The Ecology of Almonds and Birds: A Review of Birds as Occupants, Pest, Natural enemies, and Potential Pathogen Vectors in Almond Orchards of Mediterranean Climates

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Objectives: **REFER TO LITERATURE REVIEW FOLLOWING THIS COVER PAGE**

The ecology of almonds and birds: a review of birds as occupants, pests, natural enemies, and potential pathogen vectors in almond orchards of Mediterranean climates

A report to the

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Executive Summary

Birds occupy almond orchards in Mediterranean almond production regions globally. Because birds consume both marketable nuts and other pests that damage nuts, they are considered both a major almond production pest and a potential agent of almond pest control. The sustainable co-management of wild birds and almond production by almond stakeholders is necessary for both biodiversity conservation and the economical production of almonds. To inform future research on and implementation of co-management strategies in almonds, we deemed it necessary to review and synthesize the scientific literature on the ecology of birds and almonds. Our extensive review encompassed almond growing regions of Mediterranean climates worldwide and we explored four major topics: Almond orchards as bird habitat; birds as pests and natural enemies of pests in almonds; birds and food safety in almonds with a focus on pathogenic *Salmonella* and *Escherichia coli*; and the potential role of almond orchards in avian conservation. We also propose three research studies designed to address information gaps identified in the review, with a focus on almonds in California's Central Valley. The review provided several major insights on each of these topics:

- Almonds throughout the Mediterranean climate regions of the world are used by birds during all seasons; they provide resources for nesting, roosting, perching, and cover from weather and predators, are utilized during short and long distance migrations and dispersal, and contribute to avian diets.

- The most recent modeled estimate of almond yield loss attributed to birds in California is less than 2.6% on average. With few exceptions, data on bird damage to almonds tends to lack temporal, spatial, and species resolution necessary for robust damage estimates. More field research effort is needed to collect and report data on pest bird identification, behavior, and occupancy in almonds. Evidence based recommendations derived from these data can assist producers in assessing tradeoffs between minimizing crop damage and supporting biodiversity.

- A few detailed field studies in almond orchards of California, Australia, and Israel have quantified both bird damage to almonds and reduction of mummy nuts by birds. In one Australian example, these data provided estimates to assess the monetary costs and benefits of almond damage and mummy nut removal by birds. It was determined that birds provided a net benefit to growers in the year examined. Future research on pest control by birds in almonds should be expanded beyond mummy nut removal, and studies should aim to collect the type of data needed to determine net monetary outcomes of avian services and disservices to growers.

- Birds are theoretically ideal mediators of crop contamination and pathogen transmission, yet at present direct evidence for birds as vectors of *Salmonella* or *E. coli* into any agricultural crop remains scant, with only a few cases providing a genetic link between a pathogenic strain isolated from a bird and a contaminated agricultural food commodity. Overall, prevalence of pathogenic *Salmonella* or *E. coli* in agricultural birds appears to be low, but more data on bird behavior and connectivity with contamination sources is needed before risk of avian contributions to outbreaks can be adequately assessed. We were unable to locate any data that specifically addressed wild bird transmission of pathogens in almonds or other nut tree crops.

- Given that birds use almond orchards as habitat, it is important to consider the potential costs and benefits to avian survival and reproduction in these landscapes. We highlight and discuss potential costs and benefits of almond production to birds. More avian ecology studies in almond orchards are needed to fully calculate the net cost or benefit of orchard use for birds. Co-management strategies among almond stakeholders are recommended.

Contents

1. Introduction

Thirty-seven percent of Earth's terrestrial surface has been converted to agriculture, comprising permanent crops (1%, e.g., orchards and vineyards), temporary crops (3%, e.g., wheat), temporary meadows, pastures, and fallow lands (8%, e.g., cultivated livestock forage < 5 y), and permanent meadows and pastures (25%, i.e., cultivated or wild grown livestock forage > 5 y; FAOSTAT 2016). The result has been habitat loss, associated species abundance declines, extinctions (Vitousek 1997, Chapin et al. 2000, Gaston et al. 2003, Foley et al. 2005), and the emergence of *novel ecosystems* in which new assemblages of species persist and interact (Hobbs et al. 2006, 2009). Global food demand is forecast to increase 100-110% by 2050 (Tilman et al. 2011). Land conversion to agriculture and introductions of new organisms to ecosystems (i.e., *biotic exchange*) are projected to be the greatest drivers of change in biodiversity in Mediterranean ecosystems by 2100 (Sala et al. 2000). In two out of three global-change scenarios, Mediterranean ecosystems are expected to experience the greatest change in biodiversity compared to all other global biomes (Sala et al. 2000).

Estimated decreases in bird numbers in Mediterranean land types worldwide between pre-agricultural and present time is -50% in grasslands, -48% in savanna, and -67% in temperate deciduous forests (including riparian forests; Gaston et al. 2003). Contemporary bird numbers in global croplands are estimated broadly at 1-7 billion birds (Gaston et al. 2003), and nearly a third of all bird species occupy agricultural lands during at least some portion of their lifetime (Sekercioğlu et al. 2007). Croplands can provide vital resources for birds during all periods of their annual cycle, including during breeding (Rodenhouse et al. 1992, Vickery et al. 2004, Swolgaard et al. 2008, Amano 2009), bi-annual migration (Farina 1989, Estrada and Coates-Estrada 2005), and over-wintering periods (Johnson et al. 2006, Palacín et al. 2012, Strum et al. 2013, Kross et al. 2016b). At least 215 neotropical migrant bird species utilize temporary croplands in North America (Rodenhouse et al. 1992).

If quality resources in agricultural lands supplement those found in remnant natural habitats, or if agricultural lands offer better than available alternatives in severely modified landscapes, then sustainable management of them is necessary for biodiversity conservation (Koh and Gardner 2010). Evidence of bird population declines in grassland and shrubland species of temperate agricultural regions (Donald et al. 2001, Newton 2004, Mineau and Whiteside 2013), however, implies that agriculture and conservation stakeholders need to collectively address an immediate problem. In temperate agricultural lands, the ecology and status of birds utilizing grain crops has received the greatest amount of attention (e.g., Rodenhouse et al. 1992, Warner and Warner 1994, Fuller et al. 1995), while the ecology of birds utilizing orchard systems is less studied.

An economically important orchard crop in Mediterranean climate regions is the almond (*Prunus dulcis*). Though the tree crop occupies less than 0.05% of global land area (FAOSTAT 2013), it increasingly occupies greater percentages of landscapes regionally (e.g., approximately 11% of California's Central Valley region; CDFA 2015). In 2014, 77% of the world's almonds were grown in the United States (U.S.), followed by Australia (6%), Spain (4%), Iran (3%) and several other countries (INC 2015), and almonds were the highest valued crop in the U.S. (CDFA 2015). 99% of U.S. almonds are grown in California's Central Valley (CDFA 2015), where orchard area has increased by 129% over the last decade, totaling 449,201 ha (1.11 million ac) in 2015 (CDFA 2016b). In the 2014-2015 growing season, almonds were California's top exported food commodity (CDFA 2016), and global consumption of almonds is rising at a faster rate than production (USDA FAS 2015), suggesting that the trends are likely to continue.

Encompassing approximately 4 million ha, the Central Valley of California is a region of intensive agricultural development and the conversion of natural lands to farmlands has been extensive. Upland alluvial plains occupied by oak woodland savannahs, grasslands, and forblands provided fertile soils for farming and were mostly converted to croplands (Thompson 1961, Shapiro 1974, Holstein 1984, Holstein 2001). Riparian woodlands were cut for firewood or timber, and floodplains were levied, cleared, and farmed to such an extent, that by the 1980's an estimated 11% of the original riparian forest acreage remained (Thompson 1961, Katibah 1984).

The Central Valley remains a year round home and a major destination along the pacific flyway for multiple species during all seasons (Cortopassi and Mewaldt 1965, Humple and Geupel 2002, Gardali et al. 2006, Pandolfino et al. 2011, Latta et al. 2012, Dybala et al. 2015), and an important conservation region for several California Bird Species of Special Concern (Shuford and Gardali 2008). Because the land and water resources contributed to almond production are great, the reliance of birds on the region is apparent, and because of the costs and benefits that bird utilization of almond orchards might engender both producers and birds, we deemed it necessary to review and synthesize the scientific literature on the ecology of birds and almonds.

Our review encompasses almond growing regions of Mediterranean climates worldwide (Figure 1). In particular, we explore four main topics: Almond orchards as bird habitat; birds as pests and natural enemies of pests in almonds; birds and food safety in almonds with a focus on pathogenic *Salmonella* and *Escherichia coli*; and the potential role of almond orchards in avian conservation. We conclude by proposing three research studies designed to address information gaps identified in the review, with a focus on almond orchards in California's Central Valley.

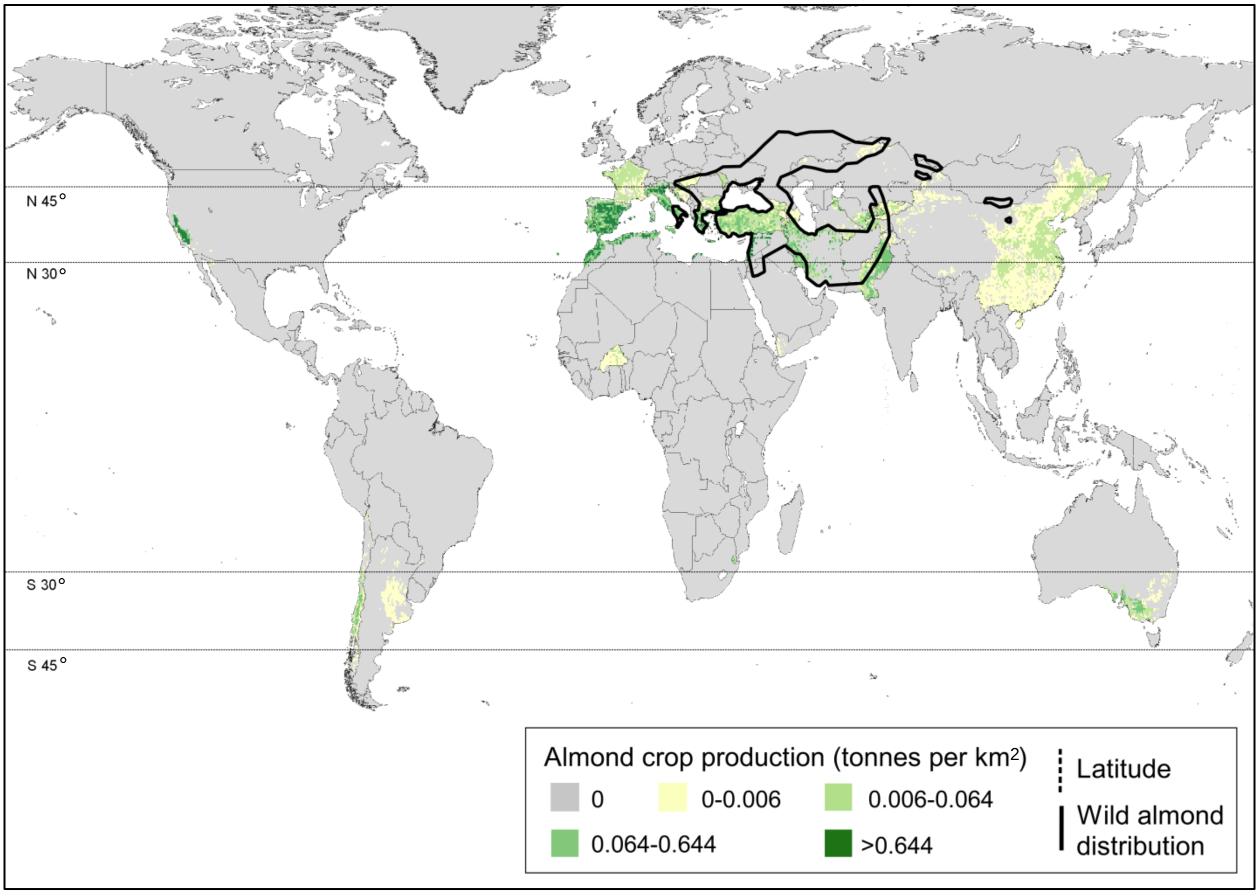

Figure 1. Global cultivated almond (*Prunus dulcis*) distribution and production, contemporary distribution of wild almond (*P.* subg. *Amygdalus* sect. *Amygdalus*), and approximate North and South latitudinal brackets in which Mediterranean climates reside on western sides of continents. Base map with almond production pixels modified from Monfreda et al. (2008), wild almond distribution drawn from (Browicz and Zohary 1996).

2. Survey of the Literature

To search the literature pertaining to the four primary topics of this review, we used the CAB Abstracts and Agricola [via Ovid], BIOSIS Previews [via Web of Science], Environmental Sciences & Pollution Management [via ProQuest], and Google Scholar databases. We searched titles, abstracts, main body, and keywords with various combinations of search terms listed in Table 1. We reduced the number of citations to review by only retaining those written in English and Spanish and to those available via the University of California library system, inter library loan, or reprint requests, and by excluding literature pertaining only to poultry or domestic birds.

Table 1. Primary topic and search terms for literature search.

Primary topic	Search terms[1]
Almond orchards as bird habitat	(bird* OR avian*) AND (almond*, OR 'Prunus dulcis*' OR 'Prunus amygdalus*' OR 'nut crop*' OR nut* OR orchard*)
Birds as pests and natural enemies of pests in almonds	AND[2] (pest* OR 'pest control*' OR 'natural enemies*' OR biocontrol* OR predation* OR damage*)
Birds and food safety in almonds	AND[2] (Salmonella* OR 'E. coli*' OR 'Escherichia coli*' OR vector*) NOT (poultry* OR 'chicken*')
The potential role of almond orchards in avian conservation	AND[2] conservation*, 'habitat quality*' , ecology*, 'ecological trap*', 'ecosystem service*' agriculture*, 'working lands*', 'land sharing*', 'land sparing*', agro-environment*, agroecology*, pesticide

[1] Terms listed were used singly and/or in various combinations

[2] Combined with terms listed in first row

3. Almond orchards as bird habitat

A formal definition of the term *habitat* is ''the resources and conditions present in an area that [support] occupancy—including survival and reproduction—by a given organism'' (Hall et al. 1997). Cultivated almond orchards throughout the Mediterranean climate regions of the world are occupied by birds during all seasons. Almond orchards and individual trees provide structural resources for nesting, roosting, perching, and cover from weather and predators, are utilized during short and long distance migrations and dispersal, and contribute to avian diets. There are approximately 30 research studies that have directly or indirectly examined avian occupancy and habitat use in almonds in their wild, cultivated, and abandoned state.

