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Bird Health in California's Central Coast: Interactions Between Agricultural Land Use and Avian Life History

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ABSTRACT

The Central Coast of California has implemented bare-ground buffers to deter the presence of food-borne pathogens in produce. The destruction of natural habitats surrounding farms may place avian communities at risk. To ascertain bird health in this rapidly-changing landscape, we sampled passerine and near passerine birds on organic strawberry farms in Monterey and Santa Cruz counties. The ratio of two white blood cell types, heterophils and lymphocytes (H:L ratio), served as a proxy for bird health. Mixed-effects models revealed that song sparrow health slightly increased on farms with high proportions of agriculture ($p = 0.08$). High levels of reproductive readiness were also linked to improved song sparrow health ($p = 0.007$). The study's findings suggest that foraging and habitat resources created by agriculturalists, as well as fledging survivorship may be impacting bird health in the Central Coast. There is a need to re-evaluate human-wildlife relationships as agricultural spaces may be safeguarding avian communities.

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Keywords: Passerine and near passerine birds, organic strawberry farms, H:L ratio, bird health, mixed-effects models, ArcGIS.

INTRODUCTION

Avian communities near agricultural fields impact both human health and surrounding ecological communities. Birds provide critical ecosystem services to farmers by predating on crop pests in a variety of agroecological systems including coffee, cacao, and palm oil farms.[1,2,3] However, birds also pose challenges to agricultural production because they eat crops, and their feces can be found in adjacent waterways and on produce.[4,5,6,7] Birds are vectors for food-borne pathogens such as *E. coli*, *Salmonella* spp. and *Campylobacter* spp., and, as a result, destroying natural bird habitats near farms potentially deters the spread of infectious agents.[8,9,4,10,11] Bare-ground buffers, swaths of unvegetated land adjacent to farmland, destroy critical resources for wildlife cohabiting with agroecological systems and disrupt ecosystem services. These landscape changes are linked to decreases in bird biodiversity in the surrounding landscape.[12,13] It is evident that the study of birds in agricultural areas has been centered on human concerns; nonetheless anthropogenic actions may likewise affect avian communities.

To shift the focus from humans to wildlife in agricultural systems, the landscape matrix approach allows for discerning at multiple scales the complex interplay between an organism's health and its surroundings. This approach envisions a collection of natural habitat patches coalescing to form the landscape at large, referred to as the matrix.[14,15] Carving out portions of the natural environment for agricultural purposes potentially disturbs the overall matrix.[16] Thus, areas with more connected natural habitat patches are preferred. Adopting the established landscape matrix approach provides a more robust theoretical base for the idea of a "quality" landscape. Wildlife health studies have widely implemented this framework to discuss how landscape changes impact wildlife health in terms of: species composition, abundance and richness, gene flow, and parasitism.[17,18,19,20] Yet few molecular and cellular tools have been implemented at the landscape scale to discuss community well-being.

Immunology can assess how wildlife health is being impacted by changing landscape matrix compositions. The ratio of two white blood cell types, heterophils and lymphocytes (H:L ratio), has been used to infer a bird's future and present state of health in a variety of contexts, from confined feeding operations to national reserves.[21,22,23,24] Although the H:L ratio is a high fidelity marker of bird health, it has not been used to quantify how bird health is impacted by changing landscapes. By linking the H:L ratio to landscape quality, specific land use changes can be discerned as detrimental to birds in agroecological systems.

Using the H:L ratio as a measure of bird health within a landscape matrix framework can determine how bird health is impacted by landscape composition in agricultural areas. This study asks whether certain agricultural land use types are more critical to avian health in comparison to others. We also consider if particular species are more vulnerable to certain land use types. In addition, birds of different reproductive states are examined to determine whether this factor impacts overall health in the face of variable environmental conditions. By understanding how changing agricultural landscapes are impacting avian communities, farmers and food regulators will be able to balance human and wildlife concerns more equitably.

MATERIALS AND METHODS

I. Study Sites

During July and August of 2018, as part of the Kremen Lab at UC Berkeley and the Karp Lab at UC Davis, I mist-netted for passerine and near passerine (tree perching and dwelling) birds on 20 organic strawberry farms in Monterey and Santa Cruz Counties (Fig. 1). These 20 farms were selected to capture a spectrum of agricultural and landscape conditions. Farm sizes ranged from 0.04 to 9 km^2, with production models greatly differing. Some sites were monocultures, while others contained over 60 crops. These farms are also located along a land-use gradient, where the density of natural landscapes was 53% in some areas while in others 87% of the area corresponded to agriculture.

