102994

LANDSCAPE SCALE ASSESSMENT OF CONTAMINANT EFFECTS ON CAVITY-NESTING BIRDS

by

Kaia L. Colestock

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Ecology

Approved:

Dr. Mark Brunson
Major Professor

Dr. Jennifer Gervais
Committee Member

Dr. Jeanne Fair
Committee Member

Dr. Johan du Toit
Committee Member

Dr. Byron Burnham
Dean of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah
2007

31197

Copyright © Kaia Colestock 2006

All Rights Reserved

Landscape Scale Assessment of Contaminant Effects

on Insectivorous Birds

by

Kaia L. Colestock, Master of Science

Utah State University, 2006

Major professor: Dr. Mark Brunson
Program: Ecology

I examined the effects of contaminants on reproductive success of a Western Bluebird (*Sialia mexicana*) population nesting across a contaminant gradient at Los Alamos National Laboratory, New Mexico. Egg contents and prey were analyzed for heavy metal concentrations in home ranges to determine potential contaminant uptake. Home range size was determined using foraging observations. I tested whether home range contamination was correlated with egg and nestling reproductive parameters. Prey contaminant levels reflected the amount of contamination in home range more than egg contaminant levels. Nestling mortality was the most adversely impacted endpoint of reproductive success. Mortality was highly correlated with prey contaminant levels, specifically selenium, and a combination of selenium, beryllium and vanadium. Burned area and parasite load per nest were also associated with nestling mortality. Although there is evidence to show that lower reproductive success in bluebirds is associated with contaminant uptake in the home range, the causal factors remain unclear.

(84 pages)

ACKNOWLEDGMENTS

I am tremendously grateful to Dr. Jennifer Gervais, who served as the main advisor and assisted wholeheartedly in conducting this research. Her guidance and feedback was always patient, helpful, and professional. I am also extremely thankful that Dr. Mark Brunson agreed to serve as the major advisor following rule changes in the school of graduate studies at the end of this degree, as well as Dr. Johan du Toit for serving on this committee and offering his critiques. An extra thank you goes to Dr. Jeanne Fair for engaging my interest in the research, assisting me in starting a project, and providing resources through Los Alamos National Laboratory, New Mexico.

This project was funded in whole by the Los Alamos National Laboratory Environmental Restoration (ER) Project. I thank them sincerely for their support and guidance in the study. I am grateful to Kathy Bennett, Brad McKown, and Gil Gonzales at the Ecology Group for their assistance and everyone at the Atmospheric, Climate, and Environmental Science Group, EES-2. I was fortunate to have phenomenal field assistants: Virginia Seamster and Susan Cooper. I thank them for their sense of humor, patience, and hard work during the extensive seasons of data collection.

I want to acknowledge my lifelong friend Keith, who passed away during the making of this thesis, and whose friendship will be missed. Finally, I dedicate this thesis to my parents, without whom I would not have completed this work. I also dedicate it to my true mentor and godmother, Eunice Brooks, for her guidance, unconditional love, hope, and support during the last four years.

Kaia L. Colestock

CONTENTS

Page

ABSTRACT……...…… iii

ACKNOWLEDGMENTS…….. iv

LIST OF TABLES……. vii

LIST OF FIGURES……... ix

INTRODUCTION…….……. 1

STUDY AREA…….…….. 9

FIELD METHODS…… 12

Egg sampling……. 12
Nestling growth & productivity…… 13
Capture of adult females…… 13
Home range estimation…….. 15
Prey selection……. 16

LABORATORY METHODS…… 19

Eggs…… 19
Nests…….. 20

STATISTICAL ANALYSES…… 21

Databases…….. 21
Factors influencing egg and prey contaminant levels……... 23
Home range size and contaminants……... 29
Effects of home range contamination on reproductive success……. 30

RESULTS…….. 36

Factors influencing egg and prey contaminant levels…… 38
Home range size and contaminants…… 46
Effects of home range contamination on reproductive success……. 47

DISCUSSION…… 54

LITERATURE CITED……..…… 67

APPENDICES…… 77

Appendix A: Arithmetic means and range of heavy metal analytes (µg/kg) in egg (N=32) and prey (N=14) samples in 2005 at Los Alamos National Laboratory, New Mexico…… 78

Appendix B……. 79
B.1 Eggshell thickness as function of egg contaminants (n=29)…….. 79
B.2 Prey contaminants and nestling mortality (n=12)…….. 80
B.3 Prey contaminants and tarsus (n=9)…… 81
B.4 Prey contaminants and wing (n=9)……. 82

Appendix C: Steps to calculating Akaike's Information Criterion using the program SAS (Statistical Analysis Software)……. 83

Appendix D: Principle component factor scores from egg (N=32) and prey (N=14) samples collected at Los Alamos National Laboratory, New Mexico, in 2004 and 2005……. 84

LIST OF TABLES

Table Page

1 Weighted likelihood of *a priori* dependent egg contaminant load models (n = 28 eggs) based on Akaike's Information Criterion…….. 25

2 Weighted likelihood of *a priori* dependent prey contaminant load models (n = 12 prey samples) based on Akaike's Information Criterion…… 25

3 Minimum detection limits (MDL) (µg/kg) for heavy metal analytes in Western Bluebird eggs at Los Alamos National Laboratory, New Mexico…….. 27

4 Weighted likelihood of *a priori* dependent home range models (n = 41 home ranges) based on Akaike's Information Criterion…… 30

5 Weighted likelihood of *a priori* dependent eggshell thickness models (n = 29 eggs) based on Akaike's Information Criterion…….. 31

6 Weighted likelihood of *a priori* dependent tarsus size models (n = 9 nestlings) based on Akaike's Information Criterion…… 32

7 Weighted likelihood of *a priori* dependent mortality models (n = 11 nestlings) based on Akaike's Information Criterion…… 33

8 Mean (SE) eggshell thickness (mm), clutch size, percent eggs hatched, percent nestlings fledged, number of dead nestlings, and number of blowflies for sampled nests for 2003-2005 at Los Alamos National Laboratory, New Mexico…… 41

9 Composite insect samples (N = 14) analyzed for heavy metals from 2003-2005 at Los Alamos National Laboratory, New Mexico…… 42

10 Mean (SE) Western Bluebird home range size and percentage contaminated area within home range by location in 2005 at Los Alamos National Laboratory, New Mexico……..……..…… 46

11 Mean (SE) tarsi (mm), wing lengths (mm), and mass (g) of Western Bluebird nestlings, and number of blowflies per nest by location in 2005 at Los Alamos National Laboratory, New Mexico……...….. 49

12 General linear model of the number of parasites per nest and percent of contaminated home range, with location as the covariate; all factors fixed…… 51

13 General linear model of burned area and the percent of contaminated home range compared with mortality, with burned area as the covariate; all factors fixed…. 52

14 Results for models examining correlations between Western Bluebird nestling mortality and explanatory factors during 2004-2005 at Los Alamos National Laboratory, New Mexico…….…….…….. 53

LIST OF FIGURES

Figure Page

1 Avian nest box network in 2005 at Los Alamos National Laboratory, New Mexico……..…….. 11

2 Sampled Western Bluebird nests in Mortandad Canyon from 2004-2005 at Los Alamos National Laboratory, New Mexico…… 18

3 Historical annual precipitation from 1942-2006 at Los Alamos National Laboratory, New Mexico…… 36

4 Mean monthly precipitation during the breeding season from 2003-2005 at Los Alamos National Laboratory, New Mexico…… 37

5 Geometric means of heavy metal concentrations in Western Bluebird egg (N=32) and prey (N=14) samples in 2005, at Los Alamos National Laboratory, New Mexico……..... 40

6 Heavy metal contaminants from most upstream to most downstream reach in Mortandad Canyon in 2005, Los Alamos National Laboratory, New Mexico…….……..……..……..…….…… 45

INTRODUCTION

In the last several decades, recognition of the importance of birds as biomonitors of contaminants has increased because of their sensitivity to pollutants, ubiquitous distribution, and position in the food chain (Steidl et al., 1991; Burger and Gochfield, 1993; Furness, 1993; Eeva and Lehikoinen, 1996; Hui, 2002). Concern has grown in particular regarding detrimental effects of contaminants on avian reproduction (Eeva et al., 1997). Heavy metals are among the contaminants known to have negative impacts on avian populations; these are produced as frequent waste products of any number of industrial processes and biogeochemical cycles (Eens et al., 1999; Janssens et al., 2001; Dauwe et al., 2005). Many studies have found that heavy metals are specifically associated with decreased egg production (Scheuhammer, 1987), increased fluctuating asymmetry of bilateral traits (Eeva et al., 2003; Janssens et al., 2003), lowered reproductive success and nestling mortality (Nyholm, 1998).

Burger (1994) found that concentrations of lead, mercury, selenium and chromium were significantly high in egg contents of Herring Gulls. Because eggs have been found to sufficiently represent heavy metal levels of local environments (Morera et al., 1997), they have been widely used to reflect patterns in spatial and temporal contaminant trends (Reynolds et al., 2004). In addition, previous work on cavity-nesting birds has shown that eggshell thinning is an adequate indicator of exposure and uptake with organochlorines (Ewins et al., 1999), but eggshell thickness has yet to be widely used as a heavy metal indicator.

Fluctuating asymmetry has also emerged in studies as an indicator of developmental stability and fitness in the presence of environmental stress (Moller and

Hoglund, 1991; Bustnes et al., 2002; Kellner and Alford, 2003). Small deviations from bilateral symmetry can reflect avian condition and exposure to stressors such as contaminants (Swaddle and Witter, 1994; Fair and Meyers, 2002; Grieco, 2003). The greater the asymmetry, the greater the probability a bird is reacting to one or more negative factors. In studies on passerines, this was demonstrated in Pied Flycatchers (*Ficedula hypoleuca*) and Great Tit (*Parus major*) nestlings where tarsus length and primary wing length asymmetry increased respectively relative to proximity to heavy metal pollution (Eeva et al., 2000). Experimental studies that examined lead shot in birds found that fluctuating asymmetry varied between individual birds, however lead was not associated with the asymmetry (Fair and Ricklefs, 2002; Fair and Meyers, 2002). Fluctuating asymmetry has also been linked to declines in fitness, as demonstrated by relationships between parental asymmetry and offspring quality (Cadèe, 2000).

Furthermore, nestling mortality has been considered an effective measure of contaminant exposure and uptake (Eeva and Lehikoinen, 1996). Contaminants causing negative effects may be bioaccumulated through invertebrate prey and transferred to nestlings. In a study on heavy metal exposure during development of Pied Flycatchers (*Ficedula hypoleuca*), nestling mortality increased in the polluted site associated with exposure levels during nestling growth only (Nyholm, 1998).

Exposure of birds and prey to spatially variable heavy metal contamination can have significant impacts on avian reproduction (Marinussen and Van der Zee, 1996). Home range area and contaminant spatial pattern both affect the extent of exposure that leads to accumulation in birds (Marinussen and Van der Zee, 1996). Home ranges are a function of movements and energetic requirements of birds restricted to finite areas

around the nest (Linkhart et al., 1998), potential territoriality from nearby nests, or diverse topography of the environment. Spatial pattern can also influence how contaminants accumulate in avian tissues by the nature of historical gradients in the region, current sources of pollution, and proximity of contaminated areas to foraging areas. Local soil concentrations can be integrated with predicted hazard quotients from a spatial exposure model to yield relationships between measured productivity and modeled data.

An established home range area can be compared with soil concentration data, and resulting patterns may provide evidence of exposure and uptake. For example, if a bird exclusively selects foraging sites near or in contamination "hot spots," it may be subjected to greater risk than if it forages evenly across its home range. Conversely, birds whose nests are located in heavily contaminated areas, yet whose foraging efforts are allocated to non-contaminated regions are not necessarily at great risk, and may manifest only minor effects on productivity. Studies have also indicated that contaminant concentrations in soils and subsequent diets within foraging areas of birds were associated with residue levels in target tissues (Reynolds et al., 2001). However, little is known about associations between passerine home ranges and contaminant uptake patterns.

A few studies have used passerine distribution and nesting success as indicators of contaminant uptake across a diverse landscape gradient (Eeva and Lehikoinen, 1996; Fair and Meyers, 2002; Fair et al., 2003). Resident passerines that forage in a finite home range where heavy metal concentrations may bioaccumulate in the food web can represent local contamination in a heterogeneous environment (Janssens et al., 2001; Fair

et al., 2003). Nestlings are very effective at reflecting chronic exposure in the breeding area because of their vulnerable life stage and high association between the food quantity they are given during growth and body burden (Fair et al., 2003; Janssens et al., 2003). Although previous studies have examined precocial nestling susceptibility to contaminants (Eeva and Lehikoinen, 1996; Eeva et al., 2003), altricial nestlings have been found to be extremely sensitive to detrimental effects (Scheuhammer, 1987), thus making them effective endpoints.

During yolk formation the egg is supplied with all resources necessary for development and production (Nyholm, 1998), during which time contaminants are transferred from tissues in the parent to the egg contents (Burger and Gochfield, 1993; Nyholm, 1998; Dauwe et al., 2000). The extent of this transfer could depend on the type of contaminant and its fate, transport in the female bird, the degree of exposure, and the amount of uptake in the female's immediate environment (Klaassen, 2001; Nyholm, 1998). The complete formation of an egg's contents and shell takes approximately 48 hours (Gill, 1995), assuring the majority of contaminants represent dietary resources utilized in the breeding area. Although the female is likely to acquire some contaminants on her migration stopovers, the majority of egg solids and nutrients for development are transported to the egg embryo during the latter half of egg formation (Romanoff, 1967). Authors suggest that egg laying constitutes a common excretion method for metals such as cadmium and lead (Morera et al., 1997), as well as mercury and selenium (Braune et al., 2001). These metals are highly lipophilic and concentrate in the yolk portion of the egg rather than the albumen (Klaassen, 2001; Braune et al., 2001).

Contaminants in the prey base of bird populations contribute to metal bioaccumulation and adverse effects on reproduction. Arthropod communities are responsible for the decomposition of organic matter and the exchange of nutrients for energy (Cortet et al., 2002); therefore they are some of the initial key players in bioaccumulation through upper trophic levels. Because of this link, food selection may have primary importance in associating avian susceptibility to heavy metals (Eeva and Lehikoinen, 1996). Eeva et al. (2005) discovered that lower food quality in a polluted site lead to different feeding strategies between two passerines, and increased the vulnerability of the birds due to changing diets.

Furthermore, reproductive parameters potentially can be affected by a multitude of interactions. Nestlings are often subjected to multiple stressors during the developmental growth, including predators, drought, insufficient prey, parasites, and lack of parental care. Local contamination combined with one or more stressors can have additional adverse impacts on nestling health than one stressor alone (Wittmann and Beason, 1992; Fair et al., 2003). One of the most common examples in passerines is a synergistic effect between parasites in nests and other stressors in the surrounding environment (Sabrosky et al., 1989; Wittmann and Beason, 1992; Germaine and Germaine, 2002). *Protocalliphora* are obligatory blood-feeding larval blowflies that parasitize nestlings during growth (Bennett and Whitworth, 1992; Germaine and Germaine, 2002). Factors such as blood loss (O'Brien et al., 2001), and slower rate of weight gain (Wittmann and Beason, 1992) were considered minor, recoverable effects for nestlings prior to fledging. However, other research suggests that although the larvae may not directly kill the hosts, the parasites may weaken the birds so that a combination

of other limiting factors (e.g. drought, food deprivation, malnutrition, or disease) can intercede and increase likelihood of mortality (Sabrosky et al., 1989; Wittmann and Beason, 1992; Miller and Fair, 1997). Previous work with organochlorines (OCs) in Glaucous Gulls (*Larus hyperboreus*) demonstrated a positive relationship between the intensity of parasites and OCs, suggesting increased susceptibility to parasitic loads in conjunction with contaminant burden (Sagerup et al., 2000; Bustnes et al., 2004). In addition to ectoparasites, anthropogenic stressors such as fire may also contribute additional stress upon avian populations.

Fire may have a positive impact on some avian prey types over others (Woinarski and Recher, 1997) by altering the physical soil distribution, chemical composition, prey abundance, or competition. Local concentrations of metals bound to soil particles could potentially move through processes of erosion without adequate root systems to maintain the soil. These alterations in soil distribution and spatial pattern may increase or decrease the intensity of contamination at or near nest locations, thus affecting likelihood of exposure. As a result, bioaccumulation may also be affected by altered soil chemistry and microbial composition following fire. Fires that clear ground vegetation could also potentially affect prey abundance through loss of some later successional plant species and introduction of earlier ones, therefore changing the availability of food for insects. In addition, some areas may be burned more intensely than others, altering prey distribution, and promoting areas of greater or lesser contaminant uptake. Lastly, fires that sufficiently open forest habitat and encourage edges and forest mosaics may also increase occupancy of birds favoring those conditions. Subsequent increase in nest box

occupancy may increase stress through competition or intensify individual contaminant loads by a greater demand for prey.

