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Patterns of bird species abundance in relation to granular insecticide use in the Canadian prairies[1]

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Abstract: We examined the possibility that granular insecticides, used intensively in the Canadian prairies to control flea beetles (*Phyllotreta* sp.) in canola (*Brassica napus* and *B. napa*), could contribute to bird population declines. A retrospective analysis (1971-96) was done to investigate relationships between counts of 29 bird species made on Breeding Bird Survey (BBS) routes with a spatially explicit granular use index (derived from surveys made in 1980-85) and an index of land use change (derived from Principal Components Analysis of agricultural statistics) for 30 Census Agricultural Regions (CARs). Controlling for spatial location and the land use change index, abundance of American robin (*Turdus migratorius*), horned lark (*Eremophila alpestris*), house sparrow (*Passer domesticus*), mourning dove (*Zenaida macroura*), and western meadowlark (*Sturnella neglecta*) was negatively correlated with insecticide use; only two species showed evidence of a positive correlation. At a shorter time scale, for which we had direct estimates of pesticide use (1980-85), we also found evidence that the black-billed magpie (*Pica pica*), European starling (*Sturnus vulgaris*), and killdeer (*Charadrius vociferus*) were less abundant in areas where granular insecticide use was high. Population trends (% annual change between 1971-96) were negatively correlated with the granular index for horned lark, house sparrow, and western meadowlark. Although correlational only, our results suggest that granular insecticides may be an important factor influencing population changes in some bird species in prairie farmland.

Keywords: agricultural land use change, carbofuran, farmland bird populations, granulars, insecticide use, spatial analysis, terbufos.

Résumé : Nous avons cherché à savoir si les insecticides, lorsque utilisés sous forme granulaire et de façon intensive pour contrôler l'altise (*Phyllotreta* sp.) dans le colza (*Brassica napus* et *B. napa*), jouent un rôle dans le déclin des populations d'oiseaux des prairies canadiennes. Une analyse rétrospective, couvrant les années 1971 à 1996, a été effectuée afin de vérifier les relations qui existent entre les dénombrements de 29 espèces d'oiseaux obtenus lors de recensements d'oiseaux nicheurs (Breeding Bird Survey), un indice d'utilisation spatiale des insecticides granulaires (basé sur des relevés effectués de 1980 à 1985), ainsi qu'un indice de changement dans l'utilisation des terres (basé sur l'analyse des composantes principales de statistiques agricoles) pour 30 régions de recensement agricole. Tout en prenant en considération la répartition spatiale et l'indice de changement dans l'utilisation des terres, l'abondance du merle d'Amérique (*Turdus migratorius*), de l'alouette hausse-col (*Eremophila alpestris*), du moineau domestique (*Passer domesticus*), de la tourterelle triste (*Zenaida macroura*) et de la sturnelle de l'Ouest (*Sturnella neglecta*) est corrélée de façon négative avec l'utilisation des insecticides. Deux espèces ont par contre montré une corrélation positive. À une échelle de temps plus restreinte (1980-1985) pour laquelle l'utilisation des insecticides granulaires est mieux connue, la pie bavarde (*Pica pica*), l'étourneau sansonnet (*Sturnus vulgaris*) et le pluvier kildir (*Charadrius vociferus*) étaient moins nombreux dans les zones avec forte utilisation d'insecticides. De plus, les tendances démographiques chez les oiseaux (pourcentage des changements annuels entre 1971 et 1996) sont corrélées de façon négative avec l'indice d'utilisation d'insecticides granulaires pour l'alouette hausse-col, le moineau domestique et la sturnelle de l'Ouest. Bien qu'ils soient fondés uniquement sur des corrélations, les résultats indiquent que les insecticides granulaires induiraient des changements importants chez les populations de certaines espèces d'oiseaux dans les terres agricoles des prairies.

Mots-clés : analyse spatiale, carbofuran, changement d'utilisation des terres agricoles, granules, populations aviaires des terres agricoles, terbufos, utilisation d'insecticides.

Nomenclature: Mullanney *et al.*, 1999; Cornell Lab of Ornithology, 2004-2005.

