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Pesticide use and avian diversity in California

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Pesticide use and avian diversity in California

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Abstract

Farmland bird species are known to be declining. In Europe, studies conducted at the farm-level have attributed this decline in abundance, at least partly, to agricultural practices including pesticide use. In North America, few studies have attempted to investigate the relationship between pesticide use and bird abundance and richness. Lack of sufficiently comprehensive pesticide data often limits rigorous testing of hypotheses. I therefore used the best available records of pesticide use and bird distributions: those in California. I calculated estimates of area treated with pesticides and insecticide direct toxicity. I related these to the spatial and temporal variation in bird species richness and abundance (from the Breeding Bird Survey) over a ten-year period in 5.0 km^2 plots distributed over the Central Valley of California. I found that the relationships between bird species richness and abundance and pesticide use are weak, albeit borderline significant. I suggest that, if pesticide use actually does affect breeding bird abundance, it must be at much broader spatial scales than used in this study.

Résumé

Plusieurs études ont démontré que les espèces aviaires associées aux milieux agricoles sont en déclin. En Europe, des études menées à l'échelle des fermes ont attribué ce déclin, du moins en partie, aux pratiques agricoles intensives dont l'utilisation des pesticides. En Amérique du Nord, peu d'études se sont penchées sur les relations entre pesticides et oiseaux. Cela est dû en majeure partie au fait que peu de bases de données suffisamment détaillées sur l'utilisation des pesticides sont disponibles. Pour cette étude, j'ai donc utilisé les bases de données provenant de la Californie, qui sont, à ma connaissance, les meilleures disponibles. J'ai utilisé ces données pour calculer des estimés de surface traitée avec des pesticides ainsi que des estimés de toxicité directe due aux insecticides. J'ai comparé ces estimés aux variations spatiales et temporelles de richesse en espèces et d'abondance des oiseaux (provenant des études des populations d'oiseaux nicheurs, EPON) sur une période de dix ans dans des parcelles de 5,0 km^2 dispersées à travers la vallée centrale de la Californie. J'ai trouvé que les relations entre la richesse en espèce de même que l'abondance des oiseaux et l'utilisation des pesticides sont significatives mais faibles. Je suggère que, si l'utilisation des pesticides affecte l'abondance des oiseaux nicheurs, l'effet doit être détectable à une échelle spatiale beaucoup plus grande que celle utilisée dans cette étude.

Introduction

Contemporary conservation literature suggests that the prime cause of loss of biodiversity is loss of appropriate habitat due to human activities (Roughgarden, 1995). However, earlier studies on bird diversity in southern Ontario (Pepin and Currie, unpublished) showed little evidence that areas with more extensive habitat loss have lost more species. Instead, the data suggested that bird species richness may be more strongly related to the use of agricultural pesticides. However, pesticide data collected in Canada are neither sufficiently extensive, nor compiled in a way that allows rigorous tests of hypotheses about their environmental impacts.

Agricultural pesticides are not species-selective and may affect non-target organisms such as birds. Birds can be exposed to pesticides in various ways: direct contamination, ingestion of contaminated food items, inhalation, preening, etc. (Grove et al., 1998; Grue et al., 1997). Exposure to pesticides can lead to direct mortality. Sublethal exposure may affect behavior and reproduction (Walker, 2003; Kegley et al., 1999; Grue et al., 1997; Fry, 1995), resulting in a reduced recruitment into local bird populations (Walker, 2003). Insecticide use may also affect birds indirectly by reducing their invertebrate prey (Benton et al., 2002; Robinson and Sutherland, 2002; Blackburn and Wallace, 2001; Wilson et al., 1999; Blus and Henny, 1997; Campbell and Cook, 1997; Rands, 1985). Herbicide use may lead to loss of nesting cover when herbicides drift into field borders, and may additionally reduce food supply (Robinson and Sutherland, 2002; Boutin et al., 1999; Wilson et al., 1999; Campbell and Cooke, 1997).

The goal of this study was to test whether the spatial and temporal variation in bird species richness and abundance at local sites across a region are related to the rate of pesticide use near those sites. I hypothesized that: 1) if insecticide use causes short-term mortality to birds, then one should observe a negative relationship between bird abundance and species richness of a given year and the amount of insecticide used before the bird census of that year. 2) Similarly, pesticides may reduce bird abundance and species richness through long-term effects. For example, pesticide use may decrease food availability by decreasing vegetation cover or invertebrate populations. Reduced food supply could lead to reduced reproductive success, such that bird abundance and species richness in a given year is negatively correlated with pesticide use during the preceding years. 3) Finally, I hypothesized that some types of pesticides will have disproportionate effects on particular bird guilds. For example, insectivores should be more affected by the use of insecticides. If this hypothesis is true, one would expect a negative correlation between abundance and species richness of particular guilds and corresponding pesticide types.

To test these hypotheses, I used the best available concomitant records of pesticide use and bird distributions: those in California. California requires that agricultural and commercial pesticide use be reported, including date of application and location (on a one square mile grid). Compiled pesticide and bird data are easily accessible. Further, the gradient of agricultural intensity is very pronounced. In 1997, approximately 11 million hectares of land in California were in agriculture (United States Department of Agriculture, Census of Agriculture, http://www.usda.gov/). The San Joaquin Valley (a part of the larger Central Valley) alone accounts for 60% of the total pesticide use in California (Kegley et al., 2000). Fresno and Kern, two counties in the San Joaquin Valley, were the top two counties with the highest total pesticide use in California in 1998 (Kegley et al., 1999) with respectively 14.4 and 7.1 million kilograms of active ingredients. In contrast, rates of pesticide use in Mariposa and Tuolumne counties (also in the Central Valley) are relatively low (≤ 0.5 million kilograms of active ingredients). Bird data are from the Breeding Bird Survey (BBS). BBS are conducted each year during the breeding season. The resulting data are summarized as the abundance of all individual bird species seen or heard per group of ten stops on a particular route.

Beside the effects of pesticide use, a range of other factors can also have an impact on temporal and spatial variation in bird abundance. These include characteristics of the natural environment (i.e. climate, elevation, landcover types, etc.) (Hawkins et al., 2003; Fraser, 1998, Böhning-Gaese, 1997; Wright et al., 1993), characteristics of the bird species themselves (i.e., size, foraging habits, etc.) (Crocker et al., 2002; Mineau et al., 1996,2001) and agricultural practices (i.e. crop type, etc.) (Crocker et al., 2002; Mineau et al., 2002a). In the present study, I controlled for environmental variables by looking at climate (temperature and precipitation), elevation and landcover (including crop type).

Background

Factors explaining patterns of species richness

Many hypotheses have been suggested to explain why we find more species in some places (e.g., tropical forests) and fewer in others (e.g., deserts). Climatic variables such as mean annual temperature and precipitation are thought to be the most important factors controlling diversity at large scales (Hawkins et al., 2003; Wright et al., 1993). At finer scales, variables such as vegetation cover and structure as well as topography are thought to play a major role for animals. These characteristics are grouped under the spatial heterogeneity hypothesis (Fraser, 1998; Böhning-Gaese, 1997). Human activities are also thought to have an impact on species richness, especially through habitat loss (Roughgarden,

1995) and agricultural practices (Boutin et al., 1999). Recently, it has been suggested that, in agricultural landscapes, species richness depends on habitat heterogeneity, and to a lesser extent, on farm management (Weibull et al., 2003).

Birds and pesticides

Recently, the increase in pesticide use has been proposed as one of the reasons explaining the wide range decline of some farmland bird species (Robinson and Sutherland, 2002; Chamberlain et al., 2001; Krebs et al., 1999; Siriwardena et al., 1998; Jobin et al., 1996a; Fuller et al., 1995). Pesticides are not species-selective: they may also affect non-target organisms such as birds (Pimentel and Levitan, 1986) for which croplands can be important habitats (Falardeau and DesGranges, 1991). Birds use croplands in various ways: breeding, foraging, migration stopover, wintering activities (Beecher et al., 2002). Although they mostly use uncultivated crop edges, some birds also forage in the field (Beecher et al., 2002). Birds are exposed to pesticides in several ways: direct contamination, ingestion of contaminated food items (insects, water and foliage), inhalation, preening, etc. (Grove et al., 1998; Grue et al., 1997). Exposure to pesticides can occur several times within a given breeding season. These exposures to pesticides can have many adverse direct and indirect effects to birds.

Direct effects

Birds exposed to pesticides can suffer direct acute effects (immediate mortality) or direct long-term (sublethal or chronic) effects. Direct immediate effects of a pesticide dose refer to the effects, usually leading to death, seen within 0-7 days after the exposure to the pesticide product (Kegley et al, 1999). An estimated 67 million birds per year are killed by the use of pesticides in the U.S. alone (Pimentel et al., 1992), which represents about 10% of the birds that are exposed to pesticides. However, exposure to pesticides does not necessarily immediately lead to death and can have many other direct detrimental effects. Other direct effects are classified into two categories: sublethal and chronic. Sublethal effects refer to a pesticide dose that is not enough to kill immediately but that causes adverse effects, which could potentially lead to death later on. Sublethal exposure can inhibit feeding behavior, lead to greater susceptibility to disease and impair the nervous system (Walker, 2003, Kegley et al., 1999; Grue et al., 1997). Chronic effects refer to long-term or repeated exposure to a pesticide (Kegley et al., 1999). Chronic exposure can impair reproduction and development, causes tumors, enhances the susceptibility to disease and causes damage to the liver (Kegley et al., 1999; Fry, 1995).

Most insecticides used at present are known to be neurotoxics, in contrast with herbicides and fungicides (Walker, 2003). Neurotoxic chemicals can cause direct and indirect behavioural effects that decrease the capability of birds to find food or to reproduce (Walker, 2003). They can also alter the choice, the capture and manipulation of prey (Walker, 2003). Birds are particularly sensitive to organophosphorus compounds known to be neurotoxic insecticides (Grue et al., 1997). Organophosphorus insecticides primarily act as contact poisons or by ingestion. Thus, the product must be in contact with the skin (or cuticule) or ingested to be effective. Organophosphorus pesticides inhibit the action of the enzyme acetylcholinesterase, essential to the nervous system. They have a high affinity for this enzyme and bind with it. The physiological consequence of an exposure to organophosphorus insecticides is a disruption in nervous system functioning (Cairns et al., 1991; Herbert et al., 1989; Stromborg, 1988). Birds severely exposed to organophosphorus insecticides can experience an overall reduction in activity (Grue et al., 1991). Birds intoxicated by these compounds also reduce their food and water consumption (Grue et al., 1991). For example, Grue (1982) administered an oral dose of dicrotophos to male common grackles. He noted that their food consumption decreased 76% compared to control birds. Predator avoidance and reproduction (pairing, mating, egg incubation, etc.) are other behaviours that can be impaired by exposure to neurotoxic pesticides (Walker, 2003; Wilson et al., 2001; Grove et al., 1998, Grue et al., 1991; Galindo et al., 1985). Galindo et al. (1985) gave doses of methyl parathion to bobwhite quail. Treated birds were more easily caught by domestic cats than non-treated ones. Aggressive behaviour is another possible direct effect of neurotoxic pesticides. Male wild sharp-tailed grouse exposed to malathion, showed unusual aggressive behaviour (McEwen and Brown, 1966). Predatory birds suffer indirect effects due to changes in the behaviour of their prey species (Walker, 2003). Behavioural effects can lead to bird population decline (Walker, 2003).

Reproductive impairments resulting from pesticide exposure can affect both adults and embryos (Fry, 1995). Embryos are more sensitive than adults to the effects of pesticide exposure. Effects on embryos include: death, reduced hatchability, reduced survival and skeletal abnormalities (Fry, 1995). Effects on adults include: mortality, sublethal stress, reduced fertility (Fry, 1995) and smaller brood size (Rands, 1985). Organophosphorous (malathion, dimethoate, diazinon, parathion, and acephate) are pesticides known to cause reproductive effects to birds (Fry, 1995). Organochlorine pesticides (for example, DDT, dieldrin, endrin, aldrin, lindane, etc.) are also known to cause reproductive effects to birds but most of these compounds are now banned or severely restricted in North America. Organophosphorus pesticides can alter the level of reproductive hormones as well as sexual behaviour in birds (Grue et al., 1997). To a lesser extent, some herbicides (paraquat, trifluralin, prometon, and others) and some fungicides (maneb) can also impair birds' reproduction (Fry, 1995; Mineau et al., 1994).

Indirect effects

Pesticides can also have indirect effects on birds through depletion of their food supply (Benton et al., 2003; Robinson and Sutherland, 2002; Chamberlain et al., 2000; Wilson et al., 1999; Boutin et al., 1999; Campbell and Cooke, 1997; Blus and Henny, 1997; Rands, 1985). Farmland bird species feed primarily on invertebrate species during the reproductive period (Campbell and Cooke, 1997). Indirect effects through reduction of prey abundance can be caused by insecticide, fungicide and herbicide use. Birds may be affected through direct or indirect invertebrate depletion resulting from pesticide usage (Benton et al., 2002; Robinson and Sutherland, 2002; Blackburn and Wallace, 2001; Wilson et al., 1999; Blus and Henny, 1997; Campbell and Cooke, 1997; Rands, 1985). Benton et al. (2002) showed that bird abundance is positively correlated with invertebrate (arthropod) abundance.

It has been shown that the abundance and diversity of some invertebrate species decrease after an insecticide (Wilson et al., 1999; Campbell and Cooke, 1997; Chiverton and Sotherton, 1991) or fungicide (Sotherton and Holland, 2003) application. Most invertebrate species are particularly affected by organophosphorus and pyrethroid insecticides (Wilson et al., 1999). Insecticide applications can have long-term impacts on invertebrate populations and effects can be seen several years after the initial spraying (Aebischer, 1990), although some species can recover as quickly as a month after the application (Wilson et al., 1999).

Some invertebrate species may also be affected indirectly by herbicide (Robinson and Sutherland, 2002; Boutin et al., 1999; Wilson et al., 1999; Campbell and Cooke, 1997) and fungicide (Rands, 1985) applications that remove their host plant and/or their food supply.

Herbicide use destroys habitat for both birds and their insect preys (Kegley et al., 1999) and decreases plant diversity (Boutin et al., 1999; De Snoo and van der Poll, 1999; Wilson et al., 1999; Jobin et al., 1996a) and biomass (Chiverton and Sotherton, 1991). Some targeted weed species are important food sources for invertebrates (Beecher et al., 2002; Wilson et al., 1999; Chiverton and Sotherton, 1991). Some granivorous bird species may also be directly affected by a reduction in their food supply due to herbicide use (Beecher et al., 2002; Boutin et al., 1999; Wilson et al., 1999; Campbell and Cooke, 1997). Studies have shown that most invertebrate and plant species known to be declining due to pesticide use are also important food items in the diet of farmland bird species (Campbell and Cooke, 1997).

Pesticide use also decreases the quality of the habitat available for bird breeding (Robinson and Sutherland, 2002; Chamberlain et al., 2000; Campbell and Cooke, 1997; Pimentel and Edwards, 1982). Decreased habitat quality as well as depletion in food supply may both result in a reduced recruitment (Grove et al., 1998; Walker, 2003) and survivorship (Grove et al., 1998) into local bird population.

Pesticide use in California

Pesticide is a general term used to describe any chemical designed to kill a pest. Herbicides, insecticides and fungicides are used respectively to control weeds, insects and molds/mildews. Pesticides are widely used in agriculture. Massive amounts are applied each year to crops to kill problematic pests. Although during the last decade, the amount of pesticide active ingredient applied has decreased, the extent and number of applications has increased (Robinson and Sutherland, 2002).

California uses a lot of pesticides. Approximately, 5% of the pesticides used worldwide and 25% of the pesticides used in the U.S. are used in California (Liebman et al., 1997; Kegley et al., 2000) even though planted acreage constitutes only 2-3% of the U.S. cropland (Kegley et al., 2000). Thus, the intensity of pesticide use is quite high, and these figures do not include home and garden uses (Liebman et al., 1997) which, according to pesticide sale data, would add another 50-70% to the total amount of pesticide use (Kegley et al., 2000). In California, insecticides represent around 26% (average use from 1991 to 1998) of total pesticide use reported (Kegley et al., 2000). Herbicide use is quite low: around 13% of total pesticide used (Kegley et al., 2000). Fungicides are the most used chemicals: 41% of total pesticide use reported (Kegley et al., 2000). The remaining 20% of pesticide used are fumigants (17%) and other types of pesticides (e.g. acaricides, rodenticides, etc.) (3%) (Kegley et al., 2000).

This figure of pesticide use is quite different than in the rest of the United States. Most of the pesticides used in the United States are herbicides which account for about 60 % of total pesticide use (data from Pesticides Industry Sales and Usage 2000 and 2001: Market Estimates, U.S. EPA, May 2004). Insecticide use is ca. 10% and fungicide use is around 22 %. These differences in pesticide use between California and the rest of the United States are primarily due to planting of different kinds of crops and different pests. The primary crops planted in most of the United States are corn and soybeans, which account for about one third of the pesticide use in the United States and, over 90% of the pesticides used on these crops, are herbicides (Larry Wilhoit, California Department of Pesticide Regulation, personal communication). The primary crops in California are grapes and cotton; about 90% of the pesticides used on grapes are fungicides and the main use on cotton is defoliants (Larry Wilhoit, California Department of Pesticide Regulation, personal communication).

Methods

Study area

California collects pesticide use data in a unique way: it requires full Pesticide Use Reporting (PUR). In 1990, the California Department of Pesticide Regulation (DPR) started to collect data on commercial pesticide applications (Kegley et al., 2000). Every pesticide active ingredient applied by a commercial applicator or a grower must be reported. The information is collected at a resolution of one square mile and includes the name and amount of the chemical applied, the exact geographic location of the application, the planted and treated acreage, the site name (usually crop type) on which the application occurred and the date of application. Inert ingredients and home and garden pesticide applications are not subject to reporting. The database obtained is quite large: it contains around 2-3 million records per year (Kegley et al., 2000). Every year since 1990, these data as well as a report on pesticide use are released on DPR website. California PUR system represents an incomparable source of information on pesticide use.

Within California, my study was restricted to the Central Valley. Because the Valley has relatively little variation in landcover types (i.e. agriculture vs. forest areas), elevation and climate, few other environmental variables would be expected to have strong effects on bird richness. The Central Valley of California (Figure 1), also called the Great Valley, is a large alluvial plain. It extends for more than 725 km from Northwest to Southeast (Small, 1974). It is as much as 128 km wide in some places between the Sierra Nevada on the East and the Coast Range to the West (Small, 1974). In California, ca. 60% of the agriculture is carried out in the Central Valley (Small, 1974).

The Central Valley is a relatively dry area. Almost 100% of the land in agriculture in this area is under irrigation (Baryohay Davidoff, California Department of Water Resources, personal communication). A large variety of crops are grown in the Central Valley. Fruit, nut and vegetable crops, including tomatoes, grapes, almonds, carrots, walnuts, oranges, as well as rice, cotton and alfalfa account for most of the agricultural production (Kegley et al., 2000).