3.1. Almond trees, orchards, and landscapes as year round resources for birds

Non-cultivated wild almonds (*Prunus* subg. *Amygdalus* sect. *Amygdalus*) are distributed throughout the Irano-Turanian floristic region (Figure 1; Browicz and Zohary 1996, Yazbek and Oh 2013, Delplancke et al. 2016), with most of the 26 species found in Iran and eastern Turkey (Yazbek and Oh 2013). Patterns in bird occupancy of wild almond habitat can contribute some insight into the types of bird genera we might expect to find in cultivated almond, and the characteristics of almonds which birds might select for or against (i.e., *habitat selection*). The spatial configuration of cultivated almonds (i.e., rowed monoculture), is different to that of wild almonds (i.e., non-uniform structural and species heterogeneity). Nonetheless the branching structure, wood hardness, and flowers and buds of *P. dulcis* are similar to those of the four wild species with ranges that overlap the studies discussed here, and more so for three of these that achieve tree form (Browicz and Zohary 1996).

An ornithological expedition into the montane regions of southern Iran noted several breeding bird species associated with wild almond trees or scrub in what was termed the 'Pistachio-Almond zone'; these included shrikes (*Lanius*), warblers (*Sylvia*), wheatears (*Oenanthe*), robin (*Irania*), sparrows (*Petronia*), and goldfinches (*Carduelis*; Desfayes and Praz 1978). In a woodland oasis of the semi-arid region of central Iran, mountain almond (*P. arabica scoparia*), pistachio (*Pistachia atlantica*), and Montpellier maple (*Acer cinerascens*) were available nest tree species for the Syrian Woodpecker (*Dendrocopos syriacus*), yet only pistachio trees were selected for nest hole construction (Aghanajafizadeh et al. 2011). Compared to almond and maple, pistachio offered softer wood and more resin; the former was potentially more attractive to a hole-drilling species and the latter was hypothesized to attract more insect food items for the woodpecker. This selection strategy could have implications for cultivated landscapes in which both almond and pistachio orchards are grown within proximity and are available to woodpeckers (*Picidae*).

Cultivated almond orchards are distributed across Mediterranean climatic regions of the globe, and less so in other climates (Figure 1). In the agricultural region of south-east Australia, year round bird species richness was compared between almond orchards, apple orchards, vineyards, and eucalypt wood lots and was found to be highest in almonds and eucalypt (Luck et al. 2015). Additionally, bird *species diversity* and the *richness* of *functional traits* associated with foraging (i.e., foraging behavior, foraging location, foraging substrate, and diet) were both highest in almonds. Luck et al. (2015) suggested that the high functional richness value in almond orchards reflected the diversity of avian diet types observed there, including *nectarivores* (nectar consumers), *granivores* (seed consumers), *omnivores* (generalist consumers), and tree and ground foraging *insectivores* (invertebrate consumers). Finally, in 2 out of 3 comparisons to native Australian woodland types, the cumulative number of spring and summer bird species detected was highest in almond orchards (Luck et al. 2014). For wintering bird communities utilizing the agricultural/semi-natural landscapes of Cyprus, birds of nearly all foraging substrate types were more abundant along transects characterized by higher percentages of almond and other fruit tree cover (Ieronymidou 2012); this was also the case for summer abundances of birds that foraged high in closed-canopies and low among the herbaceous layer. Species richness of steppe-foraging birds was lower among these same almond and fruit dominated transects. In Israeli almond orchards, Schäckermann et al. (2015a) found that bird communities were more species rich at orchard edges than orchard interiors, but were similarly abundant and species rich among orchards of different age or area.

Several bird genera utilize almond orchards for nesting sites. In an agricultural region of southern Spain, crows (*Corvus*) predominantly nested in scattered holm oaks (*Auercus rotundifolia*) and almond orchard trees, and magpies (*Pica*) preferentially selected almond orchards for high density nesting and were the predominant European hosts of the nest parasite the Great Spotted Cuckoo (*Clamator glandarius*; Soler 1990, Martinez et al. 1996). Upon leaving the nest, groups of fledgling cuckoos attended by a few adult magpies preferentially selected areas with higher almond tree densities (2.2 ± 0.7 trees·10m^{-2} in occupied areas versus 0.8 ± 0.7 trees·10m^{-2} in unoccupied areas), presumably because higher tree densities provided more substantial cover for vulnerable young at greater risk of predation (Soler et al. 1995). Shrikes occasionally nested in almond trees of northern Spain orchards (Campos et al. 2011), and Red-shafted Flickers (*Colaptes auratus cafer*) nested in California almond orchards for two consecutive years (Emlen 1937).

Landscape scale effects on avian community patterns and life histories in and around almond orchards are geographically variable and likely reflect regional differences in avian traits, and in the type and configuration of natural vegetation communities, crops, and other land uses. For example, in southern Spain, although groups of cuckoo fledglings and magpie adults demonstrated local scale preferences for higher versus lower densities of almond trees within orchards, at the landscape scale they did not discern between landscapes with high or low percentages of almond cultivation (Soler et al. 1995). In contrast, shrikes in the cereal-crop dominated agroecosystems of northern Spain mostly selected native shrub vegetation and sometimes cultivated grape (*Vitus vinifera*) for nesting sites, but clutch and brood size were positively correlated with the percent cover of almond and olive orchards within a 1 km radius around the nest site (Campos et al. 2006). Neither bird abundance nor species richness in Israeli almond orchards were influenced by the percentage of natural habitat (mostly shrublands) within 1 km of orchards, but the number of bird species did increase as the amount of semi-natural habitat (planted pine forest and some broadleaf trees) increased (Schäckermann et al. 2015a). In the almond growing region of Australia, Regent Parrots (*Polytelis anthopeplus*) preferred almond orchards that bordered native vegetation in some years, and several species of small parrots (genera *Platycercus*, *Psephotus*) were more likely to occur in almond orchards close to riparian vegetation and away from farm buildings (Luck et al. 2013).

Resources provided by almond orchards are utilized during long-distance migrations of birds with geographically distinct wintering and breeding areas, during short-distance migrations (i.e., up to 250 km) of year round residents, and as corridors for daily short-distance movement. Indirect evidence of almond use during a long-distance migration was presented by Laursen et al. (1997) who found *Prunus* pollen horns attached to individuals of 5 species of spring migrant warbler (*Sylviidae*) captured in Denmark. They suggested that birds used almond orchards as stopovers during migration and consumed flower nectar on their way to breeding areas in Denmark. Direct evidence of birds using almonds as long-distance migratory stopover habitat was found on the Greek island of Antikythira where during spring migration, 85.3% of shrike hunting attempts were made from > 0.8 m vegetation perches with strikes toward prey on the ground, and 8.3% of these attack perches were almond trees (Apageorgiou et al. 2016). In Spain, Great Bustard (*Otis tarda*) males made short-distance post-mating migrations to summering areas with lower temperatures, lower human population densities, more rainfall, and landscapes with higher percent cover of oak pastures and almond orchards than found on the mating grounds (Alonso et al. 2009). Once there, birds preferentially selected sunflower fields and almond orchards, which provided shade from midday heat and cover from predators. In Australia, the preferred breeding and foraging/roosting areas of the threatened Regent Parrot are restricted to distinct native vegetation types often separated by large tracts of almond orchards, grazing pastures, and row crops with a linear network of roadside native vegetation (Luck et al. 2014). A simulation model that assumed no almond use by parrots predicted that daily movements between nesting and foraging/roosting areas would be completely reliant on roadside corridors of native vegetation; when the model assumed almond orchard use by parrots (which was empirically supported), landscape connectivity between nesting and foraging/roosting sites was improved (Luck et al. 2014). These results suggest that in absence of restoring large tracts of preferred native vegetation, almond orchards could facilitate connectivity between vital resources needed by parrots.

Birds also utilize resources in abandoned almond orchards colonized by native species and in restoration sites where almond trees have been retained, a habitat selection behavior which apparently benefitted birds and the restoration process. In an agricultural and natural habitat mosaic of north east Spain, 29 of 34 bird species observed were found in abandoned almond orchards (Quesada and MacGregor-Fors 2010); 31% were insectivores, 31% omnivores, 21% granivores, 10% *frugivores* (consumers of fruits), and 7% carnivores. Fourteen bird species were unique to the abandoned orchards compared to newly established row crop garden allotments that in total replaced about 2.4 hectares of abandoned area, and birds predominantly used the abandoned orchards for perching. Restoration of Spanish almond orchards to native vegetation was facilitated by birds that brought seeds onto the restoration site, perched on retained almond trees, and deposited the seeds via defecation (Bonet and Pausas 2007). In California's Sacramento Valley, old almond trees were left standing in restoration sites among newly planted riparian species to provide nesting and feeding habitat for cavity nesters that would otherwise not benefit from the restoration until several years later when restored trees grew to diameters sufficient for nest hole construction (Elliott and Small 2003).

Cultivated almond nuts (botanically, the almond seed) comprise part of the diet of several bird species throughout the major almond growing regions of the world (Table 2). From the perspective of a high metabolism animal like a bird, almond orchards represent a readily available nutritious food source; with this in mind, ecologists might define almonds as *food* and the taking of nuts as *consumption*. From the perspective of many producers, however, any bird entering an orchard can represent a yield loss and a labor and equipment expenditure and thus define consumed nuts or fleshy hulls as *damage* (see section 4). In Australia, the Regent Parrot and several species of small parrots apparently depend on almond nuts as an alternative food source during drought conditions when natural food supplies are limited (Luck et al. 2013). Woodpeckers are reported consumers of almond nuts, including *Melanerpes*, *Picoides*, and *Colaptes* woodpeckers in California (Gignoux 1921, Emlen 1937, Miller and Bock 1972), and *Dendrocopos* woodpeckers in Israel (Moran and Keidar 1993). *Corvidae* (ravens, crows, jays, and magpies) forage on almond nuts in California (Emlen 1937, Marsh and Salmon 1996), Israel (Moran and Keidar 1993), and Australia (Luck et al. 2013). In southern Spain, a combination of almonds and cereal grains comprised 1% of magpie nestling diet in arid habitats (no irrigation, fallow bare land, scatterings of principally young almond trees) and 14% of magpie nestling diet in irrigated habitats (extensive irrigation, cultivated fields, orchards of mature almond trees; Neve et al. 2007).

Avian consumption of almond flower nectar has been reported for the Eurasian Blue Tit (*Cyanistes caeruleus*) in England and four species of *Sylvia* and two species of *Phylloscopus* warblers in the Mediterranean region of Europe and the Middle East (Yeo 1972, Laursen et al. 1997, da Silva et al. 2014). Experimental feeding of almond pollen grains to captive birds resulted in the pollen remaining largely undigested (86% on average), leading Brice et al. (1989) to suggest that pollen did not provide a significant source of energy or protein to the study species (lorikeets (*Trichoglossus*) and cockatiels (*Nymphicus*)). In California, almond flower buds are reported food items for finches (*Haemorhous*) and sparrows (*Zonotrichia*; Marsh and Salmon 1996), as are almond flower petals for *Zonotrichia* sparrows (Heath, unpublished data).

4. Birds as pests and natural enemies of pests in almonds

4.1. Bird damage to almond crops

The literature on bird damage to almond crops inconsistently reports damages inflicted by bird species, groups, or vertebrates (typically birds and rodents combined) and often lacks the pest species resolution necessary for the development of damage thresholds and a precise balancing of tradeoffs for individual producers. Generalized pest control guidelines that refer to only 'birds' or 'mammals' or 'vertebrates' ignore important species specific behavioral, temporal, and spatial factors that can help growers minimize crop damage while also supporting biodiversity. As can be done for invertebrate pest management guidelines in almonds (UC IPM 2016), robust small-scale field study quantifications of damage can provide the species and orchard level resolution needed for more efficient and effective management (e.g., Luck et al. 2013), and meta-analyses of locally derived data can be used to make larger scale inferences about bird damage to almond crops (e.g., Gebhardt et al. 2011).

The best large-scale estimates for avian almond consumption in California, given the available data, are those in which damage inflicted by birds and rodents were grouped together and modeled by Gebhardt et al. (2011). Because of the paucity of published empirical data on the specific vertebrate species damaging almonds, the meta-analysis relied on 52 almond crop damage estimates from 13 published and unpublished reports derived from four data types: surveys of county Agricultural Commissioners (one study), seven field studies, one combined literature review and survey study, and four expert interviews conducted by the authors. The type of animal damage reported was vertebrate (five studies), specific rodent species (one), specific bird species (five; crows), and bird group (two). For the Central Valley almond growing region of California, after controlling for crop type, year, and data type, Gebhardt et al. (2011) estimated that birds and rodents were responsible for, on average, 2.6% of almond yield loss. In other words, it is expected that birds inflict less than 2.6% damage on almonds statewide.

There are a few published examples of detailed quantifications of almond damage caused by birds. Emlen (1937) painstakingly documented behaviors of avian almond consumers in three experimental orchards in northern California. Each of the top three almond consumers (American Crow (*Corvus brachyrhynchos*), Acorn Woodpecker (*Melanerpes formicivorus*), and California Scrub-Jay (*Aphelocoma californica*)) utilized a different hull and shell opening strategy for nut consumption, leaving distinguishing marks on the hulls from which to identify the species. The most frequent feeding strategy of crows and jays was to leave empty hulls on the ground beneath the trees on which the nuts grew. Thus, to quantify the extent of pre-harvest damage to almonds by birds, Emlen collected and counted hulls every few days, noting the unique signs of hull damage (i.e., nut consumption) by specific birds. Acorn Woodpeckers typically removed the entire almond from the orchard before opening the hull and shell while perching on nearby trees; damage inflicted by them were quantified by visual observations and tallies from a blind.

