

Modelling effects of chemical exposure on birds wintering in agricultural landscapes: The western burrowing owl (*Athene cunicularia hypugaea*) as a case study

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ABSTRACT

We describe an ecotoxicological model that simulates the sublethal and lethal effects of chronic, low-level, chemical exposure on birds wintering in agricultural landscapes. Previous models estimating the impact on wildlife of chemicals used in agro-ecosystems typically have not included the variety of pathways, including both dermal and oral, by which individuals are exposed. The present model contains four submodels simulating (1) foraging behavior of individual birds, (2) chemical applications to crops, (3) transfers of chemicals among soil, insects, and small mammals, and (4) transfers of chemicals to birds via ingestion and dermal exposure. We demonstrate use of the model by simulating the impacts of a variety of commonly used herbicides, insecticides, growth regulators, and defoliants on western burrowing owls (*Athene cunicularia hypugaea*) that winter in agricultural landscapes in southern Texas, United States. The model generated reasonable movement patterns for each chemical through soil, water, insects, and rodents, as well as into the owl via consumption and dermal absorption. Sensitivity analysis suggested model predictions were sensitive to uncertainty associated with estimates of chemical half-lives in birds, soil, and prey, sensitive to parameters associated with estimating dermal exposure, and relatively insensitive to uncertainty associated with details of chemical application procedures (timing of application, amount of drift). Nonetheless, the general trends in chemical accumulations and the relative impacts of the various chemicals were robust to these parameter changes. Simulation results suggested that insecticides posed a greater potential risk to owls of both sublethal and lethal effects than do herbicides, defoliants, and growth regulators under crop scenarios typical of southern Texas, and that use of multiple indicators, or endpoints provided a more accurate assessment of risk due to agricultural chemical exposure. The model should prove useful in helping prioritize the chemicals and transfer pathways targeted in future studies and also, as these new data become available, in assessing the relative danger to other birds of exposure to different types of agricultural chemicals.

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1. Introduction

The widespread degradation and loss of native ecosystems due to the environmental impacts of agriculture is increasing globally (Butler et al., 2007; Benton, 2008). Exposure of native fauna to agricultural chemicals is one of the impacts of greatest concern, and has contributed to widespread population declines of birds (McLaughlin and Mineau, 1995; Mineau and Whiteside, 2006; Mineau and Tucker, 2002a,b; Benton, 2008). Although most research has focused on the lethal effects of acute exposure to agricultural chemicals, the sublethal effects of chronic, low-level,

exposure on fauna living in agricultural landscapes also may have serious impacts on populations of native fauna (Lacher, 1994; Maurer and Holt, 1996; Crocker, 2005; Mineau, 2005). Some species of raptors are particularly at risk because of specialization on agricultural pests, utilization of agricultural areas as foraging grounds, and a high probability of detecting and foraging on primary pesticide kills (Mineau et al., 1999; Mineau and Tucker, 2002b). Additionally raptors have shown increased sensitivity to insecticides, resulting in large numbers of mortalities (Mineau et al., 1999; Fleischli et al., 2004; Mineau and Tucker, 2002b).

For example, insecticide use has been strongly implicated as a possible cause of population declines in the western burrowing owl (*Athene cunicularia hypugaea*) (Klute et al., 2003), which was listed as a Federal Species of Conservation Concern in the United States in 2002 (USFWS, 2002). Habitat loss on the wintering grounds in

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southern Texas has led to increased use of agricultural landscapes as foraging and roost sites (Woodin et al., 2006), and chronic insecticide exposure has been documented by detection of low levels of organophosphate (OP) and carbamate (CB) insecticides in western burrowing owl pellets (Woodin et al., 2006). In addition to the ingestion of contaminated prey, the use of agricultural culverts as roost sites may further increase risk of exposure to insecticides and other agricultural chemicals through dermal exposure to agricultural runoff (Texas Gulf Coast Field Research Station, 2003; Woodin, 2004; Woodin, personal communication; Woodin et al., 2006).

Published studies of the effects of contaminants on burrowing owls (e.g., Garcia-Hernandez et al., 2006; Gervais et al., 2000, 2003; Gervais and Anthony, 2003; Gervais and Catlin, 2004; Gervais et al., 2006) have focused primarily on organochlorine (OC) insecticides and their residues. However, the use of most OC insecticides was discontinued in the United States during the 1970s, and insecticide use shifted to organophosphates (OP) and carbamates (CB) (Mineau, 1991). Although OP and CB insecticides are less persistent in the environment than OC insecticides, they have been responsible for numerous cases of mortality in owls and other raptors (Blus, 1996; Sheffield, 1997; Mineau et al., 1999). Sublethal doses of OP and CB insecticides can affect avian behavior and physiological functions, including alterations in thermoregulation, food consumption, reproductive behavior, and migration (Grue et al., 1997). The lack of research on the impact of OP and CB insecticides on burrowing owls, despite the extreme negative impact that these insecticides have had on other raptor populations, has led to a need to evaluate how current insect control practices affect burrowing owl populations (Mineau et al., 1999; Klute et al., 2003). Furthermore, while non-insecticidal agricultural chemicals, such as herbicides, may also negatively impact bird populations, the effect of these agricultural chemicals on burrowing owl populations has not been assessed (Newton, 2004; Colborn and Short, 1999).

This oversight is not limited to burrowing owls. The health risks to humans and other wildlife of non-insecticidal agricultural chemicals such as herbicides, despite their wide use, have not been adequately assessed (Colborn and Short, 1999). Other deficiencies typical of many avian risk assessments include the exclusion of chemical exposure occurring from dermal absorption (Fite et al., 2004; Mineau, 2002) and the absence of evaluation for the effects of low-level chronic pesticide stress on bird populations (Crocker, 2005; Mineau, 2005).

Despite the numerous models described in the literature for estimating the impact on wildlife of chemicals used in agroecosystems, to our knowledge none have included all of the components necessary to model avian species, such as the burrowing owl, that winter in cotton-dominated agricultural areas of the southwestern United States. Such a model would need to include both dermal and oral exposure routes, and assess lethal and sublethal effects of chronic low-level exposure to the wide variety of agricultural chemicals typically used on cotton and sorghum crops.

Simulation models used to evaluate ecological risks to birds (i.e. Corson et al., 1998; Pisani, 2006) have focused on user-specified chemical applications, and have examined effects of oral exposure to only organophosphate and carbamate insecticides, rather than combining dermal and oral exposure in a comparison of relative risk under typical use scenarios of a suite of all types of agricultural chemicals. Additionally, these simulation models have focused on acute exposure and did not assess chronic low-level exposure scenarios. Several risk assessment models (e.g. Hope, 1995; Mineau, 2002; Fite et al., 2004) included dermal exposure but do not provide guidelines for assessing sublethal effects from chronic exposure scenarios. Recently, methods have been developed to assess long-term effects of agricultural chemicals by using reproductive effects within population models (Bennett et al., 2005; Hart and Thompson, 2005; Shore et al., 2005; Mineau, 2005; Schmolke



Fig. 1. Burrowing owl distribution in North and Central America (Haug et al., 1993).

et al., 2010). While these long-term risk assessment procedures are extremely applicable to avian species during their breeding season, they are not relevant for the assessment of chronic, long-term exposure to migratory birds during the non-breeding period of their life cycle.

In this paper, we first describe development of an ecotoxicological model that simulates the sublethal and lethal effects of chronic, low-level, chemical exposure through both oral and dermal exposure routes on birds wintering in agricultural landscapes. We then evaluate the ability of the model to represent the movement of agricultural chemicals through soil, insects, rodents, and birds. Finally, we demonstrate use of the model by simulating the impacts on wintering western burrowing owls of exposure to mixtures of herbicides, insecticides, defoliants, and growth regulators typically found in agricultural landscapes in southern Texas, United States.