Bird abundance and species richness

Bird abundance and species richness were calculated using Breeding Bird Survey (BBS) data from 1992 to 2001. BBS data were obtained from the United States Geological Survey (USGS) Patuxent Wildlife Research Center website (http://www.pwrc.usgs.gov/). The BBS was formally launched in 1966. It is carried out in the US by the United States Department of the Interior. By 1994, around 3700 BBS routes were active across Canada and United States and more than 2750 are surveyed annually (Peterjohn, 1994). Each year during the breeding season (June for most of the United States) routes are surveyed by volunteers skilled in avian identification (Peterjonh, 1994; Rich et al., 1986). Each BBS route is about 40 km long with 50 stops located at 0.8 km interval. A three-minute point count is conducted at each stop during which the observer records all birds seen or heard within a radius of 0.4 km. Routes are generally located along secondary roads and randomly within physiographic strata, a stratification intended to reduce variability in counts associated with turnover in habitat (O'Connor et al., 2000). Surveys are conducted only during suitable weather conditions; precipitation and high winds are avoided because these conditions reduced the number of species and individuals counted along the routes (O'Connor et al., 2000). The data are available aggregated over groups of 10-stops (and, since 1995, at every stop).

I adjusted these observed abundances for interspecific differences in detectability using correction factors provided by Peter Blancher (Canadian Wildlife Service, Environment Canada) (Butcher et al, 2003; Rosenberg and Blancher, 2003) (Appendix 1). These factors adjust bird abundance in two ways. First, they correct abundance for the maximum distance at which the species can be seen or heard relative to the nominal 0.4 km radius sampled (including the radius of its movement during three minutes). Second, since species detectability varies with the time of day (some species declining from a dawn chorus, and others peaking after sunrise or later in the morning), and therefore among stops, correction factors also correct for the time of day (it adjusts counts to the maximum time of detection). For an example of calculations, see Appendix 2.

Detectability correction factors were based upon averages over all North American sites. To test whether the warm and dry climate of California affects time of day detectability in a different way than the North American average, I calculated detectability factors using Californian data only (following Rosenberg and Blancher, 2003), and I compared the estimated correction factors to those for the whole continent. I found a weak significant difference between the two data sets except for a few species whose sample size in California was very small (Appendix 3). I therefore used North American values for all species.

I analyzed five aspects of the bird abundance – pesticide use relationship. First, I used the total abundance of the 95 species of birds (out of a total of 187 species observed) that were sufficiently abundant to calculate corrected densities (Appendix 4). In practice, this meant that I included all birds present on at least two groups of 10-stops. These species together constituted ca. 93% of the total bird abundance. I summed the total corrected abundance of the 95 species for each group of 10-stops for a given year.

For the second analysis, I limited the sample to common species (i.e., present on at least 20% of the route-segments) associated with agriculture as defined by Small (1974). This included 25 species (Appendix 5). I summed the total corrected abundance of these 25 species for each group of 10-stops for a given year.

For the third analysis, species were separated into foraging guilds using the 95 species (Ehrlich, 1988; De Graaf et al., 1985). I distinguished 7 categories: carnivores, frugivores, granivores, herbivores, insectivores, omnivores and waterbirds (crustaceovores and piscivores). I then summed the total corrected number of individuals per guild at each group of 10-stops for a given year.

For the fourth analysis, I considered the corrected abundance of the 95 individual species at groups of 10-stops for a given year. Finally, for the fifth analysis, I considered the 13 bird species, among the 95 included in the study, that are significantly in decline in California over the past 30 years (Appendix 6), based on trends reported by the USGS Patuxent Wildlife Research Center website (http://www.pwrc.usgs.gov/).

Species richness was obtained by tallying the number of bird species present per group of 10-stops per route for a given year using all 187 species. I also summed the number of guilds present per group of 10-stops per route per year.

Breeding Bird Survey (BBS) routes

A shapefile of the Breeding Bird Survey (BBS) routes was obtained from the National Atlas of United States website (http://www-atlas.usgs.gov/). The BBS routes map layer was compiled by the United States Geological Survey (USGS) Patuxent Wildlife

Research Center. For the purpose of the study, I chose BBS routes that passed through at least one square mile of land in cultivation within the study area. This gave a total of 27 routes (since each route is not surveyed every year, the sample size varies from year to year. See appendix, 7). Paper maps for 25 of these routes were obtained from the USGS Patuxent Wildlife Research Center. I compared the digitized routes with the paper maps ones when both were available to make sure that they were accurate.

The stops on the 27 routes were digitized using ArcView 3.2a. There are a total of 50 stops per route. For most routes, stops are located at 0.8 km intervals but this is not always the case. For 18 of the 27 routes, stops were indicated on the paper maps. For these routes, I therefore used the paper maps to find the exact position of the stops and to digitize them. For the 9 other routes, I assumed that the stops were located 0.8 km apart. I also used the paper maps to find the starting point of the routes.

I then produced a map with buffer zones of 0.4 km radii around BBS stops using ArcView 3.2a. For all of the analyses that follow, the unit of sampling is the pooled buffer zones around a group of 10 BBS stops (area = 5.0 km^2, n = 27).

Habitat

Because some crops support more wildlife than others, I controlled for landcover type. I distinguished five landcover types: 1) crops composed of trees or shrubs (e.g., apple, pear, peach, etc.), 2) wide row crops (e.g., carrot, onion, lettuce, etc.), 3) narrow seeded (cereal) and forage crops (e.g., wheat, alfalfa, barley, etc.), 4) native vegetation, and 5) urban areas. I derived the habitat data from two sources: from aerial photos and from the pesticide database.

To estimate the proportion of each landcover type per sample unit (i.e. per group of ten stops), I began with the Land Use Survey data from the California Department of Water Resources (http://www.waterplan.water.ca.gov/landwateruse/landuse/luindex.htm). The survey is based on aerial and satellite photos. It is done by county and there are four or more counties surveyed per year. In general, counties are surveyed every seven to ten years, although counties with major agricultural development are surveyed more often than the other counties. Resulting digital maps (shapefiles) have a resolution of ca. 0.2 ha. For counties with more than one survey, I chose the most recent map.

Since the Land Use Survey was not carried out every year, I had to assume that the proportions of the five landcover types within the buffers around a group of ten stops remained more or less constant during the study period. I tested this assumption for three counties that were surveyed twice during the years of the study for 2337 quads (Appendix 8). Non-agricultural landcover types, i.e. urban and native vegetation, were grouped for the purpose of this testing because the resolution of these landcover types is poor (the main emphasis and detail of the surveys is agricultural land). I found that non-agricultural areas and orchards remained reasonably constant during the study period ($R^2 = 0.835$ for non-agricultural areas and $R^2 = 0.783$ for orchards, $n = 2337$, $p < 10^{-15}$). Therefore, I estimated acreages for non-agricultural areas (urban area and native vegetation) and orchards for the entire study period by overlaying the buffer zones and the Land Use Survey maps. In contrast, the proportion of 10-stop segments in wide row and cereal and forage crops did not remain as constant from year to year ($R^2 = 0.545$ for wide row crops and $R^2 = 0.155$ for large and forage crops, $n = 2337$, $p < 10^{-15}$). Therefore, I estimated coverage of these crops from acreages recorded yearly in the pesticide database for those square mile areas intersecting the wide row and cereal and forage crop portions of the buffer zones.

The amounts of each of the five landcover variables (orchards, wide row crops, cereal and forage crops, urban areas and native vegetation,) estimated to be within the buffers were then summed per group of 10-stops. Two indices of habitat diversity were also calculated. The first one is simply the number of different landcover types per group of 10-stops. The second is a Shannon-Wiener diversity index of the landcover calculated for each group of ten stops:

$$1.1 \qquad H = -\sum_{i=1}^{5} p_i \ln(p_i)$$

Where:

H = Shannon-Wiener diversity index of the landcover for a group of ten stops

i = 1 to 5 landcover types (orchards, wide row crops, cereal and forage crops, urban areas, native vegetation)

p_i = is the proportion of a given landcover type for a group of ten stops

Pesticide data

Pesticide data were provided by the Pesticide Action Network (PAN), North America for the years 1992 to 2001. These data were collected by the California Department of Pesticide Regulation (DPR). The database contains information on the types, the amounts and geographic locations of pesticides used for a given year at a resolution of one square mile (about 2.6 km^2). See appendix 9 for a list of the 20 most used pesticides in the Central Valley of California for the years 1992 and 2001.

Two types of pesticide use indices were derived. First, I calculated the area treated with insecticides, herbicides and fungicides within the buffers surrounding a group of 10-stops as a crude measure of overall treatment intensity. To do this, I estimated the ratio of area treated to area planted within the square-mile quadrats reported by the California Department of Pesticide Regulation. The total area treated could exceed one square mile if there had been multiple applications of pesticides. I then overlayed the BBS stop buffers, the square mile quadrats, and the Land Use Survey maps (Appendix 10) and I calculated the area of the buffer that is under cultivation (including orchards, wide row and cereal and forage crops). A given buffer may partly overlap as many as four different square mile quadrats. I then summed the resulting indices per group of 10-stops. In summary, pesticide use indices were calculated as follow for fungicide, herbicide and insecticide use:

1.2 $$P_c = \sum_{j=1}^{10} \sum_{i=1}^{4} \frac{T_i}{C_i} \bullet B_{ij}$$

Where:

P_c = cultivated area in the buffers around 10 stops that are treated with pesticides

T_i = area in square mile i that is treated with pesticides

C_i = area in square mile i that is cultivated

B_{ij} = area in square mile i and in the buffer around stop j that is cultivated

The non-cultivated area treated with pesticides was calculated similarly and added to P_c. I did not distinguish between agricultural and non-agricultural applications (I summed both together) for these calculations although non-agricultural applications were very small in comparison to agricultural applications. To estimate the use of pesticide per buffer, I assumed that with any given buffer, the proportion of the area in cultivation that is exposed to pesticides is the same as it is in the square mile in which the buffer is located.

For these indices, I ignored the identity or application rates of the products within pesticide classes (fungicides, herbicides, insecticides); I assumed that a single application of one pesticide product was equivalent in its toxicity to the pest organism to any other and that growers used the appropriate dose of a given product to achieve pest control. To build these indices in that fashion is logical for insecticides and herbicides where the indirect impact on birds can be assumed to be through removal of insect biomass or vegetative cover. For fungicides however, the assumption that all applications are equivalent does not hold as well since any impact on birds is likely to be through direct chronic toxicity rather than through removal of fungal organisms. Unfortunately, there is no other choice here because systematic information on the chronic or reproductive toxicity of fungicides is lacking. This index is therefore the weakest.

The second type of pesticide use index was one of direct toxicity to birds. It was based on insecticide applications only and was calculated using a probabilistic model developed by Mineau (2002a,b). This empirical model gives the probability of bird mortality following application of a given insecticide as a function of the 5% hazardous dose (a measure of oral toxicity) (Mineau et al., 2001), the Henry's law constant (a crude measure of the volatility), the dermal toxicity index (a measure of dermal exposure) and the application rate of this given insecticide. The probability of a kill was multiplied by the area treated in the square mile to estimate the number of hectares that presented a risk of bird mortality due to an insecticide application. The resulting acute toxicity index is in units of "bird kill hectares". The "bird kill hectares" were then summed over each square mile quadrat to estimate the proportion of hectares at risk within a square mile. In summary, I calculated the acute toxicity index using the equation 1.2 by replacing T_i with bird kill hectares summed over the square mile quadrat. Once again, agricultural and non-agricultural applications were summed. Toxicity data were not available for solvents, emulsifiers, or natural products, which are assumed to have fairly low toxicity to birds (Appendix 11). I also had to assume a negligible risk for two products suspected to be toxic to birds because of their mammalian toxicity (emamectin benzoate and indoxycarb), but for which reliable data were not available to me. Applications of these two products accounted for less than 1% of the total insecticide applications. Acute toxicity factors were not determined for herbicides or fungicides. Relative to insecticides, few of these products are sufficiently toxic to give rise to acute lethal effects.

Pesticide indices were then summed for particular periods, relative to the dates when the BBS routes were surveyed for each year (obtained from the USGS Patuxent Wildlife Research Center website, http://www.pwrc.usgs.gov/) in order to obtain short- and long-term pesticide use indices. Short-term indices correspond to applications that were made from March to the BBS survey date. For example, if I was looking at bird abundance and species richness of 2001, the corresponding short-term pesticide use was the sum of pesticide applications that were made from March 2001 to the 2001 BBS survey date. Long-term indices were the sum of applications that were made during the two year preceding the BBS survey date. Therefore, for bird abundance and species richness of 2001, the corresponding long-term pesticide use was the sum of pesticide applications that were made from March 1999 to the 2001 BBS survey date. Consequently, they were no long-term indices for the year 1992 and 1993. I obtained seven pesticide use variables: short-term avian toxicity, long-term avian toxicity, long-term area treated with fungicides, short-term area treated with herbicides, long-term area treated with herbicides, short-term area treated with insecticides and long-term area treated with insecticides (Table 1). I did not derive a short-term index for fungicides because they usually have low acute toxicity to birds (like herbicides). Although some fungicides may have effects on food supply, these are not common. Therefore, I did not test for such effects. However, repeated (long-term) exposures may have adverse effects (Roperto and Galati, 1998) including reproductive effects (Mineau et al., 1994) on birds.

Topography and climate

To control for variations in topography, I obtained a global digital elevation model (DEM) from the USGS Land Processes and Distributed Active Archive Center (http://edc.usgs.gov/). The image has a horizontal grid spacing of 30 arc seconds (approximately 1 km). Using ArcView 3.2a, I extracted the elevation of each BBS stop. I then calculated mean elevation and variance in elevation for each 10-stop segment.

To control for variations in climate, I obtained temperature and precipitation data from the National Oceanic and Atmospheric Administration (NOAA) website (http://www.noaa.gov/). The data consisted of mean monthly temperature and total monthly precipitation from 1992 to 2001 for 395 stations across California. I calculated mean annual temperature and mean annual precipitation for each station. Using the DEM, I adjusted temperature values to sea level (because temperature decreases of about $1^{o}C$ at every 100 meter of elevation). Using ArcView 3.2a, I then interpolated maps of both temperature and precipitation. I extracted temperature and precipitation values for each stop and I then back-adjusted the temperature data to the true elevation. I calculated mean temperature and mean precipitation for each 10-stop segment for every year.

Statistics

Before analysis, all pesticide and habitat variables were transformed to be approximately normal using Systat 10. I then tested for spatial autocorrelation. Moran's I was calculated for abundance and species richness using Rookcase software (Sawada, 1999). Moran's I is a standard measure, similar to a correlation coefficient, of the strength of the spatial (linear) association between the value of a variable at one location and its value at neighboring locations.

Pesticide use variables proved to be strongly collinear, as were the environmental variables. I therefore did three principal component analyses (PCA): one for the seven pesticide variables (short-term avian toxicity, long-term avian toxicity, long-term area treated with fungicides, short-term area treated with herbicides, long-term area treated with herbicides, short-term area treated with insecticides and long-term area treated with insecticides), one for the four physical environment variables (temperature, precipitation, mean elevation and variance in elevation), and one for the seven landcover variables (orchards, wide row crops, cereal/forage crops, urban areas, native vegetation, number of different landcover and Shannon-Wiener landcover diversity index). Using the principal components of these PCAs, I did stepwise forward multiple and logistic regressions on the total abundance and the 95 individual bird abundance/presence.

Results

Spatial autocorrelation

Spatial autocorrelation in the dependant variables decreases to zero after a distance of 40 km (Figure 2). As the length of a route is around 40 km, the first and last group of ten stops can be considered independent. Routes were always separated by > 40 km and were considered independent one from each other. Consequently, I treated analyses as having 54 independent degrees of freedom (27 routes x 2 segments). Correlations of $r \geq 0.27$ are significant at $p \leq 0.05$ for $n \geq 54$.

Physical environment and landcover

Environmental variables were collinear. I therefore did two Principal component analyses (PCA), one for the physical environment variables (temperature, precipitation and elevation) and one for the landcover variables (cereal and forage crops, wide row crops, orchards, urban areas, native vegetation, number of different landcover and Shannon-Wiener landcover diversity). Physical environment PC-I seems to be related to mean elevation whereas PC-II seems be related to climate (temperature and precipitation) (Appendix 12). Together, these two principal components explain about 75% in the physical environment variability. Landcover PC-I seems to be related to landcover diversity, PC-II to orchards vs. cereal and forage crops, and PC-III to native vegetation (Appendix 13). These three principal components explain around 80% of the variation in landcover.

Avian abundance and diversity do not covary with environmental variables within the Central Valley of California. Correlations between abundance of 95 species, abundance of 25 farmland species and total species richness and PC factors (PC-I and PC-II) representing physical environment are weak and not significant (absolute Pearson's $r = 0.005$ to $r = 0.150$, $n = 54$, $p \geq 0.05$; Appendix 14) if we account for spatial autocorrelation. Relationships with PC factors (PC-I, PC-II and PC-III) representing landcover were similar (absolute Pearson's $r = 0.022$ to $r = 0.246$, $n = 54$, $p \geq 0.05$; Appendix 10). However, two relationships (landcover PC-I and abundance of 25 farmland species and landcover PC-III and species richness) were significant although still relatively weak (absolute Pearson's $r = 0.296$ and $r =$

0.330 respectively, $n = 54$, $p \leq 0.05$). I expected these weak relationships because my study area is relatively uniform.

Pesticide use

Pesticide use indices (for insecticide, herbicide and fungicide) were also highly collinear (Pearson's $r = 0.620$ to $r = 0.998$, $n = 54$, $p \leq 0.05$; Appendix 15). This is not due to an artifact introduced in the calculation, since they are strongly correlated in the original dataset (Pearson's $r = 0.907$ to $r = 0.997$, $n = 10948$, $p \leq 0.05$; Appendix 16). This suggests that areas treated with any one type of pesticide tend to be treated with all three. I therefore did a principal component analysis (PCA) on my seven pesticide use indices. The first two principal components (PC-I and PC-II) explained about 80% of the variance in pesticide use. PC-I was related to the amount of pesticide used and PC-II seems to distinguish between insecticide use on the short-term versus the use of other pesticide types (including insecticide use on the long-term) (Table 2).

Bird abundance

Total abundance of the 95 species depends weakly on the amount of pesticide use (Second-degree polynomial $R^2 = 0.08$, $n = 54$, $p < 0.04$; Figure 3A). Relationship between total abundance of 25 bird species associated with farmland and the amount of pesticide used is similar (Second-degree polynomial $R^2 = 0.10$, $n = 54$, $p < 0.02$; Figure 3B). The relationships with the amount of pesticide used (PC-I) are both moderately peaked: as pesticide use increases, abundance increases too until it reaches a certain point where it starts decreasing. Thus, abundance is highest in areas in which moderate amounts of pesticide are used.