Emlen (1937) found that crows visited orchards several times throughout the day between sunrise and sunset, consumed 40% of collected hulls daily, and in captivity could consume up to 30 almonds per day (Table 2). Acorn Woodpeckers removed approximately 5% of the estimated potential yield of one orchard. Hull damage inflicted by California Scrub-Jays and Red-shafted Flickers did not exceed 1% in any of the study orchards. Because all daylight hours were surveyed across the entire almond growing season, Emlen (1937) was able to document the *absence* of nut consumption by species occupying orchards as well, concluding that though Brewer's (*Euphagus cyanocephalus*), Red-winged (*Agelaius phoeniceus*), and Tricolored Blackbirds (*A. tricolor*) were frequently accused of taking almonds, he found no direct evidence of them damaging pre-harvest almonds.

Recent studies in Israeli almond orchards estimated vertebrate damage to almonds by both a modified Emlen (1937) method described above and by using netting to exclude birds and rodents separately and together (Schäckermann et al. 2015a). Birds damaged approximately 3% of pre-harvest almonds and damaged significantly fewer almonds than birds and rodents combined. There was no correlation found between granivorous bird abundance (i.e., seed and nut eaters) and the number of pre-harvest almond hulls with bird consumption marks on orchard floors (Schäckermann et al. 2015b). When rates of almond damage by birds were estimated with the exclosures, however, Schäckermann et al. (2015a) found that nut damage *was* positively correlated with abundance and species richness of all birds combined and with granivorous bird species in particular (species not reported). Corroborating a finding by Emlen (1937), Schäckermann et al. (2015a) found that almond trees on orchard edges suffered higher nut damage by birds than those in orchard interiors. At the landscape scale, almond damage was not strongly influenced by the percentage of natural or semi-natural habitat within 1km of orchards. These results led Schäckermann et al.(2015a) to conclude that the promotion of agri-environmental schemes that retain natural habitats would not increase avian damage in their system.

4.2. Perception of almond damage by birds and control method choices

Crop damage estimation by social surveys rely on human perception, and it appears that estimates derived from expert opinion (i.e., producers, academics, and professional wildlife damage controllers), are higher than those derived from other methods (7.7% higher; Gebhardt et al. 2011). Nonetheless, systematic surveys can provide quantifiable data and they provide insight into the perceptions of agricultural professionals (e.g., Baldwin et al. 2013, 2014) and almond producers (Dobb 2014) on almond crop damage by wildlife. Because activities of professionals and producers influence decisions that affect birds utilizing orchards, understanding the experiences behind management decisions can lead to co-developed solutions among almond stakeholders.

Table 2. Bird species reported empirically [e] or heuristically [h] to inflict damage on almonds, location of report, damage type, estimated losses, and report citation. Scientific names for common names and 4-letter codes in Appendix II.

Bird species or group	Location	Tree part damaged	Empirically [e] and heuristically [h] estimated crop losses	Citation
California Scrub-Jay	California	nut	- 7.9% of crop with YBMA and AMCR [e] - ½ ton per season, 1 orchard [h] - 2% of daily collected hulls [e] - ≤ 1% total yield in any orchard [e] - 0.1-6.1% with YBMA, AMCR per acre [e]	Marsh and Salmon (1996) Bryant (1912) Emlen (1937) Emlen (1937) Gebhardt et al. (2011)
American Crow	California	nut	- 7.9% of crop with CASJ and YBMA [e] - 30 nuts a day in captivity, 1 bird [e] - 40% of daily collected hulls [e] - $85 million 1 season (Tulare Co.) [e] - 35% of growers reported damage [h] - 0.004-29.53% per acre per county [e] - 0.1-6.1% with YBMA, CASJ per acre [e]	Marsh and Salmon (1996) Emlen (1937) Emlen (1937) De Grazio (1978) Hasey and Salmon (1993) Gebhardt et al. (2011) Gebhardt et al. (2011)

Yellow-billed Magpie	California	nut	- 7.9% of crop with CASJ and AMCR [e] -13% of growers reported as pest [h] - 0.1-6.1% with CASJ and AMCR per acre [e]	Marsh and Salmon (1996) Hasey and Salmon (1993) Gebhardt et al. (2011)
Acorn Woodpecker	California	nut	- 1-10% of crop in one drought year [e] - 12% of daily collected hulls [e] - 5-7% of total yield in one orchard [e]	Bryant (1912) Emlen (1937) Emlen (1937)
Lewis's Woodpecker	California	nut	- 10% and 1% grower reported [h]	Bryant (1912)
Nuttall's Woodpecker	California	nut	- 'seen consuming' [h]	Emlen (1937)
Downy Woodpecker	California	nut	- 'seen consuming' [h]	Emlen (1937)
Red-shafted Flickers	California	nut	- 'occasional' [h] - ≤ 1% total yield in any orchard [e]	Bryant (1912) Emlen (1937)
Red-breasted Sapsucker	California	nut nut trunk	- 2% daily collected nuts [e] - 5% total yield with CASJ and ACWO [e] - reported	Emlen (1937)
Rock Dove	California	nut	- 'rarely' [h]	Marsh and Salmon (1996)
European Starling	California	nut	- eat almonds to a 'lesser degree' [h]	Marsh and Salmon (1996)
blackbirds	California	nut	-10% of growers reported [h]	Hasey and Salmon (1993)
House Finch	California	bud	- 'observed disbudding' [h]	Emlen (1937)
White-crowned Sparrow	California	bud	- 'observed disbudding' [h]	Marsh and Salmon (1996)
birds	California Israel	Nut	- 9.6% grower reported for all nut crops [h] - < 5% of nut consumption [e]	Baldwin et al. (2011) Schäckermann et al. (2015a)
Syrian Woodpecker	Israel	Fruit	- recorded damaging [h]	Moran and Keidar (1993)
Eurasian Jay	Israel	Fruit	- sporadic damage [h]	Moran and Keidar (1993)
cockatoos	Australia	nut	- 31% transects with damage, 68% = 0% [e]	Luck et al. (2013)
small parrots	Australia	nut	- 43% transects <1% damage, 19% = 0% [e]	Luck et al. (2013)
Regent Parrot	Australia	nut	- 16% transects >2% damage, 38% = 0% [e]	Luck et al. (2013)
Australian Raven	Australia	nut	- recorded feeding [e]	Luck (2013)
Australian Ringneck	Australia	nut	- recorded feeding [e]	Luck (2013)
Blue Bonnet	Australia	nut	- recorded feeding [e]	Luck (2013)
Eastern Rosella	Australia	nut	- recorded feeding [e]	Luck (2013)
Sulphur-crested Cockatoo	Australia	nut	- recorded feeding [e]	Luck (2013)
Galah	Australia	nut	- recorded feeding [e]	Luck (2013)
Little Corella	Australia	nut	- recorded feeding [e]	Luck (2013)
Little Raven	Australia	nut	- recorded feeding [e]	Luck (2013)
Long-billed Corella	Australia	nut	- recorded feeding [e]	Luck (2013)
Mulga Parrot	Australia	nut	- recorded feeding [e]	Luck (2013)
Red-rumped Parrot	Australia	nut	- recorded feeding [e]	Luck (2013)
Yellow Rosella	Australia	nut	- recorded feeding [e]	Luck (2013)
Burrowing Parrot	Argentina	nut	- grower survey denoted damage [h]	Failla et al. (2008)

Modeled estimates derived from an almond producer survey (n = 49 producers) revealed that the per acre cost of avian almond crop damage in California was $5.61 with and $12.28 without control measures in place, and estimated almond yield losses were 2.14% with and 8.37% without bird control measures in place (Dobb 2014). In Sutter and Yuba counties of California, growers reported a willingness to pay, on average, $24 per acre (range $0-$100) to reduce crow damage by 50% in their orchards (Hasey and Salmon 1993). One-hundred percent of almond producers responding to surveys reported using some method for avian deterrence in orchards; these included sound devices (45%), shooting (41%), visual scare devices (29%), promotion of predators (8%), land management (4%), and netting (4%;

Dobb 2014). Zero percent of reporting growers claimed to use fencing/tree guards, chemical repellents, toxicants, or trapping (Dobb 2014).

Sixty-one percent of California agriculture professionals responding to a survey (n=143) indicated their preference for an Integrated Pest Management (IPM) approach to controlling vertebrate pests (Baldwin et al. 2014); reasons given for their clientele not using IPM (n=83) included clientele preference for a single proven method (43%), the lack of any effective control methods (30%), lack of awareness of IPM (11%), and the lack of IPM cost-benefit studies (11%) or IPM effectiveness studies (5%) for vertebrates. The attributes of vertebrate control methods most important to clientele (in order of most to least important) were efficacy, quick and inexpensive, minimal hazard to applicator, environmentally safe, and humane toward pests (Baldwin et al. 2014). Explanations (n=37) for why growers chose against the most effective bird deterrence methods were cost (43%), overly restrictive or certification needed (27%), the presence of endangered species (14%), lack of knowledge of most effective method (8%), timing inconsistencies (3%), methods not allowable in organic settings (3%), and inhumane treatment of animals or environmental sensitivity (3%; Baldwin et al. 2014).

The Eastern Regent Parrot (*P. a. monarchoides)* is an endangered Australian species perceived by producers to substantially damage fruit crops, and 500 individuals were killed in 1944 by producers under permit (Condon 1947) despite evidence suggesting their impact is minor compared to several other species (Baker-Gabb and Hurley 2010). Recent empirical work in almonds (Luck et al. 2013) found that damage caused by Regent Parrots and small parrots was low and variable among the 32 transects on which damage was quantified. For example small parrots were responsible for <1% almond damage on 14 transects, and while Regent Parrots were responsible for >2% damage (6.2% max) on 5 transects, there was no damage attributed to them on 12 transects. Nonetheless, as the frequency of occurrence of small parrots and Regent Parrots increased in almond orchards, so did nut damage attributed to them (Luck et al. 2013). Regent Parrots and small parrots preferred almond orchards adjacent to native vegetation and riverine vegetation respectively, but Luck et al. (2013) hypothesized that annual variation in these relationships suggested that parrots might have relied more heavily on almonds for food when alternative food sources were limited during drought conditions.

In total, these findings led Luck et al. (2013) to propose that a strategy for managing impacts on almond yields while promoting species diversity and avian conservation could be to provide decoy crops of preferred native plants. This idea was tested for *Peromyscus* mice by Schartel and Schauber (2016), who found that if more preferred food items (sunflower seeds) were provided to mice, there existed localized refuges for less preferred food items (almonds) at intermediate distances from the sunflower seeds. If researchers provided less preferred food (corn), the risk of almond consumption close to the corn increased (Schartel and Schauber 2016). Since traditional methods of bird deterrence, such as shooting, were not effective in deterring birds from consuming almonds during years of food scarcity, Luck et al. (2013) suggested that these types of alternative deterrence methods should be considered.

There is a substantial and applicable body of research to assist growers in determining the economic thresholds for invertebrate pest damage to their crops and relatively efficient and effective recommendations for invertebrate pest management strategies for growers (e.g., UC IPM Project 2001, Flint 2002). Conversely, there has been a lack of quantitative research on the economic threshold of bird damage (pest population level or extent of crop damage at which the value of the crop destroyed exceeds the cost of controlling the pest). Fortunately, efforts are underway to guide future research for methodological improvements in IPM strategies for vertebrates (Sterner 2008, Baldwin et al. 2014), as this appears to be a good way forward for both producers and birds.

4.3. Birds as natural enemies of insect and vertebrate pests in almonds

In agroecosystems, *natural enemies* are the predators, parasites, or pathogens that kill or reduce the numbers of crop pests (Flint et al. 1998). Invertebrates have predominantly been the natural enemy taxa encouraged or released in biocontrol efforts (Huffaker et al. 1971, Letourneau et al. 2009), but there is a growing body of evidence that birds can also provide invertebrate and vertebrate pest reduction services (Kirk et al. 1996, Whelan et al. 2008, Mäntylä et al. 2011, Wenny et al. 2011, Whelan et al. 2015). Many bird species are opportunistic foragers and can respond to sudden outbreaks in prey; responses can be *functional* in which avian individuals respond to increased prey densities by taking greater numbers of prey, or *numeric* in which greater prey populations are met with increased abundances of avian predators through higher rates of reproduction, immigration, or temporary dispersal (Avery 2002).

To our knowledge the only published empirical examples of avian pest reduction services in almonds are those which quantify the consumption of *mummy nuts* by birds. Mummy nuts are the almond hulls, shells, and nuts retained on trees or orchard floors after harvest (Engle and Barnes 1983). Depending on the region, mummy nuts can harbor important invertebrate pests of almonds including the almond wasp (*Eurythoma amygdali*) in Israel (Schäckermann et al. 2015b) or the carob moth (*Ectomyelois ceratoniae*) in Australia (Luck 2013). In U.S. orchards, overwintering mummy nuts can harbor late instar larvae of navel orangeworm (*Amyelois transitella*) which emerge as adults in spring and lay eggs on remaining mummy nuts or newly developing fruits. First-instar larvae then hatch and bore into the nutmeat, develop into successive instar stages while consuming the nut and render the almond unmarketable. Navel orangeworm is a particularly important agent of almond nut damage in California, not only due to the direct damage caused, but also because larvae damaged nuts have increased infestations of *Aspergillus* fungi which synthesizes aflatoxins that are carcinogenic to humans and are heavily regulated by countries throughout the globe (Campbell et al. 2003, FAO 2004, UC Statewide IPM Program 2016). California almond industry thresholds for navel orangeworm damage is 2% or less on average (Higbee and Siegel 2009).

The University of California (UC) Statewide IPM Program (2016) recommended guidelines for reducing mummy nuts on trees are based on research which has found that about 1% navel orangeworm damage is expected for every mummy nut left on a tree. Guidelines recommend that growers count the remaining number of mummy nuts on a sampling of trees, to estimate the average number per tree, to knock them off mechanically or by hand-poling during the winter before bud swell, and to destroy them. The recommendation is to reduce mummy nuts to two or less per tree on average in orchards where the presence of birds, squirrels (*Sciuridae*), and winter storms favor natural mummy nut removal (e.g., in California's Sacramento Valley), and to fewer than this on average in orchards that lack natural removal (e.g., in California's San Joaquin Valley; UC Statewide IPM Program 2016). In some regions, such as Kern County, California, research has shown that mummy nuts need to be removed to 0.7 mummy nuts per tree on average (Higbee and Siegel 2009).