II. Landscape Diversity

To determine each site's landscape diversity, I digitized land use types on and surrounding each farm. I downloaded National Agricultural Imagery Project (NAIP) photographs corresponding to Santa Cruz and Monterey Counties and imported them into ArcGIS.[25,26] I overlaid the farms' GPS waypoints onto NAIP imagery to locate the sites within the larger landscape matrix. A one kilometer buffer circle was drawn around each farm and all land uses within this region were digitized. Using the Gonthier Lab's landscape digitization protocol (K. Garcia, personal communication), land uses were categorized into the following types: forest and woodlands; shrublands; herbaceous vegetation; low to no vegetative cover; agriculture; urban or built up; exurban; suburban; or water features. Google Maps was also used to confirm land use categorizations.[27] Based on the focal bird species' life histories, I used the proportion of agriculture and natural habitats (oak woodlands and shrublands combined) in the final mixed-effects model (Table 1). For instance, when considering breeding habitat (Table 1), the focal species require either forested areas, brushland, or thickets, which roughly corresponded to the oak woodlands and shrubland vegetation types I digitized.

III. Study Organisms

Although California's Central Coast has diverse flora and fauna, I focused on passerine and near passerine birds as these taxa often serve as indicators of environmental health, and more specifically landscape changes in agricultural areas.[32] Of the captured birds, I selected a subset representing the 4 most common agricultural species: song sparrows (*Melospiza melodia*), house finches (*Haemorhous mexicanus*), Oregon juncos (*Junco hyemalis*), and spotted towhees (*Pipilo maculatus*). Each bird species' banding alpha code is: house finches (HOFI), Oregon juncos (ORJU), song sparrows (SOSP), and spotted towhees (SPTO). The subset selected amounted to 200 birds, approximately 15% of the entire mist-netted sample of 1303 birds. These 200 birds represent 13 of the 20 sampled farms. Each bird species has different foraging, nesting, and breeding habits (Table 1). The differences in biological functional traits are expected to be predictive of certain bird species being more vulnerable to changes in the natural landscape.