Bird abundance is unrelated to the type of pesticide used. The relationship between abundance of 95 bird species and pesticides PC-II is weak and not significant if we take spatial autocorrelation into consideration ($R^2 = 0.01$, $n = 54$, $p = 0.47$). Again, a similar result is observed between total abundance of 25 bird species associated with farmland ($R^2 = 0.02$, $n = 54$, $p = 0.36$).

Within bird guilds, there are no significant relationships between abundance and the amount or type of pesticide used (PC-I and PC-II) (absolute Pearson's $r = 0.010$ to $r = 0.255$, $n = 54$, $p \geq 0.05$; Table 3). The strongest correlations between pesticides PC-I and guild abundance are for granivorous and insectivorous birds (Pearson's $r = 0.196$ and $r = 0.158$, $n = 54$, $p \geq 0.05$). These two guilds are highly associated with agriculture. These results could therefore reflect a habitat or irrigation effect more than a pesticide one.

Species richness also does not depend on pesticide use. There are no significant relationships with total species richness and the amount (PC-I: Second-degree polynomial $R^2 = 0.02$, $n = 54$, $p > 0.38$) or type of pesticide used (PC-II: $R^2 = 0.01$, $n = 54$, $p = 0.61$). There are also no significant relationships between guild species richness and the amount or type of pesticide used (absolute Pearson's $r = 0.046$ to $r = 0.265$, $n = 54$, $p \geq 0.05$; Table 3).

Individual bird species

In contrast, the presence/absence and abundance of many individual species is statistically related to pesticide use (Tables 4 and 5; Appendix 17 and 18). The number of significant relationships is greater than expected by chance for both presence (proportion test: 26 significant relationships with pesticides out of 95 tested, $p < 10^{-4}$) for pesticides PC-I and abundance (proportion test: 15 significant relationships out of 95 tested, $p < 10^{-4}$) although they generally account for only small amounts of variance (except for few cases).

Most of the species whose presence was negatively related to the amount of pesticide used (PC-I) are non-agricultural (10 of 15, compared to 60 non-agricultural species among 95 within the entire data set, which is less than expected by chance; proportion test, $p = 0.98$). Non-agricultural species seems to be more present where few pesticides are used. Because habitat type was included in my models and because the correlations between treated area and planted area are relatively small (Pearson's $r = 0.073$ to $r = 0.479$, $n = 10948$, $p \leq 0.05$; Appendix 12) for the three types of pesticide (fungicide, herbicide and insecticide), I can conclude that the presence of these species is negatively related to pesticides, and not simply to agricultural areas.

In opposition, about half (6 out of 11 which is more than expected by chance; proportion test, $p < 10^{-4}$) of the species whose presence correlated positively with the amount of pesticide (PC-I) are agricultural. Farmland species are therefore more likely to be present where pesticides use is high. Again, because I controlled for habitat type, I can conclude that it is an effect of pesticide use and not agricultural areas although more intensively farmed areas receiving pesticides are probably more irrigated also which may be a positive factor for birds.

Presence of non-agricultural bird species is negatively related to the use of insecticides on the short-term (PC-II), while presence of farmland bird species is negatively related to the use of other types of pesticides (herbicides, fungicides and insecticides used on the long-term) (PC-II) (Table 4).

The results are quite similar for bird abundances (Table 5). About half (3 out of 7 which is more than expected by chance; proportion test, $p < 10^{-4}$) of the species, whose abundance positively correlated with the amount of pesticide used (PC-I), are agricultural. Abundance of farmland bird species is negatively related to the use of herbicides and fungicides, while presence of non-agricultural ones is negatively related to the use of insecticides (PC-II). Farmland species are not more susceptible than non-agricultural ones to pesticides (Proportion test: 35 farmland bird species out of 95 species, $p < 10^{-4}$).

Bird species significantly declining in California

Of the 13 bird species among the 95 included in my study whose abundance is significantly declining in California (USGS Patuxent Wildlife Research Center), the abundance of seven is significantly although weakly related to pesticides (Table 6 and Appendix 19). This is more than expected by chance (proportion test, $p < 10^{-4}$). Five out of the thirteen have a negative relationship with the amount of pesticide used (PC-I) (which is more than expected by chance; proportion test, $p < 10^{-4}$) and three are related (one negatively and two positively) to the relative use of insecticides versus of herbicides and fungicides (PC-II) (which is more than expected by chance; proportion test, $p < 10^{-4}$). Of the five species that are negatively related to the amount of pesticide used, four are associated with farmland (which is more than expected by chance; proportion test, $p < 10^{-4}$).

Discussion

Using the best available records of pesticide use and bird abundance, I was unable to detect more than a marginal effect of pesticide use on bird species richness or total bird abundance at the scale that I studied, i.e. with a spatial grain of 5.0 km^2 (group of 10 stops). The abundances of several individual species were related significantly to patterns of pesticide use. However, these relationships were also generally weak. Moreover, they were sometimes positive, sometimes negative, without obvious patterns.

My hypotheses are therefore rejected at this spatial scale. Pesticide use does not seem to affect bird species richness and abundance either through short-term direct mortality (hypothesis 1) or through long-term depletion of food supply (hypothesis 2). Also, specific bird guilds do not seem to be more affected by their corresponding type of pesticide (hypothesis 3).

Why is the abundance-pesticide relationship so weak? A weak abundance-pesticide relationship would be observed if: 1) the variance in either abundance and richness or pesticide use were small; 2) error variance in either variable were large; 3) pesticide effects on bird abundance were manifested at some spatial scale other than the one studied here; 4) pesticides used today have negligible impact on bird abundance and species richness; 5) other environmental variables had much stronger effects on bird abundance.

Weak observed abundance-pesticide relationships are not due to lack of variation in abundance or pesticide use. Pesticide use varies strongly spatially within my study area (C.V. = 0.55 to C.V. = 1.41 for the seven pesticide use variables). Total bird abundance of the 95 bird species included in the study also varies considerably (C.V. = 0.65). Therefore, it is not because there was no variance to explain that I was unable to detect any strong effect of pesticide use on total bird abundance.

Error in the pesticide variables is also unlikely to have led to weak relationships, but errors in estimates of bird abundance may have done so. Interannual variability in abundance and pesticide use gives an upper bound to the error of estimation of these variables, since it includes pure error plus real interannual change. Interannual variability in pesticide use for a given group of 10-stops is small, averaging about 7%. Bird abundance, in contrast, varies substantially (about 35%), from year to year for a given group of 10-stops. This suggests that error in the estimates of abundance may mask abundance-pesticide relationships. To test if this were the case, I related mean total abundance of the 95 bird species to mean pesticide use (PC-I). Taking the mean over the 9-year study period should reduce much of this noise. However, I obtained approximately the same results: a polynomial relationship with $R^2 = 0.084$ ($n = 103$, $p > 0.05$). Therefore, the interannual variability does not hide the relationship between total bird abundance and pesticide use: the relationship is truly weak.

It is possible that the spatial scale at which the study was done was not the spatial scale at which effects occur. The grain of my analysis was approximately 5.0 km^2. Fuller et al. (1995) found that large changes in some bird species distribution were not evident at a scale of 10.0 km^2 although these species showed large population declines at the country scale (Britain). On very local spatial scales (i.e., on a farm following a single application), there is evidence that bird mortality can be frequent (Mineau, 2002a) but it is not obvious that this leads to net changes in diversity or population densities. It is possible that pesticides use affects broader scale metapopulation dynamics.

Metapopulation dynamics over broad spatial scales could potentially hide the relationships at the spatial scale that I studied. I focused primarily on areas with at least some agricultural development. Small, fragmented habitats in agricultural landscapes may be demographic sink (Froppen et al., 2000). These sinks may persist, even with exposure to pesticides, if there is immigration from near-by source areas (Brawn and Robinson, 1996). Despite the fact that, without this constant immigration from the source, these sink populations would eventually disappear, sinks may support very large populations (Murphy, 2001; Pulliam, 1988). Therefore, these local sink populations are loosing individuals but the effect is hidden by the constant arrival of individuals from the source populations. In the case of the arid Central Valley, it is possible that attraction to cultivated areas as a result of irrigation out-weighs any pesticide effects.

There is some evidence that the relationship between pesticide use and bird abundance can be detected at a broader spatial scale. Mineau and Whiteside (in prep.) correlated the use of toxic insecticides to the decline in farmland bird species among states in the United States. Also, Mineau et al. (2005) found that several agricultural species correlated negatively with the intensity of granular insecticide treatment on the Canadian Prairies at the scale of the large Census Agricultural Regions.

The improvement of pesticide regulations over the past few years may have resulted in the substitution of toxic products by less toxic ones. These less toxic products may have negligible effect on bird species richness and abundance or be used in concentrations that cause relatively little impact. The effect of moderate pesticide use may be compensated by an increase in habitat heterogeneity or in habitat suitability because of greater water availability, due to irrigation, in an otherwise arid climate. Heterogenous agricultural landscapes are obtained by an amalgamation of different habitats (arable fields, pastures, forests, etc.) within the extent of the farm (Weibull et al., 2003). Agricultural landscape heterogeneity has been observed to be more important than farming practices for birds (Weibull et al., 2003). It sometimes explains more of the variability in bird species richness (Benton et al., 2003; Weibull et al., 2003; Jobin et al., 1996a) than any other factor.

Factors other than pesticide use may also be responsible for the decline seen in some bird species (Campbell and Cooke, 1997). The intensification of agriculture in general has often been pointed out as a potential cause of these declines (Chamberlain et al., 2000; Siriwardena et al., 1998; Fuller et al., 1995). According to Fuller et al. (1995), different species would be declining for different reasons. For example, in Britain, the decline of some species is associated with particularly cold winters and increased level of predation (Fuller et al., 1995).

There are several other possible explanations as to why I did not detect a strong effect of pesticide use. First of all, the use of pesticides may induce a change in bird community composition rather than a change in total abundance. In other words, species found in heavily pesticide sprayed areas may not be the same as the species found in less sprayed ones. Second, perhaps the rare species that I excluded from the analysis are, in fact, the most sensitive to pesticides and would have been better indicators. Third, as noted by Chamberlain et al. (2000), there may be a time lag between the use of pesticides and their observable effects on bird abundance and species richness. However, this study was conducted over a 10-year period, from 1992 to 2001, which is long, relative to bird generation times. It seems unlikely that time lags are an issue in this case.

Since the areas treated with insecticides, herbicides and fungicides are highly correlated, it was impossible to distinguish among my toxicity indices: they all measure more or less the same thing. Chamberlain et al. (2000), in a study conducted in England and Wales, also found a high correlation between their agricultural variables including those of pesticide use. The Principal Component Analysis permitted me to distinguish the effects of amount of pesticide used from the effects of types of pesticide used only to a limited degree. This Collinearity among rates of pesticide use makes it essentially impossible to distinguish short- versus long-term effects, or effects of different classes of pesticides. Preliminary analyses showed that the relationships between individual pesticide use indices and bird abundance and species richness were in general better than the relationships with the two pesticides PC factors ($R^2 = 0.19$ to $R^2 = 0.38$, $n = 54$, $p \leq 0.05$). This suggests that the Principal Component Analysis limited my resolution.

Even with the best pesticide dataset, it remains difficult to separate the effect of pesticides from the effect of agricultural practices in general (irrigation, fertilizer input, etc.). The apparent positive effect of pesticides may therefore reflect an effect of other agricultural practices beneficial to birds more than an effect of pesticide use. It is clear that farmland bird species are attracted to agricultural land but it is unlikely that they benefit from pesticide usage.

Correlations with habitat were stronger than correlations with pesticides suggesting that, at this spatial scale, habitat may be more important than pesticide use. As agriculture is introduced, there is an increase in productivity, in habitat diversity and in water availability. These factors may be strongly attractive to birds which could explain why abundance is higher where pesticides are used.

The major limitation of this study is probably the Breeding Bird Survey (BBS) data. These are the most extensive data available in North America on bird abundance and species richness. Nonetheless, several biases affect the quality of the data gathered (O'Connor et al., 2000; Jobin et al., 1996b). Differences in observers' abilities, weather conditions and survey dates are some example of biases (O'Connor et al., 2000; Jobin et al., 1996b).

California Pesticide Use Reporting database is amongst the most comprehensive pesticide database throughout the world. Although database managers had developed a method for identifying and processing data outliers, there were still some major problems with the database (Pesticide Action Network website; Pesticide Action Network Germany, 2002; Liebman et al., 1997). There are frequent errors in acreages reporting, which make calculations of treated and planted surfaces difficult. The smallest unit in Pesticide Use Reporting is one square mile (approximately 2.6 km^2). I therefore have no information on what is going on at the field level, i.e. it does not reflect the size and the location of the fields, which can lead to erroneous estimations of the intensity of pesticide use (Pesticide Action Network Germany, 2002). Inaccuracy of pesticide use reporting from growers can also be a major source of bias. Finally, the habitat data that I used in the present study are not available yearly. This could also introduce some variability.

Conclusion

This study was undertaken to test for a relationship between pesticide use and bird species richness and abundance at a relatively fine spatial scale. I did not detect a strong effect of pesticide use on birds at that scale suggesting that the effect, if there is one, must be at a broader scale. The high correlations between the seven pesticide indices made the testing of specific pesticide effects difficult. Nevertheless, I was able to test the effect of the total amount of pesticide used on bird species richness and abundance. I found a few significant, but weak, relationships between quantity of pesticide products and bird abundance or species richness. I conclude that pesticides have little impact on bird species richness or abundance at this spatial scale. Different bird species' abundance relates to different aspects of the environment.

Future work should focus on whether pesticides have effects at broader scales, and on the conception of a methodology to assess the effect of pesticide use on bird species richness and abundance.

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Table 1. Hypotheses behind the pesticide use indices.

Index	Hypothesis	References
Avian toxicity on the short-term	Toxic insecticides use on the short-term can cause direct mortality to birds.	Mineau, 2002a; Fry, 1995
Avian toxicity on the long-term	Toxic insecticides use on the long-term can affect bird recruitment by killing youngs.	Fry, 1995
Area treated with fungicides on the long-term	Fungicides are usually of low toxicity to birds. However, repeated long-term exposure may have negative reproductive effects to birds.	Sotherton and Holland, 2003; Roperto and Galati, 1998; Fry, 1995; Mineau et al., 1994; Rands, 1985
Area treated with herbicides on the short-term	Herbicide use on the short-term decreases vegetation cover which decreases bird nesting opportunities as well as food and cover for insects. Therefore, invertebrate populations decrease which decreases food for birds.	Robinson and Sutherland, 2002; Boutin et al., 1999; Wilson et al., 1999; Blus and Henny, 1997; Campbell and Cooke, 1997; Rands, 1985
Area treated with herbicides on the long-term	Herbicide use on the long-term decreases vegetation cover which decreases bird nesting opportunities as well as food and cover for insects. Therefore, invertebrate populations decrease which decreases food for birds.	Robinson and Sutherland, 2002; Boutin et al., 1999; Wilson et al., 1999; Blus and Henny, 1997; Campbell and Cooke, 1997; Rands, 1985
Area treated with insecticides on the short-term	Insecticide use on the short-term decreases invertebrate populations which decreases food for birds.	Robinson and Sutherland, 2002; Blackburn and Wallace, 2001; Wilson et al., 1999; Blus and Henny, 1997; Campbell and Cooke, 1997; Chiverton and Sotherton, 1991
Area treated with insecticides on the long-term	Insecticide use on the long-term decreases invertebrate populations which decreases food for birds.	Robinson and Sutherland, 2002; Blackburn and Wallace, 2001; Wilson et al., 1999; Blus and Henny, 1997; Campbell and Cooke, 1997; Chiverton and Sotherton, 1991; Aebischer, 1990

Table 2. Pesticides PCA component loadings for the first two PC factors. Avian toxicities are a measure of direct toxicity calculated using a probabilistic model from Mineau (2002a,b). The other five indices are simply a measure of treated area. Short-term indices were calculated with data from March to the BBS census date, while long-term indices were calculated with data from the two year preceding the BBS survey date. PC-I seems to be related to the total amount of pesticide used, whereas PC-II is related to the type of pesticide used: insecticide use on the short-term versus other types of pesticide use (including insecticide use on the long-term).

Pesticide variables	PC-I	PC-II
Avian toxicity on the long-term	0.855	-0.357
Avian toxicity on the short-term	0.877	-0.181
Fungicide use on the long-term	0.968	0.216
Herbicide use on the long-term	0.949	0.290
Herbicide use on the short-term	0.872	0.395
Insecticide use on the long-term	0.958	0.275
Insecticide use on the short-term	0.846	-0.264

Table 3. Pearson's correlations between bird guild abundance or species richness and the first two PC factors (PC-I and PC-II) summarizing seven variables measuring pesticide use and toxicity ($n = 528$). Taking into consideration spatial autocorrelation, there are $\geq$ 54 independent degrees of freedom, and therefore, correlations of $r \geq 0.27$ are significant at $p \leq 0.05$.

Guild abundance	PC-I	PC-II
Carnivores	0.092	0.219
Frugivores	0.112	-0.255
Granivores	0.196	-0.102
Herbivores	0.069	0.138
Insectivores	0.158	0.010
Omnivores	0.112	-0.010
Waterbirds	0.130	0.169
Guild Species richness		
Carnivores	-0.069	0.164
Frugivores	-0.134	-0.127
Granivores	0.101	-0.067
Herbivores	0.135	0.265
Insectivores	-0.145	0.100
Omnivores	0.130	-0.054
Waterbirds	0.046	0.200

Table 4. Bird species showing a significant positive or negative relationship between presence/absence and the first two PC factors (PC-I and PC-II) summarizing seven variables measuring pesticide use and toxicity (n = 54). These results are taken from stepwise forward logistic regressions (see Appendix 13). McF R^2 is the McFadden's R^2, a default measure of the strength of a logistic regression. It is analogous to the classical R^2 except that the value is lower: a value of 0.3 or 0.4 is considered high. Species in bold are agricultural bird species (Small, 1974). In all cases, $p \leq 0.05$, assuming 54 independent degrees of freedom.