A few bird species have been documented consuming mummy nuts in orchards, including crows in California (Marsh and Salmon 1996), several unidentified bird species in California (Eilers and Klein 2009), and parrots and cockatoos in Australia (Luck 2013). Presumably many of the same bird species that consume pre-harvest nuts can also consume post-harvest mummy nuts. In Australia, mummy nut removal by birds was 55% and 27% per orchard edge and interior respectively, and 36% per tree over a 3 month winter period (Luck 2013). Bird and/or rodent consumption of mummy nuts ranged from 2% - 96% per orchard in California's Sacramento Valley, was 60.2% at orchard edges and 14.4% at orchard interiors, and was positively correlated with the number of plant species in orchard understories and the proportion of natural habitat within 1 km of orchards (Eilers and Klein 2009).

In California, orchards with higher percentages of vertebrate-damaged empty mummy hulls sampled from the ground had lower percentages of navel orangeworm infestation of mummy nuts sampled from trees, suggesting that birds might preferentially select and consume nuts from infested mummies (Eilers and Klein 2009). Researchers using experimental sentinel almond nuts exposed in post-harvest California orchards in fall (to simulate mummy nuts) and again in pre-harvest orchards during the nut growing season (to simulate harvestable nuts), found that bird damage of sentinel nuts was positively correlated with navel orangeworm infestation of sentinel nuts, and concluded that bird damage to nuts might increase infestation (Hamby and Zalom 2013). The experiment was not designed to separately summarize the fall mummy nut damage by birds (a service to growers) and the spring/summer harvestable nut damage by birds (a disservice to growers), hence the net cost or benefit of almond consumption by birds and its correlation with navel orangeworm damage is unclear in this study. Additionally, the sentinel nuts were removed from the orchard and hung from the porch of a human residence during winter, which likely diminished the beneficial mummy nut removal (and potential consumption of navel orangeworm larvae) that birds might have provided in the orchards during that time. Hamby and Zalom (2013) reported that birds rarely removed entire nuts from remaining sentinel hulls, and implied that birds did not remove entire almonds glued to the simulated branches. This behavior is in conflict with documented almond consumption behavior by birds in which almonds are removed from trees and nuts are completely removed from hulls and shells (Emlen 1977, Eilers and Klein 2009, Luck et al. 2013). It is logical that nuts damaged but not fully consumed by birds would increase naval orangeworm access to kernels and thus increase infestation, and this potential disservice by birds should be evaluated further. The sentinel approach, however, might not have effectively simulated almonds as they are available to birds in orchards.

Under certain economic conditions dependent on the highly fluctuating price/kg of almonds offered to growers, the monetary savings incurred by avian mummy nut consumption can exceed the pre-harvest cost of bird damage to marketable nuts. For example in Australia, Luck (2013) estimated the cost of pre-harvest avian consumption of marketable almonds in one year as AUD \$57.50 ha^{-1}, and the benefit value for avian mummy nut removal services as AUD \$82.50-\$332.50 ha^{-1} based on a range of labor wages for mechanical or hand-poling removal methods that would be necessary without bird removal of mummies (i.e., replacement cost), to calculate a positive net return of AUD \$25-\$275 ha^{-1} for Australian almond growers. This type of cost benefit analysis would be beneficial for stakeholders in other regions of almond production and could be enhanced by using a range of spatial and temporal data on almond prices, labor costs, and extent of bird inflicted damage and mummy nut consumption.

Several other pest types inflict damage on almonds (Strand and Ohlendorf 2002); and 12% of the cost per ha of almond production in California was spent on pest control (i.e., insects, vertebrates, disease, and weeds) in 2011 (Klonsky 2012). Though there are no published examples of birds as natural enemies of the many other almond vertebrate or invertebrate pests, there is a growing set of examples of wild insectivorous and carnivorous birds reducing similar pest groups in other perennial tree crops (Table 3). Though rarely occurring in practice, an ideal applied pest control research program would simultaneously involve multiple natural enemies, multiple pests, and multiple life cycle phases and seasons in order to accurately account for the total net costs or benefits of natural enemies and pests for a particular crop (Peisley et al. 2015).

5. Birds and food safety in almonds

5.1. Background on *Salmonella* and *Escherichia coli* risk in almonds

Historically, nut products have not been associated with high risk of foodborne illnesses in humans. Despite the fact that nuts generally provide a hostile environment for the survival and growth of pathogens, and prevalence is typically low on nuts, the combination of pathogenic *Salmonella* and *Escherichia coli* (*E. coli*) and almonds does pose a risk because 1) both pathogens have low infection doses and the ability to withstand harsh environments, and 2) almonds are predominantly consumed raw (Keller 2014). There are over 2500 identified *Salmonella* serotypes, and most are innocuous to humans. Most *Salmonella* related human illnesses stem from types Enteritidis, Heidelberg, Javiana, Newport, and Typhimurium (Jay-Russell 2013). The first recorded human salmonellosis outbreak derived from the consumption of contaminated almonds was during the winter of 2000/2001 when infection of the rare strain of *Salmonella* Enteritidis phage type 30 was confirmed in 168 human cases and traced back to 22 almond orchards of three farms in California (Isaacs et al. 2005). Many birds (and other animals and production surfaces) were sampled from the identified California orchards for isolates of the strain linked to the illnesses, but all tested negative (Isaacs et al. 2005, Uesugi et al. 2007). After a second outbreak traced back to California orchards (CDC 2004), risk analysis-informed regulations were passed that required a mandatory program to reduce *Salmonella* bacteria in almonds. As of 2007, all California grown almonds sold in North America are processed with pasteurization treatments capable of achieving a minimum 4-log reduction in *Salmonella* (Federal Register 2007).

Table 3. Summary of common almond mammal and insect pests, types of damage they inflict (UC Statewide IPM Program 2016), and research on bird pest removal services in comparable terrestrial perennial cropping systems.

Almond pest	Types of almond damage	Birds consuming similar pest taxa in perennial tree crops
small mammals *Thomomys* spp. (gophers) *Microtus* spp. (voles) *Sciurus* spp. (squirrels)	- feed on tree roots, plastic tubing, burrows - gnaw on trunk, roots, can girdle, kill trees - feed on nuts, bark, cause building damage	• Barn owls (*Tyto alba*) in California consumed more *Thomomys* when a higher proportion of perennial crops (including almonds), were within 1 km of nest boxes, and more *Mus*, *Reithrodontomys*, and *Microtus* in landscapes dominated by annual crops (Kross et al. 2016a).
moth larvae *Malacosoma disstria* *Arcyips argyrospila* *Choristoneura rosaceana* *Amyelois transitella* - *Grapholita molesta* *Anarsia lieatella* *Syanthedon exitiosa* - *Bondia comonana* *Euzophera semifuneralis*	- defoliate young trees - hollow out nuts - increase *Amyelois transitella* infestation - bores into nutmeat, consumes nut, contributes to mycotoxin contamination - mines young shoots, occasionally nutmeat - channels, surface grooves on nutmeat / shoots - bores into crown and trunk, causes girdling and death - bore into trees, leaving frass and gum pockets, can introduce canker spores which may kill tree	• In California walnuts, woodpeckers and nuthatches (*Sitta*) fed on winter *Cydia pomonella* larvae, Nuttall's Woodpecker fed on mummy nuts (Heath unpublished data). • In Florida pecans, titmice (*Parus*) fed on *Acrobasis nuxvorella.* Other locations: 3 bird spp. Fed on *A. juglandis*, 5 on *Datana*, 5 on *Hyphantria cunea*, and blackbirds on winter *C. caryana* (in Tedders et al. 1983). • In Australian macadamia, 3 pest larvae spp. consumed by 8 landbird spp. (Crisol-Martínez et al. 2016) • In apples of Nova Scotia, England, and U.S., woodpeckers, tits fed on *C. pomonella* larvae in winter (MacLellan 1959, Solomon et al. 1976, Stairs 1985), in growing season by 2 landbird species in Australia, reducing fruit damage by 12.8% (Peisley et al. 2016), and by tits in Netherlands, reducing damage 2.6%, increase yield 3.1 kg/tree (Mols and Visser 2002).
mites *Bryobia rubrioculus* *Panonychus ulmi* *Aculus cornutus* *Tetranychus pacificus*, *T. urticae*, *T. turkestani*	- can beneficially feed mite predators - damage foliage and leaf stippling - chlorotic spots on leaves, necrotic spots - leaf stippling, yellowing, and loss	• No examples found in temperate perennial crop systems.
scales *Parthenolecanium corni* *Diaspidotus perniciosus*	- copious honeydew can damage leaf and fruit - inject toxins into limbs, reduce tree vigor	• No examples found in temperate perennial crop systems.
ants *Solenopsis xyloni*, *S. molesta*, *Tetramorium caespitum* *S. ivicta*	- consumes entire nutmeats while almonds are drying on orchard floors - chew on soft plant tissue and growing buds	• No examples found in temperate perennial agricultural systems.
beetles *Polyphylla decemlineata*, *P. sobrina*	- feeds on roots, severe injury to mature trees	• In pecans, 4 species of bird fed on *Knulliana cincta*, 5 on *Hypermallus villosus,* and 45 on *Scolytidae* (citations in Tedders et al. 1983).

true bugs: sucking and piercing mouth parts *Leptoglossus clypealis*, *L. occidentalis*, *L. zonatus* *Acrosternum hilare*, *Chlorochroa uhleri*, *Thyanta pallidovirens*	- feeds on nuts, causes dropping or gumming - punctures kernel causes exude, wrinkles, and spots	• In Australian macadamia orchards, *Nysius vinitor* were consumed by 4 different landbird species, and *Nezara viridula* were consumed by 6 landbird species (Crisol-Martínez et al. 2016).

Most *E. coli* strains are harmless to humans, but a subset of strains may cause severe illness. *E. coli* O157:H7 and six other shiga toxin-producing *E. coli* (STEC) groups (O26, O45, O103, O111, O121, O145) are the cause of most human disease (Jay-Russell 2013). Outbreaks of *E. coli* O157:H7 illnesses in humans has not been associated with almonds, though they have been epidemiologically associated with consumption of in-shell hazelnuts (CDC 2011) and raw walnut kernels (Canadian Food Inspection Agency 2011).

In response to the *Salmonella* outbreak and a growing concern for food safety, the Almond Board of California, informed by the USFDA, Occupational Safety and Health Administration, and California Department of Health Services guidance documents and regulations, developed and adopted Good Manufacturing Practices (GMP; ABC 2009). Among the discontinuation of obvious routes of contamination (e.g., the use of and proximity to non-composted manure, biosolids, primary and secondary sewage effluent, or untreated dairy lagoon water; Isaacs et al. 2005), the GMP outlines guidelines for reducing possible wildlife contamination of almond orchards, processing facilities, and products:

> *"All animals, including mammals, birds, reptiles, and insects, are potential sources of contamination in processing environments because they harbor, or could be a vector for a variety of pathogenic agents, such as Salmonella or E. coli. Each facility should establish a pest control program to reduce the risk of contamination rodents, insects, birds and any other pests."* (ABC 2009)

5.2. Wild birds as vectors of pathogenic *Salmonella* and *Escherichia coli* in almonds

The scientific literature on the potential role of wild birds in the prevalence and transmission of human infectious disease is copious. This body of work is widely distributed in medical, veterinary, public health, zoological, ecological and wildlife journals, and is the subject of many reviews. A recent rigorous scoping review found that of 963 research citations on the role of wildlife in the transmission of bacterial pathogens, 97 were reviews or commentaries, and 410 of 866 primary research articles pertained to wild birds. 38.0% and 33.8% of papers covered *E. coli* and *Salmonella*, respectively. Yet only 11 primary literature papers investigated the potential of wildlife transmissions of pathogens in any agricultural crop (Greig et al. 2015). Beyond brief mention of birds in the literature specifically addressing the recent almond salmonellosis outbreaks, we were not able to locate any publications that specifically addressed wild birds and pathogens in almonds or other nut tree crops.

Salmonella Typhimurium is the serotype commonly found in avian intestines that is also pathogenic in humans (Tizard 2004). The most important reservoir for pathogenic *E. coli* O157:H7 is ruminants (particularly cattle) but it can be isolated from birds and other mammals (Clark 2014). Pathogenic serotypes of both bacteria have been isolated from several species of wild bird (Kruse et al. 2004, Benskin et al. 2009, Langholz and Jay-Russell

2013, Table 4). Pathogen prevalence in sampled bird populations tends to be low, as is pathogen concentration in feces of individual birds, especially small sized species (Nice 1994, Abulreesh et al. 2007, Daoust and Prescott 2007, Ferens and Hovde 2011, Langholz and Jay-Russell 2013). Nonetheless, even originally low levels of fecal contamination in a crop production system can be amplified during harvesting and processing to reach a large number of consumers, posing a nontrivial public health concern (Jay-Russell 2013). A prerequisite and major risk factor for avian transmission of pathogenic *E. coli* or *Salmonella* to crops is the birds' exposure to environmental contamination sources such as contaminated sewage, human refuse, water sources, feces of domesticated farm animals, or large quantities of bird feces at communal feeding stations, roosts, or nesting sites (Benskin et al. 2009).

A recent study illustrates the importance of multiple factors (e.g., landscape configuration and type, proximity to domesticated farm animals, bird species identity and traits) when determining the likelihood that a bird will be infected by an enteropathogen from a contamination source. In northeast Spain, prevalence of pathogenic *Salmonella* in fecal samples from 921 birds of 42 species at locations near pig farms were compared to prevalence in fecal samples from 581 birds of 39 species at natural settings greater than 2 km from pig farms (Andrés et al. 2013). Most species sampled were Passeriformes (songbirds) and some were Columbiformes (pigeons and doves); species identities were reported for only the seven species testing positive for pathogenic *Salmonella* (Table 4). The overall pathogenic *Salmonella* prevalence of 1.85% (95% CI 0.93–2.77%) was low, but prevalence was significantly more likely in the birds sampled near pig farms than in the birds sampled in natural areas, and in year round residents/short distance migrants versus long distance migrants. Pathogenic prevalence tended to be less likely in granivorous birds than in insectivores and higher in spring than in summer, fall, or winter. Pathogenic isolates collected from feces of European Starlings (*Sturnus vulgaris*), Barn Swallows (*Hirundo rustica*), and House Sparrows (*Passer domesticus*) at one pig farm were genetically identical. Genetically similar pathogenic isolates were also found for Rock Doves (*Columba livia*) at a second farm, and between a House Sparrow and Blackcap (*Sylvia atricapilla*) at a third farm. These results led Andrés et al. (2013) to suggest that pig farms may act as amplifiers of pathogenic infection among wild birds and that species that exhibit high abundance flocking behavior may increase the risk of transmission among birds.