2. Methods

2.1. Western burrowing owl: relevant life history information

Western burrowing owls have resident and migratory populations in northern Texas, and have a migratory population that winters in the southern part of the state (Fig. 1). In addition to occurring in grasslands, western burrowing owls wintering in southern Texas are known to use agricultural culverts in cotton and sorghum fields as roost sites (Woodin et al., 2006; Williford et al., 2009). The area of interest for this model was chosen based on documented western burrowing owl roost sites from two agricultural areas in southern Texas: (1) the Gulf Coast area including Kleberg, Nueces, San Patricio, Refugio, and Jim Wells counties and (2) the Rio Grande Valley including Cameron and Hidalgo counties (Fig. 2).

Western burrowing owls in the Gulf Coast study area were studied intensively from 2000–2005 by the USGS Texas Gulf Coast Field Research Station (Woodin et al., 2006). In the Gulf Coast study area 87% of 46 roost sites were located in agricultural areas (Williford et al., 2007). Of these an estimated 67.4% of western burrowing owl roosts were typically located in fields that were used for cotton, sorghum, or corn during the previous summer (Woodin et al., 2006).

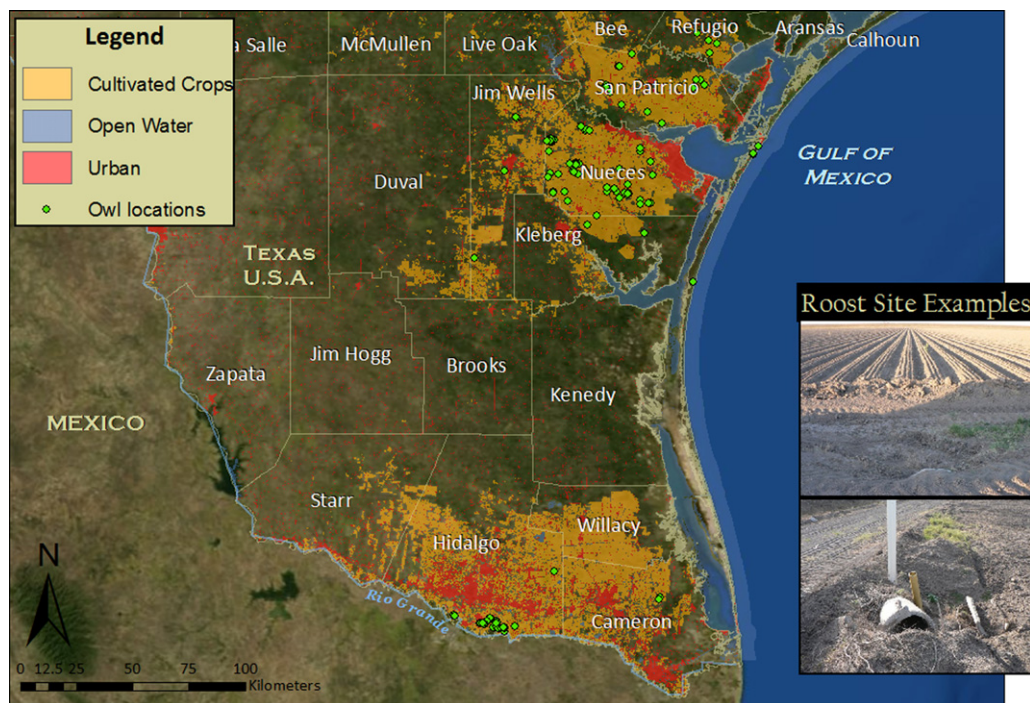


Fig. 2. Detections within our study areas of western burrowing owl roost sites in agricultural areas of south Texas.

A second study area was chosen in the Rio Grande Valley and a short-term survey was conducted during the winter of 2006. This survey located 46 culverts used as roost sites by western burrowing owls. Western burrowing owl detections were clustered in agricultural fields in the Rio Grande floodplain north of Santa Ana National Wildlife Refuge. Sixty-four percent of the western burrowing owl roost sites were located in fields that were used for cotton or sorghum the previous summer. Although the majority of roost sites were completely surrounded by bare fields in which cotton or sorghum had been grown the previous summer, there were two roost sites located in cotton or sorghum fields adjacent to a cabbage crop and four roost sites located in cotton or sorghum fields adjacent to an onion crop. Both the cabbage and onion crops were being cultivated during the winter (Engelman, 2008).

Western burrowing owls are typically only present in southern Texas during the winter, (ca. October 1 through March 1). During this time of year the cotton and sorghum fields are in a post-harvest stage and appear as wide expanses of bare soil. However, onions and cabbage are actively cultivated during the winter in the Lower Rio Grande Valley. Throughout southern Texas cotton and sorghum crops are typically rotated annually so that if cotton is grown one year, the next year sorghum is grown.

In both of these survey efforts described, burrowing owls were located opportunistically rather than through a standardized survey. Therefore the proportion of wintering owls utilizing agricultural areas versus non-agricultural areas in south Texas is unknown. Based on the roost sites surveyed it seems that the majority of owls wintering in agricultural areas utilize fields which do not have any active crops nearby. Additionally, it is unknown how frequently burrowing owls roosting in agricultural areas utilize other areas such as roadsides, ditches, or actively grown crops (e.g. cabbage and onions) if they are nearby.

The diet of western burrowing owls wintering in agricultural areas of south Texas is predominantly composed of insects followed by vertebrates, primarily rodents (Woodin et al., 2006). Owls may also incidentally ingest soil while foraging. Estimated soil ingestion rates in birds range from <2.0% to 30%, and vary with a species foraging habits or intentional soil ingestion for grit (Beyer et al.,

1994). However, to our knowledge, there are no documented cases of intentional ingestion of soil in owls.

2.2. Conceptual model

The model represents the foraging and roosting behavior of an individual western burrowing owl in crops that have received treatments with agricultural chemicals, provides estimates of the accumulation of these chemicals in owls resulting from dermal and oral exposure, and predicts the risk of lethal or sublethal effects. The model contains four submodels representing (1) foraging behavior of an individual bird, (2) chemical applications to crops, (3) transfers of chemicals among soil, insects, and rodents, and (4) transfers of chemicals to the bird via ingestion and dermal exposure (Fig. 3).

Submodel 1 controls bird foraging behavior within three separate scenarios modelling different combinations of four crops; cotton, sorghum, cabbage, and onions. In all three scenarios, a cotton/sorghum field is designated as a roost site. The western burrowing owl forages during the night in the fields surrounding the roost site, and remains at the roost site during the day. Scenario 1 represents two cotton/sorghum fields as foraging sites adjacent to the roost site. Each cotton/sorghum field alternates annually between cotton or sorghum crops grown during the summer, and the two foraging fields are offset so that there is always one cotton field and one sorghum field. In scenarios 2 and 3, a cabbage field or an onion field, respectively, was added as a foraging site, in addition to the cotton/sorghum fields. Scenario 1 represents chronic exposure to agricultural chemicals, which is typical for the majority of western burrowing owls wintering in southern Texas. Scenarios 2 and 3 add the potential for acute exposure to agricultural chemicals in addition to chronic exposure.

Submodel 2 represents the application of agricultural chemicals to these crops. Insecticides, herbicides, growth regulators, and defoliants are applied during appropriate seasons, with the specific chemicals and application dates chosen randomly based on historic patterns of use. Some of the applied chemicals are lost through (wind-driven) drift.