Pesticide PC-I				Pesticide PC-II			
Negative		Positive		Negative		Positive	
Species	McF R^2	Species	McF R^2	Species	McF R^2	Species	McF R^2
Acorn Woodpecker	0.251	American Bittern	0.358	**American Crow**	0.210	American Bittern	0.358
American Kestrel	0.050	**American Crow**	0.210	**Brewer's Blackbird**	0.115	**American Kestrel**	0.050
Ash-throated Flycatcher	0.199	**American Goldfinch**	0.192	**Horned Lark**	0.117	American White Pelican	0.163
Bewick's Wren	0.178	**American Robin**	0.161	**House Finch**	0.200	Black Tern	0.461
Bushtit	0.102	Black-crowned Night-Heron	0.182	**Song Sparrow**	0.169	Common Moorhen	0.378
House Sparrow	0.300	Blue Grosbeak	0.165	**White-tailed Kite**	0.040	Great Blue Heron	0.059
House Wren	0.109	Great Egret	0.080			Great Egret	0.080
Lark Sparrow	0.057	**House Finch**	0.200			**Northern Mockingbird**	0.095
Lesser Goldfinch	0.095	Mallard	0.126				
Northern Mockingbird	0.095	**Rock Dove**	0.047				
Oak Titmouse	0.146	**Yellow-headed Blackbird**	0.052				
Pacific-slope Flycatcher	0.073						
Song Sparrow	0.169						
White-breasted Nuthatch	0.221						
Wild Turkey	0.119						

Table 5. Bird species showing a significant positive or negative relationship between abundance and the first two PC factors (PC-I and PC-II) summarizing seven variables measuring pesticide use and toxicity (n = 54). These results are taken from stepwise forward multiple regressions (see Appendix 14). Species in bold are agricultural bird species (Small, 1974). In all cases, $p \leq 0.05$, assuming 54 independent degrees of freedom.

Pesticide PC-I				Pesticide PC-II			
Negative		Positive		Negative		Positive	
Species	R^2	Species	R^2	Species	R^2	Species	R^2
Acorn Woodpecker	0.212	American Avocet	0.267	**American Crow**	0.211	American Bittern	0.101
American Kestrel	0.070	**American Crow**	0.211	**Cliff Swallow**		Ash-throated Flycatcher	0.249
Ash-throated Flycatcher	0.249	Common Yellowthroat	0.483	Common Yellowthroat	0.483	Bewick's Wren	0.341
Bullock's Oriole	0.133	Forster's Tern	0.771	**European Starling**	0.187	Black Tern	0.406
California Quail	0.187	**House Sparrow**	0.074	**House Finch**	0.070	Common Moorhen	0.537
Lesser Goldfinch	0.077	Mallard	0.114			Forster's Tern	0.771
Loggerhead Shrike	0.103	**Western Kingbird**	0.074			Gadwall	0.197
Mourning Dove	0.077					Great Blue Heron	0.086
						Lazuli Bunting	0.163
						Mourning Dove	0.077
						Red-winged Blackbird	0.079
						Western Wood-Pewee	0.121

Table 6. Bird species significantly declining in California showing a significant positive or negative relationship between abundance and the first two PC factors (PC-I and PC-II) summarizing seven variables measuring pesticide use and toxicity (n = 54). These results are taken from stepwise forward multiple regressions (see Appendix 15). Species in bold are agricultural bird species (Small, 1974). In all cases, $p \leq 0.05$, assuming 54 independent degrees of freedom.

Pesticide PC-I				Pesticide PC-II			
Negative		Positive		Negative		Positive	
Species	R^2	Species	R^2	Species	R^2	Species	R^2
American Kestrel	0.070			**House Finch**	0.070	**Mourning Dove**	0.077
Bullock's Oriole	0.133					Western Wood-Pewee	0.121
Loggerhead Shrike	0.103						
Mourning Dove	0.077						

Figure 1: Location of the study area in California, United States.

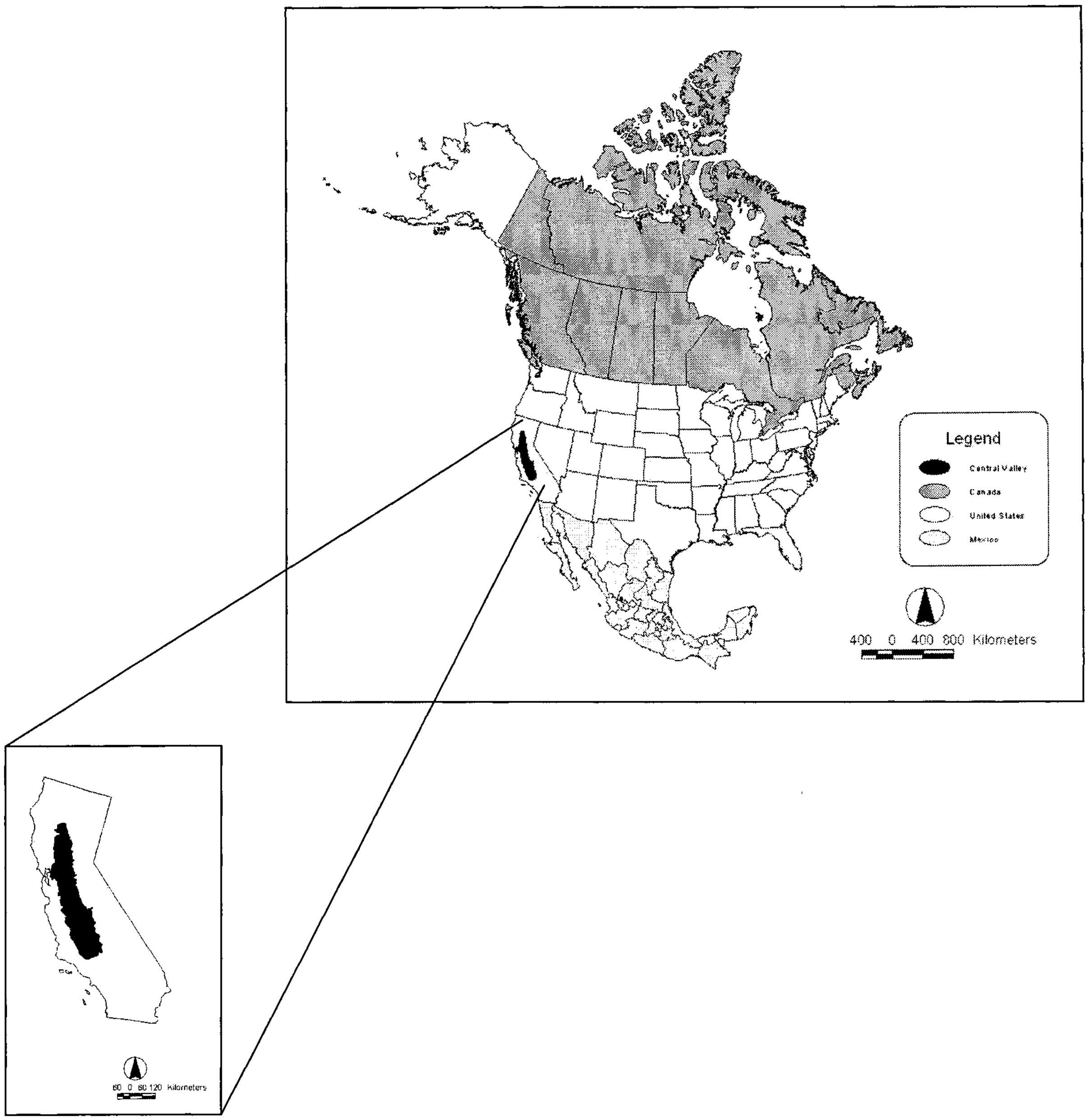
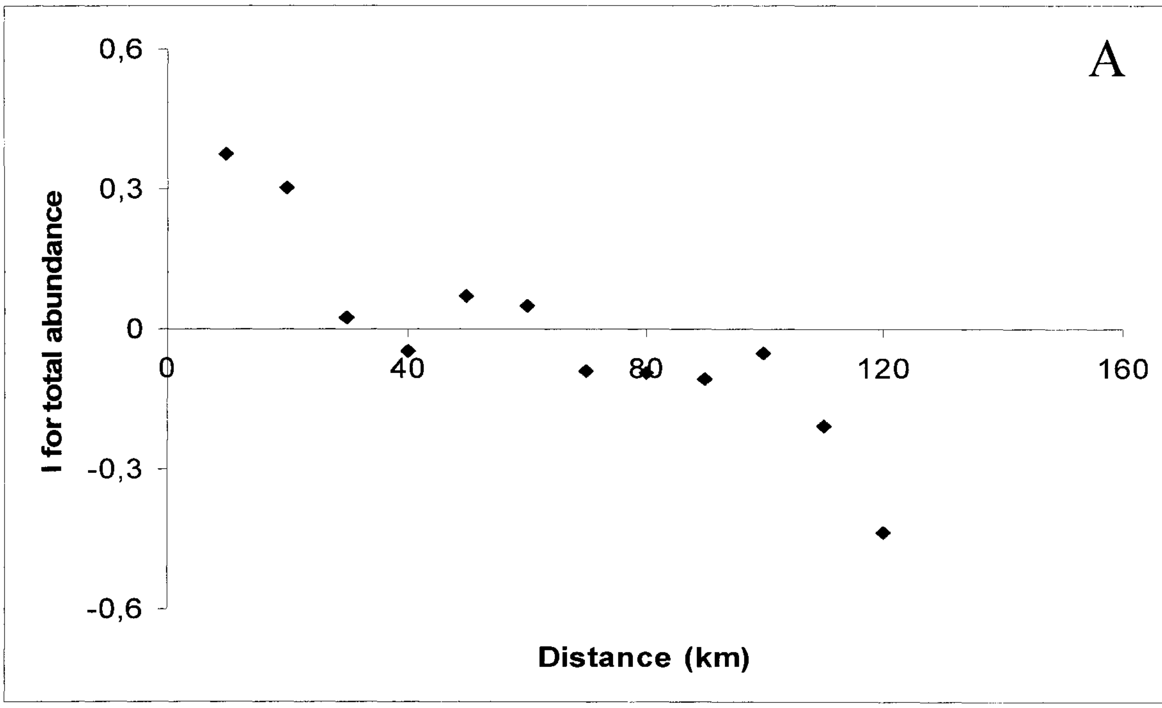

Legend
Central Valley
Canada
United States
Mexico
400 0 400 800 Kilometers

Figure 2. The relationships between: A. Moran's I for total abundance of 95 bird species and distance; and B. Moran's I for species richness of all 187 bird species and distance.


A
0,6
0,3
0
-0,3
-0,6
0
40
80
120
160
I for total abundance
Distance (km)

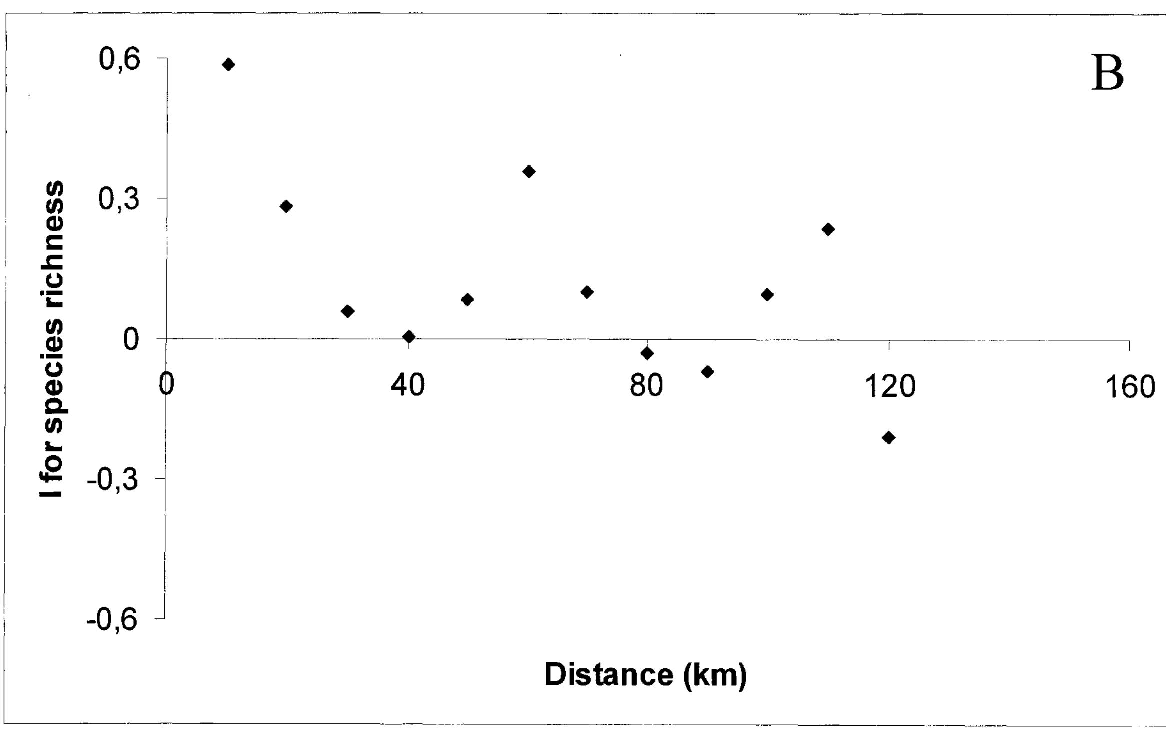
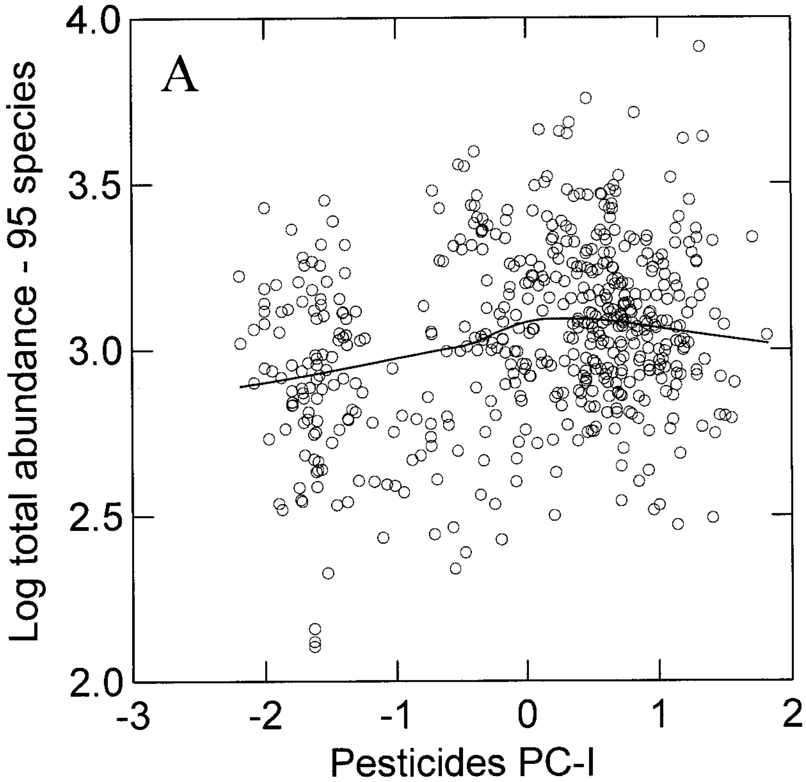
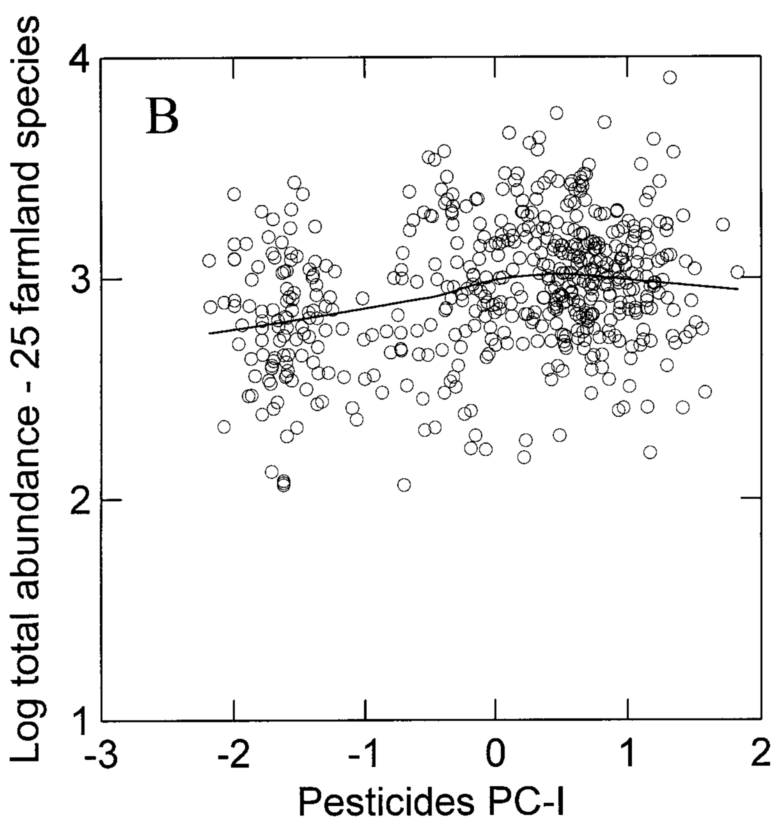

B
0,6
0,3
0
-0,3
-0,6
0
40
80
120
160
I for species richness
Distance (km)

Figure 3. The relationships between: A. log total abundance of 95 bird species and the amount of pesticide used (pesticides PC-I) (Second-degree polynomial $R^2 = 0.08$, $n = 528$, $p < 0.04$); and B. log total abundance for 25 common species associated with farmland and the amount of pesticide used (pesticides PC-I) (Second-degree polynomial $R^2 = 0.10$, $n = 528$, $p < 0.02$). Curves are LOWESS fits, tension = 0.7.


A
Log total abundance - 95 species
4.0
3.5
3.0
2.5
2.0
-3
-2
-1
0
1
2
Pesticides PC-I


B
Log total abundance - 25 farmland species
4
3
2
1
-3
-2
-1
0
1
2
Pesticides PC-I

Appendix 1. Avian detectability correction factors (Butcher et al, 2003; Rosenberg and Blancher, 2003). These factors have been used to adjust Breeding Bird Survey (BBS) abundances because bird species don't have the same level of detectability.

