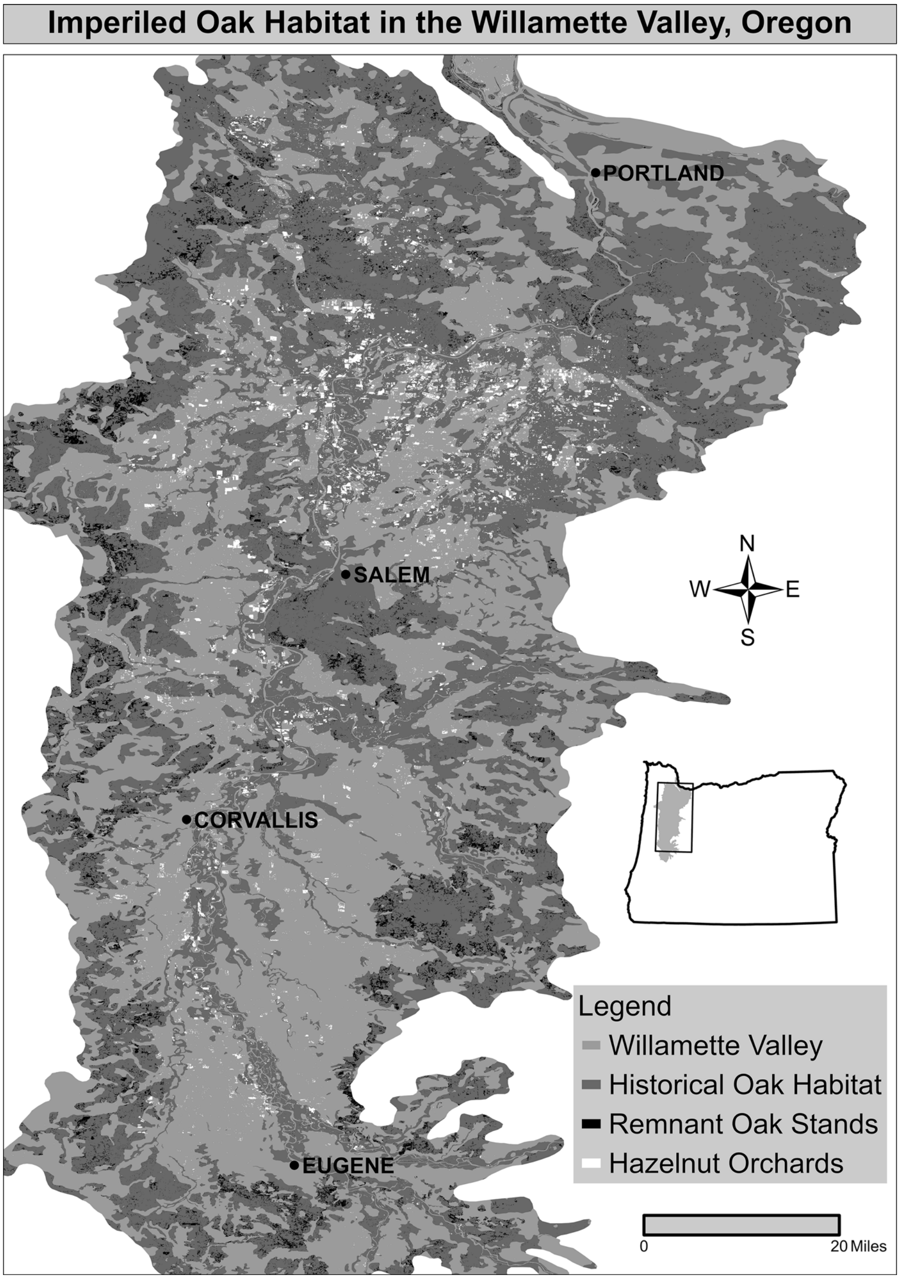

Fig. 1 Historical (circa 1850; Christy and Alverson 2011) and 2016 remnant Oregon white oak habitat (Kagan et al 2018) in the Willamette Valley (ODFW 2016), Oregon (BLM 2001, DLG 1970). Crops that have direct economic conflict with these remaining stands due to the spillover of pests, such as hazelnuts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

squash and blueberry fields (Clark and Gage 1996; Wenig and Farm 2013), sheep have been used in grain and alfalfa systems (Hatfield 2011), and hogs have been used for pest control in apple orchards (Nunn et al. 2007). In all of these cases, livestock 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-foraging in oak woodlands has the potential to impact source populations directly, reducing FBW spillover while creating additional revenue, and incentivizing oak habitat conservation in the process.