Previous studies on passerine population health were conducted in northern New Mexico along a diverse contaminant gradient (Fair and Meyers, 2002; Fair et al., 2003). Preliminary work in the region revealed that the impact of PCBs, organochlorines and radionuclides on reproduction of several species of passerines were negligible, however a suite of heavy metals was detected in the eggs (Fair and Meyers, 2002). Soils and sediments were not sampled and the nature and extent of mixed contaminants in the region were uncharacterized (Fair and Meyers, 2002). Heavy metals were detected primarily in Western Bluebird (*Sialia mexicana*, hereafter referred to as WEBL) populations in northern New Mexico (Fair and Meyers, 2002; Fair et al., 2003).

WEBLs exhibit life history traits that establish them as an effective avian indicator of risk. WEBLs are native, sexually dichromatic, monogamous secondary cavity-nesting birds (Fair and Meyers, 2002). They utilize man-made nest boxes in mountainous regions, with particular preferences for ponderosa pine (*Pinus ponderosa*) and piñon-juniper woodland habitat (Koenig and Dickinson, 1996). They are very common in northern-central New Mexico and frequently remain as year-round residents with strong site tenacity (Fair and Meyers, 2002). Because WEBLs have been found to forage short distances (ie. 50-100m) from their nests during the breeding season (Fair, unpublished data), and maintain an exclusively insectivorous diet, they are valuable for monitoring local heavy metal contamination. Because they also utilize man-made nest boxes they are much easier to monitor and study than other passerines.

The main objective of this research is to characterize heavy metal exposure uptake and examine its effects on reproductive parameters of WEBLs at Los Alamos National Laboratory (LANL), New Mexico. Specifically, does heavy metal contamination affect reproductive parameters in Western Bluebird populations? Based on previous knowledge of the effects of metals on avian reproduction, and what is already known about the study site, I predicted that avian eggshell thickness would decline as contaminant loads increased, consistent with preliminary work done in the area (Fair and Meyers, 2002). I anticipated that nestling tarsi asymmetry would increase as contaminant load in eggs and diet also increased. In addition, I expected nestling mortality to increase with greater contaminant loads, consistent with previous studies using Pied Flycatchers (Eeva and Lehikoinen, 1996; Nyholm, 1998). A negative relationship was expected between productivity and home range hazard quotients from soil concentrations. In areas where nest parasite counts are high, I expected a negative synergistic effect with contaminant loads in eggs and prey. I tested my predictions using field observations of WEBL populations at LANL, New Mexico. There were three sub-objectives in this study:

1. Estimate individual productivity of Western Bluebird populations, and relate it to egg and prey contaminant levels;
2. Evaluate spatial relationships between home range area and soil contaminants;
3. Examine potential relationships between contaminant uptake and reproductive success.

STUDY AREA

Los Alamos National Laboratory (LANL) occupies 112 km^2 of land situated on the Pajarito Plateau, in Los Alamos County of northern-central New Mexico. It is located between the eastern side of the Jemez Mountains and the Rio Grande Valley. LANL consists primarily of steep canyons alternating with mesa tops, which decline southeast towards the Rio Grande River. LANL covers an elevation gradient of approximately 720 m extending from 1,620 m to 2,340 m from the Rio Grande to the base of the Jemez Mountains, respectively. The two most abundant vegetation types represented on LANL consist predominantly of ponderosa pine (*Pinus ponderosa*) forest in the canyon bottoms and piñon-juniper (*Pinus edulis; Juniperus osteosperma*) woodland on mesa tops (Goldman et al., 2000). Piñon-juniper habitat experienced a regional die-off following severe drought and bark beetle infestations from 2002-2003 (Ogle et al., 2000; Mueller et al., 2005). Breshears et al. (2005) quantified piñon mortality at >90% in just over a year in the southwest region in 2003.

Principal sources of contamination on LANL involve both point-source potential release sites (PRS) and non-point-source pollution. The Environmental Restoration Project (ER) personnel defined PRSs as various industrial and sanitary waste outfalls that currently or historically discharge[d] to Mortandad Canyon and its tributaries (Pratt, 1997). These contaminated areas include: firing sites, septic tanks, seepage and solid waste disposal pits, liquid radioactive waste, landfills, outfalls, storage areas and organic effluence. Generally, heavy metals are among the contaminants of greatest concern.

In 1997, a nest box network was established to monitor avian populations on LANL. The current network consisted of 791 nest boxes in 2005. Sites were defined as

reference areas if no information existed on contaminant occurrence historically. Contaminated and reference sites were chosen based on proximity to potential release sites (PRSs) of contamination. Nest boxes were placed at varying distances to PRSs. Each nest box was approximately two meters above the ground and 50-75 m apart. An average of 30 boxes were placed in clumped formation at 24 locations, in both contaminated and reference sites (Figure 1).

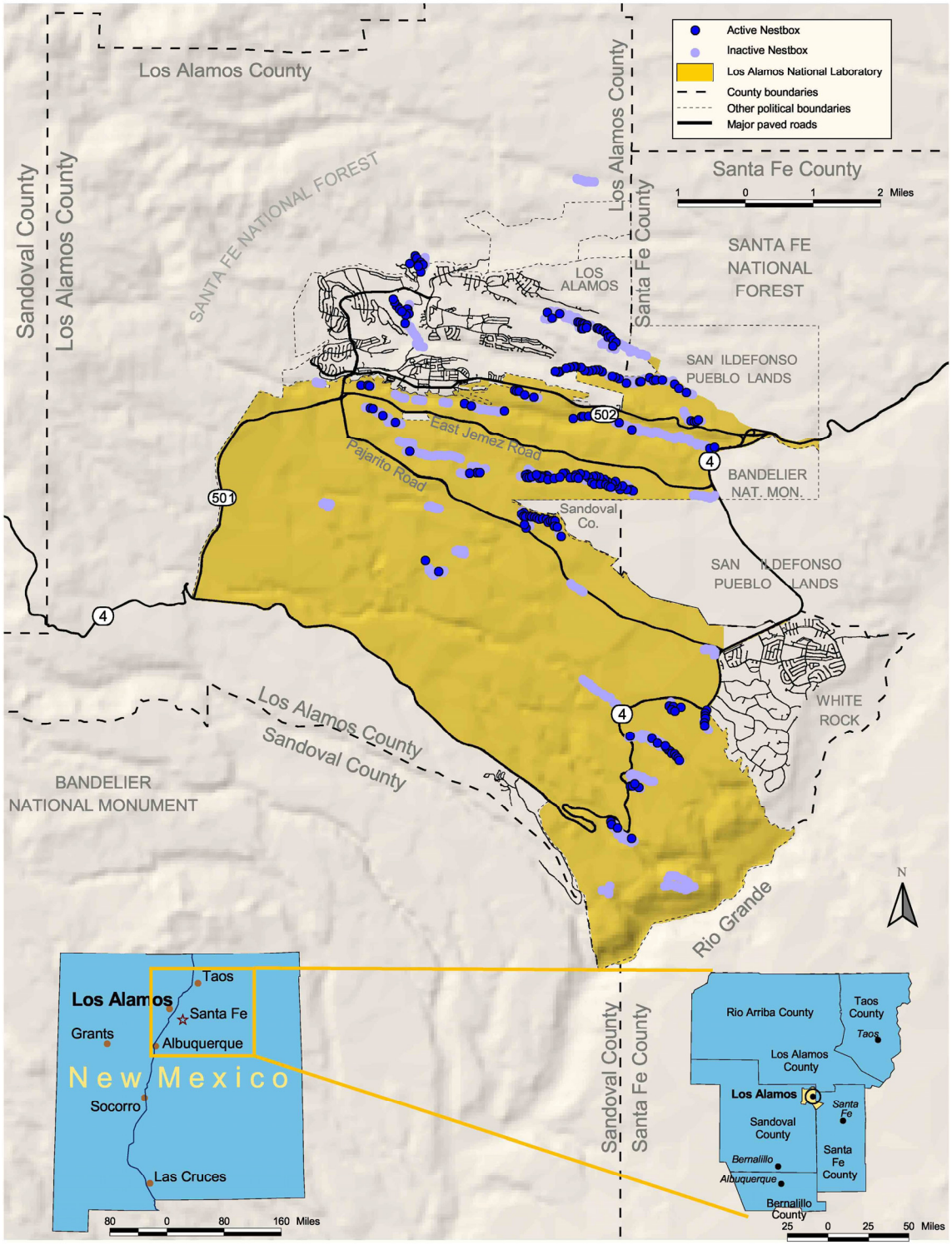


Fig 1. Avian nest box network in 2005 at Los Alamos National Laboratory, New Mexico.

FIELD METHODS

Western Bluebird nests were monitored daily on LANL during the breeding season from May to August in 2004 and 2005. Nests chosen for inclusion in the study were close to or within the bounds of a PRS. A subset of previously identified reference sites was selected based on occupancy of one or more nest boxes. Prior to comparison with a continuous soil contaminant database, a distance of 100 m or less between a nest box and PRS was arbitrarily classified as potentially contaminated. Continuous soil contaminant data became available following the 2005-breeding season, from which point on, only PRS areas were considered contaminated. Western Bluebird nests were monitored immediately following egg laying. Nests with warm eggs were considered active and monitored every two days until the clutch was complete. A clutch was considered complete when no new eggs appeared for four days following the last egg laid. Western bluebird clutches typically contained four to five eggs.

Egg Sampling

I collected eggs from active nests during incubation to examine potential contaminant levels. Egg collection was conducted using a diagram representing several possible clutch arrangements of three, four, and five eggs. Each diagram was oriented due north, numbered clockwise, and used to identify eggs in real nests. A die was rolled to randomly choose an egg. One potentially viable egg was collected from 30 nests (18 potentially contaminated; 12 reference) following clutch completion (Figure 2). Clutches with a greater number of eggs on the first visitation were monitored prior to clutches in earlier developmental stages with fewer eggs. If a clutch was partially predated or the

nest abandoned, no collection was made since nest fate would be confounded between contaminants and predation. Collected eggs were stored in plastic vials in the field at ambient temperatures of 18 to 14 degrees Celsius for one to five hours prior to being stored in a refrigerator. Each egg remained in the refrigerator from one to 24 hours until processed in the laboratory.

Nestling Growth and Productivity

After eggs hatched (day zero), active nests were visited every two days to monitor nestling productivity. Productivity was considered any activity that promotes the health and development of an individual. Parameters measured included clutch size, hatching success, fluctuating asymmetry, weight, brood size, and fledging success. Each nestling was banded with a standard USFWS band on day ten. The sex of WEBL nestlings was determined by plumage color at 13 days of age or older. Nestling fluctuating asymmetry of the first primary feather and weight were measured between day 15-18 to represent greatest wing and tarsus growth prior to fledging (day 20). The number of nestlings present just prior to fledging was considered the number that fledged. Fledging is a synchronous process for bluebird nestlings. Individuals were assumed to be dead if any evidence of one or more individuals remained. Nestling fate was considered unknown if individuals disappeared at least three days prior to their anticipated fledging date and no evidence of predation remained.

Capture of Adult Females

Adult female bluebirds were captured and banded so that movements within their

home ranges could be documented. Females were chosen for their ability to transfer contaminant loads into the egg at reproduction (Burger and Gochfield, 1993), and thus female space use and diet would be most related to contaminant exposure in the young prior to hatching. In addition, females contributed the majority of parental care in terms of feeding the young. Individuals for color banding were selected based on whether an egg had been sampled from the nest.

Adult WEBL females were captured following egg hatching to avoid introducing effects from handling, such as nest abandonment, on incubation. No cases of abandonment were found among sampled nests. Adult females were caught using one of two methods: a wooden door that was screwed onto the nest box adjacent to the nest box opening and pulled shut using a string once the female had entered the nest box, or mist nets placed directly in front of the nest box opening. The former method was used immediately following egg hatching, and if necessary, the latter was used once nestlings were approximately a week old and female trips to the nest box were more infrequent. Capture attempts were conducted between 5:00 am to 11:00 am. If a wooden door was used, a person remained present to capture the female upon entering a box. If mist nets were used, a person would either remain present or check the net approximately every half hour for captured birds. Once caught, adult females were measured. Standard size measurements were taken in addition to fluctuating asymmetry in wing chord and tarsus. Wing length and tarsus was measured according to the guidelines in *Identification Guide to North American Birds* (Pyle, 1997). Tarsus length was measured as the distance between the intertarsal joint and the distal end of the last leg scale before the toes, on both left and right legs. Wing length was measured using the unflattened method of the

distance between the carpal joint and the tip of the longest primary (Pyle, 1997).

Once we caught the female at each nest, we removed the net to avoid capturing males and non-target species. Each bird was handled for less than five minutes in accordance with the *Guidelines for the Use of Wild Birds in Research* (Gaunt and Oring, 1997). All methods were approved by both LANL and Utah State University Institutional Animal Care & Use Committees.

Home Range Estimation

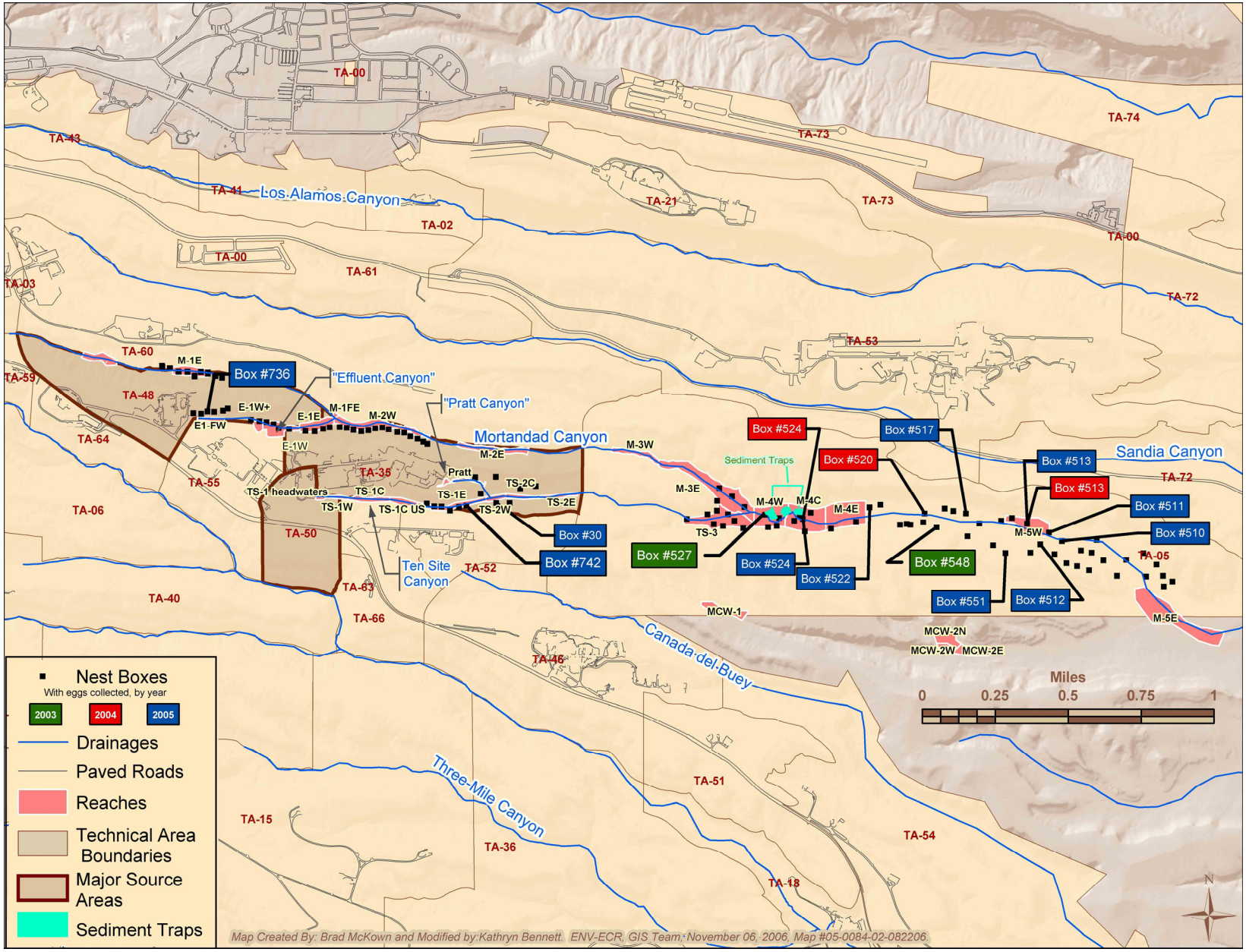
Female activity was visually tracked during the nestling stage of each clutch from early May through August 2004-2005. If a nest failed (i.e. total loss of eggs and/or nestlings), the closest active WEBL nest (i.e. not exceeding 150 m away) was chosen for tracking and subsequent morphological measurements. If all nest boxes could not be monitored simultaneously due to logistics, locations with the highest density of nest boxes adjacent to PRS were monitored first. Tracking locations were confirmed using binoculars or a spotting scope. A minimum of two observers were stationed at opposite ends of the female's estimated home range, and remained within a few meters of a fixed point during the tracking session. Each tracking session was a minimum of ten locations or 30 minutes in duration. At the end of an observation session, GPS points were taken at all locations using a GEOIII Explorer (USA) GPS unit. A location was recorded if the observer verified that a bird was in that particular spot with the aid of binoculars or a spotting scope. Points were differentially corrected by the Los Alamos base station. At least three tracking sessions were made for each color-banded female. Sessions were typically two days apart and were conducted within two weeks of hatching, to represent

nestling growth. If foraging activity was observed, it was noted and its corresponding GPS point recorded. If an observational location was not conducive for viewing bird activity, an observer relocated to a better area for viewing on a different day. If an observer followed a bird a few meters beyond his/her observation spot, disturbance was frequently observed. In this case, the GPS point was discounted completely. Therefore, if observers were able to relocate a bird by moving less than a few meters, and no behavioral changes were observed, observations and data collection continued.