Species	Distance adjustment (relative to 400m)	Time of Day adjustment	1st group of 10-stop adjustment	2nd group of 10-stop adjustment	3rd group of 10-stop adjustment	4th group of 10-stop adjustment	5th group of 10-stop adjustment
Acorn Woodpecker	4	1.25	1.35	1.01	0.82	0.87	1.11
American Avocet	4	1.43	1.74	0.87	0.54	1.38	1.43
American Bittern	1	3.16	0.41	0.76	1.48	2.65	4.80
American Coot	4	1.08	1.14	0.90	0.94	1.12	0.95
American Crow	1	1.55	0.76	0.80	1.03	1.27	1.48
American Goldfinch	4	1.32	2.74	1.10	0.85	0.77	0.80
American Kestrel	4	1.20	1.58	1.05	0.96	0.85	0.83
American Robin	4	2.28	0.71	0.99	1.05	1.17	1.29
American White Pelican	0.25	1.07	0.91	0.93	1.11	1.19	0.92
Anna's Hummingbird	25	1.18	1.63	0.93	0.86	0.97	0.89
Ash-throated Flycatcher	4	1.33	0.82	0.80	0.96	1.26	1.43
Barn Owl	10.24	7.32	0.41	2.48	2.03	1.66	0.97
Barn Swallow	4	1.19	1.69	1.03	0.89	0.85	0.88
Belted Kingfisher	4	1.28	1.42	0.82	0.87	0.99	1.11
Bewick's Wren	4	1.26	0.89	0.86	1.01	1.16	1.17
Black Phoebe	4	1.43	0.87	0.92	0.98	1.11	1.18
Black Tern	0.25	1.38	1.44	1.12	0.97	0.86	0.82
Black-chinned Hummingbird	25	1.30	1.63	0.99	0.89	1.00	0.80
Black-crowned Night-Heron	4	1.49	0.66	0.81	1.01	1.53	1.65
Black-headed Grosbeak	4	1.34	0.83	1.02	1.02	1.06	1.12
Black-necked Stilt	4	1.46	1.33	0.59	1.18	1.25	1.11
Blue Grosbeak	4	1.40	0.79	0.87	1.01	1.17	1.35
Brewer's Blackbird	4	1.23	1.15	0.84	0.93	1.02	1.13
Brown-headed Cowbird	4	1.18	1.42	0.87	0.88	0.96	1.04
Bullock's Oriole	4	1.17	1.05	0.90	0.98	1.05	1.03
Burrowing Owl	4	1.21	1.04	0.92	1.09	1.10	0.89
Bushtit	10.24	1.14	1.40	0.92	0.87	0.96	0.99
California Quail	1	1.43	0.86	0.73	0.93	1.27	1.63
California Towhee	4	2.37	0.57	1.03	1.19	1.33	1.46
Canada Goose	0.25	1.26	1.29	0.80	0.90	1.11	1.04
Cattle Egret	1	1.68	0.77	1.03	1.20	1.04	1.07
Cinnamon Teal	4	1.02	1.12	0.89	0.99	1.02	1.00
Cliff Swallow	4	1.31	2.37	1.16	0.85	0.82	0.76
Common Moorhen	4	1.13	0.79	1.19	1.32	0.73	1.29
Common Raven	0.25	1.30	1.06	0.82	0.93	1.09	1.19
Common Yellowthroat	4	1.15	0.90	0.92	1.01	1.07	1.14
Double-crested Cormorant	0.25	1.34	1.02	1.02	0.64	1.37	1.33
Downy Woodpecker	10.24	1.34	1.58	0.78	0.83	0.98	1.17
European Starling	4	1.19	1.58	0.85	0.86	0.93	1.05

Appendix 1. continued

Species	Distance adjustment (relative to 400m)	Time of Day adjustment	1st group of 10-stop adjustment	2nd group of 10-stop adjustment	3rd group of 10-stop adjustment	4th group of 10-stop adjustment	5th group of 10-stop adjustment
Forster's Tern	0.25	1.23	1.15	0.76	1.19	0.80	1.39
Gadwall	4	1.26	1.30	0.79	0.90	1.13	1.02
Great Blue Heron	1	1.16	1.09	0.87	1.01	1.02	1.05
Great Egret	1	1.68	0.71	0.96	1.28	1.04	1.25
Green Heron	4	1.25	1.31	0.78	0.89	1.00	1.19
Hooded Oriole	4	1.38	1.46	0.92	1.06	1.03	0.76
Horned Lark	4	1.35	0.93	0.96	0.98	1.05	1.10
House Finch	4	1.04	1.00	0.97	1.01	1.01	1.01
House Sparrow	4	1.06	1.09	0.94	0.97	1.00	1.01
House Wren	4	1.13	0.96	0.90	0.95	1.05	1.19
Killdeer	4	1.17	1.23	0.86	0.88	0.98	1.16
Lark Sparrow	4	1.16	1.24	0.92	0.92	0.99	0.98
Lazuli Bunting	4	1.34	0.79	0.97	1.08	1.18	1.08
Lesser Goldfinch	4	1.17	1.36	0.94	0.98	0.94	0.90
Loggerhead Shrike	4	1.19	1.44	0.86	0.89	0.94	1.05
Mallard	4	1.21	0.96	0.83	0.97	1.04	1.30
Marsh Wren	10.24	1.93	0.71	0.78	1.36	1.21	1.31
Mourning Dove	4	1.31	0.84	0.82	0.99	1.19	1.37
Northern Harrier	1	1.29	1.79	1.08	0.95	0.79	0.84
Northern Mockingbird	4	1.08	1.00	0.94	0.98	1.02	1.06
Northern Pintail	4	1.25	1.23	0.96	1.00	0.98	0.89
Northern Rough-winged Swallow	4	1.19	1.58	0.97	0.90	0.92	0.88
Nuttall's Woodpecker	4	1.30	1.25	0.78	1.02	1.03	1.04
Oak Titmouse	4	1.18	1.44	0.96	0.96	0.91	0.88
Pacific-slope Flycatcher	10.24	1.12	0.89	0.94	1.02	1.07	1.11
Pied-billed Grebe	4	1.63	0.66	0.89	1.09	1.34	1.45
Redhead	4	1.15	1.44	0.88	0.98	0.85	1.02
Red-shafted Flicker	4	1.17	1.65	0.90	0.88	0.94	0.93
Red-shouldered Hawk	4	1.19	1.19	0.90	1.12	0.98	0.88
Red-tailed Hawk	0.25	1.61	1.64	1.09	1.03	0.90	0.72
Red-winged Blackbird	4	1.13	1.12	0.89	0.93	0.98	1.12
Ring-necked Pheasant	1	2.08	0.53	0.69	1.14	2.20	3.16
Rock Dove	4	1.59	2.59	0.69	0.71	0.97	1.39
Snowy Egret	1	1.16	0.94	0.73	1.47	0.88	1.31
Song Sparrow	4	1.40	0.91	0.98	1.01	1.04	1.08
Spotted Towhee	4	1.96	0.65	0.94	1.16	1.28	1.30
Swainson's Hawk	0.25	1.26	1.31	1.02	0.93	0.98	0.87
Tree Swallow	4	1.10	1.14	0.99	0.94	0.94	1.01
Tricolored Blackbird	4	1.32	1.31	1.34	0.84	2.41	0.53
Turkey Vulture	0.25	2.61	4.86	2.75	1.61	0.69	0.43
Violet-green Swallow	4	1.29	1.22	1.16	0.78	0.90	1.07
Western Bluebird	4	1.36	1.03	0.92	0.98	1.05	1.03

Appendix 1. continued

Species	Distance adjustment (relative to 400m)	Time of Day adjustment	1st group of 10-stop adjustment	2nd group of 10-stop adjustment	3rd group of 10-stop adjustment	4th group of 10-stop adjustment	5th group of 10-stop adjustment
Western Kingbird	4	1.55	0.89	0.99	1.05	1.05	1.04
Western Meadowlark	1	1.23	0.88	0.83	0.96	1.14	1.34
Western Scrub-Jay	4	1.14	1.10	0.90	0.89	1.02	1.13
Western Wood-Pewee	4	1.22	0.96	0.95	0.99	1.03	1.09
White-breasted Nuthatch	10.24	1.31	1.65	0.81	0.82	0.99	1.08
White-faced Ibis	1	2.72	0.44	1.06	1.30	1.53	2.63
White-tailed Kite	1	1.47	1.01	0.89	1.23	0.91	1.04
Wild Turkey	4	1.47	0.73	0.81	1.04	1.19	1.68
Wilson's Warbler	10.24	1.14	1.20	1.00	1.01	0.96	0.89
Wood Duck	4	1.80	1.14	1.18	0.42	1.95	2.70
Wrentit	4	1.63	0.84	0.77	1.19	1.14	1.26
Yellow Warbler	4	1.09	0.96	0.96	0.98	1.01	1.10
Yellow-billed Magpie	1	1.69	0.91	0.77	0.97	1.36	1.19
Yellow-headed Blackbird	4	1.45	1.01	0.73	0.97	1.21	1.26

Appendix 2. Example of calculations for the avian detectability correction factors.

Suppose we want to adjust the abundance of Western Kingbird over the five groups of ten stops. Suppose the abundances are 9, 18, 14, 9, 8 for the first, second, third, fourth and fifth group of 10-stops respectively. From the table in Appendix 1, we know that the detectability correction factors are:

Species	Distance adjustment (relative to 400m)	Time of Day adjustment	1st group of 10-stop adjustment	2nd group of 10-stop adjustment	3rd group of 10-stop adjustment	4th group of 10-stop adjustment	5th group of 10-stop adjustment
Western Kingbird	4	1.55	0.89	0.99	1.05	1.05	1.04

Therefore, for the first group of 10-stops, the adjusted abundance would be:

Adjusted abundance = Distance adjustment x Time of day adjustment x 1st group of 10-stop adjustment x abundance for the 1st group of 10-stops

Adjusted abundance = 4 x 1.55 x 0.89 x 9 = 49.7

We would proceed the same way for the four other groups of 10-stops.

Appendix 3. Comparison between time of day adjustment factors calculated using data from California, versus from North America as a whole.

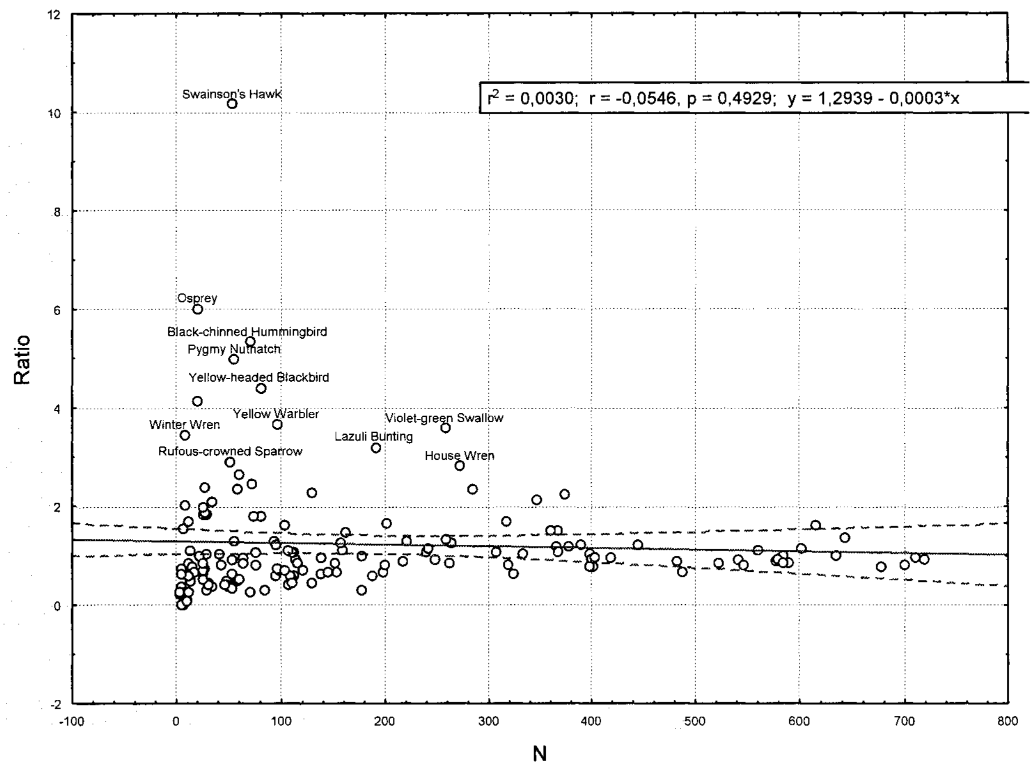


Fig. 1: The ratio of the time of day adjustment factors for the first group of ten stops calculated using Californian data, to that calculated with all on North American data. N is the sample size in number of route-years. Adjustment factors are the mean abundance for a given species divided by the abundance of that species on a given 10-stop segment. There is no significant difference between Californian factors and North American one except for a few species for which the sample sizes are small.

Appendix 3. continued

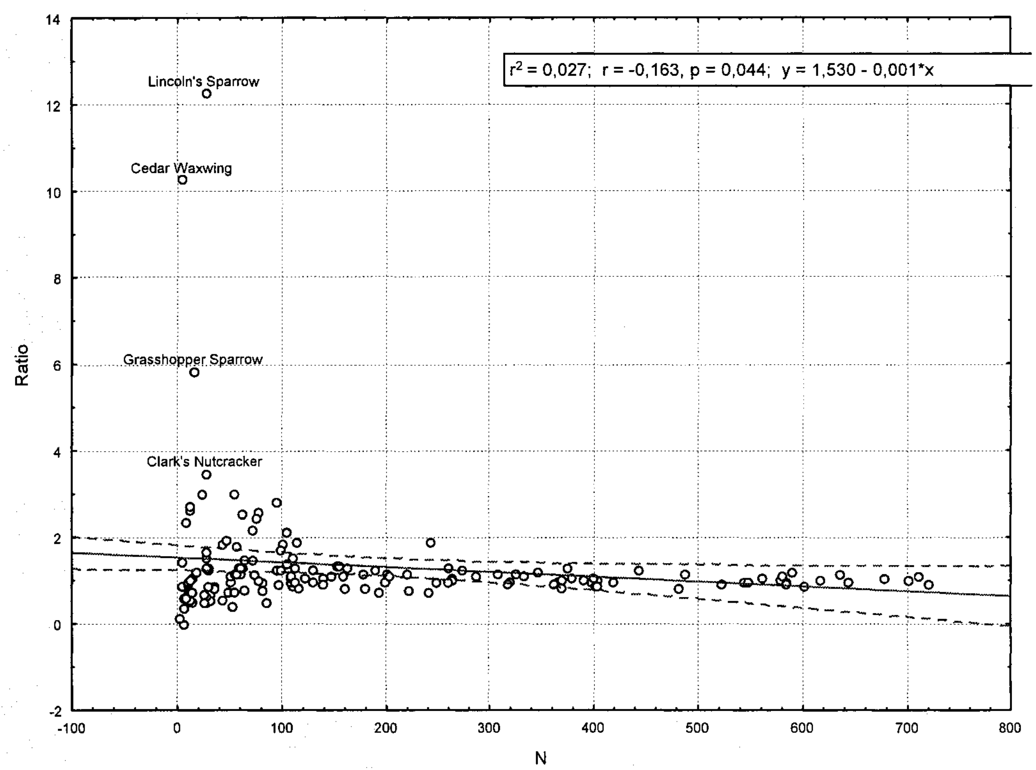


Fig. 2: The ratio of the time of day adjustment factors for the second group of ten stops calculated using Californian data, to that calculated with all on North American data. N is the sample size in number of route-years. Adjustment factors are the mean abundance for a given species divided by the abundance of that species on a given 10-stop segment. There is a weak significant difference between Californian factors and North American one except for a few species for which the sample sizes are small.

Appendix 3. continued

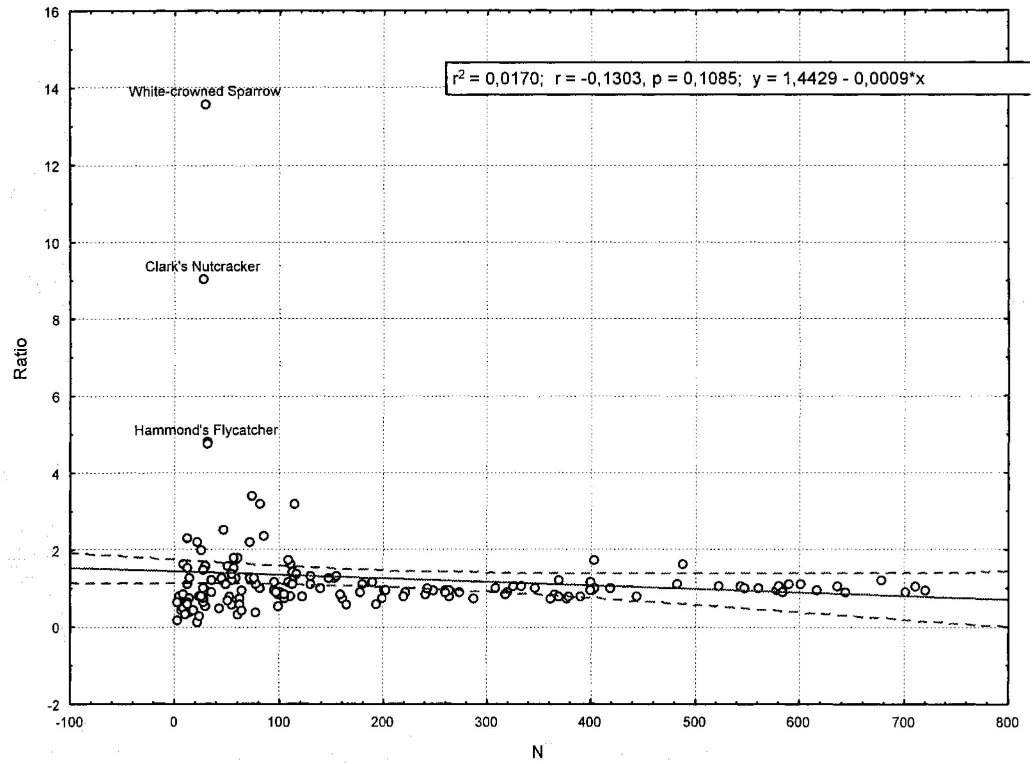


Fig. 3: The ratio of the time of day adjustment factors for the third group of ten stops calculated using Californian data, to that calculated with all on North American data. N is the sample size in number of route-years. Adjustment factors are the mean abundance for a given species divided by the abundance of that species on a given 10-stop segment. There is no significant difference between Californian factors and North American one except for a few species for which the sample sizes are small.

Appendix 3. continued

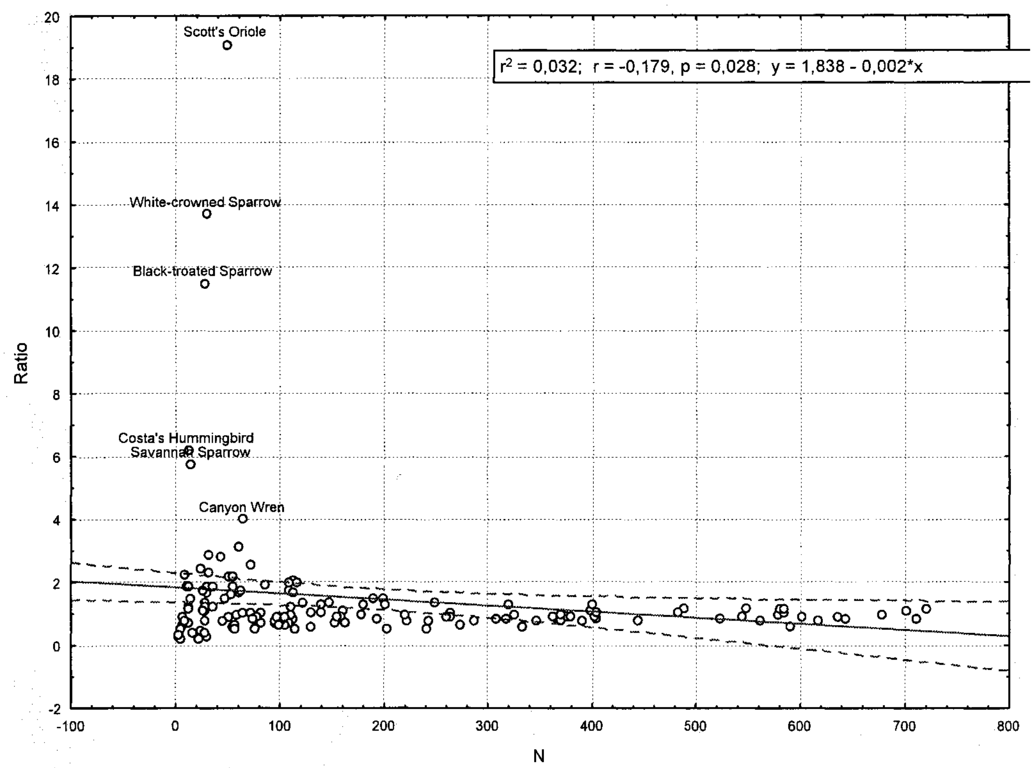


Fig. 4: The ratio of the time of day adjustment factors for the fourth group of ten stops calculated using Californian data, to that calculated with all on North American data. N is the sample size in number of route-years. Adjustment factors are the mean abundance for a given species divided by the abundance of that species on a given 10-stop segment. There is a weak significant difference between Californian factors and North American one except for a few species for which the sample sizes are small.