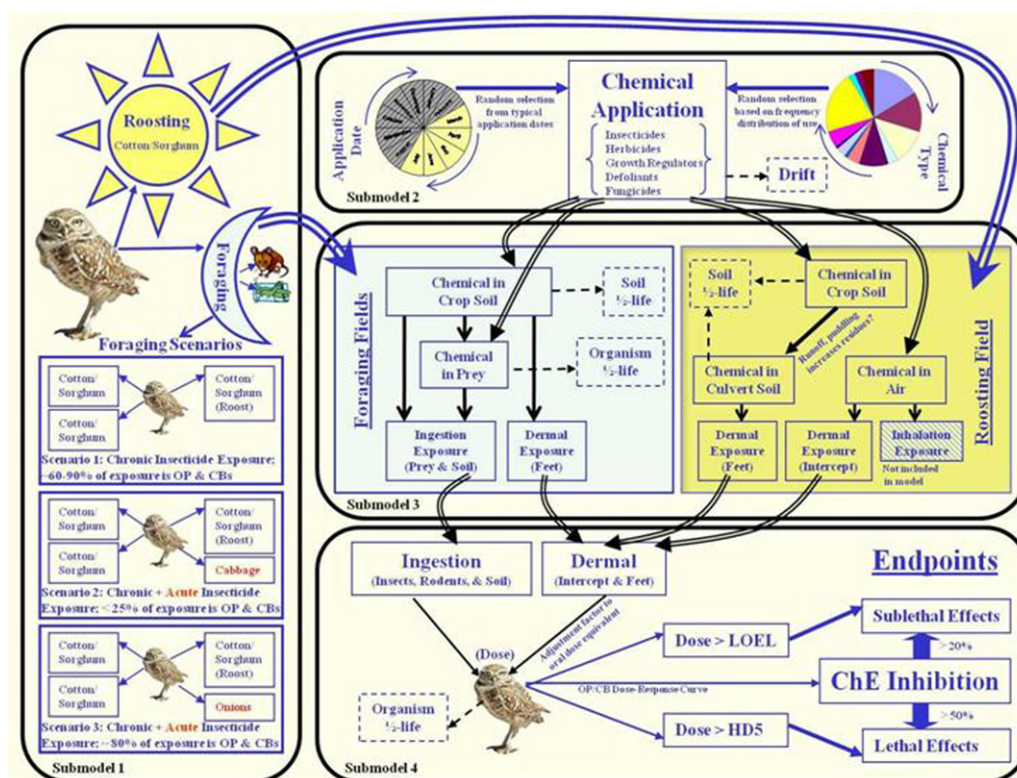


Fig. 3. Conceptual model of the effect of chemical exposure on western burrowing owls (*Athene cunicularia hypugaea*) wintering in agricultural landscapes. The model contains four submodels representing (1) foraging behavior of individual birds, (2) chemical applications to crops, (3) transfers of chemicals among crop, soil, insects, and rodents, and (4) transfers of chemicals to birds via ingestion and dermal absorption (OP = Organophosphates, CB = Carbamates, LOEL = Lowest observed effects level, HD5 = Hazardous dose resulting in mortality of 5% of the population, ChE = Cholinesterase). Black lines represent material transfers, blue lines represent processes, dashed lines represent material losses, and hollow lines represent interactions between submodels (for interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).

Submodel 3 represents the transfer of the applied chemicals to the soil in both foraging fields and the roost site, and subsequently to the prey (insects and rodents) of the owl. Chemicals are lost from soil, insects, and rodents depending on their respective half-lives, with the net accumulation in soil, insects, and rodents representing the chemical exposure risk to owls.

Submodel 4 represents the entrance of chemicals into the owl through both dermal and ingestion pathways, and the loss of chemicals depending on their respective half-lives. We used the net accumulations of chemicals within the owl as indicators of potential sublethal (LOEL) or lethal (HD5) effects, and for OP and CB insecticides as indicators of the level of cholinesterase (ChE) inhibition. LOEL and HD5 are defined formally as the "Lowest Observed Effects Level" and the "Hazardous Dose resulting in mortality of 5% of the population", respectively.

2.3. Quantitative model description

We developed the model as a stochastic compartment model based on difference equations ($\Delta t = 1/2$ day, which enables modelling of the owl's bimodal foraging behavior which differs between daytime and nighttime periods), programmed in STELLA® 7 (High Performance Systems, Inc., NH) (High Performance Systems, 2001). Parameters associated with (1) operational details of the STELLA program, (2) general ecology of the western burrowing owl, (3) growing seasons and common chemical treatments for crops in the southern United States, (4) application rates and frequencies for common agricultural chemicals in the southern United States, (5) soil half-life values for common agricultural chemicals, (6) chemical half-life values in vertebrate and invertebrates, (7) dermal toxicity indices for common agricultural chemicals, (8)

LOEL values to indicate sub-lethal effects resulting from chemical exposure, (9) HD5 values to indicate lethal effects resulting from chemical exposure, and (10) dose-response curve equations to estimate ChE inhibition from exposure to OP or CB insecticides, are summarized in Supplementary material, Tables 1 through 10, respectively.

2.3.1. Submodel 1: foraging behavior of individual birds

We based our representation of foraging behavior on personal observation and expert opinion on the general ecology of western burrowing owls (Supplementary material, Table 2). We assumed that the owl arrived on the wintering grounds on 1 October and departed on 1 March. We also assumed the owl would forage preferentially in a cabbage or onion field, if available, and otherwise would exhibit a slight preference for foraging in its roost-site field over foraging in an adjacent cotton/sorghum field. Cabbage and onion fields in addition to cotton/sorghum fields were chosen because they are representative of the habitat surrounding several roost sites found in the Rio Grande Valley study area. Anecdotal evidence from local birders in the area suggests that burrowing owls may use cabbage and onion fields for foraging. Thus, in Scenario 1, we assumed there was a 40% chance the owl would forage in the field in which its roost site is located, a 30% chance it would forage in one of the adjacent cotton/sorghum fields, and a 30% chance it would forage in the other adjacent cotton/sorghum field. In Scenarios 2 and 3, we assumed there was a 50% chance the owl would forage in the cabbage or onion field, a 30% chance it would forage in its roost-site field, a 10% chance it would forage in one of the adjacent cotton/sorghum fields, and a 10% chance it would forage in the other adjacent cotton/sorghum field.

2.3.2. Submodel 2: chemical applications to crops

We parameterized the model to represent the growing seasons and common chemical treatments for crops in the southern United States, specifically in southern Texas (Supplementary material, Tables 3 and 4). The growing seasons are based on earliest possible planting dates and latest possible harvest dates. Treatments often consist of multiple applications of the chemical selected, and multiple treatments can occur during the growing season. A date is selected randomly within the appropriate treatment period. For example, cotton, on average, receives 1.82 herbicide treatments per year. Thus, the first simulated treatment always occurs at a randomly selected date during the first treatment period, and there is an 82% chance that a second treatment will occur at a randomly selected date during the second treatment period. The number of treatments was calculated from NASS (2004) or NASS (2006) as: (the sum of percent area applied for all pesticides within each class)/(percent of total area to which each type of pesticide class was applied). The specific agricultural chemicals applied are selected randomly based on frequency distributions of crop-specific use in Texas. The number of applications within each treatment and the application rate are designated specifically for each chemical (Supplementary material, Table 4).

2.3.3. Submodel 3: transfers of chemicals among soil, insects, and rodents

We parameterized the transfers of chemicals among soil, insects, and rodents based on half-life values for common agricultural chemicals in soil (Supplementary material, Table 5) and in vertebrate and invertebrates (Supplementary material, Table 6). In the cotton/sorghum fields a crop is planted in the spring and grows until it is harvested. Agricultural chemical treatments occur during crop growth, however, by the time the owl arrives, the crop has been harvested and the soil is bare. We chose to simplify the net processes within our model by assuming that by the time the owls had arrived all of the chemicals applied to the crop were either washed off of the vegetation into the soil during rain or irrigation events, or were incorporated into the soil along with the plants at harvest. Thus, at application, the residues of each chemical are present in the soil, and subsequently decay at the rate listed for that compound:

$$CS_{t+1} = CS_t + (A_t - CS_t \times (1/2)(1/d_s)) \Delta t, \quad (1)$$

where CS_t represents the chemical residue concentrations in the soil ($\mu\text{g}/\text{cm}^2$) present at time t , A_t represents the concentration of chemical ($\mu\text{g}/\text{cm}^2$) applied at time t , and d_s represents the half-life of the chemical in the soil (Supplementary material, Table 5).