Prey Selection

Color-banded females were monitored for prey selection. During tracking sessions, ten or more observations were made of the female returning prey to the nest box. Prey delivered to the nest box that was visible to observers was identified to taxonomic order using binoculars or spotting scope. Nests were collected after nestlings fledged and kept at room temperature for four to eight hours prior to storage. Nests were then stored frozen at –30°C until processing in the lab. Prey observations at the nest box were compared with proportions of identified arthropods collected from nests.

Fig 2. Sampled Western Bluebird nests in Mortandad Canyon only from 2003-2005 at Los Alamos National Laboratory, New Mexico. "TA" refers to a Technical Area boundary. "Reach" is defined by the Laboratory as an area of high concern for contamination. *Note: These samples do not constitute all eggs collected in 2004-2005.


TA-00
TA-43
TA-41
Los Alamos Canyon
TA-02
TA-21
TA-73
TA-74
TA-61
TA-03
TA-72
TA-53
TA-60
TA-59
TA-48
M-1E
Box #736
"Effluent Canyon"
"Pratt Canyon"
E-1W+
E-1E
M-1FE
M-2W
E1-FW
E-1W
Mortandad Canyon
M-2E
M-3W
TA-64
TA-35
Pratt
TS-2C
TS-1 headwaters
TS-1C
TS-1E
TS-2E
TS-1W
TS-1C US
TS-2W
TA-55
TA-06
TA-50
Box #30
Box #742
Ten Site Canyon
TA-52
TA-63
TA-40
TA-66
TA-46
Box #524
Box #517
Box #520
Sediment Traps
M-3E
M-4W
M-4C
M-4E
TS-3
Box #527
Box #524
Box #522
Box #548
Box #513
Box #513
Sandia Canyon
Box #511
Box #510
M-5W
Box #551
Box #512
MCW-1
MCW-2N
MCW-2W
MCW-2E
M-5E
Canada del Buey
Three-Mile Canyon
TA-51
TA-54
TA-15
TA-36
TA-18
Miles
0
0.25
0.5
0.75
1
N
Nest Boxes
With eggs collected, by year
2003
2004
2005
Drainages
Paved Roads
Reaches
Technical Area Boundaries
Major Source Areas
Sediment Traps
Map Created By: Brad McKown and Modified by:Kathryn Bennett. ENV-ECR, GIS Team, November 06, 2006. Map #05-0084-02-082206

LABORATORY METHODS

Eggs

Eggs were cleaned of all fecal residue or other matter and measured for length, width, and volume. Volume was determined by measuring the amount of water displacement by placing an egg in 20 mL of water in a graduated cylinder. Each egg was opened along the equator. Entire egg contents were stored in glass vials, weighed, and frozen at –30°C until further analysis.

All heavy metal analyses in eggs were completed by Paragon Analytics, Inc., Fort Collins, CO. Contaminants measured included 21 heavy metals (Table 1). Prior to analysis, all samples were filtered and acidified for digestion using nitric acid (EPA, 1996). Concentrations were determined using inductively coupled plasma-atomic emission spectrometry. Two types of "blank" samples are required for quality control, including one calibration and one method blank per sample batch, in order to determine the analytical curve and identify potential contamination resulting from acids used in processing, respectively (EPA, 1996). Sample matrices were duplicated. Spike recoveries for analytes were required to be ±25% of the actual value. Mercury samples were subjected to dissolution, following by cold-vapor atomic absorption spectrometry (EPA, 1994).

Shells were dried a minimum of seven days at ambient room temperature. Eggshell thickness was measured on all collected eggs using a minimum of four points along the equator of each shell half. A Starrett 1010M (The L.S. Starrett Company, Glendale, AZ) dial gauge micrometer (units of 0.01 mm) was used for all eggshell thickness measurements.

Nests

Collected nests were each rinsed through a fine-mesh double sieve. Nesting material was separated from prey and discarded. Blowfly larvae and empty cases were inventoried and stored separately from prey specimens. All insect specimen cavities and fragments from each nest were stored at room temperature and dried for a minimum of seven days. All identifiable specimens were cataloged to taxonomic order. The total amount of prey recovered from each nest (i.e. one sample) ranged from 0.1-1.0 g with an average of 0.3 g overall. Due to insufficient mass for contaminant analyses, composite insect samples were created from nests that were in close geographic proximity to each other (Figure 2). Composite mass refers to total mass of pooled insect samples. Samples from Mortandad canyon were separated into "reaches" or sections of canyon whose contamination levels were categorized by LANL as areas of greater concern. Samples were combined into one composite based on whether nests fell within the same reach. Twelve composite samples were analyzed by Paragon Analytics Inc., Fort Collins, CO, and tested for 23 heavy metals (Table 1). Samples were digested with hydrochloric acid prior to analysis (EPA, 1996), followed by inductively coupled plasma-atomic emission spectrometry and the same control procedures used with egg samples (EPA, 1996). Mercury was omitted from the analysis scan if the mass of the composite sample did not exceed 0.5 g. Contaminant concentrations reported from Paragon Laboratory were standardized to μg/kg prior to statistical analyses.

STATISTICAL ANALYSES

Databases

I used precipitation data collected from the Technical Area-6 Weather Station, located in the western-central area of the Laboratory. Monthly, annual and normal averages were obtained from the station for analyses. Normal levels refer to combined monthly averages from 1961 to 1990 (Bowen, 1990).

The Cerro Grande Fire in 2000 burned approximately 7,600 acres on LANL property, 62% of which was in Ponderosa Pine forests (Morgan, 2004; Balice et al., 2004). Burn severity and intensity levels were determined for vegetation classes by overlaying land cover maps with geographic information systems (GIS), and conducting damage assessments with field data (Balice et al., 2004; Mynard et al., 2003). Burned area was used as a binary variable where habitat was either designated burned or unburned based on proportion of ≥ 50% of boxes in a location that had evidence of fire damage.

Information on soil heavy metals levels at LANL was obtained using a database already maintained by LANL (Ryti et al., 1998; McDonald et al., 2003). Soil sampling was conducted outside LANL boundaries to determine background concentrations of naturally occurring metals within the region (Gonzales et al., 2004). These external background concentrations were subtracted from soils sampled within LANL, leaving all concentrations considered added specifically by the Laboratory since its establishment in 1943.

A spatially explicit model (ECORSK.7) was developed at LANL to integrate biological and toxicology information to assess animal risk at the Laboratory and predict

potential adverse effects (Gonzales et al., 2004). The custom model estimates animal exposures over large spatial areas such as the entire LANL boundary. First, inorganic analytes were identified as chemicals of potential ecological concern (COPECs) in Mortandad reaches, based on detected or non-detected analytical results that exceed sediment background values for inorganic chemicals (Pratt, 1997). Using a gridded GIS format, assumed health effect levels are compared with animal exposure estimates, resulting in computed hazard indices (HIs) using the equations:

$$HQ_{ij} = \frac{exposure_{ij}}{effect_{ij} \text{ (or TRV)}} \quad \text{and} \quad HI_i = Hq_{ij},$$

where HQ_{ij} = hazard quotient for receptor *i* to contaminant of potential ecological concern (COPEC) *j* (unitless), *exposure* = exposure to COPEC *j* for receptor *i* (units are mg of COPEC per kg body weight per day or mg/kg/day), *effect* = effect level or safe limit (no-observed-adverse-effect-levels [NOAEL]; represented by a toxicity value [TRV]) for exposure to COPEC *j* for receptor *i* (mg/kg/day), and HI_i = hazard index for receptor *i* to *n* COPECs (unitless) (Gonzales et al., 2004). The model was developed on the basic spatial unit of a 30 x 30 m grid that corresponds to New Mexico State Plane Coordinate System. All COPEC concentrations are cataloged by individual grid cells and extend to LANL boundaries. Upon integrating large spatial datasets with Geographic Information Systems (GIS), the model evaluated contaminants in sediments, integrates model and empirical measures, and uses field data to test model assumptions. Bioaccumulation is assumed to be linear with cumulative doses (Gonzales et al., 2004).

The ECORSK model accounts for habitat type, bottom depth and location. All individual grid cells containing a nest box that was sampled for an egg (n=30) were run in models as one hazard value per home range. In a separate analysis, hazard indices for all cells overlapped by a home range were compiled and analyzed as one composite hazard index for its corresponding nest. I utilized these modeled hazard indices as a single independent variable in conjunction with my measured field data. Soil contamination was used as a continuous variable in all analyses.

Factors influencing egg and prey contaminant levels

I examined potential temporal, spatial and environmental factors influencing home range contaminant uptake in biological tissues. I looked at the uptake in eggs and prey with a suite of *a priori* linear models. I used general linear models to specify statistical hypotheses that were then compared using Akaike's Information Criterion (AIC). In SAS, this is done using the generalized linear modeling procedure with the no scale option. I specifically examined the differences in egg load means between sites and years. Second, I looked at the relationship between location and egg load. Egg concentrations were examined as a function of the percentage of contamination in home range. The percentage of foraging points in contaminated home range was also considered as a potential alternative to the null hypothesis. Differences in prey contaminant levels between sites were examined. Prey load was also tested for correlations with percentage of contaminated home range overlap.

AIC is used to identify the most appropriate models in the set, given the data, and is based on maximum likelihood theory that offers an alternative to significance testing by evaluating multiple hypotheses at once (Burnham and Anderson, 1998). AIC provides a theory for estimation of model parameters in balance with bias (Burnham and Anderson, 1998). This method selects the best-fit model in a group of possibilities by assessing the weight of one hypothesis over another, ranking each model from best to worst. The model with the lowest AIC score is the most appropriate of the available choices. Burnham and Anderson (1998) argued that a strong model is one where the ratio of an AIC model score to the "best" model in the suite has a difference of less than four-seven units. The principle of parsimony states that choosing the simplest model, given the data, should simultaneously minimize variance and bias through a tradeoff (Burnham and Anderson, 1998). If the sample size is small in a given model, strong inferences cannot be derived from the data. For this reason, AIC_C was used as a second-order estimator is suggested for adjusting bias when the ratio n/K is <40 (Burnham and Anderson, 1998; Appendix C). An R^2 value was calculated for the best model to determine how well the model explained the data. The Statistical Analysis System was used for all analyses (SAS Institute Inc., 1987). Appendix C provides a guideline for calculating AIC_C specifically using SAS software.

Table 1

Weighted likelihood of *a priori* dependent egg contaminant load models (n = 28 eggs) based on Akaike's Information Criterion. "HR" is defined as home range. "PRS" is defined as the contamination within home range. R^2 for the best model = 0.43.

	AIC_C	AIC_C Weight
Egg load = PRS + Location + (PRS*Location)	0.00	0.735646
Egg load = Location	2.07	0.260927
Egg load = .	11.29	0.002599
Egg load = Site	13.78	0.000750
Egg load = Year	18.39	0.000075
Egg load = % Forage points in HR	24.44	0.000004

Table 2

Weighted likelihood of *a priori* dependent prey contaminant load models (n = 12 prey samples) based on Akaike's Information Criterion. "PRS" is defined as the contamination within home range. "Site" is defined as either contaminated or uncontaminated. R^2 for the best model = 0.75.

	AIC_C	AIC_C Weight
Prey load = PRS + Location	-7.45	0.955623
Prey load = .	0.00	0.023085
Prey load = Site	0.16	0.021292

The variable "site" was defined using the soil contaminant database that designated areas as either contaminated or uncontaminated based on historical release of local heavy metals. Egg and prey concentrations were a combination of background levels and contamination added by LANL. All contaminants were above the minimum detection limits (N=32 eggs, N=14 composite prey samples). Detection limits were measured in mg/kg on a wet weight basis and standardized to μg/kg (Table 3).

Log- and square root-transformations were conducted on the majority of reproductive variables, egg contaminants, and prey contaminants depending if the data was positively or negatively skewed, respectively. If the normality of a variable did not improve after transformation, the original untransformed data was used in analysis. Shapiro-Wilk statistics were examined and variables were transformed accordingly to meet assumptions of normality and homogeneity of residual variances. I removed an extreme outlier from the egg width variable distribution due to sampling error. All other outliers in remaining contaminant variables were not removed because of their potential biological significance.

Table 3

Minimum detection limits (MDL) (µg/kg) for heavy metal analytes in Western Bluebird eggs at Los Alamos National Laboratory, New Mexico.

Metal	MDL	Metal	MDL
Al	0.3900	Mg	0.3600
Sb	0.2300	Mn	0.0080
As	1.0000	Hg	0.0021
Ba	0.0045	Ni	0.0230
Be	0.0064	K	3.7000
Cd	0.2800	Se	1.3000
Ca	0.4100	Ag	0.1500
Cr	0.0150	Na	1.9000
Co	0.0290	Tl	0.1100
Cu	0.0240	V	0.0180
Fe	0.2900	Zn	0.0440
Pb	0.0980		

Principle components analysis (PCA) was used as an exploratory analysis to reduce the dimensionality of contaminant data and summarize the most important components. The method approximates a new regression line, or principal component, to represent the best summary of relationship between the variables (Lattin et al., 2003). Multiple heavy metal variables were combined into one composite independent variable. Single contaminant scores of the new composite variable were used to represent the best linear combination of the original variables. Normalization, however, can sometimes remove noise and make the data less variate, which could affect the ability of PCA to capture data structure (Yeung and Ruzzo, 2001). Therefore, PCA was determined using non-transformed contaminant data.

PCA analysis was conducted on egg and prey samples to transform a linear combination of 22 compounds into a new composite variable (Appendix D). This new variable was created based on the lack of information available on most of the metals and their individual effects on birds. Mercury was the only compound removed due to too few observations in the dataset. A correlation matrix was used in each PCA to account for large differences in orders of magnitude in the data. In eggs, the first eigenvector explained 66% of the variability captured by PCA, whereas in prey the first eigenvector explained 48% of the variability. Due to low sample sizes, no more than the first principal component factor was used to replace contaminants in each model (Appendix D). I used these composite variables in analyses to represent contaminants. I also explored several individual metals as alternative representations of contaminants.

Due to lack of data availability on biological effects for many of these metals, exploratory analyses were necessary to isolate potential relationships. Therefore, simple

linear regressions were used to examine the effects of individual contaminants on response variables (Appendix B). Single contaminants with an R^2 greater than 10% were used as an initial subset for further analysis. From this group, a second subset was determined by using contaminants with the most prominent slopes and corresponding p-values. Each of these contaminants was used as single independent variables in models. Pearson correlations were run on all egg and prey contaminants against each other, respectively. Contaminants with high correlations (>0.90) were excluded, and compounds were only used in the same model if they had no correlation with each other.