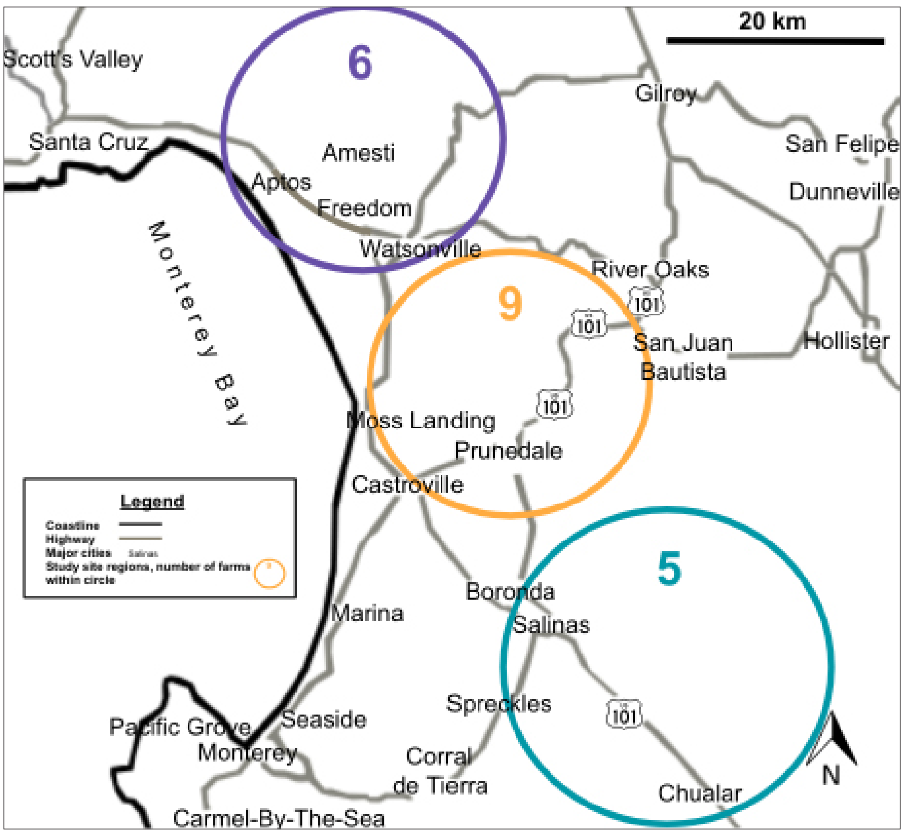

Figure 1. Spatial distribution of the 20 sampled farms in Monterey and Santa Cruz Counties. *Each circle encloses a region of sampled farms. The number of farms found within each circle is denoted at the top of the region. The base map was created using National Agricultural Imagery Project (NAIP) photographs.*[25]

Species	Food Guild	Cover	Nestling	Clutch Size	Start of Breeding Season	Breeding Habitat
House finch (*Haemorhous mexicanus*) HOFI	Fructivore and granivore	Trees, tall shrubs, and buildings	Trees, abandoned nests, and human-made structures	Lay 2-6 eggs, 2-3 broods per year	March or April	N/A
Oregon junco (*Junco hyemalis*) ORJU	Insectivore and granivore	Trees, shrubs, and ground herbage	On ground, small tree or shrub near water	Lay 3-5 eggs, 2-3 broods per year	April into August, peaking in May and June	Forests, woodlands, and forest edges
Song sparrow (*Melospiza melodia*) SOSP	Omnivore, eats litter	Low dense vegetation near moist areas	On ground, small trees and shrubs	Lay 3-6 eggs, 2-3 broods per year	April	Dense riparian thickets and wetlands
Spotted towhees (*Pipilo maculatus*) SPTO	Omnivore, eats litter	Shrubs, ground herbage, and thickets with abundante leaf litter	On ground, in slash pile, dense shrub, or vine tangle.	Lay 2-6 eggs, 2 broods per year	Late April to late August, peaking in May and June	Dense brush or thickets with substantial accumulation of litter

Table 1. Summary of house finches, Oregon juncos, song sparrows, and spotted towhees' life histories. *All taxa are from the family passerellidae, order* passeriformes.[28,29,30,31] *Each bird species' banding alpha code is included (i.e. house finches as HOFI).*

IV. Mist-netting

To representatively sample avian communities surrounding farms, we implemented the standard mist-netting protocol. Mist-netting uses nets to capture and sample avian communities in a given area. We set up 10 mist nets per site along field edges, bordering strawberry fields, other crops, and natural areas alike. A diversity of mist-net locations ensured that we captured birds that were using various land use types. We recorded GPS waypoints for each net to later locate them on satellite imagery. Following standard protocol, all nets were opened at sunrise (around 5 AM) and left open for 5-6 hours.[33] Nets were checked at 20 minute intervals and all birds caught were brought back to the banding station for data collection. We worked on each farm for three continuous days to reach sample saturation. Doing so ensured that most, if not all, birds surrounding the farms were sampled.

V. Sample Collection

To collect data on each captured bird, we transported specimens from the nets to the on-site station for banding and morphometric calculations. Each bird was banded with a metal ring, imprinted with a unique serial number provided by the United States Geological Service (USGS) to prevent a bird from being counted as a unique observation after the initial collection. Each captured bird was sexed based on its plumage and/or visible reproductive organs. Birds were aged via the level of skull ossification and/or plumage.[34] An individual's beak length, beak width, tail length, and tarsus length were also measured.[33] Lastly, we noted the presence of strawberry residue on a bird's beak, and evidence of ectoparasites such as wing lice and head ticks.

To determine a bird's state of reproduction, we calculated a "reproductive readiness" index. Reproductive readiness was determined by examining a bird's cloacal protuberance or brood patch, for males and females respectively. Cloacal protuberance and brood patches' size, color, and texture indicate a bird's state of sexual maturity.[34] These organs were assigned a score ranging from 0-4, where larger numbers indicate a bird is more prepared for reproduction. Using cloacal protuberance and brood patch scores as proxies for "reproductive readiness", I calculated z-scores for both male and female breeding parameters and combined them into a single metric called "reproductive readiness." Standardizing the scores via a z-score calculation allowed for models that included a single term to describe a bird's current or potential sexual activity.