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Introduction

Many grassland or farmland bird species have undergone range contractions and/or population declines in recent decades in both northern Europe and North America (Fuller *et al.,* 1995; Knopf, 1995; Siriwardena *et al.,* 1998; Peterjohn & Sauer, 1999; Dunn, Downes & Collins, 2000; Sauer *et al.,* 2000; Donald, Green & Heath, 2001). In Britain, 24 of 28 (86%) typical farmland species suffered range contractions between the late 1960s and early 1990s and populations of 15 out of 18 species decreased over the same period (Fuller *et al.,* 1995; Siriwardena *et al.,* 1998). Most notable are dramatic (and ongoing) declines in previously abundant birds such as the Eurasian skylark (*Alauda arvensis*), yellowhammer (*Emberiza citrinella*), and tree sparrow (*Passer montanus*). Similarly, recent analyses of the North American Breeding Bird Survey (BBS), a continent-wide roadside count used to monitor land birds, demonstrate that grassland birds are declining at a greater rate than birds of any other biome (Sauer *et al.,* 2000; Murphy, 2003); in Canada, 16 of 21 (76%) grassland bird species declined between 1969 and 1998 (Dunn, 1998).

A key uncertainty is what factors are causing changes in bird populations in agricultural landscapes. Over the last 50 y, the shift from heterogeneous farming with mixed arable crops and livestock to increasingly specialized homogeneous farming either for row and field crops on the one hand or intensive livestock production and associated forage grasses on the other has significantly altered landscape patterns of different agricultural habitats (McLaughlin & Mineau, 1995; Rodenhouse *et al.,* 1995; Chamberlain *et al.,* 2001; Robinson, Wilson & Crick, 2001; Murphy, 2003). At the same time, there have been increases in the intensity of pesticide and fertilizer use on cropped land.

As one component of agricultural intensification, herbicides and insecticides have been linked to population declines in some bird species in the United Kingdom, primarily via indirect, food-mediated effects (Campbell *et al.,* 1997; Potts, 1997). In countries where products most toxic to birds have not been as severely restricted (*e.g.,* the United States and Canada; Mineau *et al.,* 1999; Mineau, 2004), the cholinesterase-inhibiting carbamate and organophosphorus compounds have been a focus of concern because of their high toxicity. It has long been known that these acutely toxic insecticides, especially their granular formulations, can kill thousands of birds at a time (Mineau, 1993; US EPA, 1998) when the granules are mistaken for grit or food (Best & Gionfriddo, 1991; Best & Fischer, 1992; Best & Gionfriddo, 1994). Based on intensive field studies and extrapolations from use data, it has been conservatively estimated that a sand-based formulation of carbofuran, at the peak of its popularity in the early 1980s, was killing between 17 and 91 million songbirds annually in the US cornbelt alone (Mineau, in press). In Canada, the Pest Management Regulatory Agency (PMRA) conservatively estimated that between 109,000 and 958,000 birds were being killed annually by a corncob-based carbofuran formulation mixed with canola (oilseed rape) seed at planting (Segstro, 1998). Here, we ask whether granular insecticide use in canola could contribute to bird population decreases at the scale of the Canadian prairie region.

About two-thirds (62%) of all farmland in Canada is in the Prairie ecozone, and almost 93% of this 465,090 km^2 region is agricultural land (McRae, Smith & Gregorich, 2000). Until recently, government incentives encouraged the ploughing of native prairie and replacement by grain crops or introduced crested wheat grass (*Agropyrum cristatum*) (Houston & Schmutz, 1999). Other recent changes (post 1981) include a 3% expansion of total farmland and reductions in summer fallow as farmers have shifted to permanent cover and continuous cropping/no-till to prevent soil erosion (McRae, Smith & Gregorich, 2000). One striking change in cropping patterns in the prairies over the last 40 y has been the dramatic increase in canola (oilseed rape, *Brassica napus* and *B. napa,* for edible oil production) acreage (5.7% of the farmed area in 1971 to 10.2% in 1996; Statistics Canada, 1961-1996). Flea beetles (*Phyllotreta* sp.) are a major pest in canola, and lindane (used as a seed treatment) and two other insecticides, carbofuran (Furadan™, FMC Corporation, Philadelphia, Pennsylvania, USA) and terbufos (Counter™, BASF Canada Inc., Toronto, Ontario, Canada), applied as corncob granular formulations have been widely used for their control. First registered in Canada in 1969, carbofuran became increasingly popular with farmers because of its effectiveness and economical price. However, its use declined in the early 1990s and was prohibited beyond the 1999 growing season (A. Rock, pers. comm.); the terbufos granular product is to be phased out after 2004 (PMRA, 2003). Both carbofuran and terbufos are acutely toxic to birds: a 5% carbofuran granule can kill a house sparrow (scientific names of species not mentioned in the text are in Appendix I) within a few minutes, and the probability of surviving the ingestion of one terbufos granule is about 50% (P. Mineau, unpubl. data). These insecticides are applied prophylactically at seeding in areas where flea beetle "pressure" is typically high. Their application (mid/late May to early June) coincides with the intensive use of canola fields by large numbers of northward-bound migratory songbirds, shorebirds, and geese; in addition, many nesting resident species are on territory at this time. Because flea beetle pressure is geographically predictable in the prairie region (provinces of Manitoba, Saskatchewan, and Alberta), the relative spatial pattern of granular application has remained relatively stable over the years even though infestation severity fluctuates annually. In this paper, we test whether an index of granular insecticide use within 30 census agricultural regions influenced 1) differences in route-level abundance of individual species and 2) bird population trends for individual species derived from the Breeding Bird Survey (BBS).