Home range size and contaminants

I examined possible correlations between home range size and contamination using a suite of *a priori* models with AIC_C and general linear models (Table 4). Specifically, I explored differences in home range size between sites. I also tested whether home range size differed between years, and burned versus unburned area. Home ranges were estimated by using the minimum convex polygon (MCP) method, in which the home range is the smallest polygon containing all observed locations and the area therein (Jennrich and Turner, 1969; Anderson, 1982; Seaman et al., 1999). Areas of contamination have been designated as spatial polygons by LANL. These areas were overlaid with all GPS home range points collected from field data. Points included in the overlap were both foraging locations and general use of the breeding area (i.e. perching, preening, and miscellaneous activities). The amount of contamination overlap in each home range was quantified for analysis. ArcGIS© was used for all spatial manipulations and calculations involving home range estimation and contamination data (ESRI, 2001).

Table 4

Weighted likelihood of *a priori* dependent home range models (n = 41 home ranges) based on Akaike's Information Criterion. R^2 for the best model = 0.

	AIC_C	AIC_C Weight
Home range size = .	0.00	0.801856
Home range size = Site	4.12	0.102010
Home range size = Year	5.41	0.053546
Home range size = Burned area	5.87	0.042588

Effects of home range contamination on reproductive success

I explored a suite of potential independent factors affecting reproductive success using AIC_C and general linear models (Tables 5-7). First, I looked at eggshell thickness as a function of volume and egg contaminant load. Egg load is defined as the factors of the new composite variable constructed by PCA. I examined correlations between egg calcium and sodium load with eggshell thickness. Next, I evaluated differences in tarsus size between sites, and months of the same breeding season. Differences in nestling mass between months of the same season were examined. I also looked at differences in the number of parasites per nest. Nestling fluctuating tarsi asymmetry was evaluated as a function of prey contaminant load. Lastly, I looked at differences in nestling mortality between years, months of the same season, burned versus unburned areas, and contaminated versus reference sites. Mortality was calculated as the number of dead nestlings found per nest. I also explored mortality as a function of home range

contamination and parasites in the nest. I looked at the interactive effect between burned area and home range contamination. I examined the effects of prey contaminant load on mortality, specifically selenium (Table 7). Potential effects of the percentage of foraging points in contaminated home range were also considered as an alternative hypothesis for mortality. Finally, I looked at the effects of soil hazard indices on mortality. Ryan-Einot-Gabriel-Welsch Multiple Range tests (REGWQ) were used as post-hoc comparisons for significant mean effects.

Table 5

Weighted likelihood of *a priori* dependent eggshell thickness models (n = 29 eggs) based on Akaike's Information Criterion. Location is defined as a specific canyon or mesa top within the general site. R^2 for the best model = 0.69.

	AIC_C	AIC_C Weight
Shell thickness = Location + Egg volume + Egg load	0.00	0.999667
Shell thickness = Egg Ca + Egg Na	16.45	0.000267
Shell thickness = Location + Egg volume	19.73	0.000052
Shell thickness = .	22.40	0.000014

Table 6

Weighted likelihood of *a priori* dependent tarsus size models (n = 9 nestlings) based on Akaike's Information Criterion. Tarsus size refers to length (mm). Site is defined as either a contaminated or uncontaminated area. Location is defined as a specific canyon or mesa top within the general site. R^2 for the best model = 0.

	AIC_C	AIC_C Weight
Tarsus size = .	0.00	0.775287
Tarsus size = Location	3.04	0.169381
Tarsus size = Site	5.53	0.048743
Tarsus size = Month	9.54	0.006589

Table 7

Weighted likelihood of *a priori* dependent mortality models (n = 11 nestlings) based on Akaike's Information Criterion. R^2 for the best model = 0.57.

	AIC_C	AIC_C Weight
Mortality = Be + Se + V + (Se*Be)	0.00	0.584745
Mortality = Se	0.69	0.415060
Mortality = .	16.51	0.000152
Mortality = Location + PRS + parasites + (PRS*parasites)	21.05	0.000016
Mortality = Month	21.81	0.000011
Mortality = Year	21.93	0.000010
Mortality = Burned area	24.81	0.000002
Mortality = Site	25.28	0.000002
Mortality = Prey load	25.85	0.000001
Mortality = % Forage in PRS	45.92	0.000000
Mortality = Burn + PRS + (Burn*PRS)	47.60	0.000000

Double clutches (N=3) were considered to be those nests laid by the same female in the same season. Data collected from the second clutch was removed from all models to avoid independence problems. In models that linked reproductive success to temporal effects, I divided the season between May and June/July. The amount of local precipitation is typically much less in May than the remainder of the season (Bowen, 1990). In addition, May comprises the busiest nesting period of the season (Colestock, unpublished data), where June and July represent the less-synchronized period of double nesting.

Modifications were made to variables in eggshell models to alleviate potential biases. First, egg volume was used as a covariate to account for potential correlations between eggshell thickness and egg size (Fair and Meyers, 2002). Second, when comparing the effects of egg contaminant load on eggshell thickness, two boxes in 2005 that were also sampled in 2004 were removed to avoid reflecting contaminant uptake at the same box twice.

I measured asymmetry on wing chord and tarsi and compared levels of asymmetry in each. Bilateral measurements of each variable were measured twice and averaged, respectively. Asymmetry traits were calculated as the absolute value of the normalized difference of the left and right sides:

$$Y_i = \frac{|L - R|}{L + R}$$

where Y_i = asymmetry for bird *i*; L = left tarsus/wing; and R = right tarsus/wing.

Dividing mass by nestling age normalized nestling mass. Summing the left and right sides and dividing by age normalized nestling tarsus size. In analyses of nestling mass and tarsi size, I used brood means to avoid pseudoreplication (Eeva et al., 2003).

Because prey samples were composites of contaminants from multiple boxes, they also corresponded to multiple home ranges. To avoid introducing bias by selecting one home range to represent an entire composite prey sample, we compared prey load to an average of all home ranges in that sample.

RESULTS

The number of active nest boxes increased from 122 in 2004 to 139 in 2005, resulting in 19.6 and 20.9 percent network occupancy, respectively. Annual precipitation at LANL was 18.8 and 21.3 inches in 2004 and 2005, respectively (Bowen, 1990). Prior to 2004 Los Alamos had experienced an overall consistent decline in rainfall since 1998 (Figure 3) (WRCC). The lowest monthly precipitation in 2004 occurred in May just prior to the breeding season at 0.02 inches, whereas it increased to 0.75 in June and 3.13 in July (Figure 4) (WRCC).

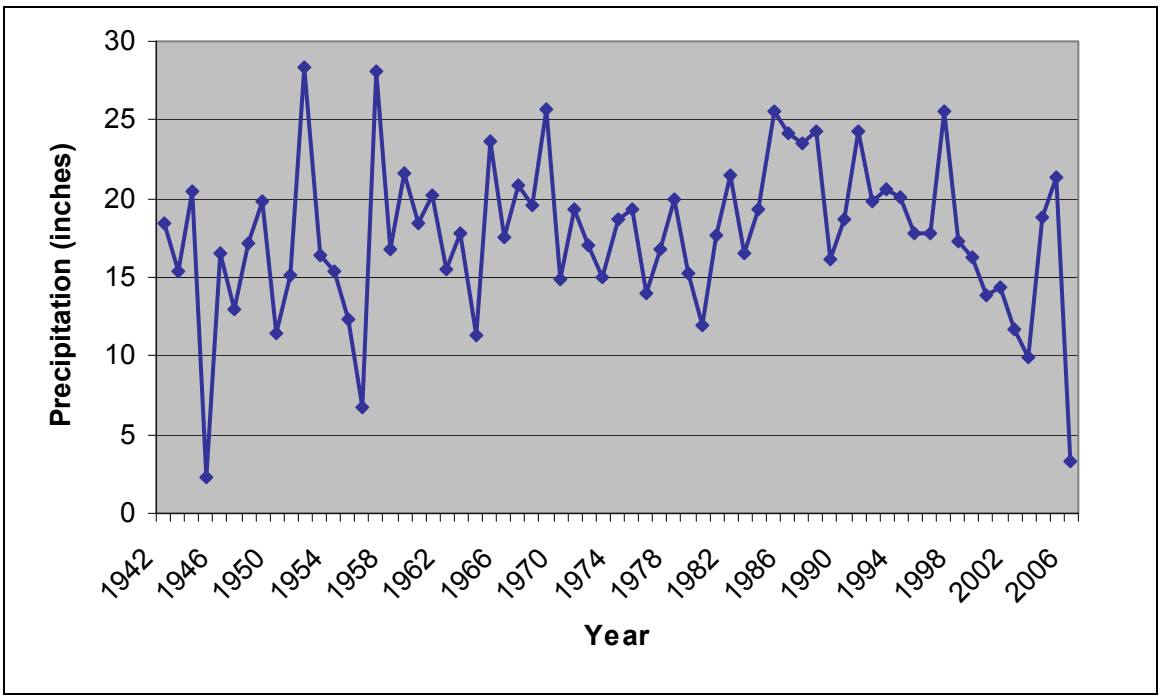


Fig 3. Historical annual precipitation from 1942-2006 at Los Alamos National Laboratory, New Mexico.

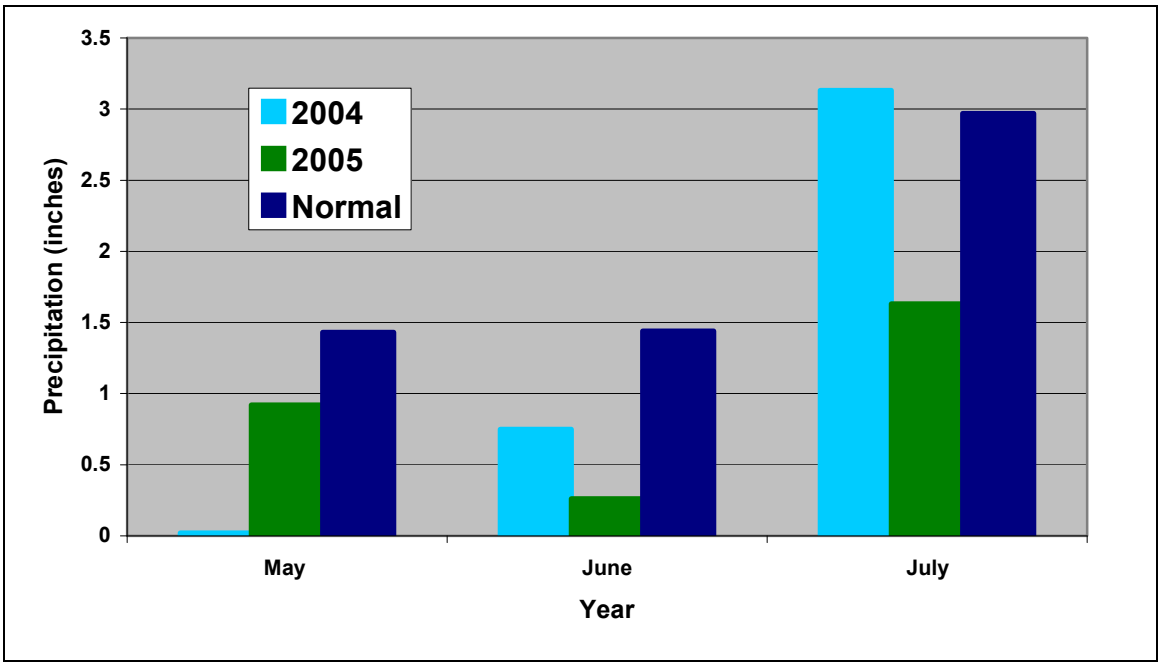


Fig 4. Mean monthly precipitation during the breeding season from 2003-2005 at Los Alamos National Laboratory, New Mexico. Normal levels refer to combined monthly averages from 1961 to 1990 (Bowen, 1990).

Mortandad Canyon was the only location considered burned by the Cerro Grande Fire in 2000, where 51 out of 111 boxes were completely destroyed, and another 27 boxes had blackened burn marks, indicating disruption to box occupants and surrounding habitat. Therefore based on these criteria, an estimated 70% of all boxes in Mortandad were affected by fire. All other locations among my study sites were not burned.

Factors influencing egg and prey contaminants

I collected four eggs in 2004, 26 in 2005, and included an additional two eggs collected in 2003 for a total of 32 eggs (Table 8). Every analyte of the 23 compounds tested was found in all egg samples. Sodium (range: 500,000-2,200,000 μg/kg, 1,542,308 ± 46734 [mean ± 1 SE]) and calcium (range: 330,000-5,300,000 μg/kg, 1,525,769 ± 238,532 [mean ± 1 SE]) were detected in 31 eggs with the largest concentrations of any other contaminant (Appendix A; Figure 5). Mean soil background levels were 304,000 μg/kg for sodium, and 2,640,000 μg/kg for calcium (Ryti et al., 1998).

Egg contaminant load did not differ between sites ($\bar{x}_1$ = -0.98, SE_1 = 0.12, n_1 = 14; $\bar{x}_2$ = -0.83, SE_2 = 0.13, n_2 = 9) or years ($\bar{x}_1$ = -1.00, SE_1 = 0.13, n_1 = 4; $\bar{x}_1$ = -0.93, SE_2 = 0.09, n_2 = 23). Means for egg concentrations are unitless because they are based on the composite scores of the principal component factor. Egg load was arguably correlated with location (F = 2.89, p = 0.06, n = 23), although an REGWQ post-hoc test revealed that none of the four locations were significantly different from one another. Some evidence showed that egg contaminant load was also correlated with an interaction between location and percentage of contaminated home range (F = 2.44, p = 0.06, n = 26), but again, locations were not significantly different from one another. However, no evidence showed that egg load was correlated with the percentage of foraging points in the contaminated area of the home range (F = 0.01, p = 0.92, n = 25). AIC_C weights indicate that the best model of the set, where egg load is a function of PRS overlap and location, is approximately 3 times more likely than the second-best model (Table 1).

Fig 5. Geometric means of heavy metal concentrations in Western Bluebird egg (N=30) and prey (N=12) samples in 2005, at Los Alamos National Laboratory, New Mexico.

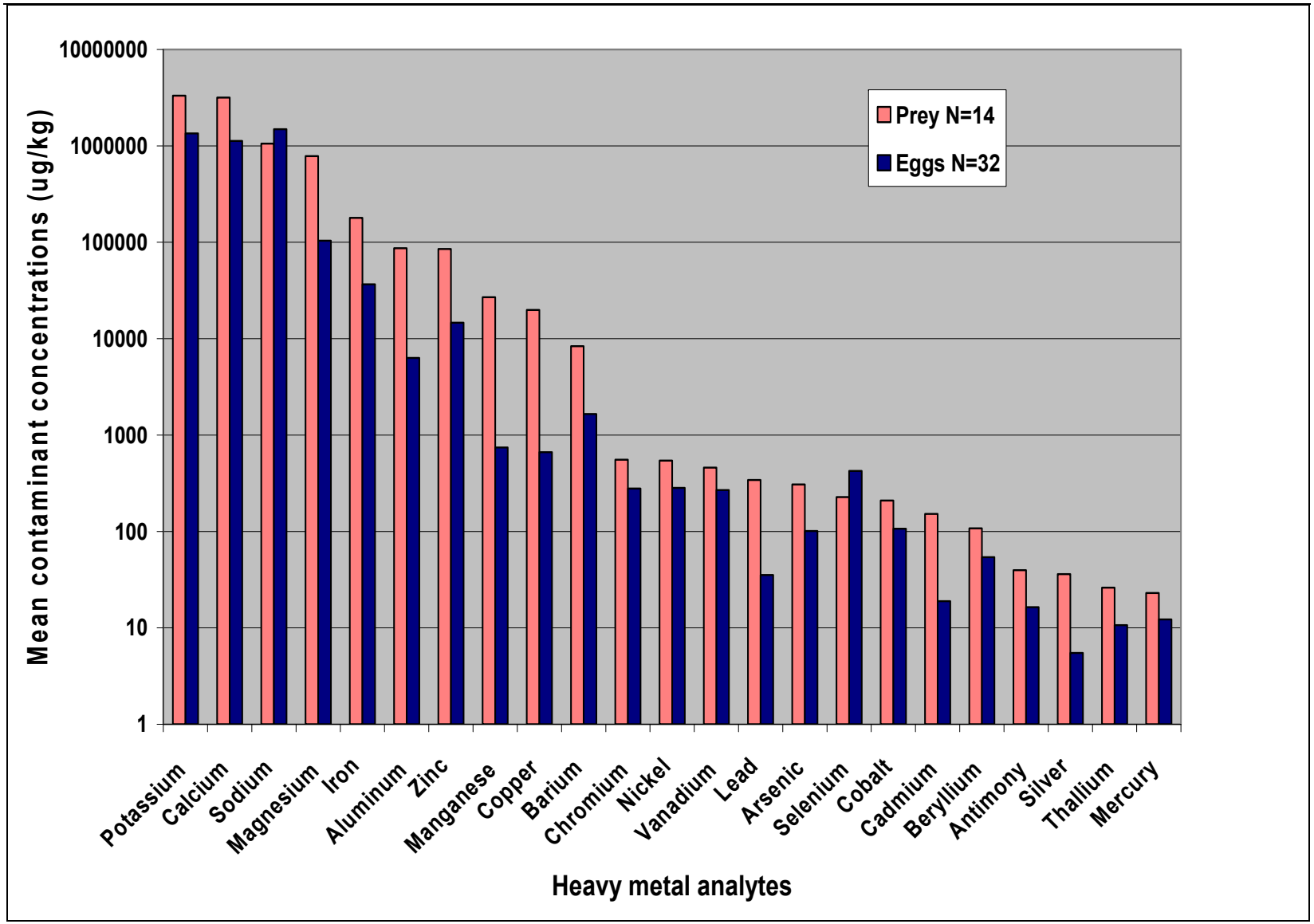

Mean contaminant concentrations (ug/kg)
10000000
1000000
100000
10000
1000
100
10
1
Prey N=14
Eggs N=32
Potassium
Calcium
Sodium
Magnesium
Iron
Aluminum
Zinc
Manganese
Copper
Barium
Chromium
Nickel
Vanadium
Lead
Arsenic
Selenium
Cobalt
Cadmium
Beryllium
Antimony
Silver
Thallium
Mercury
Heavy metal analytes

Table 8

Mean (SE) eggshell thickness (mm), clutch size, percent eggs hatched, percent nestlings fledged, number of dead nestlings, and number of blowflies for sampled nests for 2003-2005 at Los Alamos National Laboratory, New Mexico.