Chemical residues are transferred to insects and rodents during application, and subsequently during each time step based on the amount of chemical residues present in the soil. We used estimates of residues in prey items from Forsyth and Westcott (1994), Martin et al. (1996), Cobb et al. (2000), Block et al. (1999) to derive equations for the transfer of chemical residues to prey items (insects and rodents). In these studies, residues on invertebrate prey items ranged from 1.57 to 7.44 times the application rate. We used a value of 2.5 times the application rate, which was the average value estimated from Forsyth and Westcott (1994) to represent the amount transferred to invertebrate prey at application. An average of 0.21 times the application rate was extrapolated from Block et al. (1999) to represent the amount of residue transferred to mammalian prey at application. We used the residue concentration in soil, divided by 100, to estimate accumulation in both insects and rodents during each time step:

$$CI_{t+1} = CI_t + ((A_t \times 2.5) + (CS_t/100) - (CI_t \times (1/2)(1/d_i))) \Delta t \quad (2)$$

$$CM_{t+1} = CM_t + ((A_t \times 0.21) + (CS_t/100) - (CM_t \times (1/2)(1/d_m))) \Delta t, \quad (3)$$

where CI_t and CM_t represent the chemical residue concentrations ($\mu\text{g}/\text{g}$) present at time t in insects and rodents, respectively, and d_i and d_m represent the half-lives of the chemical in insects and rodents, respectively (Supplementary material, Table 6). We estimated half-lives in insects as 1/10 the soil half-life, unless the half-life in vertebrates was greater, in which case the vertebrate half-life value was used. We chose this ratio because it gave values that generally fit our assumption that chemicals would decay faster in insects than in soil, but not as rapidly as in vertebrates which have a more efficient excretion system. We estimated half-lives in rodents from values on vertebrate half-lives obtained from Pesticide Information Profiles (<http://extoxnet.orst.edu/pips/ghindex.html>, accessed 2007). If a vertebrate half-life value was not available, we estimated a half-live value based on a trend line ($y = 1.624x^{0.5865}$) (Supplementary material, Table 6 and Fig. 1), that was fitted to values of vertebrate half-lives (y) (Supplementary material, Table 6) and soil half-lives (x) (Supplementary material, Table 5) using Microsoft® Office Excel 2003 (Microsoft Corp.).

2.3.4. Submodel 4: transfers of chemicals to birds via ingestion and dermal exposure

We parameterized the transfers of chemicals to owls via ingestion and dermal exposure based on ingestion rates and body surface area (Supplementary material, Table 2), and dermal toxicity indices for common agricultural chemicals (Supplementary material, Table 7). Ingestion of chemicals occurs when the bird consumes prey items, or through soil ingestion:

$$IR_{t+1} = IR_t + (((\sum_i (C_{i,t} \times B_i) + (CS_t \times S))/W) - (IR_t \times (1/2)(1/d_m))) \Delta t, \quad (4)$$

where IR_t represents the concentration of chemicals ($\mu\text{g}/\text{g}$) in the owl at time t that have been accrued through ingestion. $C_{i,t}$ represents the concentration of chemicals ($\mu\text{g}/\text{g}$) in the i th prey consumed at time t , B_i represents the biomass consumed (g) of the i th prey, CS_t represents the quantity of chemicals ($\mu\text{g}/\text{cm}^2$) ingested via consumption of soil at time t , S represents the soil ingestion rate (cm^2), and W represents the weight (g) of the owl. We used mammalian half-lives (d_m) because avian half-lives were unavailable.

Dermal absorption of chemicals occurs through the owl's legs and feet from contaminants present in the soil. This occurs as the western burrowing owl roosts in or near its culvert during the day, and during the night while foraging:

$$DF_{t+1} = DF_t + (((CS_t \times SA_f \times G_t)/W) \times DO) - (DF_t \times (1/2)(1/d_m))) \Delta t, \quad (5)$$

where DF_t represents the quantity of chemicals ($\mu\text{g}/\text{g}$) that have come into dermal contact with the owl's legs and feet up to and including time t , SA_f represents the surface area (cm^2) of the owl's legs and feet, G_t represents the percentage of the time step the owl's legs and feet were in contact with the soil, and DO_i represents a dermal to oral toxicity index that converts a dermal dose to an equivalent amount of an oral dose (Supplementary material, Table 7).

Dermal absorption also can occur as a dermal intercept dose if the owl is present during or immediately after an agricultural chemical treatment. We estimated the dermal intercept dose based

on the amount of chemical present in the air that lands on the dorsal half of the owl's body surface, and is absorbed through their skin:

$$DI_{t+1} = DI_t + (((A_t \times SA_b)/W) \times DO) - (DI_t \times (1/2)(1/d_m)) \Delta t, \quad (6)$$

where DI_t represents the quantity of chemicals (μg) that have come into dermal contact with the owl's dorsal surface up to and including time t , and SA_b represents the dorsal surface area (cm^2) of the owl.

2.3.5. Model output

To interpret the accumulation of chemicals within the owl in terms of overall impact, we used three indices, or “endpoints”: (1) frequency and duration of accumulations >LOEL, (2) frequency and duration of accumulations >HD5, and for OP and CB insecticides (3) level of ChE inhibition. We used the additive concentrations of the converted dermal and oral doses to estimate these endpoints.

We obtained LOEL levels from a wide variety of sources, primarily through the U.S. E.P.A. (Supplementary material, Table 8). Due to the lack of information on birds, we used LOELs obtained from studies using mammals. We used the lowest reported value of a LOEL, or LEL, for each chemical as the threshold level of effect in the model. For the chemicals where no information was available, we did not evaluate this endpoint. We obtained HD5 levels primarily from Mineau et al. (2001) (Supplementary material, Table 9). In the cases where the HD5 for a chemical was not estimated, we used Microsoft® Office Excel 2003 (Microsoft Corp.) to plot HD5 values against avian LD50 values and used the fitted trendline ($y = 0.1662x^{0.9133}$) to estimate HD5 (Supplementary material, Table 9 and Fig. 2). We estimated the level of ChE inhibition caused by the accumulation of each chemical in the owl using dose–response curves for OP and CB insecticides (Supplementary material, Table 10). We then estimated the total level of ChE inhibition by summing the ChE inhibitions from the individual chemicals. As a point of comparison with the other two endpoints, a ChE inhibition >20% indicates a level of accumulation likely to result in sublethal effects, and a ChE inhibition >50% indicates a level of accumulation likely to result in lethal effects (Ludke et al., 1975).

2.3.6. Model verification and calibration

To verify the model was performing in a reasonable manner, we ran numerous trial simulations representing both low-level, chronic exposure and high-level, acute exposure to a variety of agricultural chemicals. During each trial, we traced the movement of each chemical through the system, monitoring chemical accumulations in soil, water, insects, and rodents, as well as the portions of the accumulation in the owl resulting from consumption, and dermal absorption.

2.3.7. Sensitivity analyses

We explored the sensitivity of model predictions to uncertainty in parameter estimates by running 10 series of replicate stochastic (Monte Carlo) simulations in each of the three scenarios. The first series consisted of 200 replicates run in each of the three scenarios as a baseline. The additional nine series consisted of 80 replicates in each of the three scenarios, representing a worst-case scenario with regard to one of the key model parameters (Table 1). For each simulation we recorded values for the endpoints for each half-day time step throughout one season. We then determined the mean and maximum levels of ChE inhibition in the owl, and frequency and duration of ChE inhibition >20% and >50%. We also recorded the maximum number of chemicals with accumulation levels >HD5, the maximum number of chemicals with accumulation levels >LOEL, as well as the duration of exposure exceeding these accumulation levels. The results were analyzed to compare each parameter change with the baseline simulations. We used a one-way ANOVA with a Bonferroni post hoc test because it is

Table 1

Summary of changes made to model parameters during sensitivity analysis. Baseline values of model parameters are presented in Supplementary material, Table 1.