Hogs and oaks are a particularly good fit; as oak systems have widely been used as silvopasture for hogs across the world and can increase sustainable land-use while enhancing biodiversity across the landscape (Díaz-Caro et al. 2019; Eichhorn, M.P. et al. 2006; Nunn et al. 2007). The disturbance-adapted nature of Oregon oak woodlands may mean that the system is particularly well suited for hog-foraging as a management practice. Oak habitat in the Willamette Valley evolved with indigenous burning and requires some level of disturbance to persist (Christy and Alverson 2011; Kimmerer and Lake 2001; Ulrich 2010; Stein 1990). Likewise, the lack of management in these remnant woodlands leads to encroachment and vulnerability of invasive species (ODFW 2016; Vesely and Rosenberg 2010). 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 foragers and grazers (Dagar and Tewari 2016; Nunn et al. 2007) with an extensive history of beneficial use in European and Mediterranean systems (De Oliveira, M. I. F. et al. 2013; Díaz-Caro et al. 2019). In these systems, oak woodlands may not be considered wildlands due to their historical and current management for hog silvopastures—unlike the Willamette Valley, where they have not been actively managed for production since colonization. Although hog-foraging in oak habitat is common in other parts of the world, its implementation in the Willamette Valley as an adaptive management strategy for pest spillover is a novel one.

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 larvae inside are vulnerable to predation and a well-timed intervention has the potential to reduce populations 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 and Olsen 1997; Olsen 2002). The same principle could be applied in nearby oak patches, where infested acorn removal could reduce FBW source populations. While mechanically removing acorns is not practical, a carefully managed hog silvopasture program has the potential to be an ideal pest management tool in the region.

Introducing an omnivore to a complex natural system is a major intervention, however, as hogs uproot areas of soil for forage and graze understory plants (Ickes 2001; Wang et al. 2018). 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 prescribed hog-foraging on understory vegetation will be important to weigh potential co-benefits or trade-offs of this management strategy. However, the use of hog-foraging to adaptively control key pest populations in wildlands could help bridge the gap between cost avoidance and ecological intensification practices in the developing oak-hazelnut savanna landscape.

To test the effectiveness of hog-foraging on controlling FBW, we conducted a three-year experiment in an oak woodland near an adjacent hazelnut orchard. Our expectation was that hogs would be effective at reducing FBW populations, while controlled rotation would minimize disturbance. Specifically, we hypothesized that foraging in the oak woodland would effectively reduce the number of infested acorns relative to an un-foraged 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. Since hogs have been known to cause severe understory damage, we hypothesized that foraging would also reduce the percent cover of herbaceous vegetation on the woodland floor and increase bare ground. Many landowners have positive attitudes towards preserving oaks as a legacy within the landscape, but also want to reduce costs associated with their potential pest load (Fischer and Bliss 2008; Vesely and Rosenberg 2010). If successful, this approach could help reconcile this conflict between oak conservation and hazelnut farms by decreasing the potential of pest spillover from oak habitat and incentivizing conservation through non-timber forest production of previously unmanaged patches 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 and Bartlett 1993). The twenty-six-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), and represents a typical remnant oak patch within the landscape. This oak woodland is approximately 500 m from the hazelnut orchard (Online Resource 1). Aerial photography indicated that it has had a consistent mixed-oak canopy during the last century (University of Oregon 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-foraging

Using a Before-After-Control-Impact (BACI) experimental design, we divided the oak woodland into foraged and un-foraged control sections in 2018. Within the foraged section, we established five approximately two (± 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 foraging 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 forage 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 foraging 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 foraged and control 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-foraging at removing acorns, we counted all acorns in situ before and after foraging took place in 2018 and 2019. Acorns were visually inspected for physical integrity, bore holes, and/or insect frass as evidence of infestation (Perry and Mangini 1997; Rohlfs 1999). We considered the proportion of infested acorns before foraging each year as a baseline infestation rate. We repeated baseline infestation monitoring again in 2020 to evaluate the 2019 foraging effect.