Year	Thickness	Clutch	% Hatched	% Fledged	Mortality	Blowflies
2003 [n=2]	0.29 (0.03)	5.0 (0.0)	80.0 (0.0)	87.5 (12.5)	0.5 (0.5)	42 (28)
2004 [n=4]	0.20 (0.004)	4.55 (0.31)	93.0 (2.94)	96.43 (2.85)	0.25 (0.14)	9 (4)
2005 [n=26]	0.19 (0.004)	4.8 (0.12)	94.63 (2.64)	84.93 (5.59)	0.48 (0.17)	38 (7)

I also collected 14 prey samples, five of which were composites containing two to six boxes each (Table 9). The mass of each prey sample ranged between 0.12 and 2.7 g. Out of 14 samples, 11 were from potentially contaminated and three were from reference sites. Similar to eggs, every one of the 23 compounds tested was found in all prey samples. Calcium (range: 730,000-33,000,000 μg/kg, 9367143 ± 2304905 [mean ± 1 SE]) and potassium (range: 1,200,000-9,700,000 μg/kg, 6,125,000 ± 449,368 [mean ± 1 SE]) comprised the greatest concentrations of all compounds (Appendix A). Mean potassium background concentrations in soil were 1,750,000 μg/kg (Ryti et al., 1998).

Prey contaminant load did not differ between contaminated ($\bar{x}_1$ = -1.30, SE = 1.47, n = 7) and reference sites ($\bar{x}_1$ = -1.42, SE = 0.65, n = 2). Means for prey concentrations are unitless and based on composite scores of the principal component factor. Prey load was correlated with percent contamination in home range and location (F = 5.14, p = 0.03, n = 12), and post-hoc tests showed that the Cemetery was significantly different from the other locations. AIC_C weights indicate that the best

model of the set, where prey load is a function of home range contamination and location, is approximately 41 times more likely than the second-best model (Table 2).

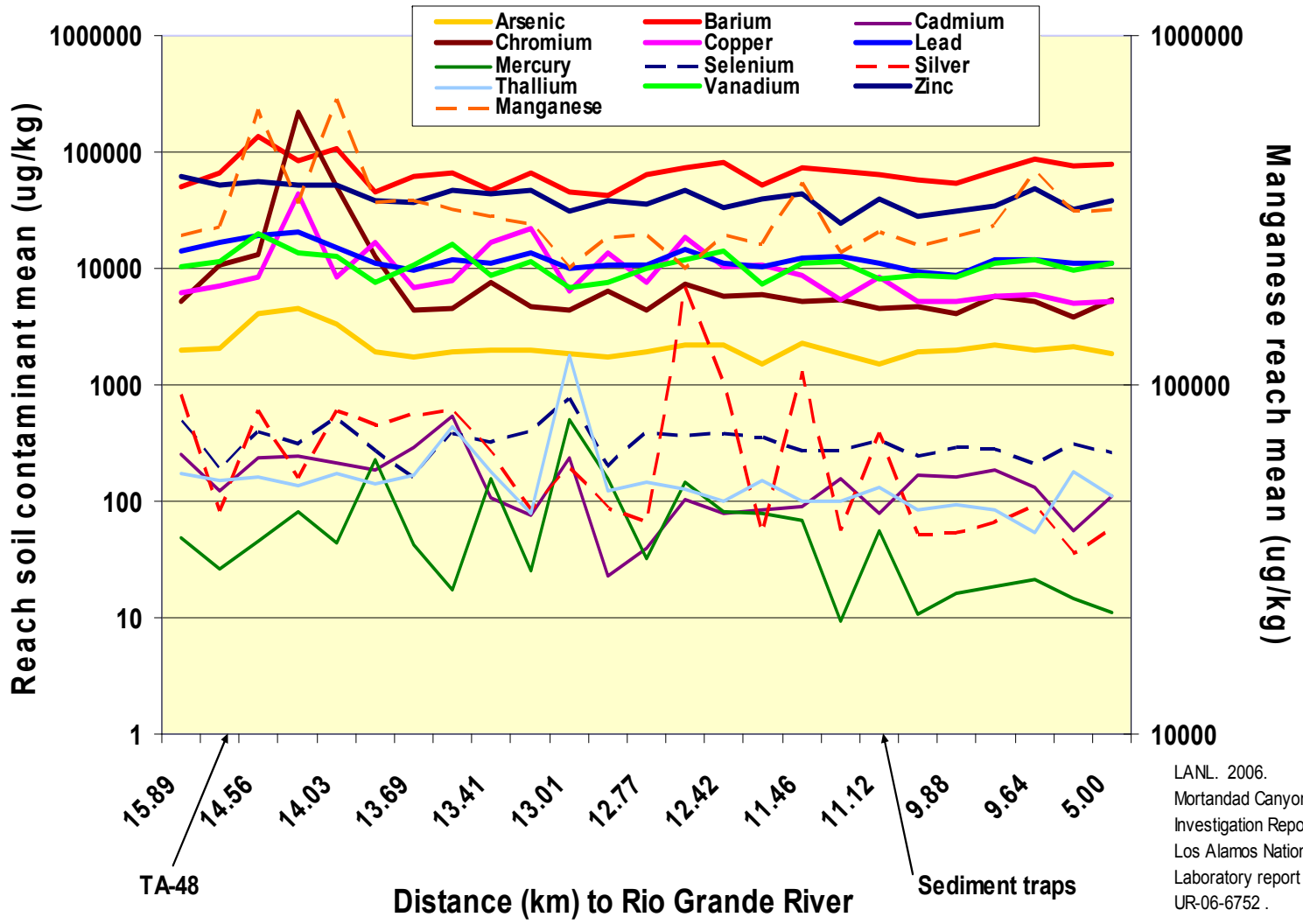
Table 9

Composite insect samples (N = 14) analyzed for heavy metals from 2003-2005 at Los Alamos National Laboratory, New Mexico.

Year	Location	Reach	Number of boxes	Mass (g)
2003	Mortandad	M-4W	1	0.35
2003	Mortandad	M-4E	1	0.418
2004	Mortandad	M-4	1	0.271
2004	Mortandad	M-5W	2	0.252
2004	Cemetery	Cemetery	1	0.34
2005	Mortandad	E-1FW	1	0.491
2005	Mortandad	TS-1E	1	0.317
2005	Mortandad	TS-2W	1	0.272
2005	Mortandad	M-4	1	0.535
2005	Mortandad	M-4E	1	0.115
2005	Mortandad	M-5W	6	2.701
2005	Golf Course	Golf Course	5	2.497
2005	Cemetery	Cemetery	6	1.253
2005	Cañada del Buey	Cañada del Buey	4	1.565

Soil contamination was greatest in upper reaches of Mortandad Canyon, particularly between M1-E (East) at 14.56 km from the Rio Grande, and E-1E (East) at 13.82 km away (Figures 2 and 5). The greatest source of contamination for Mortandad Canyon is a radioactive waste storage facility, Technical Area-48, which is upstream at approximately 14.6 km from the Rio Grande River (Steven Reneau, Environmental Restoration Program, EES Division, personal communication). Contamination was worst in upstream reaches, which exhibited the greatest amounts of soil contaminant load, specifically manganese, chromium, and barium (Figure 5).

Fig 6. Heavy metal contaminants from most upstream to most downstream reach in Mortandad Canyon in 2005, Los Alamos National Laboratory, New Mexico. Note that concentrations are on a log scale, and manganese is plotted on the right.



LANL. 2006. Mortandad Canyon Investigation Report: Los Alamos National Laboratory report LA-UR-06-6752 .

Home range size and contaminants

The mean WEBL home range size overall was 6,030 m^2. Home range size did not differ between contaminated ($\bar{x}_1$ = 5617 m^2, SE_1 = 945, n_1 = 15) and reference sites ($\bar{x}_2$ = 5803 m^2, SE_2 = 798, n_2 = 11). Home range size also did not differ between years ($\bar{x}_{2004}$ = 4814 m^2, SE_{2004} = 873, n_{2004} = 11; $\bar{x}_{2005}$ = 5696 m^2, SE_{2005} = 630, n_{2005} = 26). There was no significant difference in home range size between burned ($\bar{x}$ = 6069 m^2, SE = 1239, n = 11) and unburned areas ($\bar{x}$ = 5422 m^2, SE = 642, n = 15). AIC_C weights indicate that the best model of the set, or null in this case, is approximately 8 times more likely than the second-best model (Table 4). Because the null is the most plausible model, there is little evidence to indicate that home range size is related to site, year, or burned area. Home range size was largest in Mortandad Canyon with the largest percentage of contamination within the home ranges ($\bar{x}$ = 90.3%) over any other area (Table 10).

Table 10

Mean (SE) percentage contaminated area within home range by location in 2005 at Los Alamos National Laboratory, New Mexico. None of the four measured home ranges in Canada del Buey were located within a potentially contaminated area.

Location	HR Contaminated area (m^2)	SE	Percent contamination (%)
Mortandad Canyon (n=12)	64388	1041	90.3
Canada del Buey (n=4)	0	0	0
Golf Course (n=7)	36696	922	71.3
Cemetery (n=6)	3424	447	12.1

Effects of home range contamination on reproductive success

Eggshell thickness was not correlated with volume ($F = 0.88$, $p = 0.50$, $n = 23$), or egg contaminant load ($F = 1.01$, $p = 0.44$, $n = 24$). The principle component analysis factor was used in place of egg contaminant load. Eggshell thickness was not correlated with levels of calcium and sodium in the egg contents ($F = 1.49$, $p = 0.25$, $n = 23$). Calcium and sodium were examined over other metals based on their importance in eggshell development (Gill, 1990).

Tarsus size did not differ between contaminated ($\bar{x} = 25.0$ mm, SE = 0.45, n = 16) and reference sites ($\bar{x} = 24.9$ mm, SE = 0.18, n = 11). Tarsus size corrected for age also did not differ between months of the same season (May = 25.2 mm, $SE_1 = 0.39$, $n_1 = 18$, June/July = 24.4 mm, $SE_2 = 0.14$, $n_2 = 9$). Although tarsus size was slightly smaller in Mortandad Canyon than other locations (Table 11), the difference was not significant ($F = 0.12$, $p = 0.95$, $n = 26$). AIC_C weights indicate that the best model of the set (the null in this case), is approximately 5 times more likely than the second-best model (Table 6). The fact that the null is the most plausible model shows that none of the other tarsus models adequately represent the data, and tarsus size is not a good measure of contamination in home range.

Nestling mass corrected for age did not differ between months of the same season (May = 1.94 g, $SE_1 = 0.08$, $n_1 = 17$, June/July = 1.99 g, $SE_2 = 0.08$, $n_2 = 9$). Number of parasites per nest also did not differ between May ($\bar{x} = 4.7$, SE = 0.79, n = 17) and June/July ($\bar{x} = 6.47$, SE = 1.07, n = 9). The number of blowfly cases and larvae that were inventoried from nests were overall lower in the reference Cemetery ($\bar{x} = 21$, SE = 11, n

= 6) than other locations, however the greatest number of blowflies was found in the Golf Course ($\bar{x}$ = 62, SE = 19, n = 7), the second reference site (Table 11). Fluctuating asymmetry of the tarsi was not correlated with prey contaminant load (F = 0.68, p = 0.67, n = 7).

Table 11

Mean (SE) tarsi (mm), wing lengths (mm), mass (g) of Western Bluebird nestlings, and number of blowflies per nest by location in 2005 at Los Alamos National Laboratory, New Mexico.

Location	Left tarsus	Right tarsus	Left wing	Right wing	Mass	Blowflies
Mortandad Canyon (n=12)	22.3 (0.03)	22.3 (0.3)	56.4 (2.5)	56.6 (2.4)	24.7 (0.5)	38 (9)
Canada del Buey (n=4)	23.5 (0.2)	23.3 (0.2)	63.3 (1.3)	63.7 (1.5)	28.1(1.0)	26 (9)
Golf Course (n=7)	23.5 (0.4)	23.4 (0.3)	59.6 (4.2)	59.4 (4.3)	27.0 (0.7)	62 (19)
Cemetery (n=6)	23.2 (0.1)	23.3 (0.1)	64.0 (2.1)	64.2 (2.0)	26.4 (0.8)	21 (11)

Since no research was found showing that WEBLs eat blowfly larvae, blowflies were excluded from potential prey material found in nests. Therefore, the greatest number of prey items per nest was in the Order *Hymenoptera*. Of the insects in this Order, the majority inventoried were ants.

Mortandad Canyon had a greater mean number of dead nestlings per nest ($\bar{x}$ = 1.0, SE = 0.35, n = 12) relative to all other locations. Nestling mortality did not differ between years ($\bar{x}_{\mathbf{2004}}$ = 0.25 nestlings, SE_1 = 0.16, n_1 = 8, $\bar{x}_{\mathbf{2005}}$ = 0.44, SE_2 = 0.17, n_2 = 27), although it did differ significantly between months of the same season ($\bar{x}_{\mathbf{May}}$ = 0.17, SE = 0.09, n = 18; $\bar{x}_{\mathbf{June/July}}$ = 1.00, SE = 0.44, n = 9). Mortality also significantly differed between burned ($\bar{x}$ = 0.83 nestlings, SE = 0.35, n = 12) and unburned area ($\bar{x}$ = 0.13, SE = 0.09, n = 15). Unexpectedly, mortality did not differ between contaminated and reference sites (F = 1.65, p = 0.21, n = 27 nest boxes). Percentage home range contamination and parasites were independently correlated with mortality (Table 12). Although the p-value does not equal 0.05, there is some evidence to support that the interaction between parasites and contamination are arguably related to mortality (Table 12), however post-hoc tests revealed that no locations are significantly different from one another. When modeling mortality as a function of burned area and home range contamination, the effects were significant (Table 13). Prey contaminant load was highly correlated with mortality (r^2 = 0.75, β = 0.24, F = 20.48, p = 0.003, n = 9), specifically selenium (r^2 = 0.95, β = 1.39, F = 49.14, p = <.0001, n = 12) with a slight positive relationship (Table 14). When vanadium was added to an interactive effect between selenium and beryllium, the correlation was highly significant (r^2 = 0.90, F = 15.17, p = 0.002, n = 12) (Table 10). This model was constructed based on information of these

three metals upstream in Mortandad Canyon (Pratt, 1997). Mortality showed a positive relationship with the percentage of foraging points in contaminated home range area (r^2 = 0.22, β = 0.16, F = 5.76, p = 0.03, n = 23). Lastly, mortality was unexpectedly not linked to soil hazard indices from the ECORSK database (F = 0.05, p = 0.82, n = 9) (Table 14). AIC_C weights indicate that the best model of the set, where mortality is a function of selenium, beryllium and vanadium, is approximately 1.4 times more likely than the second-best model (Table 7).

Table 12

General linear model of the effects of the number of parasites per nest and percent of contaminated home range on nestling mortality, with location as the covariate; all factors were fixed.