No.	Parameter change	Additional explanation
1	Increased soil in diet	Estimated soil ingestion rates in birds range from <2.0% to 30% (Beyer et al., 1994). There are no documented cases of intentional ingestion of soil by owls, and any soil ingested by burrowing owls would occur incidentally while foraging. The soil in the diet was set at the lower end of the spectrum at 3%. This sensitivity analysis increased the value to 10%.
2	Increased dermal exposure during foraging	During winter, western burrowing owls forage at night (Woodin, 2004). It was assumed that the owl spent the majority of this time flying, and spent 1 h on the ground during which time it was exposed to chemicals through its legs and feet. In this sensitivity analysis the duration of time on the ground while foraging was increased to 9 h.
3	Increased half-life in bird	The chemical in the owl was either excreted or metabolized by the owl according to a vertebrate half-life value. These half-life values were estimated or derived primarily from studies on half-life values in mammals. Because the half-lives in mammals may differ from half-lives in birds, in this sensitivity analysis the vertebrate half-life values were increased by five times their original amount.
4	Decreased loss due to drift	Drift decreases the concentration ($\mu\text{g}/\text{cm}^2$) in the field due to the pesticide landing in a larger area than the crop. In the model drift was set at 0.05%. For this sensitivity analysis was decreased to 0%.
5	Increased half-life in insects	Invertebrate half-lives were estimated primarily as 1/10 the value of the soil half-lives. In this sensitivity analysis the half-lives in invertebrates were increased to the value of half-lives in soil.
6	Increased accumulation in prey	Estimated transfer of residues at application to prey items ranged from 1.57 to 7.44, for invertebrates, and 0.21 for mammals, times the application rate (Forsyth and Westcott (1994); Martin et al., 1996; Cobb et al., 2000; Block et al., 1999); and a value of the concentration in soil divided by 100 was used to estimate accumulation during each time step for both invertebrates and vertebrates. In this sensitivity analysis both invertebrate and vertebrate transfer rates at application were increased to 7.44 times the application rate, and the amount of accumulation in each time step was increased to the concentration in soil divided by 10.
7	Increased soil half-life values	Soil half-lives were obtained primarily from PAN (Pesticide Action Network database) and PIP (Pesticide Information Profiles database) (PAN, 2007; PIP, 2007), in most cases the aerobic half-life value from PAN was used. However, if the PAN and PIP values differed widely, an intermediate value was chosen. In this sensitivity analysis, the highest possible soil half-life values were used.
8	Increased dermal to oral toxicity indexes	Dermal toxicity indexes based on avian oral and dermal LD50s only were available for a some of the chemicals evaluated, and the rest were estimated (Fite et al., 2004), creating a high level of uncertainty in these values. This sensitivity analysis doubles the DTI values.
9	Allowed early spring spraying prior to owl departure	In the model the dates when the first insecticide treatment on cotton or sorghum can occur and the dates that the owl is present do not overlap. This sensitivity analysis allowed an 11-day overlap in these periods.

more conservative in estimating significant differences in multiple comparisons (SPSS statistical package, SPSS Inc., 2001).

2.3.8. Model application

To demonstrate use of the model, we simulated the impacts of oral and dermal exposure to mixtures resulting from long-term agricultural use of a variety of common insecticides, herbicides, growth regulators, and defoliants on western burrowing owls wintering in agricultural landscapes in southern Texas. We ran 200 replicate stochastic (Monte Carlo) simulations for each of the three crop scenarios. Scenario 1 represented two cotton/sorghum fields as foraging sites adjacent to the roost site. Each cotton/sorghum field alternated annually between cotton or sorghum crops grown during the summer, and the two foraging fields were offset so that there was always one cotton field and one sorghum field. In scenarios 2 and 3, a cabbage field or an onion field, respectively, was added as a foraging site, in addition to the cotton/sorghum fields. For each simulation we recorded values for the endpoints for each half-day time step throughout one season. We then determined mean and maximum levels of ChE inhibition in the owl, and frequency and duration of ChE inhibition >20% and 50%. We also recorded the number of chemicals with accumulation levels >HD5, the number chemicals with accumulation levels >LOEL, as well as the duration of exposure exceeding these accumulation levels. We analyzed differences among crop scenarios using a one-way ANOVA with a Bonferroni post hoc test for each item (SPSS statistical package, SPSS Inc., 2001).

3. Results

3.1. Model verification and calibration

The model exhibited the expected general patterns of behavior with regard to the movement of chemicals through soil, water, insects, and rodents, appropriately reflecting the information contained in the various data bases (Supplementary material, Tables 1–10) used in its development. However, simulated levels of accumulation of several organophosphate insecticides failed to reach the levels reported in the prey and pellets of western burrowing owls (Woodin et al., 2006). Organophosphate insecticides are known to persist in the soil much longer than would be expected based on their half-lives (Ragnarsdottir, 2000). Thus we extended pesticide persistence in the soil and insects by calibrating d_s and d_i (chemical half-life in the soil and insects, respectively; Eqs. (1) and (2)) such that the numbers of different OP and CB residues grouped by concentration level ($\mu\text{g/g}$), accumulated in simulated prey items were similar to those reported for southern Texas, United States by Woodin et al. (2006). This calibration resulted in mixtures of pesticide residues consistent with those observed by Woodin et al. (2006) in each concentration level, although it tended to underestimate residues in the lowest range evaluated (Table 2). Final calibration consisted of increasing the value of d_s and d_i by two orders of magnitude when concentrations of a chemical fell below $0.1 \mu\text{g/g}$. We did not extend pesticide persistence in rodents since they metabolize and eliminate these chemicals more efficiently than insects, and since we had empirical estimates of pesticide half-lives in mammals (Supplementary material, Table 6). The calibrated model generated reasonable movement patterns for each chemical through soil, water, insects, and rodents, as well as into the owl via consumption, and dermal absorption (Fig. 4). By reasonable, we mean irrefutable based on available data and our current level of knowledge of system dynamics. For example, Fig. 4 demonstrates the application of the chemicals on the soil in the three different fields and the subsequent transfer to prey items and the owl followed by exponential decay. The application amount varies in each

of the chemicals graphed. Additionally we observe that the application rates of glyphosate differ as the crop rotates between cotton and sorghum. Soil concentrations of glyphosate spike in years when the crop received a second application. The rate of exponential decay is steepest in the herbicide glyphosate which has the shortest half-life (47 days), and is slowest in the defoliant tribufos which has the longest half-life (745 days). The initial chemical concentrations post-application are higher in insects than in rodents due to the higher transfer rate used for insects (Equations (2) and (3)). Finally we can track how the chemicals in the owl are accrued from all three fields, and how dermal exposure spikes when chemicals are applied to the field in which the owl roosts.

3.2. Sensitivity analyses

Results of sensitivity analysis suggested that model predictions were sensitive to the uncertainty associated with estimates of chemical half-lives in birds, soil, insects, and rodents, sensitive to uncertainty in parameters associated with estimating dermal exposure, and relatively insensitive to uncertainty associated with details of chemical application procedures such as timing of application and amount of drift (Table 3). The model exhibited sensitivity to more parameters when simulating the crop scenarios that included acute chemical exposure (Scenarios 2 and 3).

3.3. Model application

3.3.1. ChE inhibition

The mean maximum and mean ChE inhibition levels were slightly, but insignificantly, higher for Scenario 2 (with an adjacent cabbage field added) (10.0%-maximum, 3.9%-mean) than for Scenario 1 (3.9%-maximum, 2.3%-mean). With the addition of an adjacent onion field, ChE inhibition for Scenario 3 (58.2%-maximum, 16.5%-mean) was significantly higher than for Scenario 1 and Scenario 2 ($p < 0.001$) (Fig. 5). Likewise, mean durations of ChE inhibition >20% and >50% were slightly, but not significantly, longer for Scenario 2 (1.8 days—>20%, 0.7 days—>50%) than for Scenario 1 (0.0 days—>20%, 0.0 days—>50%). Mean durations of ChE inhibition >20% and >50% were significantly longer for Scenario 3 than for Scenario 1 and Scenario 2 (16.5 days—>20%, 14.0 days—>50%; $p < 0.001$) (Fig. 5).