We monitored FBW moth baseline populations in 2018 and evaluated the effect of previous year foraging in 2019 and 2020. We used two types of traps to monitor FBW moth 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 pupae 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 m up in the oak canopy of both the foraged and control sections (AliNiazee 1998; 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 2). 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-foraging 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 foraged and control sections each had three 50 m transects, spaced 30 m apart. We visually estimated percent cover in four 4 m^2 quadrats along each transect at 5, 20, 35, and 50 m. Baseline cover was collected in September of 2018, prior to the introduction of hogs two weeks later. To see how two years of hog-foraging affected vegetation, we re-surveyed the same transects in September of 2020.

Analysis

All analyses were conducted in R (Version 3.6). Foraging effects on acorns and FBW were evaluated with two-way ANOVAs, paralleling our BACI design with timing (before vs. after foraging) and foraging 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 foraging 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 foraging implementation (our timing variable). To test the effect of foraging on the baseline proportion of infested acorns, we compared counts taken before foraging 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 foraging affected FBW emergence and abundance in the oak woodlands; in which we used each trap as a replicate and grouped their counts within years (our timing variable) and looked for an interaction with hog-foraging. Finally, we compared 2018 and 2020 vegetation cover by type and foraging status to see if foraging 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 3). In 2018 and 2019, the number of infested acorns on the woodland floor decreased significantly following foraging but not in the control. The average infested acorn density in the foraged section decreased following foraging 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 foraging. In contrast, density in the control increased on average by 67.02%. Foraging 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 control section did not change significantly between these years. Across both treatments, the baseline proportion of infestation was very

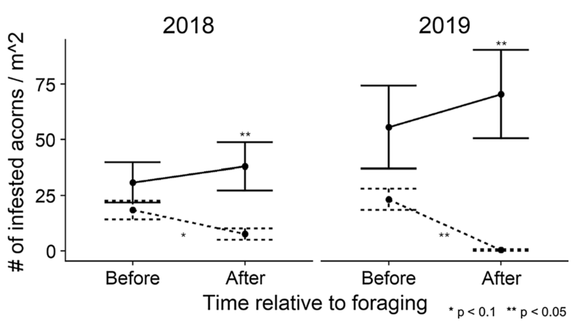

Fig. 2 Density of infested acorns on the woodland floor in foraged (dashed line) and un-foraged control (solid line) sections before and after hog-foraging. Foraging significantly reduced infested acorns during 2018 and 2019. This resulted in a high significant divergence from the control during the same time during both years, respectfully

high in 2020 (90% and near 100% in foraged and un-foraged sections, respectively) but the sample size was very low this year due to limited acorn production. 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

Between 2018–2020, only 3 FBW were ever sampled emerging 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.

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 foraged section (Fig. 4). In 2020, FBW emergence dropped in both foraged (0.16/m^2) and un-foraged control (1.86/m^2) sections despite a heavy masting year in 2019. Over the three years, emergence in the foraged section remained low and statistically unchanged ($P = 0.96$), while it varied significantly (2019, $P = 0.001$; 2020, $P < 0.001$) in the control section. In 2019, emergence was significantly lower in the foraged section than in the control ($P < 0.001$). FBW canopy abundance measured with sticky traps showed an overall increase in the control from 2018 to 2020 ($P = 0.008$), with no overall change in the foraged section.

Vegetation monitoring

Overall, foraging had no effect on vegetative cover from 2018 to 2020 (Fig. 5), as measured by the interaction between year and foraging 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 foraging 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 foraging began.