Birds are theoretically ideal mediators of crop contamination and pathogen transmission to humans. Because of their ubiquity in the environment, their mobility, their ability to cross natural and anthropogenic boundaries, and their susceptibility to enteropathogens that

Table 4. Pathogenic *Salmonella* or *E. coli* prevalence in a sampling of wild bird species. Data presented only for pathogenic serotypes implicated in human outbreaks (CDC 2016). Prioritized for inclusion were bird species associated with agriculture generally, observed in California almond (Audubon CA unpub. data) or walnut orchards (S. Heath unpub. data), or whose distributions overlap with Mediterranean climate almond growing regions. Scientific names Appendix II.

Location; Landscape type	Species	Pathogen prevalence (# individuals positive/# individuals sampled)	Citation
California, USA; Unreported	Wild Turkey	*S.* Typhimurium (21/500), *S.* Pullorum (19/524)	Charlton (2000)
California, USA; Dairies	Brown-headed Cowbird	*S.* Meleagridis (2/95), *S.* Muenster (1/95)	Kirk et al. (2002)
	House Sparrows	3 serotypes of pathogenic *Salmonella* (13/450)	
	Brewer's Blackbird	*S.* Muenster (1/44)	
	European Starling	*S.* Typhimurium (1/80)	
	Red-winged Blackbird	*S.* Meleagridis (1/78)	
	Rock Dove	*S.* Typhimurium (1/83)	
California, USA; Grassland hilltop	Red-tailed Hawk	*S.* III Arizona 38:k:z35 (3/10)	Lamberski et al.(2003)
	Cooper's Hawk	*S.* Typhimurium (2/10)	
Kansas, USA Cattle feedlot	European Starling	*E. coli* O157:H7 (0/434) *S.* Arizona 2(3[1])/434	Gaukler et al. (2009)
Ohio, USA; Dairy farms	European Starling	*E. coli* O157:H7[2] (5/430)	Williams et al. (2011)
Zaragoza and Huesca, Spain; Pig farms	European Starling	*S.* Typhimurium (1/unk[3]), *S.* Arizona (2/unk)	Andrés et al. (2013)
	Barn Swallow	*S.* Typhimurium (1/unk)	
	House Sparrow	*S.* Typhimurium (3/unk), *S.* Anatum (1/unk)	
	Eurasian Blackcap	*S.* Typhimurium (1/unk)	
	Rock Dove	*S.* Typhimurium (2/unk)	
	Cetti's Warbler	*S.* Mikawasima (1/unk)	
	White Wagtail	*S. diarizonae* (1/unk)	
	43 additional species[3]	0/379 (total for all remaining species, unidentified)[3]	
Maryland and Virginia, USA; Goat and sheep farms	Brown-headed Cowbird	*Salmonella* (0/39)	Pao et al. (2014)
	Chipping Sparrow	*Salmonella* (0/1)	
	Dark-eyed Junco	*Salmonella* (0/1)	
	European Starling	*Salmonella* (serotype not determined) (1/175)	
	House Sparrow	*Salmonella* (0/40)	
	Mourning Dove	*Salmonella* (0/39)	
	Yellow-rumped Warbler	*Salmonella* (0/1)	
	Rock Dove	*Salmonella* (0/144)	
	Savannah Sparrow	*Salmonella* (0/8)	
	Song Sparrow	*Salmonella* (0/14)	
	Zonotrichia Sparrow	*Salmonella* (0/1)	
California, USA; Sheep rangeland	Turkey Vulture	6 serotypes of pathogenic *Salmonella* (11/55) Antimicrobial-resistant *E. coli* (11/55)	Sulzner et al. (2014)
Texas, USA; Unreported	Brown-headed Cowbird	*E. coli* O157:H7 (11/309) 13 serotypes of pathogenic *Salmonella* (38/309)	Callaway et al. (2014)
	Common Grackle	*E. coli* O157:H7 (3/51) 4 serotypes of pathogenic *Salmonella* (14/51)	
	Cattle Egret	*E. coli* O157:H7 (0/16) *S.* Montevideo (2/16)	
California, USA; Urban roosts in agricultural region	American Crow	Pathogenic *Salmonella* serotypes (0/198)	Janecko et al. (2015)

[1] 3rd sample possibly positive; sample was not serotyped but 2 samples serotyped were *S.* Arizona positive

[2] Genetically related isolates found in livestock and birds, strongly suggesting transmission between them

[3] Number of samples not reported by species, additional unidentified species mostly Passeriforms, some Columbiforms

cause human illnesses, birds have the potential to link sources of pathogenic *Salmonella* or *E. coli* contamination with products of human consumption (Reed et al. 2003). At present, direct evidence for birds as vectors of *Salmonella* or *E. coli* into an agricultural crop remains scant, with only a few cases providing a genetic link between a pathogen isolated from a bird and a contaminated agricultural food commodity (Clark 2014, Greig et al. 2015). An example most comparable to almond orchards would be that of an experimental study in a sweet cherry (*P. avium*) orchard, in which the same genotype found for a generic *E. coli* isolated from birds in the orchard (species not provided) were also found on the hands of cherry pickers and sorters and in the finished fruit (Bach and Delaquis 2009). The predominant body of evidence for the pathogen-bird-crop link is circumstantial, albeit compelling (Jay-Russell 2013, Clark 2014). Based on our literature review, there are no direct examples of a pathogen from an identified contamination source being transported by an avian vector to an agricultural crop.

Steps of a hypothetical transmission route from contamination source to human intestine, mediated by an avian vector and almond production and consumption is as follows (Figure 2):

a. A bird species likely to visit and move between contamination sources and orchards in high numbers (e.g., crows, pigeons, blackbirds, Brown-headed Cowbirds (*Molothurs ater*), starlings) is exposed to pathogenic *Salmonella* or *E. coli* at an environmental contamination source (Clark 2014).
b. The bird becomes infected at one or several contamination sources (Gaukler et al. 2008).
c. The bird transports the pathogen to an almond orchard location via its gastrointestinal tract and flight (Reed et al. 2003).
d. The bird perches on an almond tree or overhead wires and defecates on the orchard floor or almond tree (Jay-Russell 2013).
e. The pathogen contained within the feces can persists in the orchard for up to at least five years for *Salmonella* Enteritidis (Uesugi et al. 2007), and an unpredictable amount of time for *E. coli* 0157:H7 (van Elsas et al. 2011).
f. During harvest, nuts are mechanically shaken from the tree and are left on the orchard floor to dry for up to two weeks (Harris and Ferguson 2013).
g. After the drying period is over, almonds are collected with a mechanical sweeper and the almonds are often mixed with the top layer of soil (Pan et al. 2012).
h. Almonds are then transported to a huller facility, where first the hulls and then the shells are removed (unless they are sold in shell). At this stage almonds from separate orchards are combined, hull dust collects, and pathogens in almonds from the contaminated orchard can be spread to uncontaminated almonds (Isaacs et al. 2005).

i. After further processing, the almonds are pasteurized (if sold in North America); this step is designed to kill pathogens and to fall below the maximum contamination risk levels mandated by federal regulations (Pan et al. 2012).
j. Almonds are then packaged, shipped around the world, stored at retailers, or processed into products like almond butter, a step which was implicated in a fifth almond-related *Salmonella* contamination and outbreak (Harris et al. 2016).
k. Finally, the almond product is purchased, stored (a stage which contributes to the salmonellosis illness risk factor (Lee et al. 2011)), and consumed by humans.

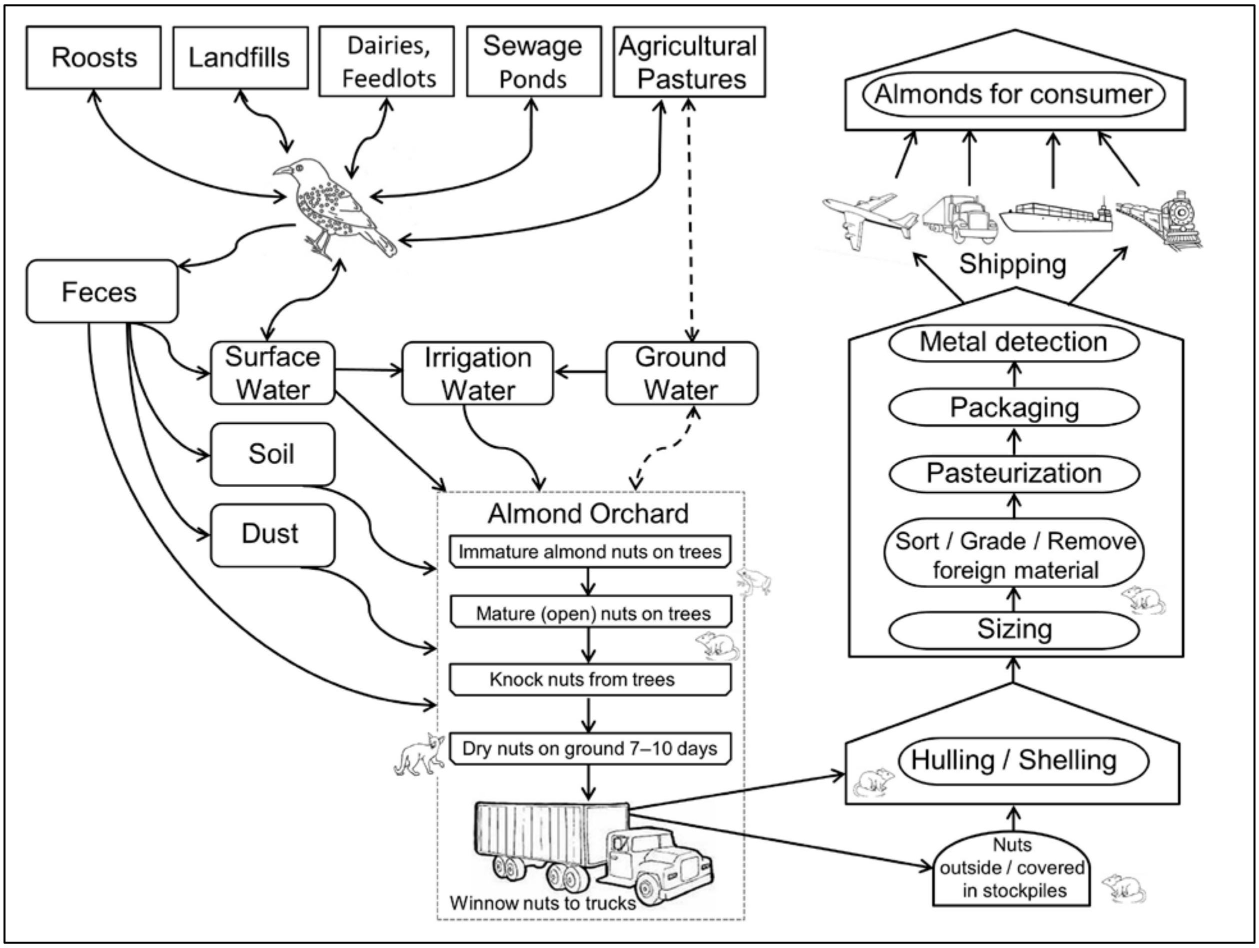

Figure 2. Possible transmission routes of pathogenic *Salmonella* or *E. coli* from contamination sources to human intestine, mediated by wild avian vectors and almond production and pasteurization steps (modified from Pan et al. (2012) and Clark (2014)). Rectangles denote environmental sources of pathogens, the bird (European Starling in this case) represents wild bird species likely to visit both contamination sources and orchards, rounded rectangles indicate media in which pathogens may reside or be transported, dotted line box represents an almond orchard and harvesting steps, peaked boxes represent facilities for indoor almond production, pasteurization, and retail steps. Other wildlife transmission sources include deer, wild boar, domestic cats, amphibians, or rodents, to name a few, and these are indicated by images of each.

5.3. Effectiveness of practices aimed at preventing, controlling, and treating avian vectored pathogens in almonds

Some preventative measures to reduce the risk of avian transmission of enteropathogens to crops are largely out of the control of individual producers because they are dependent on landscape connectivity and spatial arrangement of orchards and contamination sources. For example, a simulation study revealed that apple orchards had an increased risk of *E. coli* contamination when in proximity of landfills or sewage ponds at which gulls could become infected and then transmit the pathogen to orchards by either flying over or occupying them (Duffy and Schaffner 2002). Including landscape configuration in assessments of bird related risk is something being employed and developed by the aviation industry to reduce the risk of aircraft collisions with birds (Clark 2014). Regional land use planning and zoning entities, collaborating with growers, ranchers, feedlot operators, and wildlife professionals, could employ a similar approach when assessing preventative risk reduction of agricultural pathogenic contamination by birds (Lowell et al. 2010, Clark 2014, Karp et al. 2015b).

Farm-scale measures to effectively reduce the risk of avian transmission of pathogens are not well developed and few wildlife examples exist in the literature (Jay-Russell 2013). Nonetheless, fruit and nut producers responding to a survey by Baur et al. (2010) reported using several on-orchard control practices to reduce possible wildlife pathogen vectors including erecting owl boxes or using falconers (70%, n=82), setting poison bait (53%, n=85), or killing pest animals (48%, n=81). One proposal for preventing avian pathogen delivery into crops is for producers to integrate the bird management and control practices that have been employed to reduce crop damage (Clark 2014). To be most effective, however, these adapted measures would need to be species-specific and highly targeted (Jay-Russell 2013). One employed practice is to lethally remove flocking birds that utilize agricultural areas in large numbers (Tracey et al. 2007). Carlson et al. (2011) demonstrated in Texas livestock feeding operations that when European Starlings were killed with *Starlicide* and the population was reduced from over 3,500 to approximately 1,250 birds on average, mean *Salmonella* prevalence in one month was reduced significantly in water troughs (27% to 5%) and in feed (8.25% to 0%), while it remained the same in cattle feces (14%); the reference site, maintaining approximately 1,000 starlings throughout the month, had *Salmonella* prevalence increase in the water, feed, and feces. Producers and bird conservationists might find common ground in the culling of starlings, a non-native and invasive species that has been implicated in the displacement of native birds while also costing U.S. producers an estimated $800 million/year (Pimentel et al. 2005). In the long term, however, the practice of killing large numbers of birds in agricultural systems has been ineffective in reducing populations, especially for species with high reproductive rates. Ineffective examples include attempts to control Quelea

(*Quelea quelea*) with organophosphates in Africa, the shooting of Woodpigeons (*Columba palumbus*) in the United Kingdom, the application of the surfactant PA-14 to large roosts of Common Grackles (*Quiscalus quiscula*), Red-winged Blackbirds, and starlings in North America, and the use of explosives at starling roosts in Belgium (Tracey et al. 2007 and citations therein). The taking of migratory birds or nests without special permit is illegal in the U.S. (full protected species list, U.S. Fish and Wildlife Service 2013) and culling practices carry the risk of harming or killing non-target bird species (Jacob et al. 2002, Singleton et al. 2007), unless specific and targeted measures are employed to eliminate the risk (Treves and Naughton-Treves 2005, Tracey et al. 2007).