3.3.2. LOEL

In all three crop scenarios, a greater number of insecticides than the other chemical classes reached accumulations in the owl > LOEL. Mean insecticide exposure >LOEL occurred throughout the entire winter (144–147 days) in all three crop scenarios. In Scenario 1 the owl accumulated a greater mean number of growth regulators or defoliants (1.290) than herbicides (1.025) >LOEL. However, when cabbage or onions were added as a foraging site, the owl accumulated a greater mean number of herbicides (1.365—Scenario 2; 1.470—Scenario 3) than growth regulators and defoliants (1.050—Scenario 2; 1.025—Scenario 3) >LOEL (Fig. 6). In all three scenarios, the owl accumulated growth regulators and defoliants >LOEL for a longer period (96–119 days) than herbicides (71–85 days) (Fig. 6).

Scenario 2 had the highest mean number of insecticides >LOEL (1.670), which was significantly greater ($p = 0.010$) than the mean number of insecticides >LOEL for Scenario 1 (1.485). Scenario 3 had an intermediate value (1.605), which was not significantly different from the other two scenarios (Fig. 6). The duration of accumulation > LOEL was not different among the three scenarios (Fig. 6).

The mean number of herbicides >LOEL was significantly greater ($p < 0.001$) for Scenario 2 (1.365) and Scenario 3 (1.470) than for Scenario 1 (1.025). Scenario 3 had the highest mean number of herbicides >LOEL of all three crop scenarios (Fig. 6). The duration

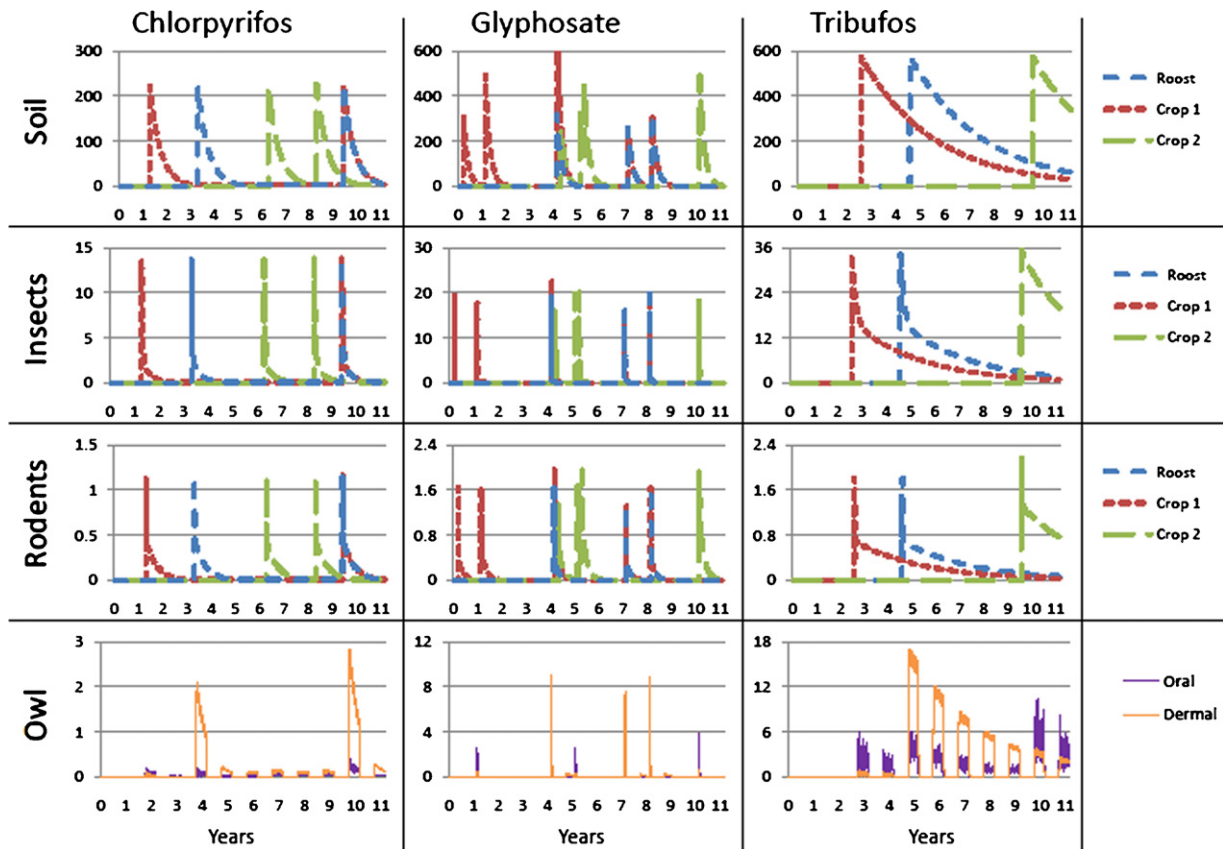


Fig. 4. Typical movement patterns through soil, insects, and rodents, as well as into the owl via consumption and dermal absorption, generated by the simulation model for a representative insecticide (chlorpyrifos), herbicide (glyphosate), and defoliant (tribufos). Graphs illustrate rapid increases in chemical concentrations in foraging (crop) fields and at the roost immediately after pesticide applications, followed by exponential declines in concentration levels. The y-axes represent concentrations of the representative chemical, while the x-axes represents time in years.

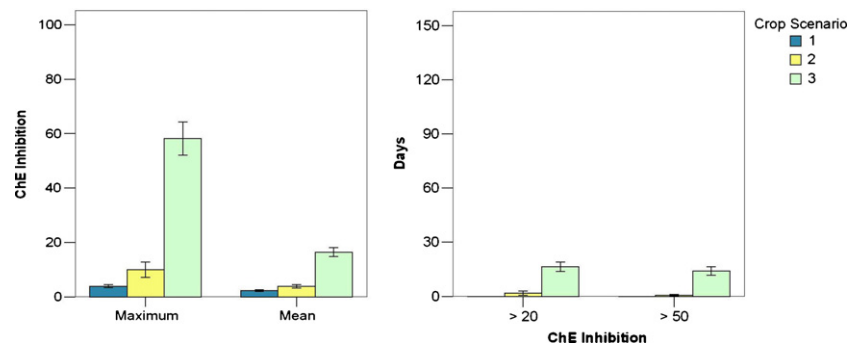


Fig. 5. Differences among crop scenarios in (a) maximum and mean levels of ChE inhibition, and (b) duration of ChE inhibition levels >20% and >50%. See text for details.

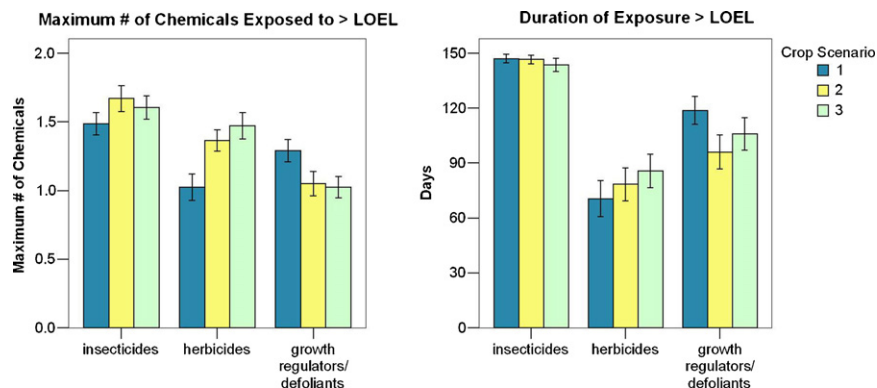


Fig. 6. Differences among crop scenarios in (a) the mean number of chemicals with accumulation levels >LOEL, and (b) the duration of such accumulation levels. See text for details.

Table 2
Comparison of the numbers of different OP and CB residues, grouped by concentration level, accumulated in prey items from five field samples collected in south Texas, United States by Woodin et al. (2006) to the corresponding values generated by the calibrated model. See text for calibration details.

Numbers of different OP and CB residues						
Concentration level ($\mu\text{g/g}$)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Simulated range
0.001–0.01	5	5	7	5	0	0–3
0.01–0.1	5	2	4	2	2	1–4
0.1–1.0	1	2	0	1	2	2–3
>1.0	0	0	0	0	4	0–1

of herbicide accumulations >LOEL was lowest for Scenario 1 (70.5 days) and highest for Scenario 3 (85.6 days); however, these differences were not significant (Fig. 6).