Source of variation	df	MS	*F*	*P>F*
Location	3	0.1109	0.34	0.80
Parasites	1	0.0056	0.02	0.90
% Contaminated home range	1	0.0313	0.10	0.76
Parasites x Contamination	1	0.8915	2.71	0.12
Error	20	0.3289		

Table 13

General linear model of burned area and the percent of contaminated home range compared with mortality, with burned area as the covariate; all factors were fixed.

Source of variation	df	MS	*F*	*P*>*F*
Burned area	1	0.2634	0.44	0.52
% Contaminated home range	1	2.8052	4.66	0.04
Burned area x Contamination	1	1.4933	2.48	0.13
Error	22	0.6021		

Table 14

GLM models summarizing results of analyses between Western Bluebird nestling mortality and explanatory factors during 2004-2005 at Los Alamos National Laboratory, New Mexico. "PRS" is defined as the contamination within home range. Note that analyses used different datasets (see methods text).

Model	n	*t-* / *F*	*P*>*F*	β	R^2
Mortality = Year	35	0.35	0.56	.	.
Mortality = Site	27	1.65	0.21	.	.
Mortality = Month	27	6.31	0.02	.	.
Mortality = Burned area	27	4.69	0.04	.	.
Mortality = Percent forage in PRS	23	5.76	0.03	0.156	0.22
*Mortality = Prey load	9	20.48	0.003	0.244	0.75
Mortality = Prey Se	12	49.14	0.0001	1.39	0.83
Mortality = Prey Se + Be + V + (Se*Be)	12	15.17	0.002	0.40	0.90
Mortality = Burn + PRS + (burn*PRS)	26	3.99	0.02	.	0.35
Mortality = Location + PRS + parasites + (parasites*PRS)	27	3.91	0.009	.	.
*Mortality = Soil hazard indices	9	0.05	0.82	0.011	0.01

*2005 only

DISCUSSION

The most significant result of this study is that the percentage of home range contamination was associated with lower reproductive success in Western Bluebirds. Furthermore, uptake of heavy metals in prey collected in the home range is also closely linked to increased nestling mortality. These findings are consistent with other passerine studies showing heavy metal contamination increased nestling mortality near the pollution source (Eeva and Lehikoinen, 1996; Janssens et al., 2003; Nyholm, 1998). In addition, the amount of exposure and uptake the birds receive is potentially influenced by the spatial distribution of heavy metals. These results suggest that nestling mortality is highly linked to contaminants in the prey base, specifically selenium, and a combination of selenium, beryllium, and vanadium.

Mortandad Canyon was the central focus for heavy metal contamination because it harbors significant amounts of selenium among many other compounds (Pratt, 1997). Primarily used for liquid waste disposal (Pratt, 1997), Mortandad is oriented in the north-central part of the Laboratory, and trends east-southeast for approximately 15.8 km. Main sources of contamination in Mortandad Canyon are include inorganic constituents and effluent wastewater from the Laboratory's Radioactive Liquid Waste Treatment Facility (RLWTF) at Technical Area 50 (TA-50), cooling tower discharges from TA-48 and -35, and stormwater runoff in the upper regions of the watershed (Figure 2) (Pratt, 1997). Pratt and Ten-Site Canyons are both tributaries into Mortandad, and prominent sources of contaminants. Ten-site and reach E-1FW have high concentrations of beryllium and vanadium, among various other metals (Figure 2). The highest concentrations upstream from Pratt Canyon are derived from TA-50. Downstream from

Pratt Canyon contaminant discharges originate mainly from TA-35. Effluent Canyon gets its largest contaminant source from TA-48. Therefore TA-48 is a combination of all three major contaminant sources, and leads directly into the upper opening of the Mortandad Canyon (Pratt, 1997). With the help of an aqueous driver, such as stormwater, these sources of heavy metals have the potential to merge and travel downstream, resulting in large-scale soil deposition.

Three sediment traps were constructed in the last 1970s about 3.2 km downstream of the TA-50 RLWTF outfall in middle Mortandad (Pratt, 1997). The function of the sediment traps is to dissipate the influx of major runoff, capture sediments, and reduce transport downstream. Discharge typically flows a short distance downstream and discharges into the alluvium approximately mid-canyon (Pratt, 1997). The wettest areas are in reaches E-1W, E-1E, M-1W, and M-2W, all down canyon from outfalls that regularly discharge into the canyon bottom (Pratt, 1997; Figure 2). The main channel in Mortandad is ephemeral so that stormwater during flows only a limited distance and occasionally reaches the sediment traps. Significant flows that transport sediment to the traps have occurred only six times in the last two decades (Pratt, 1997). Sediment deposition is less likely in the steep and narrow regions of the upper canyon, and sediments are more likely to settle in open spaces where the canyon floor widens and the gradient decreases. Heavy metal deposition in Mortandad Canyon and other locations overlaps home ranges in the area, resulting in potential exposure. Selenium, beryllium and vanadium were likely deposited since 1943 from upstream sources at TA-50, TA-48, and TA-35, and had many years to travel downstream. Although this could not be tested due to low sample sizes, birds may be at greater risk in upstream areas.

Several other stressors were influential in increasing nestling mortality. Blowfly parasites and contamination were not correlated with mortality. Although parasites did not show interactive effects in general, they did to some extent with contaminants. Because parasite load did not differ between months of the season, I suggest there is a relatively even risk of infestation over the entire breeding season. However, intra-clutch risk is not evenly distributed among nestlings. For example, in nests with four to five nestlings, one sibling was often neglected due to stronger, larger nestlings that received greater amounts of food by moving toward the box opening (Colestock, unpublished data). This neglected chick often had more parasites than the others. Multiple stressors may interact to affect health of young nestlings. The results agree with other studies that propose indirect effects rather than direct effects (Dauwe et al., 2005; Wittmann and Beason, 1992). Pinkowski (1975) reported that although heavy infestation in bluebird nests was correlated with physiological stress, the parasite load was not the *cause* of the stress. Nestlings exposed to contaminant uptake may have had higher vulnerability to parasites, therefore increasing parasite numbers (Wittmann and Beason, 1992).

It was expected that mortality was not associated with burned area. Because the burned area generally promotes higher densities of insects through complex habitat mosaics (Purcell and Stephens, 2006), the birds may have a greater abundance of prey. Wolters (2001) found that anthropogenic fragmentation of landscapes into a patchwork of habitats increases the regional species pool of soil fauna enormously. Burned areas theoretically increase prey availability, however it is possible that the prey could contain greater amounts of contamination simply because a greater volume of insects exist to uptake soil compounds. The result may be greater direct uptake through the food chain.

There are several reasons why significant differences appeared in mortality between months of the same season. This study unexpectedly revealed greater mortality in June/July rather than in May. There is a slight possibility that missing nestlings, assuming to be fledged, were predated at their fledging age. However, this is unlikely because the most common predators such as chipmunks, mice, and woodrats leave some evidence behind (Colestock, unpublished data). In addition, no studies have shown that predation varies between different months of the season. Another possibility is that lack of food availability in later months may be contributing to stress, because food limitation is known to increase nestling mortality (Eeva et al., 1997). However, since the later months of the season have ample amounts of precipitation, food limitation is not a likely scenario.

Drought may have indirect effects that account for differences in seasonal mortality. Late June-August accounts for 36% of the annual precipitation and the bulk of the rainy season (Morgan, 2004). Drought in the earliest, driest months of the season may make incubation and survival more difficult for birds nesting late in the summer. Nestlings may have higher risk of nestling dehydration. Breshears (2005) reported regional vegetation mortality across southwestern U.S. woodlands in 2002-2003 as a response to drought and associated bark beetle infestations. As a result of depleted soil water for over a year, >90% of *Pinus edulis* trees were killed (Breshears, 2005). Maximum annual temperature exceeded the 1950s drought. The actual extent was 12,000 km^2 or more as confirmed by U.S. Forest Service aerial surveys for a subset of the region (Breshears, 2005), and included the entire Pajarito Plateau.

In addition to seasonal differences, daily fluctuations in temperature were not examined. Because Los Alamos has a temperate, semi-arid mountain climate, with 1000 feet elevation gain across Laboratory property, temperatures have a wide daily range of approximately 13 degrees Celsius on average (Bowen, 1990). June daily temperatures are considered the hottest of the season even though the region receives some early monsoon rainfall during the month. It is possible that nestlings have trouble adapting to such widely fluctuating changes to extreme warm and cold temperatures, which may account for some mortality.

Mortality was not affected by year, site, or soil contamination as measured by hazard indices. First, annual differences in precipitation were not significant enough to associate with mortality between years. Bluebirds may have been able to adapt to yearly fluctuations in rainfall or prey availability through plasticity in their foraging strategies (Howe et al., 1996). For example, certain types of prey may explode in the area one year but not the next. Bluebirds may adapt to these changes by switching their preference to a different type of insect (Howe et al., 1996). Secondly, because mortality was not affected by site, it's possible that contamination uptake requires foraging in precise hot spots, rather than across general larger sites. Prey could also be found in clumped distribution, such as ant hills, and may not present a great threat unless they reside in contaminated hot spots. Lastly, hazard indices were computed using the same estimated home range size for each nest. No more than 10 standard grid cells around the center of each home range were used to represent a typical home range. This is due to the inability of the current hazard index model to estimate home ranges of different sizes. Therefore, the method

underestimated the home range of each bluebird because some ranges were larger than others.

The fact that nestling mortality increased with prey contaminant levels, indicates that the birds were not only exposed to contaminants, but utilization of those areas led to uptake in the birds' tissues. These findings are consistent with studies on warblers that showed contaminant concentrations in foraging area soil and diet are related to residues in tissues (Burger et al., 1999; Reynolds et al., 2001). The results also suggest that prey contaminant load is the most effective vector of heavy metal uptake as opposed to egg contaminant load.

Prey load is highly associated with the amount of contamination in home range and considered to be the most effective indicator of contaminant uptake. This is most likely due to the fact that contaminated insects are given directly to the nestlings during growth, rather than detouring through the digestive system of the adult into an egg. These results contrasted with a study by Reynolds et al. (2001) that concluded consumption of invertebrates directly linked to the soil or sediments is minimal. WEBLs were observed foraging directly on the ground the majority of the time (Colestock, unpublished data). Ants were by far the highest species inventoried based on legs remaining in nesting material. Relatively high concentrations of metals have been reported in ants of the genus *Formica* (Bengtsson and Rundgren, 1984; Yla-Mononen et al., 1989). Eeva and Lehikoinen (1996) suggested that heavy metals might accumulate more in ground living prey items such as beetles, ants, and cockroaches, than in foliage-living prey.

Many of the insects observed in the adult's mouth at the nest box opening were also in the larval life stage (Colestock, unpublished data), including worms and caterpillars. Larval invertebrates were discovered to have higher fat content (>30%) than adults (Barker et al., 1998). Fats have a higher caloric content (9 kcal/g) than proteins (4 kcal/g) or carbohydrates (4 kcal/g), thus providing a more concentrated energy source and higher potential for metal storage (Barker et al., 1998).

In addition, because the nestlings likely ingested the parts of insects with the highest energy content, such as lipids, it is suggested they will bioaccumulate greater amounts of metals than adults (Köhler, 2002; Klaassen, 2001). Non-essential metals and micronutrients were mainly stored in the mid-gut epithelium tissue, mid-gut gland, hepatic cells surrounding the mid-gut, hepatopancreas, and fat granules (Köhler, 2002; Lindqvist and Block, 1997; Martien, 1993). Appendages of adult insects, such as grasshoppers and beetles, were left behind in the nesting material, indicating that the nestlings consumed the most contaminated sections of their prey (Colestock, unpublished data).

It is possible that prey load did not sufficiently represent site contamination because reference areas may have been poorly characterized. However, this is unlikely because the two reference sites are residential areas with no known historical use of heavy metal contamination. Secondly, the golf course and cemetery both are located on high ground along mesa tops in Los Alamos township, contrasting with major sources of heavy metal contamination in canyon bottoms (Bowen, 1990). A more likely possibility could be that adults simply ingest contaminants elsewhere outside the local home range.

This could include feeding stops on migration routes that account for lipid storage just prior to the breeding season (Klemens et al., 2000).

In addition to potentially poor reference site characterization, an alternative is that the parents have "helpers." Offspring from other clutches in the area stay to gain feeding advantages, help adults feed nestlings, and prolong brood care for access to resources (Dickinson and McGowan, 2005). Bluebirds are also considered monogamous (Fair and Meyers, 2002), however additional "helpers" have assisted with feeding in order to gain experience and mates of their own (Colestock, unpublished data; Dickinson and McGowan, 2005). Individuals that are not tracked or monitored may bring in potentially contaminated prey from unknown heavy metals sources.

In this study, eggs are not considered adequate indicators for contaminant uptake. Although eggs have been found to effectively monitor contaminants such as PCBs (Fair and Meyers, 2002) and organochlorines (Reynolds et al., 2004), they may not be exceptional indicators of heavy metals. Further studies should be conducted involving other potential vectors as indicators of contamination. Other passerine studies that examined reproductive success in relation to heavy metal sources found that excreta is a good indicator of contamination (Dauwe et al., 2004; Eeva and Lehikoinen, 1996; Janssens et al., 2003; Eeva et al., 2003). Feathers are also known to show associated impacts of metals in birds. Janssens et al. (2001) found that nine heavy metals in feathers, including mercury and selenium were on average two to forty times higher in contaminated sites compared to reference sites. Similar results were revealed Great and Blue Tit studies using feathers (Dauwe et al., 2005). However, feathers were not used as endpoints in this study because they do not represent the pathway of contamination, but

only reflect concentrations in the final receptor species. In this case, the adult female would receive most of the contamination and it may not necessarily transfer to an egg.

Egg load was not highly correlated with contamination in home range. In some studies, inter- and intraclutch variability in egg metal concentrations biased the contaminant levels (Morera et al., 1997; Becker, 1992). For example, in seabirds, decreasing mercury levels were detected according to laying sequence (Becker, 1992). However, this is an unlikely pattern in Western Bluebird eggs for two reasons. First, laying order in gull eggs had a significant effect on mercury concentrations in two-egg clutches, but not in clutches of three eggs, indicating larger female sample sizes were needed to detect laying effect (Morera et al., 1997). Female adults with indeterminate clutches are thought to retain further resources for subsequent eggs (Gill, 1990). Therefore because WEBLs commonly lay four to five eggs per clutch, the contaminant load may also be evenly distributed. Because female passerines lay multiple eggs within a short period of approximately 24 hours per egg (Gill, 1990), macronutrients within the daily diet will be distributed to multiple eggs within the clutch (Perrins, 1970). Secondly, egg collection in this study was random and the chance of choosing the egg with the most contamination every time is unlikely. It is possible that a laying order pattern does exist in Western Bluebird clutches, but it was not detected because only one egg was sampled per nest. Studies examining organochlorines in eggs suggested that intra-clutch contaminant levels are small compared to inter-clutch trends (Newton and Bogan, 1978), and one egg represents the entire clutch (Reynolds et al., 2004). Any small variability in eggs levels could be associated with the spatial heterogeneity of contaminant distribution,

or the lacking macronutrients (Perrins, 1970; Morera et al., 1997), or the quality of the female's body reserves (Dauwe et al., 2005; Reynolds et al., 2004).

In addition, regardless of how much time the birds allocate to contaminated areas, they may not exclusively utilize insects that uptake heavy metals, particularly ground-dwelling insects. Even though WEBLs were observed foraging mainly on the ground, they also took advantage of aerial hawking techniques, foraging directly in bark of tree trunks, and eating winged-insects in upper foliage. These different insect genres may have different likelihood of accumulating body burdens of metals.

Another explanation of why egg load does not reflect home range contamination is the potential that some contaminants are transferred to eggs with greater efficiency than others. However, except for mercury and selenium, few data are available to provide evidence on other metals in eggs of wild passerine populations. Other studies do not agree on which metals are the most prominent in egg transfer processes. Burger (1994) found egg-laying constitutes an excretion method for metals such as cadmium and lead (Morera et al., 1997) whereas Furness (1993) suggested very little cadmium and lead is transferred to eggs. Braune et al. (2001) found that both mercury and selenium are transferred to the eggs, reflecting long-term assimilation, possibly from many locations.