Appendix 3. continued

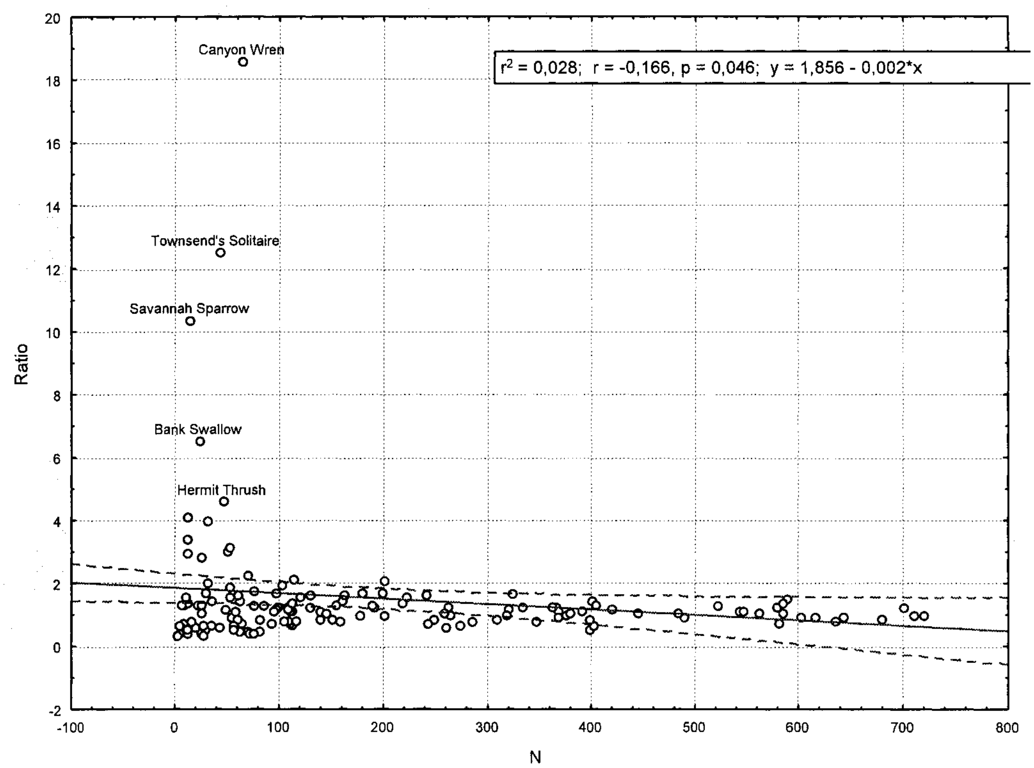


Fig. 5: The ratio of the time of day adjustment factors for the fifth group of ten stops calculated using Californian data, to that calculated with all on North American data. N is the sample size in number of route-years. Adjustment factors are the mean abundance for a given species divided by the abundance of that species on a given 10-stop segment. There is a weak significant difference between Californian factors and North American one except for a few species for which the sample sizes are small.

Appendix 4. List of the 95 species selected for the first analysis. These species are found on at least two group of 10-stops on the BBS routes within the California Central Valley (in alphabetical order of English name).

English	Scientific	French
Acorn Woodpecker	*Melanerpes formicivorus*	Pic glandivore
American Avocet	*Recurvirostra americana*	Avocette d'Amérique
American Bittern	*Botaurus lentiginosus*	Butor d'Amérique
American Coot	*Fulica americana*	Foulque d'Amérique
American Crow	*Corvus brachyrhynchos*	Corneille d'Amérique
American Goldfinch	*Carduelis tristis*	Chardonneret jaune
American Kestrel	*Falco sparverius*	Crécerelle d'Amérique
American Robin	*Turdus migratorius*	Merle d'Amérique
American White Pelican	*Pelecanus erythrorhynchos*	Pélican d'Amérique
Anna's Hummingbird	*Calypte anna*	Colibri d'Anna
Ash-throated Flycatcher	*Myiarchus cinerascens*	Tyran à gorge cendrée
Barn Owl	*Tyto alba*	Effraie des clochers
Barn Swallow	*Hirundo rustica*	Hirondelle rustique
Belted Kingfisher	*Ceryle alcyon*	Martin-pêcheur d'Amérique
Bewick's Wren	*Thryomanes bewickii*	Troglodyte de Bewick
Black Phoebe	*Sayornis nigricans*	Moucherolle noir
Black Tern	*Chlidonias niger*	Guifette noire
Black-chinned Hummingbird	*Archilochus alexandri*	Colibri à gorge noire
Black-crowned Night-Heron	*Nycticorax nycticorax*	Bihoreau gris
Black-headed Grosbeak	*Pheucticus melanocephalus*	Cardinal à tête noire
Black-necked Stilt	*Himantopus mexicanus*	Échasse d'Amérique
Blue Grosbeak	*Passerina caerulea*	Guiraca bleu
Brewer's Blackbird	*Euphagus cyanocephalus*	Quiscale de Brewer
Brown-headed Cowbird	*Molothrus ater*	Vacher à tête brune
Bullock's Oriole	*Icterus bullockii*	Oriole de Bullock
Burrowing Owl	*Athene cunicularia*	Chevêche des terriers
Bushtit	*Psaltriparus minimus*	Mésange buissonnière
California Quail	*Callipepla californica*	Colin de Californie
California Towhee	*Pipilo crissalis*	Tohi de Californie
Canada Goose	*Branta canadensis*	Bernache du Canada
Cattle Egret	*Bubulcus ibis*	Héron garde-boeufs
Cinnamon Teal	*Anas cyanoptera*	Sarcelle cannelle
Cliff Swallow	*Petrochelidon pyrrhonota*	Hirondelle à front blanc
Common Moorhen	*Gallinula chloropus*	Gallinule poule-d'eau
Common Raven	*Corvus corax*	Grand Corbeau
Common Yellowthroat	*Geothlypis trichas*	Paruline masquée
Double-crested Cormorant	*Phalacrocorax auritus*	Cormoran à aigrettes
Downy Woodpecker	*Picoides pubescens*	Pic mineur
European Starling	*Sturnus vulgaris*	Étourneau sansonnet

Appendix 4. continued

English	**Scientific**	**French**
Forster's Tern	*Sterna forsteri*	Sterne de Forster
Gadwall	*Anas strepera*	Canard chipeau
Great Blue Heron	*Ardea herodias*	Grand Héron
Great Egret	*Ardea alba*	Grande Aigrette
Green Heron	*Butorides virescens*	Héron vert
Hooded Oriole	*Icterus cucullatus*	Oriole masqué
Horned Lark	*Eremophila alpestris*	Alouette hausse-col
House Finch	*Carpodacus mexicanus*	Roselin familier
House Sparrow	*Passer domesticus*	Moineau domestique
House Wren	*Troglodytes aedon*	Troglodyte familier
Killdeer	*Charadrius vociferus*	Pluvier kildir
Lark Sparrow	*Chondestes grammacus*	Bruant à joues marron
Lazuli Bunting	*Passerina amoena*	Passerin azuré
Lesser Goldfinch	*Carduelis psaltria*	Chardonneret mineur
Loggerhead Shrike	*Lanius ludovicianus*	Pie-grièche migratrice
Mallard	*Anas platyrhynchos*	Canard colvert
Marsh Wren	*Cistothorus palustris*	Troglodyte des marais
Mourning Dove	*Zenaida macroura*	Tourterelle triste
Northern Harrier	*Circus cyaneus*	Busard Saint-Martin
Northern Mockingbird	*Mimus polyglottos*	Moqueur polyglotte
Northern Pintail	*Anas acuta*	Canard pilet
Northern Rough-winged Swallow	*Stelgidopteryx serripennis*	Hirondelle à ailes hérissées
Nuttall's Woodpecker	*Picoides nuttallii*	Pic de Nuttall
Oak Titmouse	*Baeolophus inornatus*	Mésange unicolore
Pacific-slope Flycatcher	*Empidonax difficilis*	Moucherolle côtier
Pied-billed Grebe	*Podilymbus podiceps*	Grèbe à bec bigarré
Redhead	*Aythya americana*	Fuligule à tête rouge
Red-shafted Flicker	*Colaptes cafer*	Pic rosé
Red-shouldered Hawk	*Buteo lineatus*	Buse à épaulettes
Red-tailed Hawk	*Buteo jamaicensis*	Buse à queue rousse
Red-winged Blackbird	*Agelaius phoeniceus*	Carouge à épaulettes
Ring-necked Pheasant	*Phasianus colchicus torquatus*	Faisan à collier
Rock Dove	*Columba livia*	Pigeon biset
Snowy Egret	*Egretta thula*	Aigrette neigeuse
Song Sparrow	*Melospiza melodia*	Bruant chanteur
Spotted Towhee	*Pipilo maculatus*	Tohi tacheté
Swainson's Hawk	*Buteo swainsoni*	Buse de Swainson
Tree Swallow	*Tachycineta bicolor*	Hirondelle bicolore
Tricolored Blackbird	*Agelaius tricolor*	Carouge de Californie
Turkey Vulture	*Cathartes aura*	Urubu à tête rouge
Violet-green Swallow	*Tachycineta thalassina*	Hirondelle à face blanche
Western Bluebird	*Sialia mexicana*	Merlebleu de l'Ouest
Western Kingbird	*Tyrannus verticalis*	Tyran de l'Ouest
Western Meadowlark	*Sturnella neglecta*	Sturnelle de l'Ouest
Western Scrub-Jay	*Aphelocoma californica*	Geai buissonnier
Western Wood-Pewee	*Contopus sordidulus*	Pioui de l'Ouest

Appendix 4. continued

English	**Scientific**	**French**
White-breasted Nuthatch	*Sitta carolinensis*	Sittelle à poitrine blanche
White-faced Ibis	*Plegadis chihi*	Ibis à face blanche
White-tailed Kite	*Elanus leucurus*	Élanion à queue blanche
Wild Turkey	*Meleagris gallopavo*	Dindon sauvage
Wilson's Warbler	*Wilsonia pusilla*	Paruline à calotte noire
Wood Duck	*Aix sponsa*	Canard branchu
Wrentit	*Chamaea fasciata*	Cama brune
Yellow Warbler	*Dendroica petechia*	Paruline jaune
Yellow-billed Magpie	*Pica nuttalli*	Pie à bec jaune
Yellow-headed Blackbird	*Xanthocephalus xanthocephalus*	Carouge à tête jaune

Appendix 5. List of the 25 species selected for the second analysis. These species are associated with agriculture (Small, 1974) and are present on at least 20% of the route-segments (in alphabetical order of English name).

English	Scientific	French
American Crow	*Corvus brachyrhynchos*	Corneille d'Amérique
American Goldfinch	*Carduelis tristis*	Chardonneret jaune
American Kestrel	*Falco sparverius*	Crécerelle d'Amérique
American Robin	*Turdus migratorius*	Merle d'Amérique
Black Phoebe	*Sayornis nigricans*	Moucherolle noir
Brewer's Blackbird	*Euphagus cyanocephalus*	Quiscale de Brewer
Brown-headed Cowbird	*Molothrus ater*	Vacher à tête brune
Bullock's Oriole	*Icterus bullockii*	Oriole de Bullock
California Quail	*Callipepla californica*	Colin de Californie
Cliff Swallow	*Petrochelidon pyrrhonota*	Hirondelle à front blanc
European Starling	*Sturnus vulgaris*	Étourneau sansonnet
Horned Lark	*Eremophila alpestris*	Alouette hausse-col
House Finch	*Carpodacus mexicanus*	Roselin familier
House Sparrow	*Passer domesticus*	Moineau domestique
Killdeer	*Charadrius vociferus*	Pluvier kildir
Loggerhead Shrike	*Lanius ludovicianus*	Pie-grièche migratrice
Mourning Dove	*Zenaida macroura*	Tourterelle triste
Northern Mockingbird	*Mimus polyglottos*	Moqueur polyglotte
Red-winged Blackbird	*Agelaius phoeniceus*	Carouge à épaulettes
Ring-necked Pheasant	*Phasianus colchicus torquatus*	Faisan à collier
Rock Dove	*Columba livia*	Pigeon biset
Tricolored Blackbird	*Agelaius tricolor*	Carouge de Californie
Turkey Vulture	*Cathartes aura*	Urubu à tête rouge
Western Kingbird	*Tyrannus verticalis*	Tyran de l'Ouest
Yellow-billed Magpie	*Pica nuttalli*	Pie à bec jaune

Appendix 6. List of the 13 bird species, among the 95 included in the study, significantly in decline in California from 1966 to 2003 (USGS Patuxent Wildlife Research Center website, http://www.pwrc.usgs.gov/) (in alphabetical order of English name).

English	**Scientific**	**French**
American Kestrel	*Falco sparverius*	Crécerelle d'Amérique
Belted Kingfisher	*Ceryle alcyon*	Martin-pêcheur d'Amérique
Brewer's Blackbird	*Euphagus cyanocephalus*	Quiscale de Brewer
Bullock's Oriole	*Icterus bullockii*	Oriole de Bullock
Horned Lark	*Eremophila alpestris*	Alouette hausse-col
House Finch	*Carpodacus mexicanus*	Roselin familier
Killdeer	*Charadrius vociferus*	Pluvier kildir
Loggerhead Shrike	*Lanius ludovicianus*	Pie-grièche migratrice
Mourning Dove	*Zenaida macroura*	Tourterelle triste
Northern Pintail	*Anas acuta*	Canard pilet
Northern Rough-winged Swallow	*Stelgidopteryx serripennis*	Hirondelle à ailes hérissées
Western Meadowlark	*Sturnella neglecta*	Sturnelle de l'Ouest
Western Wood-Pewee	*Contopus sordidulus*	Pioui de l'Ouest

Appendix 7. Breeding Bird Survey (BBS) sample size for each year for the 27 routes used in the study. The minimum sample size per year is 11, the maximum is 22 and the mean is 16.

Route # / Year	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Total
14012											2
14015											8
14016											8
14020											6
14021											10
14026											3
14027											1
14033											4
14042											5
14054											10
14079											9
14080											10
14125											6
14147											6
14148											9
14149											0
14155											10
14159											10
14171											5
14172											3
14179											9
14196											0
14197											2
14203											0
14245											6
14303											7
14352											4
Total	11	15	18	22	18	20	16	16	15	13	

Appendix 8. Testing that landcover proportions remain more or less constant during the study period.

We used three counties (Sacramento, Glenn and King) having two sets of land use data available to test the assumption that landcover proportions remain the same during the 9-year study period. Data from Sacramento county were available for 1993 and 2000, data from Glenn county for 1993 and 1998 and data from King county for 1991 and 1996. Using ArcView 3.2a, we extracted, from the Land Use Survey maps, the total acreages of each landcover categories for the two time periods for each county (for this purpose, native vegetation and urban areas were summed as non-agricultural areas). We then calculated the proportions of each category for every group of ten stops. We then did linear regressions of "before" and "after" proportions to test if they were the same or not. The following figures show our results.

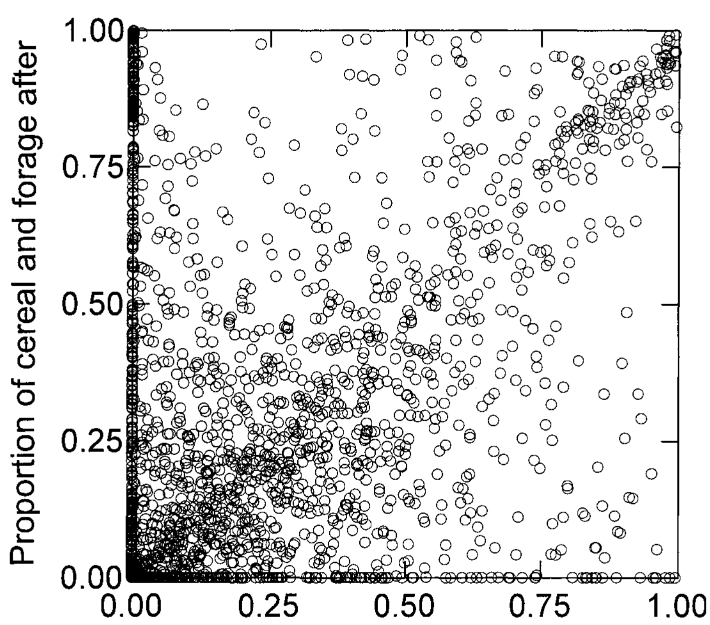


Fig. 1: The relationship between proportion of cereal and forage crops "after" and proportion of cereal and forage crops "before" ($r^2 = 0.155$, $n = 2337$, $p = 9.9 \times 10^{-16}$). "Before" means during the first three years of the study period, whereas "after" means for the last five years.

Appendix 8. continued

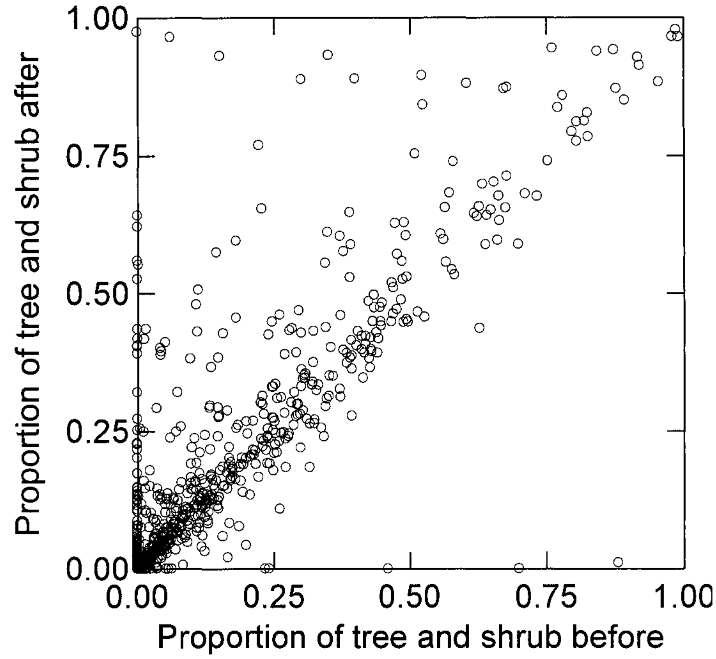


Fig. 2: The relationship between proportion of tree and shrub (orchards) "after" and proportion of tree and shrub "before" ($r^2 = 0.783$, $n = 2337$, $p = 9.9 \times 10^{-16}$). "Before" means during the first three years of the study period, whereas "after" means for the last five years.