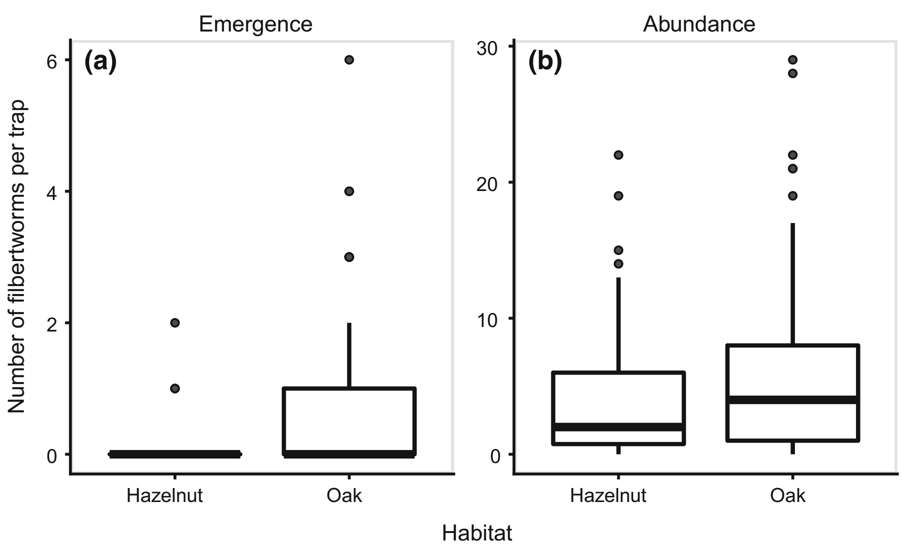

Fig. 3 Yearly average of filbertworm moth populations (2018–2020) in the hazelnut orchard and adjacent oak woodland with **a** emergence from ground traps (n = 40) and **b** aerial abundance from canopy sticky traps (n = 16). A lack of emergence but aerial presence in hazelnuts suggested source populations from oak habitat spill over into hazelnuts, increasing pest load

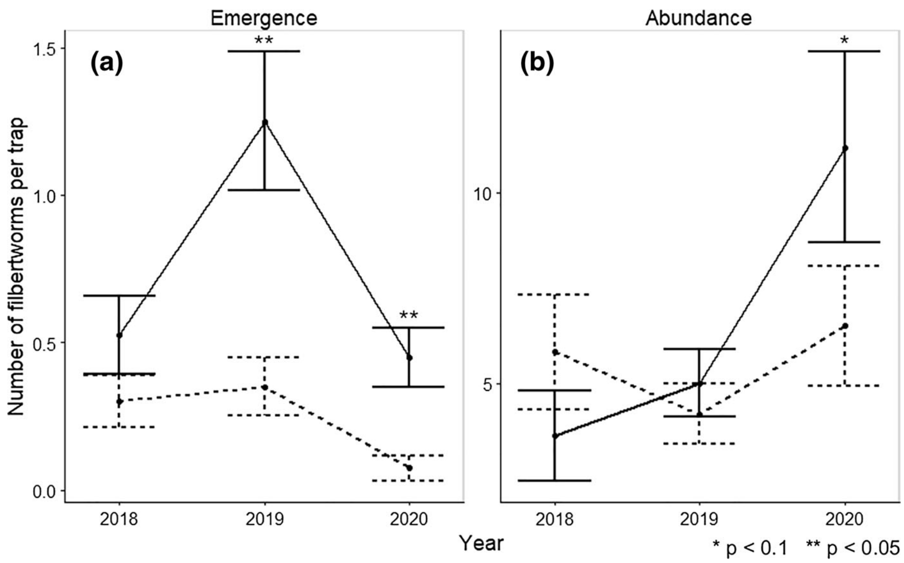

Fig. 4 Filbertworm populations in the oak woodland from **a** ground emergence traps and **b** aerial abundance sticky traps in the canopy from 2018–2020 with foraged (dashed line) and un-foraged control (solid line) sections. The control saw a significant increase in filbertworm emergence in 2019 compared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