Eggshell thickness is highly correlated with the amount of contamination in egg contents. This finding is contrary to evidence that calcium in local soils masks the effects of heavy metals that accumulate in eggshells (Graveland and Drent, 1997; Eeva et al., 2000; Scheuhammer, 1996). Calcium is very limiting in reproduction since females require a large amount of calcium for eggshell formation and growth (Graveland and Drent, 1997). Low dietary calcium greatly increased the accumulation and effects of

lead, cadmium, and aluminum in birds (Scheuhammer, 1996; Eeva et al., 2000), which has also been reflected in laboratory studies where Ca deficiency increased heavy metal toxicity (Scheuhammer, 1996). Eeva and Lehikoinen (2004) demonstrated with the Pied Flycatcher (*Ficedula hypoleuca*) that detrimental effects of heavy metals might become visible when Ca availability is poor. The soils on the Pajarito Plateau contain some of the largest deposits of calcium carbonate in North America (Fair and Meyers, 2002). However they may not be assimilated into the eggshells as anticipated, due to antagonistic inferences in transport mechanisms by other metals.

Eggshell thickness did not differ among sites, consistent with studies conducted with Blue Tit (*Parus caeruleus*) eggs (Dauwe et al., 2004; Dauwe et al., 2005). Because eggshells in reference sites were not different from contaminated areas, there is the possibility that reference sites were not characterized well or that contaminants are not linked directly to the breeding areas.

Other measures of reproductive success, including nestling mass, tarsi size, and asymmetry were not as significantly affected by contamination. Nestling mass did not differ between months of the same season. This finding shows that mass did not parallel differences in monthly precipitation, and suggests prey availability was consistent during the entire breeding season. Another study examined nestling mass in relation to pollution and found a significant decrease near contaminated sites (Janssens et al., 2003), however, it did look at nestling mass in early and later parts of the season.

Tarsi are not considered a good indicator of contaminant uptake in this study. These findings are consistent with other studies that found no significant differences in tarsus length with contaminant concentrations (Dauwe et al., 2005; Janssens et al., 2003).

Contrary to these findings were other studies that showed tarsus length varied and was shorter near contamination (Eeva et al., 2003; Fair et al., 2003), suggesting higher stress. Tarsi length might be influenced by numerous other factors such as lower food availability or exposure to organochlorines and PCBs (Dauwe et al., 2005).

Nestling tarsi asymmetry was also not a good indicator of uptake, contrary to other studies that demonstrated asymmetry increased with pollution (Eeva et al., 2000). One possibility for the lack of asymmetry could be that nestlings purge themselves of contaminants during growth, thus asymmetry does not increase toward fledging age. However, this is unlikely, because even though Nyholm et al. (1998) found that nestlings could potentially excrete some pollutants, the authors proposed it accounted for a negligible part of the total concentration in mature chicks. Fluctuating asymmetry is suggested to be more prominent in areas with greater nutritional stress and food-depravation (Swaddle and Witter, 1994), which may not be the case at Los Alamos. Nestlings in Los Alamos may have enough prey and allocate more resources to other mechanisms of compensational growth that restore symmetry between left and right sides (Grieco, 2003).

In this study, home range size had no known relationship with contamination. One possibility for this finding is that size does not necessarily reflect the amount of contamination in a home range, nor which areas the female utilizes for resources. Another study that found that larger home ranges resulted from decreased concentrations in organisms (Marinussen and Van der Zee, 1996). The authors of that study proposed that contaminant exposure increased with greater home range size, however this does not mean greater exposure will result in higher uptake. Contamination “hot spots” were only

a large risk for populations with small home ranges (Marinussen and Van der Zee, 1996). The reason for this may be that the study was based on a computer model, and not representative of field data. Therefore, there is no evidence to suggest that home range size effectively represents the pattern, distribution, or amount of contamination present.

Another possibility is that prey availability is likely higher in burned areas from an increase in habitat complexity (Purcell and Stephens, 2006). The bluebirds tend to prefer burned areas because they frequently inhabit areas similar to those following frequent, low-intensity fire (Purcell and Stephens, 2006). It is possible that prey availability and the number of secondary cavities increase to provide more nesting opportunities. In a study examining passerine reproductive success with fire regimes, birds in burned Ponderosa Pine stands had higher nesting densities than those in unburned areas (Saab et al., 2005). However, because the reference sites also had bountiful prey due to constant watering in residential areas, it's possible that prey availability was relatively equal in contaminated and reference sites. Thus, the birds would not be forced to extend their home ranges and travel farther to find food.

Overall, it appears that lower reproductive success detected in Western Bluebird populations is associated with home range contamination. Specifically, prey contaminant levels had the greatest adverse association with nestling mortality. Prey seem to be the most effective indicator of contaminant uptake as opposed to egg contents, indicating that insects exposed to contamination bioaccumulate heavy metals and pass them through the birds' food chain. Therefore it is plausible to suggest that the local soil contamination in home range is adversely affecting bird populations on a landscape scale.

LITERATURE CITED

Anderson, J.D., 1982. The Home Range: A new nonparametric estimation technique. Ecology 63, 103-112.

Balice, R., Bennett, K., Wright, M., 2004. Burn severities, fire intensities, and impacts to major vegetation types from the Cerro Grande Fire. Los Alamos National Laboratory Report, LA-14159.

Barker, D., Fitzpatrick, M., Dierenfeld, E., 1998. Nutrient Composition of Selected whole invertebrates. Zoo Biology 17, 123-134.

Becker, P., 1992. Egg mercury levels decline with the laying sequence in Charadriiformes. Bulletin of Environmental Contamination and Toxicology 48, 762-767.

Bennett, G., Whitworth, T., 1992. Host, nest, and ecological relationships of species of *Protocalliphora* (Diptera: Calliphoridae). Canadian Journal of Zoology 70, 51-61.

Bengtsson, G., Rundgren, S., 1984. Ground-living invertebrates in metal-polluted forest soils. Ambio 13, 29–33.

Bowen, B., 1990. Los Alamos Climatology. Los Alamos National Laboratory Report, LA-11735-MS.

Braune, B.M., Donaldson, G., Hobson, K., 2001. Contaminant residues in seabird eggs from the Canadian Arctic. Part I. temporal trends 1975-1998. Environmental Pollution 114, 39-54.

Breshears, D., Cobb, N., Rich, P., Price, K., Allen, C., Balice, R., Romme, W., Kastens, J., Floyd, L., Belnap, J., Anderson, J., Myers, O., Meyer, C., 2005. Regional vegetation die-off in response to global-change-type drought. Proceedings of the National Academy of Sciences of the United States of America 102, 15144-15148.

Burger, J., 1994. Heavy metals in avian eggshells: another excretion method. Journal of Toxicology and Environmental Health 41, 207-220.

Burger, J., Gochfield, M., 1993. Lead and cadmium accumulation in eggs and fledgling seabirds in the New York bight. Environmental Toxicology & Chemistry 12, 261-267.

Burger, J., Woolfenden, G., Gochfeld, M., 1999. Metal concentrations in eggs of endangered Florida scrub-jays from central Florida. Archives of Environmental Contamination and Toxicology 37, 385–388.

Burnham, K., Anderson, D., 1998. Model Selection and Inference. Springer-Verlag Inc., New York, NY.

Bustnes, J., Folstad, I., Erikstad, K., Fjeld, M., Miland, O., Skaare, J., 2002. Blood concentration of organochlorine pollutants and wing feather asymmetry in Glaucous Gulls. Functional Ecology 16, 617-622.

Bustnes, J., Hanssen, S., Folstad, I., Erikstad, K., Hasselquist, D., Skaare, J., 2004. Immune function and organochlorine pollutants in Arctic breeding Glaucous Gulls. Archives of Environmental Contamination and Toxicology 47, 530-541.

Cadèe, N., 2000. Parent barn swallow fluctuating asymmetry and offspring quality. Journal of Avian Biology 31, 495-503.

Cortet, J., Ronce, D., Poinsot-Balaquer, N., Beaufreton, C., Chabert, A., Viaux, P., Cancela de Fonseca, P., 2002. Impacts of different agricultural practices on the biodiversity of microarthropod communities in arable crop systems. European Journal of Soil Biology 38, 239.

Dauwe, T., Bervoets, L., Blust, R., Pinxten, R., Eens, M., 2000. Can excrement and feathers of nestling songbirds be used as biomonitors for heavy metal pollution? Archives of Environmental Contamination and Toxicology 39, 541-546.

Dauwe, T., Janssens, E., Eens, M., 2005. Effects of heavy metal exposure on the condition and health of adult great tits (*Parus major*). Environmental Pollution 126, 267-274.

Dauwe, T., Janssens, E., Bervoets, L., Blust, R., Eens, M., 2004. Relationships between metal concentrations in Great Tit nestlings and their environment and food. Environmental Pollution 131, 373-380.

Dickinson, J., McGowan, A., 2005. Winter resource wealth drives delayed dispersal and family-group living in Western Bluebirds. Proceedings of the Royal Society B 272, 2423-2428.

Eens, M., Pinxten, R., Verheyen, R., Blust, R., Bervoets, L., 1999. Great and Blue tits as indicators of heavy metal contamination in terrestrial ecosystems. Ecotoxicology and Environmental Safety 44, 81-85.

Eeva, T., Lehikoinen, E., 1996. Growth and mortality of nestling great tits (Parus major) and pied flycatchers (*Ficedula hypoleuca*) in a heavy metal pollution gradient. Oecologia 108, 631-639.

Eeva, T., Lehikoinen, E., Pohjalainen, T., 1997. Pollution-related variation in food supply and breeding success in two hold-nesting passerines. Ecology 78, 1120-1131.

Eeva, T., Tanhuanpää, S., Råbergh, C., Airaksinen, S., Nikinmaa, M., Lehikoinen, E., 2000. Biomarkers and fluctuating asymmetry as indicators of pollution-induced stress in two hole-nesting passerines. Functional Ecology 14, 235-243.

Eeva, T., Lehikoinen, E., Nikinmaa, M., 2003. Pollution-induced nutritional stress in birds: an experimental study of direct and indirect effects. Ecological Applications 13, 1242-1249.

Eeva, T., Lehikoinen, E., 2004. Rich calcium availability diminishes heavy metal toxicity in Pied Flycatcher. Functional Ecology 18, 548-553.

Eeva, T., Ryömä, M., Riihimäki, J., 2005. Pollution-related changes in diets of two insectivorous passerines. Oecologia 145, 629-639.

Environmental Science Research Institute (ESRI), 1996. ArcView (Version 3.2 Windows). Geographic Information Systems (GIS), USA.

Environmental Protection Agency (EPA), 1996. Test methods 3050B: Acid digestion of sediments, sludges, and soils. Available at Internet website: http://www.epa.gov/epaoswer/hazwaste/test/3_series.htm.

Environmental Protection Agency (EPA), 1996. Test methods 6010B: Inductively coupled plasma-atomic emission spectrometry. Available at Internet website: http://www.epa.gov/epaoswer/hazwaste/test/6_series.htm.

Environmental Protection Agency (EPA), 1994. Test methods 7421A: Mercury in solid or semisolid waste. Available at Internet website: http://www.epa.gov/epaoswer/hazwaste/test/7_series.htm.

Ewins, P.J., Postupalsky, S., Hughes, K., Weseloh, D., 1999. Organochlorine contaminant residues and shell thickness of eggs from known-age female ospreys (*Pandion haliaetus*) in Michigan during the 1980s. Environmental Pollution 104, 295-304.

Fair, J., Myers, O.B., Ricklefs, R.E., 2003. Immune and growth response of Western bluebirds and Ash-throated Flycatchers to soil contaminants. Ecological Applications 13, 1817-1829.

Fair, J., Ricklefs, R.E., 2002. Physiological, growth, and immune responses of Japanese Quail chicks to the multiple stressors of immunological challenge and lead shot. Archives of Environmental Contamination and Toxicology 42, 77-87.

Fair, J., Meyers, O.B., 2002. Early reproductive success of Western bluebirds and Ash-throated flycatchers: a landscape-contaminant perspective. Environmental Pollution 118, 321-330.

Fair, J., Meyers, O.B., 2002. The ecological and physiological costs of lead shot and immunological challenge to developing Western Bluebirds. Ecotoxicology 11, 199-208.

Furness, R., 1993. Birds as monitors of pollutants. In: Furness, R., Greenwood, J.D. (Eds.), Birds as monitors of environmental change. Chapman and Hall, London.

Gaunt, A.S., Oring, L., 1997. Guidelines to the Use of Wild Birds in Research. The Ornithological Council, Washington, DC.

Germaine H., Germaine, S., 2002. Forest restoration treatment effects on the nesting success of Western Bluebirds (*Sialia mexicana*). Resoration Ecology 10(2), 362-367.

Gill, F., 1990. Ornithology. W.H. Freeman and Co., New York.

Goldman, N., Summers, R., Mahan, J., Olive, D., Perez, S., Archuleta, L., Huchton, J., Solholt, L., 2000. Overview of Environmental Surveillance at Los Alamos during 2000. Los Alamos National Laboratory report, LALP-01-198.

Gonzales, G., R. Ryti, P. Newell, A. Gallegos, Sherwood, S., 2004. Modeled ecological risk to the deer mouse, Mexican spotted owl and western bluebird at the Los Alamos National Laboratory using ECORSK.7. Los Alamos National Laboratory report, LA-14118.

Graveland, J., Drent, R., 1997. Calcium availability limits breeding success of passerines. Journal of Animal Ecology 66, 279-288.

Grieco, F., 2003. Greater food availability reduces tarsus asymmetry in nestling blue tits. The Condor 105, 599-603.

Howe, F., Knight, R., McEwen, L., George, T., 1996. Direct and indirect effects of insecticide applications on growth and survival of nestling passerines. Ecological Applications 6, 1314-1324.

Hui, C., 2002. Concentrations of chromium, manganese, and lead in air and in avian eggs. Environmental Pollution 120, 201-206.

Janssens, E., Dauwe, T., Bervoets, L., Eens, M., 2001. Heavy metals and selenium in feathers of great tits (*Parus major*) along a pollution gradient. Environmental Toxicology and Chemistry 20, 2815-2820.

Janssens, E., Dauwe, T., Pinxten, R., Bervoets, L., Blust, R., Eens, M., 2003. Effects of heavy metal exposure on the condition and health of nestlings of the great tit (*Parus major*), a small songbird species. Environmental Pollution 126, 267-274.

Jennrich, R., Turner, F., 1969. Measurement of noncircular home range (terrestrial vertebrates). Journal of Theoretical Biology 22, 227-237.

Kellner, J., Alford, R., 2003. The ontogeny of fluctuating asymmetry. The American Naturalist 161, 931-947.

Klaassen, C., 2001. Casarett and Doull's Toxicology: The basic science of poisons. McGraw-Hill, New York.

Klemens, J., Harper, R., Frick, J., Capparella, A., Richardson, H., Coffey, M., 2000. Patterns of organochlorine pesticide contamination in neotropical migrant passerines in relation to diet and winter habitat. Chemosphere 41, 1107-1113.

Koenig, W., Dickinson, J., 1996. Nestling sex-ratio variation in western bluebirds. Auk: a journal of ornithology 113, 902-910.

Köhler, H., 2002. Localization of metals in cells of saprophagous soil arthropods (Isopoda, Diplopoda, Collembola). Microscopy research and technique 56, 393-401.

Lattin, J., Carroll, D., Green, P., 2003. Analyzing multivariate data. Thompson Learning Inc., Pacific Grove, CA.

Lindqvist, L., Block, M., 1997. Influence of life history and sex on metal accumulation in two beetle species (Insecta: Coleoptera). Bulletin of Environmental Contamination and Toxicology 58, 518-522.

Linkhart, B., Reynolds, R., Ryder, R., 1998. Home range and habitat of breeding Flammulated Owls in Colorado 110, 342-351.

Marinussen, M., Zee, S., 1996. Conceptual approach to estimating the effect of home-range size on the exposure of organisms to spatially variable soil contamination. Ecological Modelling 87, 83-89.

Martien, P., Hogervorst, J., Hogervorst, R., 1993. Metal accumulation in soil arthropods in relation to micro-nutrients. Environmental Pollution 79, 181-189.

McDonald, E., Ryti, R., Reneau, S., Carlson, D., 2003. Natural background geochemistry and statistical analysis of sediments, Los Alamos National Laboratory. Los Alamos National Laboratory Report, LA-UR-03-2661.

Miller, C., Fair, J., 1997. Effects of blow fly (*Protocalliphora spatulata*: Diptera: Calliphoridae) parasitism on the growth of nestling savannah sparrows in Alaska.

Moller, A., Hoglund, J., 1991. Patterns of fluctuating asymmetry in avian feather ornaments: implications for models of sexual selection. Proceedings of the Royal Society of London 245, 1-5.

Morera, M., Sanpera, C., Crespo, S., Jover, L., Ruiz, X., 1997. Inter- and Intraclutch variability in heavy metals and selenium levels in Audouin's Gull eggs from the Ebro Delta, Spain. Archives of Environmental Contamination and Toxicology 33, 71-75.