Indirect bird population reduction practices aimed at lowering crop contamination risk, such as removal or modification of remnant wildlife habitat in proximity to crops, are in conflict with biodiversity conservation and environmental stewardship goals (Gennet et al. 2013, Jay-Russell 2013). This conflict is clear among fruit and nut growers responding to a survey in which 1) growers reported *increasing* on-farm animal habitat by restoring riparian streambanks (18%, n=300), planting hedgerows or windbreaks (25%, n=307), or planting flower or native plant strips (30%, n=307), and 2) the same and/or different growers reported *reducing* on-farm wildlife habitat by clearing vegetation to expand bare ground buffers (60%, n=315) and removing vegetation from ponds or ditches (62%, n=295) for food safety purposes (Baur et al. 2010). After an *E. coli* O157:H7 outbreak originating in coastal California leafy green crops, the proliferation of these habitat reduction measures were reactively deemed necessary to eliminate pathogenic outbreaks, and were demanded of producers by some raw produce purchasers (Beretti and Stuart 2008, Gennet et al. 2013). It was estimated that from one year before to six years after the outbreak, declines in five types of non-crop vegetation ranged from 2-30% within 50 m buffers around leafy green farms, while bare ground increased by 30% (Karp et al. 2015b). The efficacy of these and other activities for reducing avian or mammal transmission of enteropathogens has not been comprehensively evaluated (Ilic et al. 2012, Karp et al. 2015a). Notably, however, Karp et al. (2015b) found that despite this extensive non-crop vegetation removal at farm field margins, generic *E. coli* prevalence increased significantly from 0.1% to 2.5% of samples in fresh produce during the same time period. Additionally, they found that among 28 California farms, *E. coli* prevalence was unchanged when riparian vegetation was removed and prevalence significantly increased by approximately 5% when non-riparian natural vegetation was removed; *Salmonella* prevalence increased significantly but slightly from 0% to 0.1% when riparian vegetation declined and remained unchanged when non-riparian natural vegetation was removed (Karp et al. 2015a).

The apple orchard contamination simulation discussed earlier predicted that the probability of gull (*Laridae*) transmitted *E. coli* contamination was higher in apples that dropped to the orchard floor; thus a prevention measure producers could practically employ would be to avoid dropped apples in the production of unpasteurized foods such as the apples themselves or unpasteurized juice (Duffy and Schaffner 2002). A major within-orchard almond contamination risk factor appears to be during the drying and harvesting of almonds from windrows on the orchard floor (Wells 2013), when the proliferation of contaminated dust can mix with drying and collected almonds (Uesugi et al. 2007), when almonds are exposed to rain which can increase pathogenic *Salmonella* concentrations (Uesugi and Harris 2006) and prevalence (Uesugi et al. 2007), when birds can perch above the large quantities of drying almonds and defecate directly onto them (Jay-Russell 2013), or when more species of ground-dwelling wildlife have increased access to the almonds (Langholz and Jay-Russell 2013). Although it has been demonstrated that almonds shaken onto and dried on a canvas ground cover had lower bacterial counts than those knocked onto and harvested from the bare ground (King et al. 1970), the modern practice of mechanically shaking and collecting almonds from the bare orchard floor is central to efficient almond harvesting, and changing the practice may not be economically feasible (Keller 2014).

Most raw-consumed produce has no post-harvest “kill step” for pathogens and preventing in-field contamination is a critical step (Jay-Russell 2013). For almonds, however, the post-harvest pasteurization step is mandatory (Federal Register 2007) and effective at reducing food borne illnesses from consumed almonds (Pan et al. 2012). Risk analysis simulations by Lambertini et al. (2012) estimated that under the current regulated pasteurization treatment step for 100% of almonds, the likelihood of illness due to raw almond consumption in North America was on average 0.008 salmonellosis cases per billion servings (with an estimated annual consumption of 6.6 billion servings), or one salmonellosis case in every 17 years. Even small reductions in the proportion of untreated almonds were predicted to frequently exceed the mandated maximum threshold of one salmonellosis case/year (Lambertini et al. 2012). Disadvantages to various pasteurization technologies is that they can affect production efficiency and the quality of the raw nuts from the consumer perspective in terms of vitamins, nutrients, flavors, and sensory quality (Pan et al. 2012). In a survey among 279 volunteer California consumers, 36% of respondents agreed that the health benefits of nuts are about the same whether the nuts are raw, pasteurized, blanched, or roasted (without amendments) while 33% did not agree with the statement and 29% were not sure (Lee et al. 2011). Finally, consumer choice is also factored into *Salmonella* illness risk assessment. Of the same group of 279 California volunteer consumers, 24% had heard and 26% believed that eating raw nuts could lead to illness from *Salmonella*, and 18% reported that this information would affect their family’s eating habits, while 78% reported that it would not (Lee et al. 2011). An unexplored line of questioning would be to survey consumers about their opinions on food borne illnesses in terms of the costs and benefits of pasteurization, and consumer choice and behavior, versus various direct or indirect wildlife prevention or control measures.

6. The role of almond orchards in avian conservation

Similar to how producers must consider the costs and benefits of different types of pest control practices, crop damage remediation, or food safety risk reduction measures, avian conservation ecologists must consider the potential costs and benefits of bird utilization of agricultural crops.

6.1. The potential costs: almond orchards as ecological traps for birds

Evidence for bird occupancy of almond orchards (see section 3) suggests that several bird species have acclimated to the novelty of this land use type. When considering the conservation potential of agricultural crops for birds, however, it is important to consider the *fitness* and population dynamics of the bird community (Komar 2006, Kleijn et al. 2011). Birds may occupy an almond orchard, but there may be features of the habitat that are unfavorable to avian survival or reproduction (i.e., *fitness*), which can lead to *ecological traps* (Battin 2004), bird declines (Newton 2004, Gibbs et al. 2009), and *local extinction* (Kuussaari et al. 2009). A habitat is considered an *ecological trap* when birds occupy it in high numbers but are unable to adequately survive or reproduce there (Battin 2004). In theory, if a cropping system is an ecological trap, it can influence population dynamics on a larger scale and lead to regional bird declines by becoming a population *sink* in which the attractive features of the habitat (e.g., an abundant but temporary food source) attracts birds to immigrate from habitats of higher quality in terms of fitness, and the reproductive rate of the regional population is unable to exceed its mortality rate (Pullium and Danielson 1991).

One feature of almond orchards that could lead to reduced survival or reproduction in birds is the use of pesticides (i.e., insecticides, fungicides, herbicides, and fumigants) for animal, fungi, and weed management. Since 1985, the number of scientific publications on wildlife pesticide effects has exceeded 4,000 for organophosphates (OPs) and pyrethroids (PYs) alone, and in recent years studies on OPs, PYs, and neonicotinoids (Ns) have had the highest rate of increase (Köhler and Triebskorn 2013). All three of these insecticide types are used in California almond orchards (Table 5; Zhan and Zhang 2014a). About 4% of pesticide effect publications have been on birds, and most have studied wild birds versus laboratory birds or domestics (Köhler and Triebskorn 2013). Overall, the literature provides only a few examples

Table 5. Pesticide groups and selected active ingredients used in almond orchards of the Central Valley, California 1996–2010[1]. Active ingredients listed if toxicity in birds was evaluated in reviews[2,3,4]. Year of active ingredient cancellation orders from Environmental Protection Agency (EPA) or California Department of Pesticide Regulation: some products (SP) and some products for almonds (SPA) federally, the last federal (NF) or California (NC) products, removal of almonds from California product labels (CA), and total U.S. cancellation (C). Utilization trends indicated as significant increases (▲), decreases (▼), or no significant trend on average for the Central Valley region or for Sacramento Valley (SV), San Joaquin Valley (SJ), and Tulare Basin (TB) only. EPA avian toxicity[5] codes represent quantitative ranges for acute oral toxicity in birds: practically non-toxic (PNT), slightly (ST), moderately (MT), highly (HT), very highly toxic (VHT); bird impact score[2]: none (1), sublethal (2), mortality (3), mass mortality (4).

PESTICIDE GROUP Active Ingredient	Cancellation order type and year	California use trend (1996-2010)[1]	Avian toxicity[2], Impact score[10]	Examples of individual bird effects in laboratory experiments, directed field studies, or incidence monitoring (Scientific names Appendix II).
INSECTICIDES (67.1%)[5]	---	▼SV, ▲TB	---	---
Carbaryl **FRUP**[6]	SP 2015	---	PNT, 1	P ChE depression in robins[7], no to slight AChE inhibition[2]
Hexachloride (lindane)	C 2019	---	PNT	---
Methomyl **FRUP**	SP 2014	---	4	Mass mortality when birds drank from leaf whorls after sprays[2]
Organophosphates (5.8%)[5b]	---	▼	---	Endocrine, reproductive disruption in birds[3]
(5) Chlorpyrifos **FRUP**	SP 2016	▲CV, ▼SJ	HT, 2-3	Residues on hawk feet and feathers in almonds[8], carcasses and aberrant behavior[2]
Malathion **CRM**	SPA 2008, SP 2015	---	ST, 1	Embryotoxicity, lowered P, B ChE in Mallards[9]
Azinphos-methyl	C 2012	---	MT, 1-3	P, B ChE depression in robins[10], Song and Chipping Sparrows[11], mortality after 1st crop spray[2]
Dimethoate **FRUP**	SP 2016	---	HT, 1-4	B ChE depression, chick weight in Great Tits[12], mortality in songbirds and sage grouse[2]
Diazinon **FRUP**	SP 2014	---	3-4	Mortality of multiple birds species after 1st apple orchard spray, golf course spray[2]
Disulfoton	NC 2009	---	2	Moderate to severe AChE depression in Blue Jays following treatment in pecan orchards[13]
Monocrotophos	C 1991	---	3-4	Large quail mortality in orange orchards after application[2]
Acephate	SP 2015	---	1-3	Ranges from AChE levels indicate exposure to observed mortality[2]
Dicrotophos **FRUP**	NC	---	3	Individuals of several species dead or debilitated[2]
Fenamiphos	C 2017	---	3	Several individuals of many bird species dead or debilitated[2]
Methyl parathion	NF 2010	---	1-3	Some mortality, brood abandonment in teal[2]
Mevinphos	C 1995	---	4	Large number of songbirds killed after drinking from leaf whorls after sprays[2]
Pyrethroids (0.4%)[5b]	---	▲ TB	---	Endocrine disruptions in birds[3]
Neonicotinoids	---	---	---	---
Imidacloprid **FRUP**	CA 2011, SPA 2012	---	MT, HT	Various effects on Mallard reproduction
FUNGICIDES (16.0%)[5]		▼		
HERBICIDES (12.7%)[5]		▲	---	---
Pendimethalin	SP 2016	---	PNT	---
Trifluralin	SP 2016	---	PNT	Embryotoxic for Mallard eggs in lab[3]
Alachlor	NF 2016	---	ST	---
Cyanazine	C 1999	---	MT	---
Bromoxynil	SP 2015	---	HT	Edema, stunted growth in Mallard embryos[14]
Glyphosate **FRUP**	---	---	PNT	---
(1) Glyphosate, isopropylamine salt **FRUP**		No Trend	PNT	---
(3) Glyphosate, potassium salt		▲	PNT	---

[1] Zhan and Zhang (2014); [2] Mineau (2002); [3] Freemark and Boutin (1995); [4] Köhler and Triebskorn (2013); [5] EPA (2016); [5a] % use/all pesticide use; [5b] use/insecticide use; [6] **FRUP** = Federal Restricted Use Pesticide, **CRM** = California Restricted Materials; [7] Cholinesterase (ChE), a sensitive indicator of OP and carbamate exposure in vertebrates in plasma (P) and brain (B) (Brehmer

and Anderson 1992); [8]Wilson et al. (1991); [9] In Brain (B) Hoffman and Eastin (1981); [10]Gill et al. (2000); [11]Graham and DesGranges (1993); [12]Cordi et al. (1997); [13] White and Seginak (1990);[14]Hoffman and Albers (1984) of evidence for causal links between individual levels of pesticide effects and population or community level effects (Köhler and Triebskorn 2013). Studies in birds provide a few of these rare examples: there is solid evidence for causal linkages between 1) pesticide oral uptake, neurotoxicity, and mass bird deaths, and 2) pesticide (e.g., DDT) oral uptake, endocrine disruption, egg shell thinning, reproductive failure, and population decline (Köhler and Triebskorn 2013). There is also evidence for links in birds between 1) chronic neurotoxin exposure, neurotoxicity, and impaired foraging, learning, and chick-rearing behaviors in captive birds, 2) pesticide exposure and altered metabolisms, and 3) pesticide exposure and immunotoxicity in birds, however these three have not been causally linked to population level impacts (Table 5; Köhler and Triebskorn 2013).

Recent studies have used modeling techniques to examine large-scale long-term bird population changes in relation to pesticide use and environmental pesticide contamination over similar time periods. These efforts are correlative and lack the causal links described above, but unlike laboratory or small scale field studies, their benefits include the ability to examine population level changes at large temporal and spatial scales using large datasets. Hallmann et al. (2014) modeled relationships between surface water concentrations of imidacloprid (a neonicitoid insecticide used in almonds; Table 5) and long-term breeding bird population trends in Denmark, and found strong evidence for significant population declines of six *landbird* species in locations of high imidacloprid water concentrations. Mineau and Whiteside (2013) examined 1980-2003 population trends for U.S. grassland bird species and found that the best predictor for species declines were estimates of lethal risk to birds posed by insecticide use. When the lethal risk of insecticide use to birds was ranked for 77 U.S. crops, California almonds ranked 20th (Mineau and Whiteside 2006).