VI. White Blood Cell Differential

To determine avian community health, we collected a blood sample from each captured individual to create blood smears. Using a 27-gauge needle, we extracted approximately 50 µL of blood from a bird's brachial vein.[35,36] The blood was then placed in a heparinized tube to prevent coagulation. With the heparinized blood, we made a blood smear for each sampled bird.[37] Blood smears were then placed in a slide box to dry and relocate to the laboratory.

To determine the white blood cell composition of each bird, I stained the blood smears with Giemsa-Wright stain and observed the slides under a microscope. Giemsa-Wright staining was selected because it causes different blood elements to acquire characteristic colors and patterns, resulting in the precise quantification of different white blood cell types.[37,38] I calculated a white blood cell differential for each smear by studying the slides under a microscope with oil immersion fluid,[39] following a snaking pattern from head to tail of the smear to avoid double counting.[40,41] White blood cell types were categorized into one of the following types: lymphocytes, heterophils, basophils, monocytes, and eosinophils. Separately, I made note of any parasites identified, particularly Haemoproteus spp. and microfilariae given they greatly place bird health at risk.[42,43] Once a

Farm	Proportion of Land as Agriculture	Proportion of Land as Shrubland	Proportion of Land as Oak Woodlands
1	**0.73**	0	0.02
2	0.29	0.09	0.19
3	0.36	0.08	0.23
4	0.34	0.01	0.27
5	0.24	0.003	0.09
6	0.02	0.16	0.37
7	0.15	0.18	0.002
8	**0.68**	0.002	0.14
9	0.14	0.1	0.21
10	**0.82**	0	0
11	**0.87**	0.00007	0.03
12	0.32	0.09	0.15
13	0.32	0.02	0.30

Table 2. Proportion of agriculture, shrublands, and oak woodlands on each farm. *Dominant land use types (proportions above 0.5) are bolded. Note that the proportions do not add up to 1 as there were additional land use types not considered in the study.*

smear had been fully analyzed, I calculated its H:L ratio by dividing a sample's heterophil count by its lymphocyte count. High H:L ratios are associated with birds in poor health.[21,22,24]

VII. Mixed-effects Model

To distill the relationship between landscape composition and bird health, I created and ran linear mixed-effects models (LMEs). I used the statistical program R version 3.6.1 (44) with the lme4,[45] lmtest,[46] and stargazer packages.[47] Visualizations were created using the ggplot2 package (48). As the H:L ratio was not normally distributed based on the QQ-plot, I first log-transformed the H:L ratio so it could be used in parametric tests. The model's syntax was determined based on the experimental design and hypotheses as:

$$\text{Bird Health} \sim \text{Reproductive Readiness} * \text{Species} + \text{Natural Habitat} * \text{Species} + \text{Agriculture} * \text{Species} + (1 \mid \text{Farm})$$

The "Bird Health" variable is the log transformed H:L ratio. Farm is the random effect, and there are three interaction effects with species: the proportion of agriculture, proportion of natural habitat, and reproductive readiness standardized score. As we are concerned with how bird health is being modulated by changes in the landscape, "Bird Health" is the predictor variable. The random effect of farm assumes that birds sampled from the same location, regardless of their intrinsic characteristics, will have similar H:L ratios given the shared context. Most importantly, by setting each variable (reproductive readiness, natural habitat, agriculture) in an interaction effect with bird species, the model may reveal that some bird species are inherently more sensitive to certain land use types and how different levels of reproductive readiness are impacting bird health.