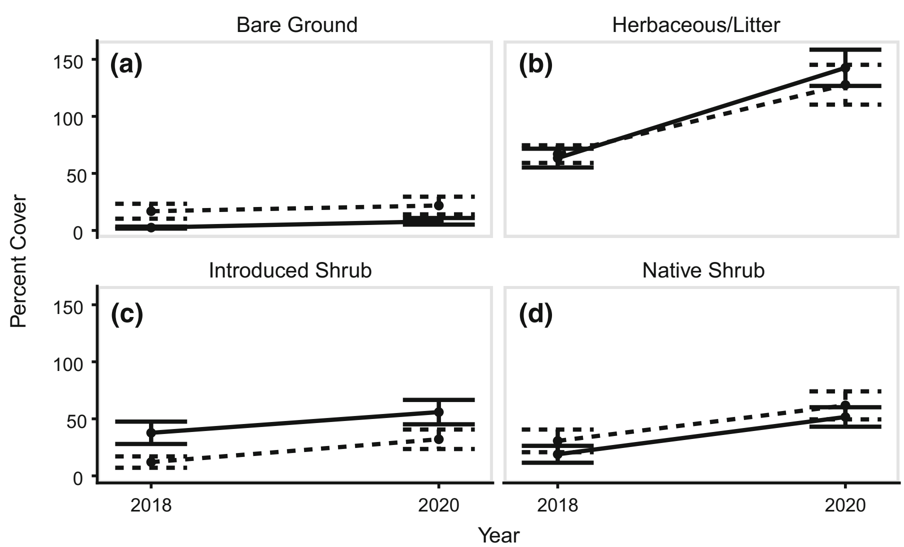

Fig. 5 Percent cover of vegetation classes in foraged (dashed line) and un-foraged control (solid line) sections of the oak woodland before foraging in 2018 and 2020. After two-years of prescribed hog-foraging, there was no significant change in percent cover of vegetation when compared to the un-foraged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

Discussion

Our results demonstrate that prescribed hog-foraging in oak patches can be effective at reducing FBW populations by removing infested acorns from the woodland floor, while minimizing impact on vegetative cover. We observed a consistent effect in which foraging reduced the rate of acorn infestation and subsequent FBW emergence. Consequently, the aerial abundance of FBW was suppressed in the foraged section even as it climbed in the un-foraged control. The fact that foraging reduced infested but not intact acorns suggests that infested acorns drop earlier and that our prescribed foraging 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 by providing a model for addressing similar challenges across the agricultural-wildland matrix through adaptive management and cost-avoidance strategies.

Although we observed an immediate effect of foraging 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 foraging has at different scales. Emergence traps are a very localized method of capturing FBW that emerge from pupa from the understory (Perry and Mangini 1997). By contrast, aerial traps are designed to attract and trap moths from up to two acres (Davis and Mcdonough 1981). While our emergence traps showed a reduction in the locally pupated FBW population, we expect that FBW emerging outside our foraged section migrated in and were caught in our aerial traps. This is not surprising given the proximity and relatively small size of our foraged and un-foraged sections, and indicates that for hog-foraging to be most effective, it must be done at scale.

A masting event in 2019, where oaks produce acorns in a multi-year boom and bust cycle to control predator populations (Peter and 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 and Bliss 2008).

While our results suggest that hog-foraging 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 and 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 wildland source can reduce farmers' dependence and expenditures on pesticides, potentially allowing them to take advantage of increasing organic market demand (Akbaba et al. 2011; Demiryurek and Ceyhan 2008; Julian et al. 2009; Mehlenbacher and Olsen 1997; Thompson 1998). The reduction of pesticides also benefits pollinators and other beneficial insects that support diverse farm systems (Demiryurek and 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 and 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 also reduces their feed costs by up to 75% (Dagar and Tewari 2016; Orefice et al. 2017; Rocadembosch et al. 2016). These additional benefits may help make the extra work involved in hog silvopasture more attractive to farmers.

Despite our concerns, two years of prescribed foraging 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-foraging 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 and Ballari 2012; Bevins et al. 2014; Mack et al. 2000). Greater effects may also be seen in wetter years or riparian areas where hogs have more destructive impacts (Barrios-Garcia and Ballari 2012; Wang et al. 2018). While we did not look explicitly at the effects of foraging on oak-recruitment and seedlings, care should be taken to allow for natural regeneration.

Although there are likely hesitancies surrounding hog-foraging in oak habitat, the long-term sustainable use of hog silvopastures in southern Europe suggests that hogs can be a part of healthy ecosystem management in the Pacific Northwest (Díaz-Caro et al. 2019, Eichhorn, M.P. et al. 2006). Further research will suggest if, and how, hogs can be integrated with landscape management practices such as prescribed fire—which is used to control FBW populations in northern California and encourages the presence of native shrubs (Long et al. 2016). Likewise, incorporating oak thinning and release can facilitate hog-foraging by increasing acorn production and oak vitality (Devine et al. 2013), while increasing foraging access and reducing fuel load. These actions taken in combination, offer landowners adaptive management strategies that can increase production and diversify their farms, ultimately, preserving oak legacy and intensifying ecological processes across the landscape.

Conclusion

In a nutshell, this study demonstrates that prescribed foraging by hogs can be a practical and effective tool for controlling FBW source populations in remnant *Q. garryana* 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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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

Declarations

Conflict of interest Not applicable.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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