The mean number of growth regulators and defoliant >LOEL was significantly higher ($p < 0.001$) for Scenario 1 (1.290) than for the other two scenarios (Scenario 2 = 1.050, Scenario 3 = 1.025) (Fig. 6). In addition, the duration of accumulation of growth regulators and defoliant >LOEL was greatest for Scenario 1 (118.7 days) (Fig. 6).

3.3.3. HD5

Insecticides were the only chemical class accumulated to levels >HD5 within the owl, and the duration of such accumulations only encompassed a small portion (5–9 days) of the winter period (Fig. 7). The mean number of insecticides accumulated to levels >HD5 was significantly greater for Scenarios 2 (0.380) and 3 (0.335) than for Scenario 1 (0.125) ($p < 0.001$), and was highest for Scenario 2 (Fig. 7). The duration of accumulations >HD5 also was significantly longer for Scenario 2 (Scenario 1 = 4.9 days, Scenario 2 = 8.8 days, Scenario 3 = 5.2 days) (Fig. 7).

4. Discussion

4.1. Model strengths

This model provides a framework for comparison of different classes of chemicals, individual chemicals, as well as different crops; in terms of their potential lethal or sublethal effects in birds. To our knowledge this is the first model to use three separate endpoints, including LOEL values, to assess sublethal effects of agricultural chemical exposure on wintering birds. While reproductive effects have been used as endpoints for assessing risk of sublethal effects in birds, (Shore et al., 2005; Mineau, 2005; Bennett et al., 2005), a reproductive endpoint is less pertinent during the non-breeding season. For this reason we chose LOELs as an endpoint to assess sublethal effects. However, because the LOEL values were obtained from studies using mammals, they may indicate risk less accurately than assessments using HD5 or ChE inhibition values. The use of multiple endpoints compensates for this limitation, and allowed a more comprehensive risk analysis than assessing a single endpoint, which could present misleading conclusions.

For example, in the potential acute exposure scenarios, ChE inhibition was greatest when an onion field was used as a foraging site. Over 80% of insecticide treatments in onion fields used OP or CB insecticides, (compared to 24% in cabbage fields), and diazinon and methomyl, the two insecticides which comprised all of the reported OP and CB insecticide use on onion fields, are extremely toxic to birds (characterized by an LD50s below 40 mg/kg) (Smith, 1993; Supplementary material, Table 4). Similarly, Mineau and Whiteside (2006) found that in the United States onion rather than cabbage crops had a higher potential lethal risk to birds. So by using ChE inhibition as the only endpoint we would conclude that greater risk to the owl is incurred by foraging in onion fields than in cabbage fields.

However, this conclusion is contradicted when we consider the other two endpoints in our model. In cabbage fields over 75% of insecticide use was from types of insecticides other than OPs and CBs, including the highly toxic OC insecticide endosulfan (Smith, 1993; Supplementary material, Table 4). Concurrently, in the potential acute exposure scenarios, the lethal and sublethal effects of all insecticides based on LOELs and HD5s were greatest in the presence of a cabbage field. This discrepancy between endpoints demonstrates how, despite the uncertainty associated with the LOEL values, using multiple endpoints provides a more complete analysis of risk than using a single endpoint. In addition, concurring results from all three endpoints can provide a stronger assessment of a chemical or crop than from one endpoint alone.

4.2. Pesticide exposure on wintering western burrowing owls

Using the three endpoints we showed that the risk of chemical classes to western burrowing owls wintering in southern Texas cotton/sorghum fields can be described as highest for insecticides, second highest for growth regulators and defoliant, and lowest for herbicides; and the greatest risk of lethal or sublethal effects was due to OP and CB insecticides. These simulations also demonstrated that lethal or sublethal effects of exposure to insecticides, along with model sensitivity, increased in the presence of an adjacent crop that received agricultural chemical treatments (Scenarios 2 and 3). This was likely due to acute exposure to chemicals present in the foraging areas immediately after treatment. The importance of foraging in areas that allow potential acute exposure is corroborated by Corson et al. (1998) whose model was highly sensitive to foraging location. Likewise, an analysis of variability in risk assessments found that bird movements between treated and untreated areas was one of the most important factors and led to substantial differences in observed effects (Hart, 1990).

Ideally this model of the effects of pesticide exposure to a single wintering western burrowing owl could be used as a precursor to determining population-level effects. However, there are several unknown aspects of burrowing owl life history which should be researched through field studies prior to conducting a population-level analysis. First, there is no information on the proportion of owls utilizing agricultural fields versus other grassland areas in southern Texas (Woodin et al., 2008). Consequently, this model only allows inferences on the subset of burrowing owls roosting in agricultural areas. Second, we constructed this model assuming that wintering western burrowing owls always foraged in agricultural areas. However, the degree to which wintering western burrowing owls forage in agricultural areas versus other habitat is unknown. Gervais et al. (2003) found that breeding burrowing owls foraged in agricultural fields, and limited observations were made of western burrowing owls in the Rio Grande Valley foraging in cabbage, cotton, and sorghum fields (Engelman, unpublished data). Conversely, limited radiotelemetry work conducted on foraging behavior in the Gulf Coast study area indicated that the owls foraged in mowed roadsides or grassy patches along the edge of fields, rather than in the fields themselves (Woodin, 2010). If these areas are untreated, then similar to the findings of the models

Table 3Results of sensitivity analysis indicating significant changes ($p < 0.05$, “X”) from baseline for each endpoint in each chemical class.

Crop scenario	Endpoint	Chemical class	Data type	Sensitivity analyses									Total
				1	2	3	4	5	6	7	8	9	
Cotton/sorghum													
									Cotton/sorghum total				39
	ChE	OP/CB insecticides	Maximum		X					X	X		3
			Mean		X	X				X			2
			Duration >20%										1
			Duration >50%			X							1
	LOEL	Insecticides	Maximum		X	X				X	X		4
			Duration										0
		Herbicides	Maximum	X	X				X	X	X		4
			Duration	X	X						X		4
	HD5	Growth regulators and defoliants	Maximum			X		X	X		X		4
			Duration	X	X		X	X	X				5
		Insecticides	Maximum			X	X			X			2
			Duration			X	X			X			3
	HD5	Herbicides	Maximum										0
			Duration										0
		Growth regulators and defoliants	Maximum			X		X	X				3
			Duration			X		X	X				3
Cotton/sorghum/cabbage													
									Cotton/sorghum/cabbase total				44
	ChE	OP/CB insecticides	Maximum			X							1
			Mean			X				X			2
			Duration >20%			X							1
			Duration >50%			X							1
	LOEL	Insecticides	Maximum		X	X		X	X	X	X		6
			Duration										0
		Herbicides	Maximum	X	X			X	X	X	X		5
			Duration	X	X			X	X		X		6
	HD5	Growth Regulators and defoliants	Maximum		X	X		X	X	X	X		5
			Duration			X		X	X	X			5
		Insecticides	Maximum			X	X		X	X	X	X	4
			Duration			X		X		X			5
	HD5	Herbicides	Maximum										0
			Duration										0
		Growth regulators and defoliants	Maximum			X			X				0
			Duration			X							0
Cotton/sorghum/onions													
									Cotton/sorghum/onions total				47
	ChE	OP/CB insecticides	Maximum					X					
			Mean		X	X		X	X	X			
			Duration >20%		X	X		X	X	X			
			Duration >50%			X		X	X				3
	LOEL	Insecticides	Maximum		X	X			X	X	X		5
			Duration										0
		Herbicides	Maximum	X	X			X	X		X		5
			Duration	X	X			X					3
	HD5	Growth regulators and defoliants	Maximum		X	X		X	X				4
			Duration			X		X	X	X			4
		Insecticides	Maximum			X		X	X	X	X		3
			Duration					X	X	X			5
	HD5	Herbicides	Maximum										0
			Duration										0
		Growth regulators and defoliants	Maximum			X		X	X				3
			Duration			X							1
Sensitivity analyses totals				0	14	36	1	24	22	20	12	1	

(1 = Increased soil in diet, 2 = Increased dermal exposure during foraging, 3 = Increased half-life in bird, 4 = Decreased loss due to drift, 5 = Increased half-life in insects, 6 = Increased accumulation in prey, 7 = Increased soil half-life values, 8 = Increased dermal to oral toxicity indexes, and 9 = Allowed early spring spraying prior to owl departure).

by Corson et al. (1998) and Hart (1990), the effects of exposure to pesticides may be substantially reduced by foraging in untreated areas. Third, the differences in concentrations of agricultural chemicals between the fields, and the areas immediately adjacent to the fields in which the owls may also roost and forage, is unknown. Roost sites used by western burrowing owls in southern Texas are usually culverts or debris piles within a meter or two of the edge of the fields, but owls could also be found both inside and well outside of tilled fields. Due to the very close proximity of the owl roosts to the heavily treated farm fields, we assumed that the pesticide applications, transfers between biota, and subsequent processes were identical at the roost sites to the adjacent fields.