RESULTS

I. Farm Landscape Characteristics

The 13 farms in the study varied greatly in terms of the proportion of agricultural fields, shrublands, and oak woodlands present

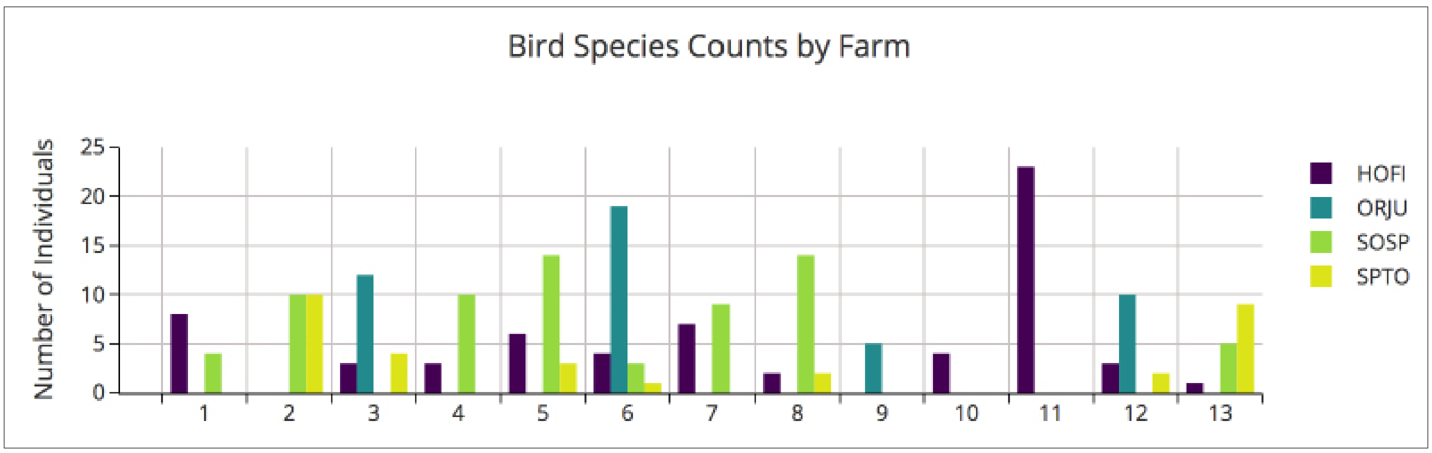

Figure 2. Bird species counts by farm. *Each bird species is referred to by its bird banding alpha code, where each species is shown as its own bar and color. Bars are grouped by farms.*

Factor	Effect Size	Standard Error	*T*-Value	*P*-value
Null	-1.90	1.04	-1.83	**0.07**
ORJU	1.40	2.02	0.70	0.49
SOSP	1.30	1.32	0.98	0.33
SPTO	2.82	2.27	1.24	0.22
Natural Habitat	0.5	2.91	0.17	0.86
Agriculture	1.53	2.08	0.74	0.46
Reproductive Readiness	-2.18	1.77	-1.23	0.22
Natural Habitat*ORJU	-6.68	7.28	-0.92	0.36
Natural Habitat*SOSP	4.84	3.70	1.31	0.19
Natural Habitat*SPTO	4.32	7.10	0.68	0.54
Agriculture*ORJU	-8.21	8.87	-0.93	0.36
Agriculture*SOSP	5.46	3.12	1.75	**0.08**
Agriculture*SPTO	2.12	8.72	0.24	0.8
Reproductive Readiness*ORJU	-2.89	3.18	-0.91	0.37
Reproductive Readiness*SOSP	6.13	2.24	2.74	0.007*
Reproductive Readiness*SPTO	-3.07	3.95	-0.78	0.44

Table 3. Relationship between bird health, proportion of natural habitat and agriculture on farms, and reproductive readiness. *The final model was as follows: Bird Health ~ Reproductive Readiness * Species + Natural Habitat * Species + Agriculture * Species + (1 | Farm). In the output table, one asterisk denote* $p < 0.01$ *and bolded terms denote* $p < 0.1$. *House finches were the reference group. The degrees of freedom associated with each factor was 98. The effect size reported is a standardized effect size, where each predictor variable was subtracted by its mean and divided by two standard deviations. Each bird species is referred to by its bird banding alpha code.*

(Table 2). Farm 11 has the largest proportion of land dedicated to agriculture, followed by farm 1, with values of 0.87 and 0.73, respectively. Farm 6 has the lowest proportion of agriculture at 0.02. Shrublands were the land use type least represented in the sample. The highest proportion of land corresponding to shrubland is 0.18, corresponding to farm 7; farms 1 and 10 do not have shrublands represented (Table 2). Conversely, the proportion of oak woodlands varies greatly between farms. Farm 10 does not have any oak woodlands, while farm 6 has over a third of its area comprised of this land use type (Table 2).