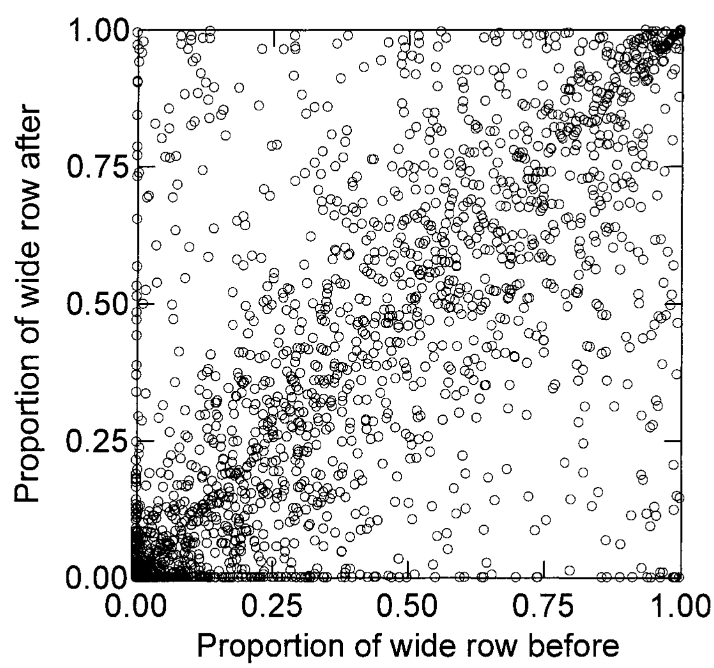


Fig. 3: The relationship between proportion of wide row crops "after" and proportion of wide row crops "before" ($r^2 = 0.545$, $n = 2337$, $p = 9.9 \times 10^{-16}$). "Before" means during the first three years of the study period, whereas "after" means for the last five years.

Appendix 8. continued

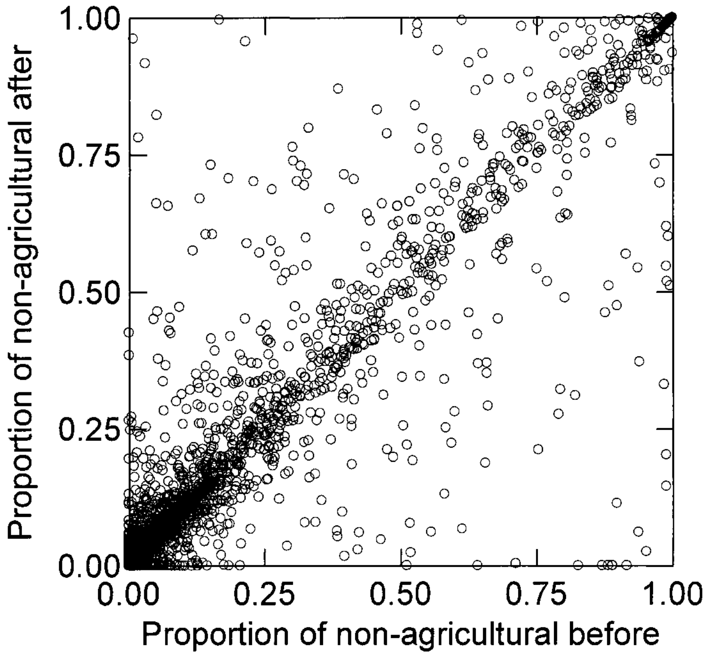


Fig. 4: The relationship between proportion of non-agricultural lands "after" and proportion of non-agricultural lands "before" ($r^2 = 0.835$, $n = 2337$, $p = 9.9 \times 10^{-16}$). "Before" means during the first three years of the study period, whereas "after" means for the last five years.

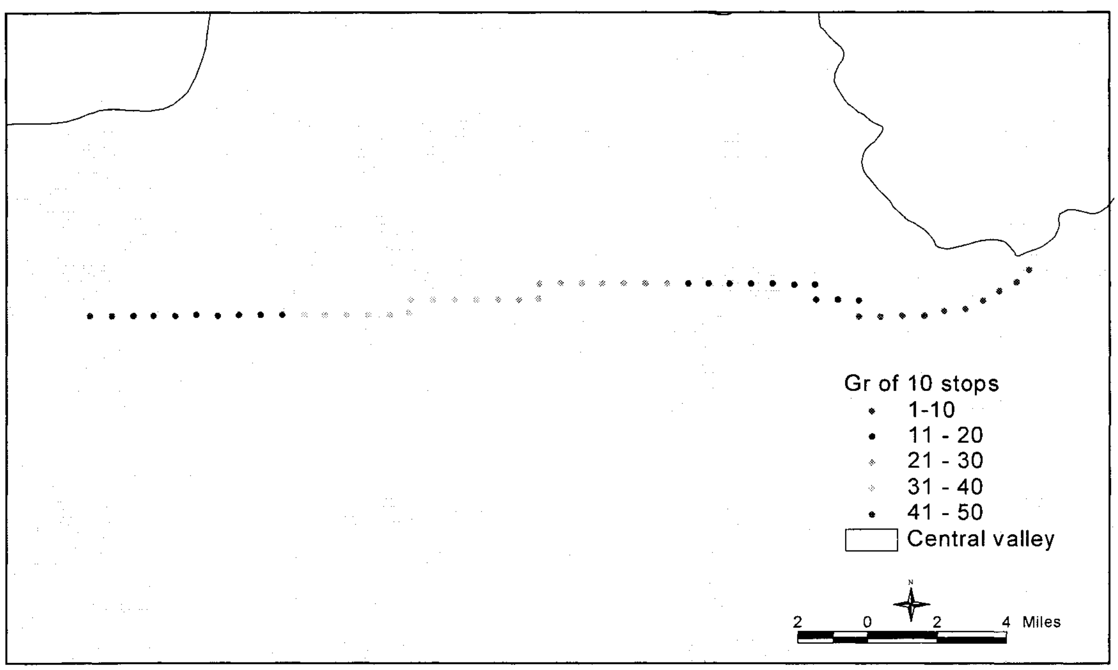
Appendix 9. List of the 20 most used pesticides in the Central Valley of California for the years 1992 and 2001.

Year	Name of the pesticide	Chemical code	Type of pesticide	Total kg applied
1992	Sulfur	560	Fungicide	20353972
1992	Petroleum oil, unclassified	765	Insecticide	6327474
1992	Methyl bromide	385	Fumigant	3808418
1992	Metam-sodium	616	Fumigant	2324228
1992	Sodium chlorate	536	Defoliant	1792605
1992	Cryolite	173	Insecticide	1336354
1992	Copper hydroxide	151	Fungicide	1076272
1992	Copper sulfate (pentahydrate)	161	Algaecide	945774
1992	Glyphosate, isopropylamine salt	1855	Herbicide	771724
1992	Propargite	445	Insecticide	749247
1992	Ziram	629	Fungicide	708702
1992	Molinate	449	Herbicide	623661
1992	Calcium hydroxide	99	pH Adjustment	619166
1992	Chlorpyrifos	253	Insecticide	515189
1992	Trifluralin	597	Herbicide	390364
1992	Diazinon	198	Insecticide	340004
1992	S,S,S-Tributyl phosphorotrithioate	190	Defoliant	337905
1992	Carbaryl	105	Insecticide	275678
1992	Ethephon	1626	Plant Growth Regulator	272982
1992	Copper sulfate (basic)	162	Fungicide	269905

Year	Name of the pesticide	Chemical code	Type of pesticide	Total kg applied
2001	Sulfur	560	Fungicide	15883466
2001	Petroleum oi, unclassified	765	Insecticide	5353903
2001	Metam-sodium	616	Fumigant	2352392
2001	Mineral oil	401	Insecticide	1351988
2001	Copper sulfate (pentahydrate)	161	Algaecide	1288328
2001	1,3-Dichloropropene	573	Fumigant	1248527
2001	Sodium chlorate	536	Defoliant	1140012
2001	Glyphosate, isopropylamine salt	1855	Herbicide	1069766
2001	Copper hydroxide	151	Fungicide	1057546
2001	Calcium hydroxide	99	pH Adjustment	649222
2001	Propanil	503	Herbicide	626389
2001	Cryolite	173	Insecticide	545871
2001	Propargite	445	Insecticide	518881
2001	Chlorpyrifos	253	Insecticide	495827
2001	Methyl bromide	385	Fumigant	428379
2001	Petroleum distillates, refined	2106	Insecticide	341579
2001	Molinate	449	Herbicide	331494
2001	Urea dihydrogen sulfate	2270	Plant Growth Regulator	309097
2001	Paraquat dichloride	1601	Herbicide	308487
2001	Ziram	629	Fungicide	307986

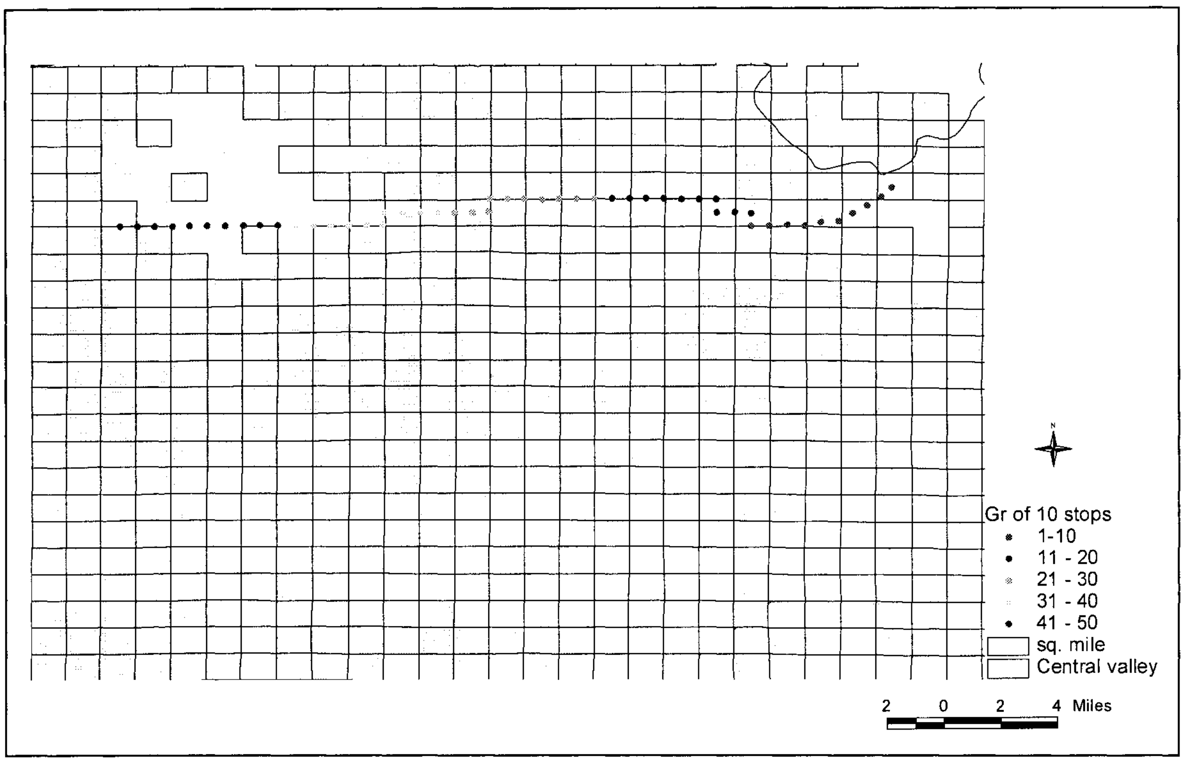
Appendix 10. Step by step detailed methodology on adjustment of pesticide indices to amount of land in agriculture and calculation of habitat variables in the buffer zones.

Step 1. A Breeding Bird Survey route with its five groups of ten stops.



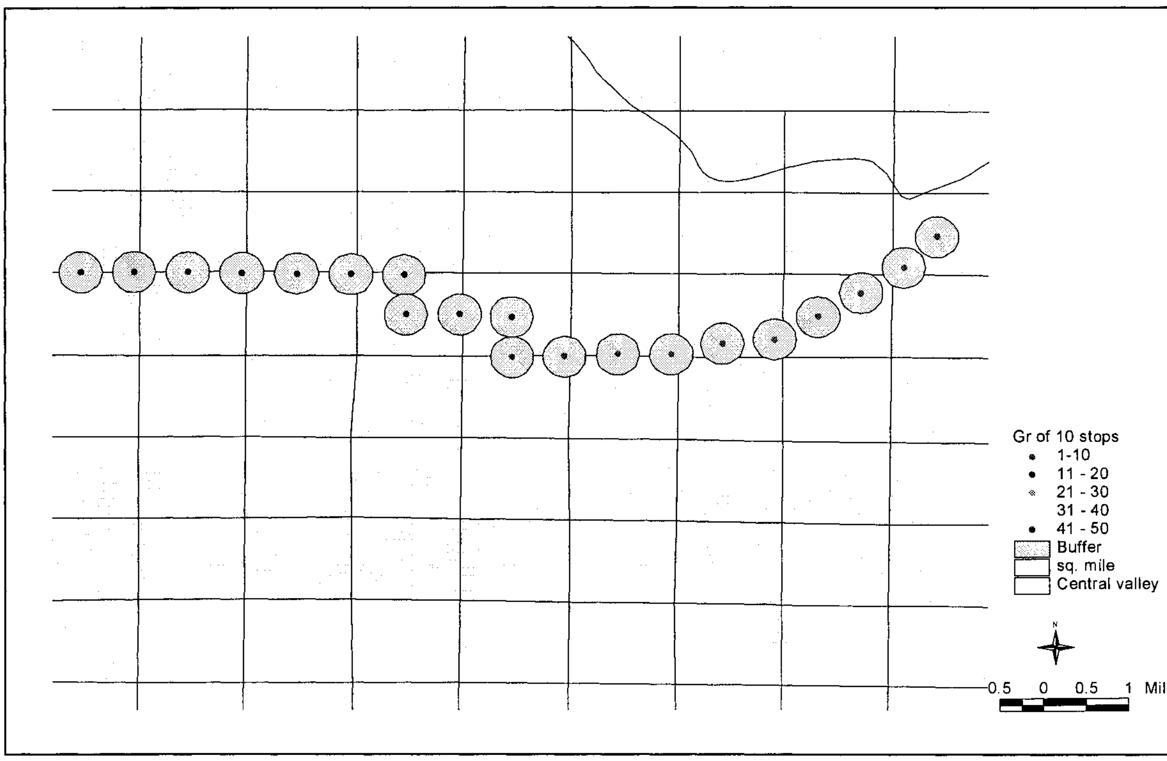
Appendix 10. continued

Step 2. Superimposition of the BBS stops and the square mile quadrats. Pesticide acute toxicity index for insecticide uses as well as ratios of area treated/area planted for insecticide, herbicide and fungicide uses were calculated for each square.



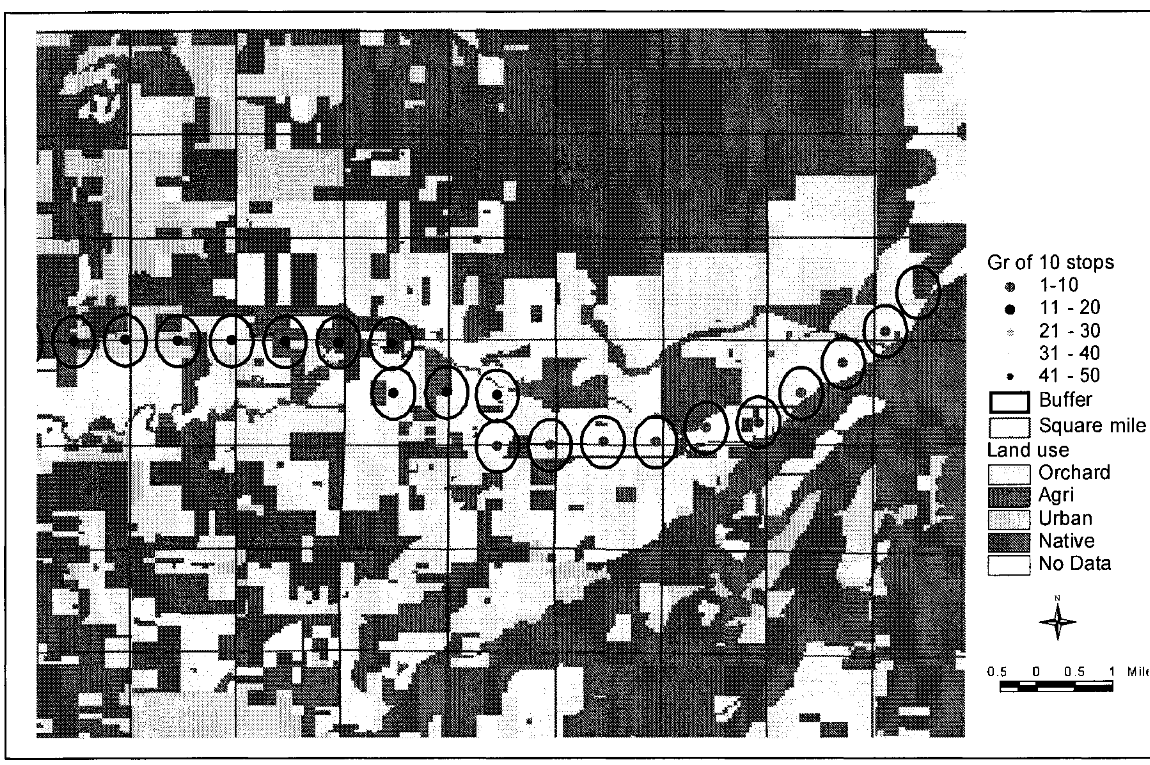
Appendix 10. continued

Step 3. Creation of buffer zones of 0.4 km around each BBS stop. Note that a given buffer may partly overlap as many as four different square mile quadrats.