Because of U.S. federal regulation (Food and Quality Protection Act of 1996) banning many OPs, local research to replace high risk pesticides like OPs with lower risk alternatives, and a concerted effort among almond stakeholders to mitigate pesticide impacts by implementing IPM practices (Klonsky et al. 1990), there has been a significant decrease in the use of this type of insecticide in California almond production since 1996 (Table 5; Zhan and Zhang 2014). OPs had long been applied to dormant winter almond and fruit orchards in California as part of an IPM program and chronic exposure to them was implicated in over-wintering Red-tailed Hawk (*Buteo jamaicensis*) poisoning and mortality (Hooper et al. 1989, Wilson et al. 1991, Fry et al. 1998). OP metabolites were also detected in the feces of California orchard-dwelling Red-shouldered Hawks (*B. lineatus*), an American Kestrel (*Falco sparverius*), and a Western Bluebird (*Sialia mexicana*), and OP residues were detected on the feet of four Red-shouldered Hawks (Wilson et al. 1991, Fry et al. 1998).

Out of 10 compounds used in Canadian apple orchards, OPs and carbamate insecticides (e.g., carbaryl, Table 5) were characterized to have the highest toxicity to Tree Swallows

(*Tachycineta bicolor*) and Eastern Bluebirds (*Sialia sialis*; Bishop et al. 2000a). OP sprays were associated with changes in foraging behavior of chick-rearing adult swallows, and higher toxicity scores in swallows and bluebirds respectively were associated with a 13% and 4% decline in fertility, and a 14% and 5.7% decline in daily chick survival in some years (Bishop et al. 2000a, 2000b). In a West Virginia apple orchard, Brown-headed Cowbird feet and feathers had detectable residue of azinphos-methyl (Table 5) when tested for three exposure period combinations: birds returned to the experimental orchard aviary 1 hr after sprays and sampled after 35 hrs and 7 days of exposure, and birds returned on day 4 after sprays and sampled after 3 days of exposure (Vyas et al. 2007).

The number of publications on wildlife effects of organochlorine (OC; e.g. DDT) insecticide exposure is nearly equal to that of OP, and OC toxicity was the source of at least one of the rare examples linking individual toxicity to population effects in birds (Köhler and Triebskorn 2013). Most OCs are now legally banned in many countries including the U.S., (Köhler and Triebskorn 2013). Nonetheless, OC residues have been shown to persist in orchard environments, and can continue to bioaccumulate in eggs, perhaps confounding contemporary research that often does not test for OC residues in concert with currently used pesticides (Bishop et al. 2000a). For example, OCs were found in the egg shells of Eastern Bluebirds and Tree Swallows nesting in Canadian apple orchards no longer sprayed with OCs and concentrations were significantly and positively associated with the occurrence of unhatched eggs in bluebird nests but not in swallows (Bishop et al. 2000a).

While California almond producers are decreasing their use of OPs, herbicide use is on the rise (Zhan and Zhang 2014), and a few herbicides used in almonds are reported to be moderately or highly toxic to birds (Freemark and Boutin 1995) with little other research on their effects that we could find (Table 5). The trend is the same for the entire U.S., the E.U., and Japan, where the application of herbicides throughout the 1990s and 2000s has far outweighed applications of fungicides or insecticides, but wildlife effects research during the same time period has primarily been on insecticides, with about 25% on herbicides, and less on fungicides (Köhler and Triebskorn 2013).

There are other potential costs to consider when assessing the conservation value of almond orchards for birds, including:

- *Non-reliable food resources*. Birds could become reliant on the abundant nut resources during the breeding season which would then abruptly end at harvest, or reliant on orchard invertebrates whose populations can dramatically decrease in the short term (i.e., indirect effects of pesticides; Boatman et al. 2004, Taylor et al. 2006, Prosser et al. 2016).

- *Predation risk*. Dense populations of predators could impose high mortality rates (e.g., owls using nest boxes placed at orchards for rodent control also eat birds, Kross et al. 2016a).
- *Lack of quality dispersal corridors or contrasting habitats*. Birds often utilize different habitat types during different critical life stages (e.g., nesting vs. fledgling development; White et al. 2005). If almond orchards are isolated and without safe dispersal routes to other bird-friendly habitats types, or surrounded by almond orchard monoculture without contrasting habitat types nearby, mortality could be high for species remaining in them (e.g., Cohen et al. 2004), or attempting to disperse from them (Driscoll et al. 2013).

The literature on bird use of agricultural systems has very few examples of the evaluation of the potential costs to avian fitness, despite its importance when considering the conservation value of agricultural landscapes (Komar 2006, Kleijn et al. 2011).

6.2. The potential beneficial contributions of almonds to avian conservation

Researchers who have studied avian ecology in almond orchards, or in agricultural mosaics containing almonds, have proposed several ways that almond orchards could contribute to the conservation of bird species and communities. Proposals summarized here are based on the evidence presented above on avian habitat use in almonds (section 3). As a conceptual starting point, Luck et al. (2015) proposed a shift in conservation tactics from one which lumps agricultural crop types together (assuming equal habitat quality among them), to one in which different crop types are delineated and categorized as avian habitats of different quality for species or biodiversity, as is done for natural habitat types. Luck et al. (2014) further suggested that when planning conservation actions, focusing on the habitat value of remnant natural vegetation in isolation from that of almonds overlooks the evidence that almonds can contribute to species persistence (e.g., the threatened Regent Parrot). These conceptual proposals align with those of a growing number of ecologists and are referred to as *land sharing* strategies (Perfecto and Vandermeer 2010). This strategy is often posed against *land sparing* tactics, which prioritize maximizing high-yield crops on less land and protecting large and separate reserves of natural habitat (Phalan et al. 2011). A third proposal is to harness the synergistic benefits of both strategies rather than treating them as mutually exclusive (Kremen 2015).

Independent studies have provided evidence that almond orchards can meet some of the

diverse life history requirements of various bird species including Southern Grey Shrikes (*Lanius meridionalis*), Great Bustard, and Red-legged Partridge (*Alectoris rufa*) in Spain (Gortazar et al. 2002, Campos et al. 2006, Alonso et al. 2009), Woodchat Shrikes (*Lanius senator*) in Greece (Apageorgiou et al. 2016), and of avian biodiversity generally in Cyprus

(Ieronymidou et al. 2012). Though none of these studies' objectives were specifically aimed at characterizing avian use of almond orchards, in all cases some component of the orchards or individual trees were deemed important for the species. These findings led all investigators to the same general conclusion: the negative effects of losing native habitats for birds to agriculture might be mitigated by retaining a mosaic of native vegetation and small farms of different crop types (including almonds), more than would converting the landscape to a homogenous monoculture of any single crop.

As native habitats are increasingly encroached upon or destroyed, crops could become some of the only available options for abundant, nutritious, accessible food for birds (Avery 2002). Recall that parrots appeared to dynamically use almonds as an alternative food source when preferred food resources were low leading Luck et al. (2013) to conclude that rapid reductions in almond orchards (e.g., due to market forces) could lead to declines in threatened Regent Parrot populations if alternative food sources are not increased at equal rates. Even temporary bird reliance on almonds, however, can be perceived as more damaging than it might be, and this type of conflict between producers and parrots (real or perceived) have sometimes ended in the deliberate or accidental killing of the threatened Regent Parrot (Baker-Gabb and Hurley 2010). In light of these conflicts, Luck et al. (2014) call for an innovative approach among almond stakeholders that could probably be applied to any almond growing region. The suggestion is to use *co-management* strategies (e.g., Lowell et al. 2010) to develop co-benefit outcomes such as minimizing almond production losses while also promoting bird conservation. Such collaborations will require an objective empirical accounting of the true costs and benefits that birds generate for producers, and a willingness to accept a low level of crop loss; likewise, diligent research, planning, and implementation on the part of conservationists and managers is needed to determine acceptable levels and locations of habitat loss, protection, or co-management with producers.

6.3. Audubon Important Bird Areas in California's Central Valley almond growing region

Important Bird Areas (IBAs) are protected or unprotected sites around the globe that have been identified as important for birds of state, continental, or global conservation concern (Audubon 2016). California's IBAs are as much a part of the agricultural mosaic of the Central Valley as are almond orchards (Figure 3). There is little direct overlap of almond production and IBAs. Rather, it appears that almond orchards border the edges of IBAs, extend away from IBAs up to approximately 60 km before abutting another IBA, or extend away from IBAs up to 100 km before abutting a major urban area. This landscape configuration is likely amenable to a descriptive research design aimed at determining patterns of bird use in almond orchards at different distances away from IBAs (see Section 7). Utilizing data from

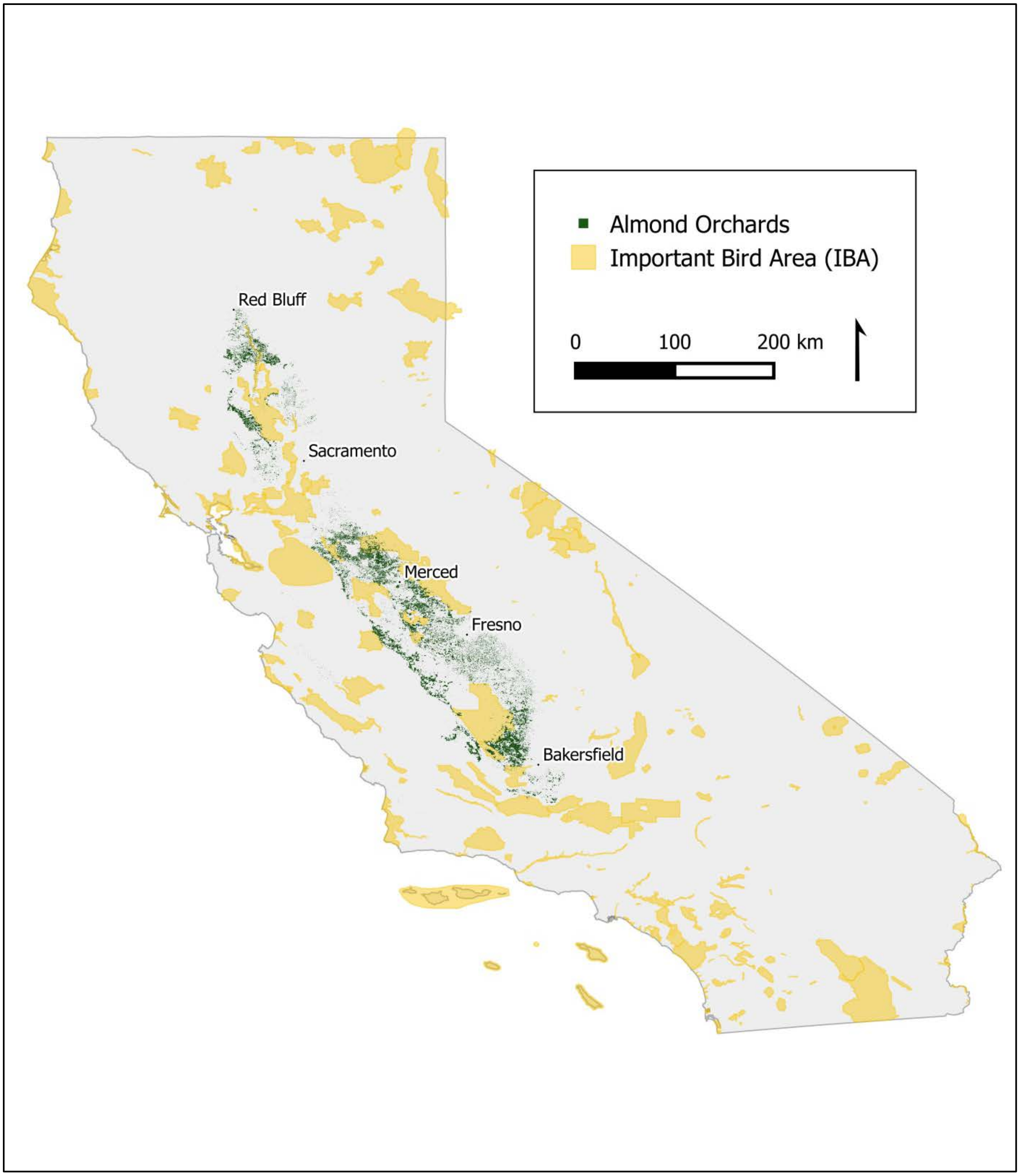

Figure 3. California's Central Valley almond orchard extent in 2015 and Audubon California Important Bird Areas as of March 2016. Cropland data layer with ground resolution of 30m , each pixel equals 0.003 ha (USDA NASS 2015).

these research efforts, the Almond Board of California and Audubon California can collaboratively identify priority regions for bird conservation and almond sustainability efforts.

7. Study design in almonds

Based on knowledge gaps identified in this literature review, and specific areas of interest of both the Almond Board of California and Audubon California, we propose the following design outlines for three topics of study:

7.1. Patterns of bird use in almond orchards of California's Central Valley

Objective: To determine patterns in avian occupancy of almond orchards in all seasons, including bird abundance and diversity measures in relation (but not limited) to distances from Audubon Important Bird Areas or a specific natural habitat type (e.g., riparian).
Type of Research: Descriptive and correlational, with opportunities to address more hypotheses.

Design: To accommodate the landscape, climatic, and ecological variability of California's Central Valley, we recommend stratifying bird sampling transects within the Sacramento Valley, Delta, San Joaquin, and Tulare Basin almond growing regions of the Central Valley. Within each region, at least three categories of increasing distances (or alternatively a gradient of continuous distances) from a chosen habitat type should be established within which bird sampling units can be randomly located to the extent possible given logistical constraints such as grower permissions. Thus, sampling units would be one bird transect in one orchard (see methods below), grouped accordingly (in order of larger to smaller geographical groupings): Central Valley[region[distance category[orchard[line transect]]]]. To adequately estimate bird abundance or diversity in almond orchards at varying distances from the chosen features, it would be prudent to perform a one year pilot study that would allow for the estimation of population variance within and between these groupings. A power analysis can then determine the sample size necessary to achieve a specific level of statistical power, given desired effect sizes. In absence of a pilot study, one could calculate population variance from other Central Valley bird studies and assume that this estimate captures the variance present in the populations of interest.