II. Bird Community Composition

Each farm had a distinct bird community composition in terms of the richness and abundance of the four focal species (Fig. 2). The highest bird count occurred in farm 6, while the lowest count occurred in farm 10. On each of these farms, 27 versus 4 birds were sampled, respectively. Only farm 6 had all 4 species of interest present; most farms had only 3 out of the 4 study species present. Within the entire sample, song sparrows were the most represented (69 birds, 35% of sample), while spotted towhees were the least sampled (31 birds, 16% of the sample) (Fig. 2).

III. Modeling Bird Health and Landscape Quality

In the mixed-effects model, only two terms emerged as significant: the interaction effect between song sparrows and the proportion of agriculture on farms, and the interaction effect between song sparrows and reproductive readiness (Table 3). The interaction effect involving agriculture was marginally significant at $p = 0.08$, while the

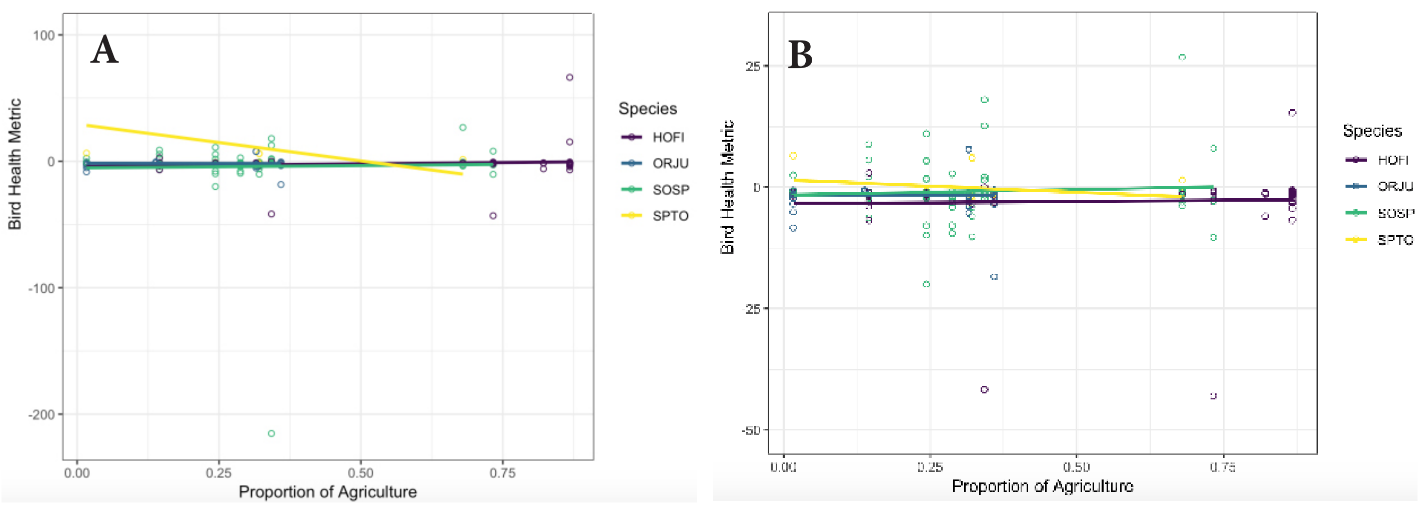

Figure 3. Relationship between the proportion of land devoted to agriculture and bird health. *The "bird health metric" is the log-transformed H:L ratio that has been inverted, such that higher values indicate better health. Each bird species is referred to by its bird banding alpha code, shown in its own color on the plot. (A) The scatterplot depicting the trends between bird health and the proportion of agriculture on farms, with all points in the data set included. (B) The same scatterplot as (a) but zoomed in to better visualize individual species' trends.*