Morgan, T., 2004. Environmental Surveillance at Los Alamos during 2004. Los Alamos National Laboratory Report, LA-14239-ENV.

Mueller, R., Scudder, M., Porter, M., Talbot, T., Gehring, C., Thomas, W., 2005. Differential tree mortality in response to severe drought: evidence for long-term vegetation shifts. Journal of Ecology 93, 1085-1093.

Mynard, R., Keating, G., Rich, P., Bleakly, D., 2003. Geographic information system (GIS) emergency support for the May 2000 Cerro Grande wildfire, Los Alamos, New Mexico, USA. Los Alamos National Laboratory Report, LA-14007-MS.

Newton, I., Bogan, J., 1978. The role of different organochlorines compounds in the breeding of British sparrowhawks. Journal of Applied Ecology 15, 105-116.

Nyholm, N., 1998. Influence of heavy metal exposure during different phases of the ontogeny on the development of Pied flycatchers (*Ficedula hypoleuca*), in natural populations. Archives of Environmental Contamination and Toxicology 35, 632-637.

O'Brien, E., Morrison, B., Johnson, L., 2001. Assessing the effects of haematophagous ectoparasites on the health of nestling birds: haematocrit vs haemoglobin levels in House Wrens parasitized by blow fly larvae. Journal of Avian Biology 32, 73-76.

Ogle, K., Whitham, T., Cobb, N., 2000. Tree-ring variation in piñon predicts likelihood of death following severe drought. Ecology 81, 3237-3243.

Perrins, C.M., 1970. The timing of birds' breeding seasons. Ibis 112, 242-255.

Pinkowski, B., 1975. Growth and development of Eastern Bluebirds. Bird-Banding 46, 273-289.

Pratt, A., 1997. Work Plan for Mortandad Canyon: Environmental Restoration Project. Los Alamos National Laboratory Report, LA-UR-97-3291.

Purcell, K., Stephens, S., 2006. Changing fire regimes and the avifauna of California oak woodlands. Studies in Avian Biology 30, 33-45.

Pyle, P., 1997. Identification Guide to North American Birds. Slate Creek Press, Bolinas, CA.

Romanoff, A. L., 1967. Biochemistry of the avian embryo. John Wiley & Sons, New York.

Reynolds, K., Rainwater, T., Scollon, E., Sathe, S., Adair, B.M., Dixon, K., Cobb, G.P., McMurry, S.T., 2001. Accumulation of DDT and mercury in Prothonotary Warblers (*Protonotaria citrea*) foraging in a heterogeneously contaminated environment. Environmental Toxicology and Chemistry 20, 2903-2909.

Reynolds, K., Rainwater, T., Scollon, E., Sathe, S., Adair, B., Dixon, K., 2001. Accumulation of DDT and mercury in prothonotary warblers (*Protonotaria citrea*) foraging in a heterogeneously contaminated environment. Environmental Toxicology and Chemistry 20, 2903–2909.

Reynolds, K., Skipper, S., Cobb, G., McMurry, S., 2004. Relationship between DDE concentrations and laying sequence in eggs of two passerine species. Archives of Environmental Contamination and Toxicology 47, 396-401.

Ryti, R., Longmire, P., Broxton, D., Reneau, S., McDonald, E., 1998. Inorganic and Radionuclide Background Date for Soils, Canyon Sediments, and Bandelier Tuff at Los Alamos National Laboratory. Los Alamos National Laboratory Report, LA-UR-98-4847.

Saab, V., Powell, H., Kotliar, N., Newlon, K., 2005. Fire and avian ecology in North America. Studies in avian biology 30, 76-96.

Sabrosky, C., Bennett, G., Whitworth, T., 1989. Bird blowflies (*Protocalliphora*) in North America (Diptera: Calliphoridae) with notes on the Palearctic species. Smithsonian Institution Press, Washington, DC.

Sagerup, K., Henriksen, E., Skorping, A., Skaare, J., Gabrielsen, G.W., 2000. Intensity of parasitic nematodes increases with organochlorine levels in the Glaucous Gull. Journal of Applied Ecology 37, 532-539.

SAS Institute, 1987. SAS/STAT Guide for Personal Computers. SAS Institute, Cary, North Carolina.

Scheuhammer, A., 1996. Influence of reduced dietary calcium on the accumulation and effects of lead, cadmium, and aluminum in birds. Environmental Pollution 94, 337-343.

Scheuhammer, A., 1987. The chronic toxicity of aluminum, cadmium, mercury, and lead in birds: a review. Environmental Pollution 46, 263-295.

Seaman, D., Millspaugh, J., Kernohan, B., Brundige, G., Raedeke, K.J., Gitzen, R.A., 1999. Effects of sample size on kernel home range estimates. Journal of Wildlife Management 63, 739-747.

Steidl, R., Curtice, G., Lawrence, N., Clark, K., 1991. Reproductive success and eggshell thinning of a re-established Peregrine Falcon population. Journal of Wildlife Management 55, 294-299.

Swaddle, J., Witter, M., 1994. Food, feathers and fluctuating asymmetries. Proceedings of the Royal Society of London 255, 147-152.

Western Regional Climate Center (WRCC). 2006. Western U.S. climate historical summaries: Los Alamos monthly precipitation. Available at Internet website: http://www.wrcc.dri.edu/.

Wittman, K., Beason, R., 1992. The effect of blowfly parasitism on nestling Eastern Bluebird development. Journal of Field Ornithology 63, 286-293.

Woinarski, J., Recher, H., 1997. Impact and response: A review of the effects of fire on Australian avifauna. Pacific Conservation Biology 3, 183-205.

Wolters, V., 2001. Biodiversity of soil animals and its function. European Journal of Soil Biology 37, 221–227.

Yeung and Ruzzo. 2001. Principal component analysis for clustering gene expression data. Bioinformatics 17, 763-774.

Yla¨ -Mononen, L., Salminen, P., Wuorenrinne, H., Tulisalo, E., Nuorteva, P., 1989. Levels of Fe, Al, Zn and Cd in *Formica aquilonia*, *F. polyctena* and *Myrmica ruginodis* (Hymenoptera, Formicidae) collected in the vicinity of spruces showing different degrees of needle-loss. Annales Entomologici Fennici 55, 57–61.

APPENDICES

APPENDIX A

Geometric means and range of heavy metal analytes (µg/kg) in egg (N=32) and prey (N=14) samples in 2005 at Los Alamos National Laboratory, New Mexico.

Analyte	Eggs		Prey	
	Mean	Range	Mean	Range
Aluminum	6299	5000-360000	86782	4800-250000
Antimony	16	15-48	40	14-230
Arsenic	101	100-480	308	95-1400
Barium	1653	590-6400	8370	1200-120000
Beryllium	54	50-140	108	48-720
Cadmium	19	15-2500	152	15-720
Calcium	1125164	330000-5300000	3164724	730000-33000000
Chromium	279	250-710	556	240-3600
Cobalt	107	100-280	209	95-1400
Copper	663	350-23000	19840	850-93000
Iron	36572	16000-650000	179046	13000-400000
Lead	35	25-1600	342	24-1800
Magnesium	103922	60000-1400000	781814	65000-2800000
Manganese	744	250-51000	26875	380-100000
Mercury	12	10-20	23	22-24
Nickel	283	250-1700	545	240-3600
Potassium	1347699	1000000-4500000	3314812	1200000-9700000
Selenium	424	120-850	227	130-1100
Silver	5	5-46	36	5-250
Sodium	1485691	500000-2200000	1054297	550000-1900000
Thallium	11	10-28	26	10-140
Vanadium	268	250-710	459	240-3600
Zinc	14641	7600-110000	85179	8600-210000

APPENDIX B

Heavy metals in egg content samples from Los Alamos National Laboratory, New Mexico, collected in 2004 and 2005.

B.1 Eggshell thickness as function of egg contaminants N=29.

Metals	R2	Slope	Lower CI	Upper CI
Al	0.6290	0.0262	0.0182	0.0341
Sb	0.5332	0.0848	0.0535	0.1161
As	0.0970	0.0447	-0.0092	0.0986
Ba	0.0562	0.0107	-0.0066	0.0280
Be	0.6096	0.0817	0.0558	0.1075
Cd	0.6390	0.0245	0.0172	0.0318
Ca	0.0023	0.0018	-0.0132	0.0169
Cr	0.5484	0.0774	0.0497	0.1051
Co	0.5323	0.0925	0.0583	0.1268
Cu	0.3980	0.0215	0.0110	0.0319
Fe	0.5250	0.0318	0.0198	0.0437
Pb	0.3803	0.0177	0.0088	0.0266
Mg	0.5693	0.0325	0.0214	0.0437
Mn	0.4954	0.0185	0.0111	0.0259
**Hg	0.1236	0.0107	-0.0044	0.0257
Ni	0.3726	0.0454	0.0221	0.0686
K	0.3922	0.0620	0.0315	0.0925
Se	0.5769	-0.0686	-0.0918	-0.0454
Ag	0.3953	0.0203	0.0104	0.0302
Na	0.3276	-0.0001	-0.0002	-0.0001
Tl	0.5179	0.0054	0.0034	0.0075
V	0.5719	0.0881	0.0580	0.1181
Zn	0.3726	0.0330	0.0161	0.0499
Prin1	0.0002	0.0000	0.0000	0.0000

**N = 18

Heavy metals in prey samples from Los Alamos National Laboratory, New Mexico, collected in 2004 and 2005.

B.2 Prey contaminants and nestling mortality N=12.

Metals	R2	Slope	Lower CI	Upper CI
Al	0.0152	0.0008	-0.0031	0.0046
Sb	0.2773	0.6100	-0.0094	1.2293
As	0.1949	0.4722	-0.1314	1.0758
Ba	0.0036	-0.0451	-0.5167	0.4265
Be	0.4200	0.7800	0.0353	1.1979
Cd	0.0031	-0.0406	-0.4998	0.4185
Ca	0.0647	-0.0001	-0.0004	0.0002
Cr	0.3574	0.6811	0.1067	1.25539
Co	0.3307	0.6234	0.0656	1.1811
Cu	0.0074	0.0523	-0.3299	0.4346
Fe	0.0730	0.0015	-0.0018	0.0047
Pb	0.0003	0.0113	-0.4254	0.4480
Mg	0.0010	0.0001	-0.0014	0.0016
Mn	0.0055	-0.0008	-0.0072	0.0057
**Hg	0.8144	0.0810	-0.4105	0.5725
Ni	0.3830	0.6835	0.1379	1.2290
K	0.0238	0.0002	-0.0006	0.0010
Se	0.8300	1.3996	0.9572	1.8420
Ag	0.0424	0.1389	-0.2764	0.5542
Na	0.0536	0.0010	-0.0016	0.0036
Tl	0.3070	0.5954	0.0328	1.1580
V	0.5400	0.9500	0.1242	1.2783
Zn	0.0002	-0.0122	-0.5818	0.5574
Prin1	0.0738	0.0000	0.0000	0.0000

**N = 3

Heavy metals in prey samples from Los Alamos National Laboratory, New Mexico, collected in 2004 and 2005.

B.3 Prey contaminants and tarsus N=9.

Metals	R2	Slope	Lower CI	Upper CI
Al	0.0609	-0.0001	-0.0004	0.0002
Sb	0.0053	-0.0034	-0.0453	0.0384
As	0.0259	0.0088	-0.0393	0.0568
Ba	0.0518	-0.0076	-0.0366	0.0214
Be	0.0051	0.0029	-0.0334	0.0392
Cd	0.0017	-0.0017	-0.0376	0.0342
Ca	0.0000	0.0000	0.0000	0.0000
Cr	0.0193	-0.0059	-0.0433	0.0316
Co	0.0243	-0.0061	-0.0410	0.0287
Cu	0.1212	0.0220	-0.0309	0.0749
Fe	0.0115	0.0000	-0.0003	0.0003
Pb	0.0120	-0.0059	-0.0535	0.0418
Mg	0.0398	0.0000	-0.0001	0.0002
Mn	0.2786	-0.0004	-0.0009	0.0002
**Hg	0.7975	0.2991	-1.6161	2.2143
Ni	0.0204	-0.0058	-0.0416	0.0301
K	0.0220	0.0000	0.0000	0.0001
Se	0.0030	0.0027	-0.0421	0.0476
Ag	0.0076	0.0027	-0.0246	0.0299
Na	0.0654	0.0001	-0.0001	0.0002
Tl	0.0253	-0.0062	-0.0404	0.0280
V	0.0164	-0.0056	-0.0443	0.0331
Zn	0.0044	-0.0101	-0.1451	0.1250
Prin1	0.0023	0.0000	0.0000	0.0000

**N = 3

Heavy metals in prey samples from Los Alamos National Laboratory, New Mexico, collected in 2004 and 2005.

B.4 Prey contaminants and wing N=9.

Metals	R2	Slope	Lower CI	Upper CI
Al	0.0071	0.0000	-0.0001	0.0001
Sb	0.0179	0.0017	-0.0094	0.0127
As	0.0069	-0.0012	-0.0141	0.0117
Ba	0.1016	0.0028	-0.0047	0.0104
Be	0.0541	0.0025	-0.0069	0.0120
Cd	0.1151	0.0036	-0.0054	0.0126
Ca	0.0038	0.0000	0.0000	0.0000
Cr	0.0051	0.0008	-0.0092	0.0109
Co	0.0288	0.0018	-0.0075	0.0110
Cu	0.0264	0.0027	-0.0121	0.0176
Fe	0.0193	0.0000	-0.0001	0.0001
Pb	0.2431	0.0070	-0.0041	0.0182
Mg	0.1476	0.0000	0.0000	0.0000
Mn	0.0508	0.0000	-0.0001	0.0002
**Hg	0.8144	0.0810	-0.4105	0.5725
Ni	0.0154	0.0013	-0.0082	0.0109
K	0.0970	0.0000	0.0000	0.0000
Se	0.0007	-0.0004	-0.0123	0.0116
Ag	0.0079	-0.0007	-0.0080	0.0065
Na	0.2576	0.0000	0.0000	0.0001
Tl	0.0328	0.0019	-0.0072	0.0109
V	0.0013	0.0004	-0.0100	0.0108
Zn	0.2194	0.0189	-0.0130	0.0508
Prin1	0.0042	0.0000	0.0000	0.0000

**N = 3

APPENDIX C

Steps to calculating Akaike's Information Criterion using the program SAS (Statistical Analysis Software).

1) Find residual sum of squares (or deviance in SAS output) and divide by the # of observations (n) to equal σ2:

$$\sigma^2 = \frac{\text{deviance}}{n}$$

n = sample observations of dependent variable

p = # of individual variables

k = p + 2

2) Using the above σ2, construct loge(£):

$$\ln(£) = -(n/2) * \ln(\sigma 2)$$

3) Find AIC:

$$\begin{aligned} AIC &= -2*\ln(£) + 2K \\ &= -2*[-(n/2) * \ln(\sigma^2)] + 2K \end{aligned}$$

5) Find AIC_C:

$$\begin{aligned} AICc &= -2*\ln(£) + 2K + \frac{(2K*(K+1))}{n - K - 1} \\ &= AICmodel_X + \frac{(2K*(K+1))}{n - K - 1} \\ &= \frac{n}{\hat{c}} *\ln(\sigma 2) + 2K + \frac{(2K*(K+1))}{n - K - 1} \end{aligned}$$

$$W_i = \frac{\exp(-\Delta i/2)}{\Sigma(\exp(-\Delta i/2))}$$

where:

W_i = weight of each model

Δ i = the difference between model *i* and the model with the lowest AIC or AICc value

APPENDIX D

Principle component factor scores from egg (N=32) and prey (N=14) samples collected at Los Alamos National Laboratory, New Mexico, in 2004 and 2005.

Analyte	Egg PCA	Prey PCA
Aluminum	0.2303	0.1854
Antimony	0.2543	0.2896
Arsenic	0.1174	0.2275
Barium	0.1820	0.1030
Beryllium	0.2598	0.2770
Cadmium	0.2001	0.0995
Calcium	-0.0414	0.0514
Chromium	0.2072	0.2834
Cobalt	0.2578	0.2819
Copper	0.2343	0.2518
Iron	0.2273	0.2042
Lead	0.1252	0.1436
Magnesium	0.2591	0.1324
Manganese	0.2607	0.1429
Nickel	0.0950	0.2829
Potassium	0.2351	0.0434
Selenium	-0.1435	0.2588
Silver	0.2378	0.2382
Sodium	-0.1496	-0.0422
Thallium	0.2577	0.2812
Vanadium	0.2618	0.2852
Zinc	0.2463	0.1969