Methods: To estimate bird abundance, evenness of abundance (Cotgreave and Harvey 1994), and indices of diversity (Macarthur and Macarthur 1961), we recommend using full distance measured line transects (Bibby et al. 2000). Based on summer and winter home range sizes of most landbirds (e.g., warblers, sparrows, woodpeckers, corvids) in the Central Valley, we assume that separating sampling units by at least 1 km will approximate independence. Typically only a single line transect of 200 – 300 m will fit inside of an orchard block. The same goes for a single point count, and this is why we recommend against the point count method for this study. The length and the sampling time of the line transect should be standardized among orchards; we recommend walking and recording birds at a rate of approximately 1 min/10 m (i.e., 20 minutes for a 200 m transect). We recommend at least two visits to each transect within each season of interest, spaced at least 7 days apart. Observers should finish all daily transects within 4-5 hours after local sunrise and should randomize the order of transects for each visit. During the timed transect, observers walk along a predetermined transect and record all birds detected by sight, song, or call, and the distance to each bird perpendicular to the transect (see Bibby et al. (2000) for further detail).

If assessing patterns in bird occupancy in relationship to additional local and landscape habitat or orchard management components is desired then we recommend utilizing a combination of digitized landscape analysis techniques (i.e., GIS) and orchard level measurements of vegetation characteristics, almond phenology, orchard management, etc.

Potential variables of interest: Region (4-level categorical variable); distance to IBA (categorical distance grouping or continuous distances); orchard scale variables (e.g., tree phenology, tree cover, number of tree stems, age of orchard, size of orchard block, presence of hedgerow on orchard edge); landscape variables (e.g., distance to nearest natural habitat type, % coverage of almond within a determined radius from transect, distance to urban area).

7.2. The economic and ecological costs and benefits of almond damage by birds (disservice) and pest reduction by birds (service) to almond growers in California's Central Valley.

Objectives: To quantify species level pre-harvest almond damage rates by birds, to quantify species level post-harvest mummy nut reduction by birds (and/or pre- or post-harvest reduction of other key almond pests by birds), and to use these data to calculate ranges of potential net costs or benefits of birds to growers under a range of spatial and temporal, and economic and ecological, conditions.
Type of Research: Descriptive, experimental, and correlational

Design: We recommend that data on patterns in bird use of almond orchards (Study Design 1) are collected either prior to or in concert with the implementation of this study. We recommend choosing one of two approaches:

A) *Net costs or benefits of birds in relationship to distances from chosen habitat type*. Select for study one of the four Central Valley almond growing regions described above. Within this region (e.g., riparian), select a subset of the transect orchards from Study Design 1 at different distances from regional chosen habitat type. For each distance category orchard, calculate the net cost or benefit estimates derived from orchard level data and the economic conditions of the current growing season, and model relationships between these net ranges and distances from IBAs.

B) *Regional and statewide net costs or benefits of birds to growers under a range of economic conditions.* Select a subset of the transect orchards from Study Design 1 within each of the four Central Valley almond growing regions, calculate ranges of net benefits or costs for each orchard based on orchard level data and a range of economic conditions expected annually across a 5 year period for that orchard or region, and derive model predicted net costs or benefit estimates for each region and the entire Central Valley.

Sample size will likely be most limited by logistics and cost for this large scale and labor intensive study. A single year pilot study in a single orchard (i.e., alongside Study Design 1) could provide great insight into logistical costs, labor needs, and methodological choices in orchards.

For approach A, we recommend at minimum a total of 30 orchards (if variation in factors such as orchard age, variety, and orchard management can be reduced, this number can be lowered). If the goal is to attempt to capture the variance in damage and mummy nut consumption in orchards at variable distances from a habitat type, we recommend locating 10 orchards in increasing distances and more or less in a line from each of three locations of a single habitat area. All orchards within and between the three lines of 10 increasingly distant orchards should be at least 1 km apart. An option for analysis flexibility would be to randomly generate 30 different distance locations in a stratified way to assure about 10 orchards at far distances, 10 at medium distances, and 10 orchards in close proximity to the habitat; this would allow for an analysis with distance from habitat type as a continuous variable (likely affording more power) or for an analysis comparing three different distance groupings (could be beneficial). If the goal is to capture the variance in damage and mummy nut consumption at distances from a habitat type in a particular region, we recommend using a similar design, but to use only 10 orchards at variable distances from each of three different habitat areas of the same general type.

Based on data presented in Gebhardt et al. (2011), the variance in avian damage and mummy nut removal across the Central Valley is likely quite high. Thus, for approach B, we recommend quantifying almond damage and mummy nut removal by birds and assessing monetary costs and benefits for at minimum 30 orchards per each of four regions for a total of 120 orchards; this would likely require four separate field crews of at least two people each. The 30 orchards per region would be selected from a subset of orchards chosen for Study Design 1.

If a different almond pest is chosen in lieu of navel orangeworms or other insect larvae infesting mummy nuts, the same design strategy could likely be implemented.

Methods: To assign monetary value to costs and benefits to growers, we recommend using archived almond production data (e.g., county level data used to produce CDFA 2015, Almond Board of California 2016) to determine several representative years of almond prices. Other sources of data (e.g., grower survey reports, existing literature, market data, expert opinion) will need to be identified to calculate regional and annual ranges of monetary costs to growers for almond damage and almond damage prevention, and replacement costs of pest control or mummy nut removal by birds (i.e., costs of labor, equipment, insecticide). Examples of single year cost benefit analyses of this type include Luck (2013) for almonds, and Saunders and Luck (2016) for apples. There are several methods used to quantify pre-harvest almond damage by birds, we recommend using a combination of randomly assigned almond branch exclosures and ground almond hull collection. Examples of studies that have used exclosure techniques to quantify bird specific almond damage include Luck (2013) and Schäckermann et al. (2015a). Resources for methods to identify and quantify almond damage by birds and rodents from almond hulls collected on orchard floors include Emlen (1977) and Eilers and Klein (2009). Studies that describe exclosure and count or collect methods for quantifying post-harvest mummy nut consumption by birds include Luck (2013) and Eilers and Klein (2009). Identifying avian almond and mummy nut consumers to species can be achieved for some species by identifiable marks left on almond hulls (as in Emlen 1977), by foraging rate observation (Morrison et al. 1990), or by use of sentinel almonds and motion sensor video cameras. We recommend a combination of these techniques as each is likely biased toward or against particular species.

For multiple studies that provide detail on techniques for measuring bird consumption of other pest types, refer to citations listed in Table 3.

Variables of interest: Annual and regional almond price, price of labor and equipment for mummy nut removal, price of labor and equipment for almond nut damage prevention, percent or number of almonds damaged by birds (and species), percent or number of mummy nuts consumed by birds (and species), distance from orchard edge, distance to IBA, region.

7.3. A quantitative assessment of enteropathogenic outbreak risk associated with avian occupancy of almond orchards and human almond consumption in California's Central Valley.

Objectives: Estimate enteropathogenic prevalence in birds utilizing almond orchards, identify potential sources of contamination within bird flying distances of almond orchards, quantify bird movement between contamination sources and orchards, estimate effects of proximity to Audubon IBAs or other wildlife habitats on pathogen prevalence, and

incorporate these data into existing almond pathogen risk assessments.
Type of Research: Descriptive, correlative, model simulation

Design suggestions: We recommend that data on patterns in avian use of almond orchards (Study Design 1) be collected and analyzed prior to the detailed design and implementation of this project. Orchard sampling locations for this project should be sub-sampled from sampling locations generated in Study Design 1 with location considerations for this study including proximity to wildlife habitat and contamination sources (proximity would ideally be variable at continuous distances from these features). The number of sampling orchards will be determined by the type of results preferred. For example, if estimates of temporal changes in prevalence of pathogens in birds are preferred, fewer orchards and more sampling events across a pre-determined period of time will be required. If estimates of spatial prevalence of pathogens during a specific time period are preferred, more orchards and fewer sampling times will be required. We highly recommend that the Almond Board of California and/or Audubon California collaborate with the University of California Western Institute for Food Safety and Security staff, or experts in this topic from a different California research group to both design and implement the pathogen prevalence component of this study. There are at least two risk assessments completed for salmonellosis outbreaks sourced from *Salmonella* in Central Valley almond orchards (Danyluk et al. 2006, Lambertini et al. 2012), and another for illness attributed to *E. coli* 0157:H7 contamination in apple orchards (Duffy and Schaffner 2002). Estimates of avian pathogen prevalence, bird behavior, and landscape risk factors derived from this study can potentially be incorporated into existing risk assessments, along with other estimates of additional risk factors in almonds (e.g., Santillana Farakos et al. 2016), to determine the contributions that birds might have to enteropathogenic disease outbreaks.

Methods: We recommend quantifying pathogenic prevalence in birds by capturing them with mist nets in orchards; identifying, sexing, and aging individuals if possible; banding them for future identification; and collecting cloacal fecal swabs from all individuals captured. Sampling start, end, and duration times should be standardized and effort data (e.g., number of mist nets, total hours opened) should be recorded. *Salmonella*, *E. coli*, and other selected isolates should be genotyped from cloacal swabs in order to confirm whether or not isolates are known pathogenic serotypes. Pathogenic prevalence should be estimated for bird species captured prior to beginning the next stage of the study. To quantify bird movement and behavior in orchards and surrounding landscapes, we recommend either of two (or both) of the following approaches: 1) use location tracking devices on bird species with the highest estimates of pathogenic prevalence as estimated during the first portion of the study. Specifically, spatially explicit movement and location data will be required to quantify distances traveled by birds outside of orchards and between orchards, to identify potential contamination sites, and to quantify movement between birds and potential contaminations sites; and 2) use GIS to locate and map potential sources of contamination at varying distance around orchards. In either case, potential contamination sites visited by these bird species (or selected by researchers via GIS) should also be sampled for pathogenic prevalence. It should be genetically determined whether distinct pathogenic strains are shared between birds in orchards and contamination sources they potentially visit. Approach 1 will require higher labor and equipment costs; the limitations of using the second approach alone is that spatially explicit movement and behavior data of potential avian vectors remains an unexplored aspect of wildlife pathogen vector research (Jay-Russell 2013) that if collected could help improve risk reduction measures in orchards. Finally, estimates of species specific prevalence, movement, location, and strain-specific pathogenic linkages between birds and contamination sites, and their accompanying uncertainties, will need to be incorporated into simulation models to identify if and how much birds contribute to outbreak risk in almonds.

Variables of Interest: Species specific pathogen prevalence; species specific mean, range, and variation estimates for distances traveled beyond orchards; locations and identities of potential contamination sources visited by orchard birds; pathogen prevalence at potential contamination sites; prevalence of strain-specific linkages between bird species and contamination sites.

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Appendix I. Glossary of italicized terms in text.

biotic exchange - introductions of new organisms to ecosystems

co-management – a management approach in which stakeholders of diverse interests negotiate, define, and manage a common resource (i.e., in agriculture, stakeholders seek to support efficient and economical food production while simultaneously conserving soil, water, air, wildlife, and other natural resources).

ecological trap - a low quality habitat that organisms prefer over higher quality habitat

fitness - an organisms ability to survive and reproduce in a particular environment

frugivores - fruit eaters

functional response - predator increases its rate of consumption when exposed to higher prey densities

functional traits - traits that define species in terms of their ecological roles (e.g. fruit eaters, cavity nesters)

granivores - nut, seed, and grain eaters

habitat selection - an organisms behavioral responses that may result in an organism using certain types of habitat disproportionately to their occurrence in the environment resulting and the subsequent effects on survival or reproduction

insectivores - consumers of insects, spiders, and allies

landbirds - an informal name for a large group of birds that occupy terrestrial habitats throughout the year (e.g., songbirds, raptors, woodpeckers)

land sparing - high yielding agriculture on a small footprint while devoting more land to reserve areas

land sharing - low-yielding, wildlife-friendly agriculture on a larger land footprint

local extinction – also called extirpation, when a species no is extinct from a chosen area of study (i.e., not an extinction of the entire species)

natural enemies – beneficial organisms that serve as biocontrol agents in agricultural systems, often refers to native wild species

nectarivores - nectar eaters

novel ecosystems – when species occur in combinations and relative abundances that have not occurred previously within a given biome (also called emerging ecosystems)

numeric response - predators become more abundant as prey density increases

omnivores - organisms that eat multiple food types

species diversity - there are different quantitative measures of species diversity, but generally it is a combination of two components, species richness (see definition) and species evenness (a measure of the variation in the abundance in individuals per species)

species richness - the number of different species

Appendix II. Scientific names for species in tables with only common names provided due to space limitations.

Mallard	*Anas platyrhynchos*
quail	*Odontophoridae*
Wild Turkey	*Meleagris gallopavo*
Turkey Vulture	*Cathartes aura*
Cattle Egret	*Bubulcus ibis*
Cooper's Hawk	*Accipiter cooperii*
Mourning Dove	*Zenaida macroura*
Red-breasterd Sapsucker	*Sphyrapicus ruber*
Nuttall's Woodpeckers	*Picoides nuttallii*
Downy Wooddpecker	*Picoides pubescens*
Galah	*Eolophus roseicapilla*
Long-billed Corella	*Cacatua tenuirostris*
Little Corella	*Cacatua sanguinea*
Sulphur-crested Cockatoo	*Cacatua galerita*
Burrowing Parrot	*Cyanoliseus patagonus*
Red-rumped Parrot	*Psephotus haematonotus*
Blue Bonnet	*Northiella*
Mulga Parrot	*Psephotellus varius*
Yellow Rosella	*Platycercus elegans flaveolus*
Eastern Rosella	*Platycercus eximius*
Australian Ringneck	*Barnardius zonarius*
Blue Jay	*Cyanocitta cristata*
Yellow-billed Magpie	*Pica nuttallii*
Little Raven	*Corvus mellori*
Australian Raven	*Corvus coronoides*
Great Tit	*Parus major*
Cetti's Warbler	*Cettia cetti*
Eurasian Blackcap	*Sylvia atricapilla*
White Wagtail	*Motacilla alba*
Yellow-rumped Warbler	*Setophaga coronata*
Song Sparrow	*Melospiza melodia*
White-crowned Sparrow	*Zonotrichia leucophrys*
Dark-eyed Junco	*Junco hymalis*
Savannah Sparrow	*Passerculus sandwichensis*
Chipping Sparrow	*Spizella passerina*