Appendix 10. continued

Step 4. Superimposition of the BBS stops, the square miles, the buffers and the Land Use Survey shapefile. For the habitat variables, the acreages of orchard, native vegetation and urban land were extracted for each buffer zone from the Land Use Survey shapefile. Acreages for wide row and cereal/forage crops were taken from the pesticide database and adjusted for the amount of agricultural land (other than orchards) in the buffer zones. Then, we summed the acreages of orchards and other agricultural lands as an index of the total amount of land in agriculture in each buffer zone. We adjusted our seven pesticide toxicity indices according to the total amount of land in agriculture in each buffer. All the variables were then summed individually per group of 10-stops.



Appendix 11. List of insecticides for which no data on toxicity were available (common name, in alphabetical order). These products are solvents, emulsifiers, or natural products and are considered to have fairly low toxicity to birds. We therefore assume a negligible probability of bird kill for these products.

2(2-butoxy ethoxy) ethyl thiocyanate
Alkyl benzene sulfonic acid
Benzoic acid
Beta-pinene polymer
Capsicum oleoresin
Coconut diethanolamide
Cottonseed oil
Diammonium phosphate
Dimethyl poly siloxane
Dioctyl sodium sulfosuccinate
Dioctyl sodium sulfosuccinate (octyl is 2-)
Emulsifiable methylated vegetable oil
Garlic
Kaolin
Lime-sulfur
Proprietary blend of linear secondary alcohols reagent
Sabadilla alkaloids
Sodium alkylaryl sulfonate
Soybean oil
Triethanolamine
Triethanolamine sulfonate
Vegetable oil

Appendix 12. Pearson's correlation matrix ($n = 54$, $p \leq 0.05$) between the first two PC factors (PC-I and PC-II) summarizing 4 physical environment variables and the 4 physical environment variables. PC-I seems to be related to mean elevation whereas PC-II seems be related to climate (temperature and precipitation). Correlations highlighted in grey are significant.

	PC-I	PC-II
Mean elevation	0,512	-0,101
Mean temperature	0,365	-0,325
Mean precipitation	-0,240	0,419
Variance in elevation	0,168	0,069

Appendix 13. Pearson's correlation matrix (n = 54, $p \leq 0.05$) between the first three PC factors (PC-I and PC-II) summarizing 7 landcover variables and the 7 landcover variables. PC-I seems to be related to landcover diversity, PC-II to orchards vs. cereal and forage crops, and PC-III to native vegetation. Correlations highlighted in grey are significant.

	PC-I	PC-II	PC-III
Cereal & forage crops	0,484	0,666	0,166
Native vegetation	-0,365	0,276	0,797
Number of landcover	0,927	-0,031	0,040
Orchards	0,373	-0,755	0,215
Shannon-Wiener landcover diversity	0,810	0,206	0,432
Urban areas	0,594	-0,509	0,102
Wide row crops	0,594	0,379	-0,537

Appendix 14. Pearson's correlation matrix (n = 54, $p \leq 0.05$) between physical environment or landcover PC factors and abundance of 95 species, abundance of 25 farmland species and total species richness. Physical environment PC factors comprise mean annual temperature, total annual precipitation, mean elevation and variance in elevation. Physical environment PC-I is positively related to the elevation variables whereas PC-II is negatively related to temperature and positively to precipitation. Landcover PC factors comprise orchard, wide row crop, cereal and forage crop, urban area, native vegetation, number of different landcover and Shannon-Wiener landcover diversity index. Landcover PC-I is positively related to habitat diversity, PC-II is negatively related to orchards and positively to cereal and forage crops and finally, PC-III is positively related to native vegetation and negatively related to wide row crops. AB95 is the total abundance of the 95 species selected for this study. AB25 is the total abundance of 25 farmland bird species. SR is the species richness of all 187 species that are present in California Central Valley. Significant correlations are highlighted in grey.

PC Factors	AB95	AB25	SR
Physical environment PC-I	-0.011	0.005	-0.100
Physical environment PC-II	-0.125	-0.150	0.131
Landcover PC-I	0.246	0.296	0.001
Landcover PC-II	-0.088	-0.110	0.022
Landcover PC-III	0.095	0.067	0.330

Appendix 15. Pesticide use indices Pearson's correlation matrix ($n = 54$, $p \leq 0.05$). Avian toxicities are a measure of direct toxicity calculated using a probabilistic model from Mineau (2002a,b). The other five indices are simply a measure of treated area. Short-term indices were calculated with data from March to the BBS census date, while long-term indices were calculated with data from the two year preceding the BBS survey date. Significant correlations are highlighted in grey.

	Avian toxicity on the long-term	Avian toxicity on the short-term	Fungicide use on the long-term	Herbicide use on the long-term	Herbicide use on the short-term	Insecticide use on the long-term	Insecticide use on the short-term
Avian toxicity on the long-term	1.000						
Avian toxicity on the short-term	0.772	1.000					
Fungicide use on the long-term	0.748	0.797	1.000				
Herbicide use on the long-term	0.697	0.780	0.990	1.000			
Herbicide use on the short-term	0.620	0.628	0.911	0.919	1.000		
Insecticide use on the long-term	0.712	0.787	0.994	0.998	0.930	1.000	
Insecticide use on the short-term	0.772	0.782	0.743	0.710	0.617	0.721	1.000

Appendix 16. Pesticides treated and planted surfaces Pearson's correlation matrix (n = 10948). Treated and planted surfaces are measured in hectares. "Treat" means surfaces that were treated with herbicides (herb), insecticides (insect) or fungicide (fung), whereas "Plant" means planted surfaces on which one of the three pesticide types were used. Highlighted correlations are either treated against treated surfaces or planted against planted ones.

	Treat_herb	Plant_herb	Treat_Insect	Plant_Insect	Treat_Fung	Plant_Fung
Treat_herb	1,000					
Plant_herb	0,479	1,000				
Treat_Insect	0,972	0,271	1,000			
Plant_Insect	0,467	0,981	0,267	1,000		
Treat_Fung	0,907	0,073	0,979	0,074	1,000	
Plant_Fung	0,459	0,972	0,263	0,997	0,074	1,000

Appendix 17. Stepwise forward logistic regressions with the individual 95 bird species presence/absence. McFR^2 is the McFadden's R^2, a default measure of the strength of a logistic regression. It is analogous to R^2 except that the value is lower: a value of 0.3 or 0.4 is considered high. McFR^2_pest&env is the value of the McFadden's R^2 when pesticide and environmental variables are included in the regressions. McFR^2_env is the value of the McFadden's R^2 when environmental variables alone are used to do the regressions. PC-I_pest is the first principal component for the pesticide variables; PC-II_pest is the second principal component for the pesticide variables, and so on. Phys is the physical environment variables (mean annual temperature, mean annual precipitation, mean elevation and variance in elevation). Land is the landcover variables (orchards, wide row crops, cereal and forage crops, urban areas, native vegetation, number of different landcover and Shannon-Wiener landcover diversity index). Black rectangle means that the estimated value is negative in the pesticide + environment regressions while grey rectangle means that the value is positive. Plus sign means that the estimated value is positive in the environment alone regressions and minus sign that the value is negative. *** Means that the variable turns negative in the environment alone regression. Species in bold are species for which there was no significant factor.

Species	McFR^2_pest&env	McFR^2_env	PC-I_pest	PC-II_pest	PC-I_phys	PC-II_phys	PC-I_land	PC-II_land	PC-III_land
Acorn Woodpecker	0.251	0.199				+	−	−	
American Avocet	0.239	0.232				−			
American Bittern	0.358	0.271			−		+		
American Coot	0.110	0.113				***			
American Crow	0.210	0.204							

Appendix 17. continued

Species	McFR^2_pest&env	McFR^2_env	PC-I_pest	PC-II_pest	PC-I_phys	PC-II_phys	PC-I_land	PC-II_land	PC-III_land
American Goldfinch	0.192	0.160					+		
American Kestrel	0.050	0.033							
American Robin	0.161	0.163							
American White Pelican	0.163	0.189			−				+
Anna's Hummingbird	0.107	0.096							
Ash-throated Flycatcher	0.199	0.168					−		
Barn Owl									
Barn Swallow		0.043			−		+	+	−
Belted Kingfisher		0.022			−				
Bewick's Wren	0.178	0.118					−		
Black Phoebe	0.030	0.036							
Black Tern	0.461	0.205							
Black-chinned Hummingbird	0.207	0.191							
Black-crowned Night-Heron	0.182	0.092					X		
Black-headed Grosbeak	0.065	0.041				X			
Black-necked Stilt	0.180	0.202					+		
Blue Grosbeak	0.165	0.125					+		
Brewer's Blackbird	0.115	0.096							
Brown-headed Cowbird	0.049	0.056						−	
Bullock's Oriole	0.052	0.056							
Burrowing Owl	0.065	0.048							
Bushtit	0.102	0.068					−		+
California Quail	0.126	0.119							
California Towhee	0.246	0.212							
Canada Goose	0.222	0.192							
Cattle Egret	0.194	0.180							
Cinnamon Teal	0.137	0.135							
Cliff Swallow	0.008	0.006							
Common Moorhen	0.378	0.273							
Common Raven	0.123	0.131							
Common Yellowthroat	0.291	0.265							

Appendix 17. continued

Species	McFR^2_pest&env	McFR^2_env	PC-I_pest	PC-II_pest	PC-I_phys	PC-II_phys	PC-I_land	PC-II_land	PC-III_land
Double-crested Cormorant									
Downy Woodpecker									
European Starling	0.161	0.166							
Forster's Tern	0.261	0.251							
Gadwall	0.105	0.148				–	–	+	
Great Blue Heron	0.059	0.060						+	
Great Egret	0.080	0.062						+	
Green Heron	0.048								
Hooded Oriole									
Horned Lark	0.117	0.111				–			
House Finch	0.200	0.134							X
House Sparrow	0.300	0.305			+				
House Wren	0.109	0.061							+
Killdeer	0.058	0.062							
Lark Sparrow	0.057	0.049					–		
Lazuli Bunting									
Lesser Goldfinch	0.095	0.126			+		–		+
Loggerhead Shrike	0.137	0.141							
Mallard	0.126	0.112					+		
Marsh Wren	0.311	0.288							
Mourning Dove	0.043	0.035							X
Northern Harrier	0.042	0.033							
Northern Mockingbird	0.095	0.074						+	
Northern Pintail	0.160	0.114							
Northern Rough-winged Swallow	0.066	0.039							
Nuttall's Woodpecker	0.059	0.048							
Oak Titmouse	0.146	0.168				+	–		
Pacific-slope Flycatcher	0.073	0.057					–		
Pied-billed Grebe	0.031	0.060					+		
Redhead									
Red-shafted Flicker	0.050	0.073							+

Appendix 17. continued

Species	McFR^2_pest&env	McFR^2_env	PC-I_pest	PC-II_pest	PC-I_phys	PC-II_phys	PC-I_land	PC-II_land	PC-III_land
Red-shouldered Hawk	0.048	0.042							
Red-tailed Hawk	0.007								
Red-winged Blackbird	0.009	0.007							
Ring-necked Pheasant	0.043	0.037						+	
Rock Dove	0.047	0.041					+		
Snowy Egret	0.041	0.043							
Song Sparrow	0.169	0.129						X	
Spotted Towhee	0.031	0.031							
Swainson's Hawk	0.080	0.099					+		
Tree Swallow	0.043	0.023						X	
Tricolored Blackbird	0.050	0.050							
Turkey Vulture	0.026	0.033							
Violet-green Swallow	0.096	0.124							
Western Bluebird	0.130	0.141							
Western Kingbird	0.115	0.090						X	
Western Meadowlark		0.014			+				+
Western Scrub-Jay	0.159	0.145							
Western Wood-Pewee	0.082	0.092							
White-breasted Nuthatch	0.221	0.238			+		–		
White-faced Ibis	0.152	0.142							
White-tailed Kite	0.040	0.011							
Wild Turkey	0.119								
Wilson's Warbler	0.123	0.117							
Wood Duck									
Wrentit	0.143	0.148							
Yellow Warbler	0.179	0.182							
Yellow-billed Magpie	0.127	0.126					+		
Yellow-headed Blackbird	0.052	0.061						+	–

Appendix 18. Stepwise forward multiple regressions with the 95 individual bird species. Null abundances were excluded from the regressions. R^2 pest&env is the value of the R^2 when pesticide and environmental variables are included in the regressions. R^2 env is the value of the R^2 when environmental variables alone are used to do the regressions. PC-I_pest is the first principal component for the pesticide variables; PC-II_pest is the second principal component for the pesticide variables, and so on. Phys is the physical environment variables (mean annual temperature, mean annual precipitation, mean elevation and variance in elevation). Land is the landcover variables (orchards, wide row crops, cereal and forage crops, urban areas, native vegetation, number of different landcover and Shannon-Wiener landcover diversity index). Black rectangle means that the estimated value is negative in the pesticide + environment regressions while grey rectangle means that the value is positive. Plus sign means that the estimated value is positive in the environment alone regressions and minus sign that the value is negative. Species in bold are species for which there was no significant factor.

Species	R^2 pest&env	R^2 env	PC-I_pest	PC-II_pest	PC-I_phys	PC-II_phys	PC-I_land	PC-II_land	PC-III_land
Acorn Woodpecker	0.212	0.090					+		
American Avocet	0.267	0.129			X		+		
American Bittern	0.101	0.113				–	+		
American Coot									
American Crow	0.211	0.146			X		+		
American Goldfinch	0.163	0.163							
American Kestrel	0.065	0.035					+		
American Robin	0.116	0.116							
American White Pelican	0.381	0.381							

Appendix 18. continued

Species	R^2 pest&env	R^2 env	PC-I_pest	PC-II_pest	PC-I_phys	PC-II_phys	PC-I_land	PC-II_land	PC-III_land
Anna's Hummingbird									
Ash-throated Flycatcher	0.249	0.102					–	+	
Barn Owl									
Barn Swallow	0.036	0.014					+		
Belted Kingfisher									
Bewick's Wren	0.341	0.101						+	
Black Phoebe	0.019								
Black Tern	0.406	0.198							+
Black-chinned Hummingbird	0.227	0.227							
Black-crowned Night-Heron									
Black-headed Grosbeak									
Black-necked Stilt	0.051	0.051							
Blue Grosbeak	0.072	0.072							
Brewer's Blackbird	0.123	0.123							
Brown-headed Cowbird	0.029	0.022					X		
Bullock's Oriole	0.133	0.046					–		
Burrowing Owl									
Bushtit	0.065								
California Quail	0.187	0.109					–		+
California Towhee	0.117	0.091			X				
Canada Goose									
Cattle Egret									
Cinnamon Teal									
Cliff Swallow	0.106	0.115				–			
Common Moorhen	0.537	0.235			–				X
Common Raven									
Common Yellowthroat	0.483								
Double-crested Cormorant									
Downy Woodpecker	0.336	0.336							
European Starling	0.187	0.141							
Forster's Tern	0.771								

Appendix 18. continued

Species	R^2 pest&env	R^2 env	PC-I_pest	PC-II_pest	PC-I_phys	PC-II_phys	PC-I_land	PC-II_land	PC-III_land
Gadwall	0.197								
Great Blue Heron	0.086	0.095						+	
Great Egret	0.090	0.090							
Green Heron									
Hooded Oriole									
Horned Lark	0.084	0.084							
House Finch	0.070	0.055							
House Sparrow	0.074	0.059					+		
House Wren									
Killdeer	0.175	0.175							
Lark Sparrow	0.072	0.072							
Lazuli Bunting	0.163								
Lesser Goldfinch	0.077								
Loggerhead Shrike	0.103	0.080						–	
Mallard	0.114	0.099							
Marsh Wren	0.080	0.092				–		X	
Mourning Dove	0.077	0.024				X	–		+
Northern Harrier									
Northern Mockingbird	0.061	0.061							
Northern Pintail									
Northern Rough-winged Swallow	0.160	0.160							
Nuttall's Woodpecker	0.107	0.107							
Oak Titmouse	0.087	0.114				+			
Pacific-slope Flycatcher									
Pied-billed Grebe									
Redhead									
Red-shafted Flicker	0.049	0.049							
Red-shouldered Hawk									
Red-tailed Hawk	0.010								
Red-winged Blackbird	0.079	0.046						X	
Ring-necked Pheasant	0.050	0.067							–

Appendix 18. continued

Species	R^2 pest&env	R^2 env	PC-I_pest	PC-II_pest	PC-I_phys	PC-II_phys	PC-I_land	PC-II_land	PC-III_land
Rock Dove									
Snowy Egret									
Song Sparrow	0.076	0.076							
Spotted Towhee									
Swainson's Hawk									
Tree Swallow									
Tricolored Blackbird									
Turkey Vulture									
Violet-green Swallow									
Western Bluebird									
Western Kingbird	0.074	0.055					+		
Western Meadowlark	0.032	0.019					–		
Western Scrub-Jay	0.096	0.113							+
Western Wood-Pewee	0.121	0.093					–		
White-breasted Nuthatch	0.133	0.133							
White-faced Ibis	0.211	0.211							
White-tailed Kite									
Wild Turkey									
Wilson's Warbler									
Wood Duck		0.128			+				
Wrentit									
Yellow Warbler									
Yellow-billed Magpie									
Yellow-headed Blackbird									

Appendix 19. Stepwise forward multiple regressions for the 13 bird species abundance, among the 95 included in the study, significantly declining in California from 1966 to 2003 (USGS Patuxent Wildlife Research Center website). R^2 pest&env is the value of the R^2 when pesticide and environmental variables are included in the regressions. R^2 env is the value of the R^2 when environmental variables alone are used to do the regressions. PC-I_pest is the first principal component for the pesticide variables; PC-II_pest is the second principal component for the pesticide variables, and so on. Phys is the physical environment variables (mean annual temperature, mean annual precipitation, mean elevation and variance in elevation). Land is the landcover variables (orchards, wide row crops, cereal and forage crops, urban areas, native vegetation, number of different landcover and Shannon-Wiener landcover diversity index). Black rectangle means that the estimated value is negative in the pesticide + environment regressions while grey rectangle means that the value is positive. Plus sign means that the estimated value is positive in the environment alone regressions and minus sign that the value is negative. Species in bold are species for which there was no significant factor.

Species	R^2 pest&env	R^2 env	PC-I_pest	PC-II_pest	PC-I_phys	PC-II_phys	PC-I_land	PC-II_land	PC-III_land
American Kestrel	0.065	0.035					+		
Belted Kingfisher									
Brewer's Blackbird	0.123	0.123							
Bullock's Oriole	0.133	0.046					–		
Horned Lark	0.084	0.084							
House Finch	0.070	0.055							
Killdeer	0.175	0.175							

Appendix 19. continued

Species	R^2 pest&env	R^2 env	PC-I_pest	PC-II_pest	PC-I_phys	PC-II_phys	PC-I_land	PC-II_land	PC-III_land
Loggerhead Shrike	0.103	0.080						–	
Mourning Dove	0.077	0.024				X	–		+
Northern Pintail									
Northern Rough-winged Swallow	0.160	0.160							
Western Meadowlark	0.032	0.019					–		
Western Wood-Pewee	0.121	0.093					–		