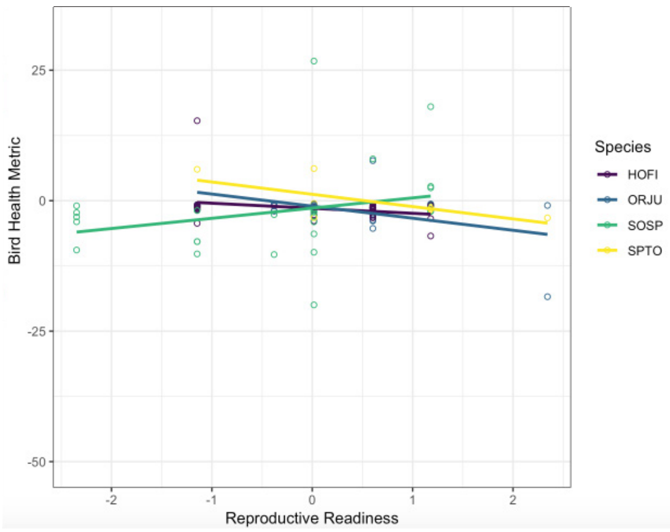

Figure 4. Relationship between reproductive readiness and bird health. *The "bird health metric" is the log-transformed H:L ratio that has been inverted, such that higher values indicate better health. "Reproductive readiness" is the standardized cloacal protuberance and brood patch scores for male and female birds, respectively. Each bird species is referred to by its bird banding alpha code, shown in its own color on the plot.*

interaction effect with reproductive readiness was highly statistically significant at $p = 0.007$ (Table 3). When comparing the effect sizes of the two significant effects, the interaction effect with reproductive readiness emerged as greater than the interaction effect with agriculture, 6.13 and 5.46 respectively (Table 3).

The positive effect sizes for the significant and marginally significant interaction effects indicate that, compared to house finches (the reference group), song sparrows experience a steeper increase in health with increasing proportions of agriculture on farms and level of reproductive readiness (Fig. 3; Fig. 4). As there is a less statistically significant relationship between song sparrow health and proportion of agriculture, this relationship is less marked on the scatterplot as compared to the relationship between reproductive readiness and bird health (Fig. 3; Fig. 4).

DISCUSSION

The proportion of agriculture on farms and birds' reproductive readiness were the two factors that most influenced song sparrow health (Table 3). Compared to house finches, song sparrows were in marginally improved health on farms with higher proportions of agriculture ($p = 0.08$). Similarly, song sparrows were the healthiest at higher levels of reproductive readiness as compared to the reference species ($p = 0.007$). In considering food guilds and the resources present on anthropogenic landscapes, our findings imply that birds may obtain critical resources from agricultural spaces in the form of habitat and forage. Trends in reproductive readiness can be interpreted through the lens of survivorship: birds that survived the breeding season had more robust immune systems. By means of the H:L ratio, we can begin to uncover how changes in the landscape matrix are impacting avian community health in the Central Coast of California.

I. Resources on Farmlands and Bird Health

During statistical modeling, song sparrows were in marginally better health as compared to the reference species as the proportion of agriculture on farms increased (Fig. 3). This trend can initially appear counterintuitive, as human intervention in the landscape has historically negatively impacted wildlife.[12,13,20] Thus the marginally significant p-value could be attributed to the small sample size of 200 birds or could indicate that the H:L ratio is not as strong of an indicator for bird health as previously assumed. Irrespective of the statistical significance of the modeling results, historical land use trends purport that agricultural land may not be the paramount stressor to avian communities. The proportion of agricultural lands in California has remained relatively stable, with the state losing only 1% of agricultural land between 1973 and 2000.[49] There has been a greater landscape pressure from suburban and exurban development. Agricultural intensification may be a more critical factor when discussing wildlife health.[50,51,52] Even if the amount of agricultural land has remained relatively stable, active farmlands favor passerine species richness in Mediterranean climates prior to the breeding season.[53,54] Specifically, this trend is due to the fallow fields, cereal crops, and soil-living invertebrates on Mediterranean farmlands as these provide critical foraging and habitat resources to wildlife.[53,54] It is also important to note that for the other three species, there was no significant trend between health and the proportion of agriculture, even if the scatterplot indicated any directionality (Fig. 3). The lack of statistically significant relationships for the other focal species probes us to consider additional factors that may be impacting house finches, Oregon juncos, and spotted towhees within the study system, such as suburban and urban development. Nonetheless, in this Central Coast study system the marginal trend between agriculture and song sparrow bird health points to the potential benefits associated with agricultural landscapes. However, study limitations require caution in ascribing anthropogenic land uses as positive to wildlife health.