To assess impacts of wintering in agro-ecosystems on western burrowing owl populations, future studies should focus on foraging ecology to determine how frequently bare fields, active crops, or roadsides are utilized by western burrowing owls, and species distribution to determine the relative proportions of burrowing owls using agricultural areas versus other habitat. This information could be used to link the reductions individual fitness from the chronic low-level pesticide exposure described in our model with population-level effects.

4.3. Model limitations

Forbes et al. (2009) states that ecological models used for risk assessment can identify important data gaps which can be used to guide future study designs. Accordingly, one of the constraints in evaluating this model is the lack of an independent data set. Field studies gathering site-specific data on contaminant residues in the soil and prey items, both within and adjacent to fields, and documenting the occurrence of lethal or sublethal effects in wintering western burrowing owls would be invaluable in testing the model's performance. Additionally, through our sensitivity analysis, we identified the data gaps in our model which would have the greatest improvement on the model's predictions. These data gaps include (1) half-lives of agricultural chemicals in birds, (2) agricultural chemical half-lives in insects and their accumulation and transfer rates in prey, (3) dermal to oral toxicity indexes and duration of effects due to dermal exposure, and 4) the frequency and timing of pre-planting insecticide treatment in sorghum.

Of these parameters the model was most sensitive to changes in the half-lives of chemicals in the bird (sensitivity analysis 3) (Table 3). Unfortunately, mammalian half-life values were used because of a lack of data for birds. In addition, the half-lives of agricultural chemicals in the bird were assumed to be the same for both oral and dermal exposure. However, the duration of exposure may vary greatly between dermal exposure and oral exposure.

For example, Henderson et al. (1994) showed that pigeons did not recover from dermal exposure to OP insecticides for up to 6 weeks, while recovery from an oral dose took approximately 5 days.

The model's increased sensitivity to the half-lives in invertebrates, and the accumulation and transfer rates in prey; (sensitivity analyses 5 and 6); in the crop scenarios that added potential acute chemical exposure (FS-2, FS-3), (Table 3), suggests that the pesticide residues in prey are likely to be most important immediately after chemical treatments. Likewise, Driver et al. (1991) showed that oral exposure was most important during the 4–24 h period after spraying and decreased in importance afterwards. Additionally, Fairbrother (2003), and Crocker (2005), both found trophic transfer levels, and chemical concentrations in soil or prey, to be among the most sensitive risk assessment parameters, which concurs with our model's sensitivity to acute dietary exposure. While we found adequate data to estimate accumulation of residues in invertebrates, more information is needed on the accumulation in small mammals.

The model was sensitive to the parameters related to dermal exposure, (sensitivity analyses 2, 7, and 8 (Table 3). Similarly, Mineau (2002) concluded that dermal exposure needed to be included in pesticide avian risk assessments, and Hill (2003) suggested that it is imperative risk assessments of ChE inhibiting insecticides account for the total accumulation occurring through all possible routes of exposure. Unfortunately, there are few data available which can be used to evaluate dermal toxicity in birds, particularly for non-insecticidal agricultural chemicals, and the majority of values were estimated from an equation rather than based on toxicity test data (Supplementary material, Table 6). The importance of dermal exposure was highlighted by Driver et al. (1991), who found that from 8 to 48 h post-spraying dermal exposure greatly exceeded exposure occurring through inhalation and ingestion.

Early spring spraying did not occur frequently enough to cause significant changes in the endpoints (sensitivity analysis 9, Table 3), but may be more important than suggested by the model. Organophosphate insecticides have been shown to alter migration in adult birds, most likely by affecting memory of the migration route (Vyas et al., 1995). Pre-planting treatments are most commonly used for control of white grubs, corn rootworm, or wireworms in sorghum fields (Cronholm et al., 1998). If pre-planting treatments occurred prior to spring migration, western burrowing owls may be exposed at a critical period when memory of the migration route is vital. However, how frequently these treatments occur before the owls migrate is unknown.

The model was insensitive to changes in amount of soil in the diet and drift (1, 4) (Table 3). Although dietary soil was not

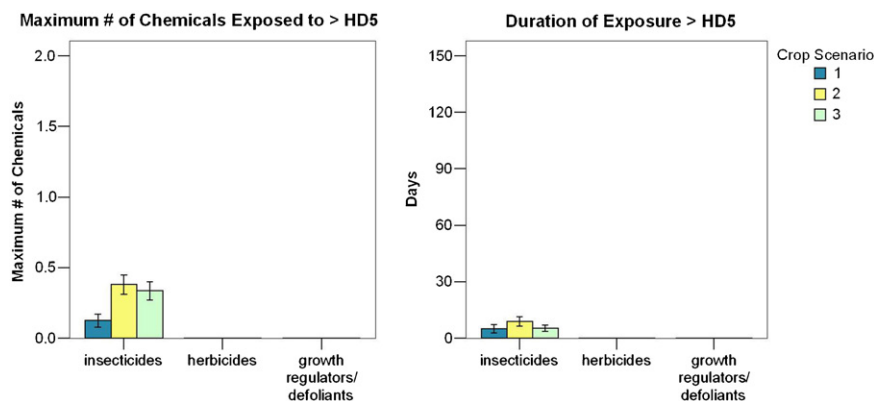


Fig. 7. Differences among crop scenarios in (a) the mean number of chemicals with accumulation levels >HD5, and (b) the duration of such accumulation levels. See text for details.

an important factor for western burrowing owls, it may be an important for species such as sandpipers that have a higher percentage of soil in their diet (Beyer et al., 1994). The amount of drift was set at an amount close to 0% in the baseline simulations, and may be more important with greater variation in the drift rates.

This study shows differential accumulation of insecticides, herbicides, and other agricultural pesticides on birds, exposed under three different foraging scenarios. The model could be re-parameterized for further avian risk assessments in agroecosystems, such as examining comparative risk of different individual chemicals to the focal species, however, these applications are beyond the scope of the current paper. The model is useful in explaining the potential impacts to which resident and wintering birds can be exposed when using agricultural environments in south Texas. To our knowledge this type of model of avian exposure to agricultural pesticides has not been utilized for any wildlife species in south Texas.

5. Summary and conclusions

In summary, we have developed an ecotoxicological model simulating sublethal and lethal effects of chronic, low-level, pesticide exposure on birds wintering in agricultural landscapes which includes submodels depicting bird foraging behavior of birds, and transfer of chemicals among soil, prey, and birds via ingestion and dermal exposure. Model predictions were sensitive to uncertainties in parameter values representing chemical half-lives and degree of dermal exposure, but general trends in chemical accumulations and relative impacts of different chemicals were robust to changes in the values of these parameters. Simulation results suggested that insecticides pose a greater potential risk to owls of both sublethal and lethal effects than do herbicides, defoliant, and growth regulators under crop scenarios typical of southern Texas. Simulation results also suggested that use of three different endpoints (ChE inhibition, LOEL, HD5) provided a more accurate and comprehensive risk analysis of both lethal and sublethal effects in birds due to agricultural chemical exposure.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2011.10.017.

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