II. Food Guilds in Rapidly Changing Agricultural Landscapes

For song sparrows, food guilds may elucidate why there was a positive association between health and the proportion of agricultural land. Food guilds refer to the food resources a bird exploits for subsistence. Disturbances within the landscape promote the presence of specialist species, while heterogeneous landscapes promote generalists.[54] Song sparrows are generalists as they are omnivorous birds (Table 1) so they are able to utilize various food resources within the landscape. Furthermore, these birds reproduce and survive well on or outside forest reserves.[30,55] These findings imply that song sparrows are a resilient species, as they can persist in changing land use configurations and efficiently use the resources present. Song sparrows' generalist nature may contribute to the modelling results that indicate this species was less severely impacted by increases in agriculture.[55] Considering food guilds provides a more holistic and species-centered perspective on how birds interact in complex landscape mosaics, and yet a bird's reproductive readiness presents an added stressor that may compound the impacts of changing landscapes.

III. Reproductive Readiness and Bird Health

Reproductive readiness was the variable that most strongly modulated a song sparrow's state of health (Table 3; Fig. 4). The relationship between the variables was positive, such that higher levels of reproductive readiness resulted in improved health. A bird's sexual maturity and state of reproduction is known to impact its health, particularly in terms of immunological stress. Although bird species have differing baseline levels of stress associated with reproduction,[56,57] higher levels of reproductive stress are strongly correlated with lower reproductive success and fledgling survival rates.[23,24,21,22] In taking a survivorship perspective, our findings would suggest that only the fittest song sparrows survived the breeding season.[58,59,60] This is because parents often bear the costs of anthropogenic landscape changes in order to supply for their young.[61]

Breeding seasons are loosely defined, so even when attempting to standardize and account for different levels of reproduction, the z-score calculation with cloacal protuberance and brood patch scores may not holistically capture the different levels of sexual activity between bird species. It may be that song sparrows were the only species that had finished their reproductive cycle, while spotted towhees, Oregon juncos, and house finches had just begun brooding when the sampling period was conducted. The index may not have a high enough granularity to distinguish these two life stages.

IV. Further Work

The limited sample size and spatial replication, alongside the species represented, limit the level of generalizability of the study. We can only discuss trends for the four study species, restricted to the study region in the Central Coast of California. Bird-landscape studies typically tend to implement larger spatiotemporal scales.[21,52,62] Our sample represented 13 farms sampled over a two-month period. Further site sampling within the Central Coast would allow for more cogent discussions on large-scale trends of bird health on agricultural lands in the region. It may also be useful to sample over larger spans of time, both during and outside the summer growing season. This wider sampling period would not only allow for more data to be modeled, but could also more rigorously account for differences in the reproductive cycles of species. Limitations in spatiotemporal reproducibility and our sample's characteristics require us to be cautious when discussing larger agricultural trends but also foment further research on bird-agriculture interactions.

CONCLUSION

The Central Coast of California is facing rapid agricultural change that needs to be quantified in order to assess its impacts on wildlife.[11] Within this study, bird health was impacted by landscape quality in an unexpected fashion. Higher proportions of agriculture resulted in better "quality" landscapes in terms of improved bird health for one species, song sparrows. Conversely, reproductive readiness most strongly drove bird health, where higher levels of readiness were associated with improved health for song sparrows. Our preliminary findings suggest that agriculturalists may be providing foraging and habitat resources to song sparrow communities, linked to marginally improved health for this species.[52,53] This finding is not to ignore the deleterious impacts humans have had on their surroundings, such as rapid deforestation and pollution of the biosphere. Nonetheless, our work encourages us to more critically assess and describe humans' impacts on their surroundings. Bird health was either slightly improved or not significantly impacted by landscape composition changes. We need to provide farmers with incentives to foment multi-use spaces that both provide critical resources for birds and maintain productivity. Thresholds for particular crops or land cover types may be a tactic to foment multi-use landscapes.[51] Similarly, it may be necessary to provide additional safeguards for birds at the peak of their reproductive cycle, such as by moving mowing and pesticide application dates, but further research is required to substantiate such policy prescriptions.[63]. A larger sample size, other bird species, and additional metrics of bird health should be considered to ascertain at a larger spatiotemporal scale how agricultural land use changes in the Central Coast are impacting avian community health. Farmers should be supported in becoming active ecosystem managers that improve landscape heterogeneity and avian health.

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