Methods

STUDY SITES

We used three main sources of information for our analyses: 1) The BBS, a continent-wide breeding season count conducted by approximately 300 volunteer observers in Canada and used to monitor land birds since

1967. Birds are counted at 50 stops at 0.8 km intervals for a 3-min duration along 39.4 km sections of secondary roads (Dunn, Downes & Collins, 2000). 2) A report on the use of pesticides in wheat, barley, and canola in Canada (Madder & Stemeroff, 1986), as well as expert opinion (I. Wise, Agriculture and Agri-Foods Canada, pers. comm.) on past and current areas of flea beetle infestation. 3) The quinquennial Census of Agriculture statistics collected by Statistics Canada from 1961 to 1996 (Statistics Canada, 1961-1996). Until 1981, Statistics Canada reported agricultural statistics by Census Division. In 1986, a new unit was introduced, the census agricultural region (CAR) (Figure 1). This was the geographical reporting system used by Madder and Stemeroff (1986) in their evaluation of granular insecticide use. For many provinces, census divisions were simply amalgamated to form CARs. However, this was not the case for Saskatchewan, where new boundaries for CARs were developed, making it impossible to derive accurate trends from published reports. Therefore, we custom-ordered statistics from Statistics Canada recompiled by CAR for the years 1971-1996. Because of other changes in census division boundaries in the 1961 and 1966 surveys (B. Houle, Statistics Canada, pers. comm.), these years were dropped from the analysis.

CANDIDATE BIRD SPECIES

Our goal was to include a range of bird species typical of prairie farmland. We therefore included 19 of the 48 species recorded in canola fields in Saskatchewan by Martin, Arnold & Forsyth (2005) based on the following criteria: 1) the species typically breeds in prairie farmland; 2) it uses the interior or at least perimeter of canola or other crop fields where it could be exposed to granular insecticides (Best, Whitmore & Booth, 1990); and 3) it has a granivorous or omnivorous diet and thus is more likely to ingest granular insecticides as grit or food (Best & Gionfriddo, 1991) or is carnivorous and potentially susceptible to secondary poisoning (*e.g.,* raptors, shrikes). We added 10 more species to the list because we considered it possible that they use canola fields also despite a lack of quantifiable data (K. E. Lindsay & D. A. Kirk, unpubl. data). Some are characteristic of hayfields or shrubby fields rather than of row or field crops (*e.g.,* Le Conte's sparrow) but may use cropland for foraging. Others are grassland specialists (*e.g.,* Baird's sparrow, bobolink) but may likewise forage in treated fields in an agricultural cropland/grassland mosaic (see Herkert, 1997; Davis, Duncan & Skeel, 1999). We included several species considered commensal with humans (*e.g.,* house sparrow and European starling) because many of these are also showing long-term population declines according to the BBS (Dunn, Downes & Collins, 2000) and they serve as indicators of agricultural change. Also, some of the species were included because they have been killed by granular carbofuran formulations in the past, some in the area under study (*e.g.,* chipping sparrow, American goldfinch). The 29 species selected are listed in Appendix I.

Although we used spatial pattern analyses to account for variations in abundance throughout a species' range, the species selected overlapped broadly with the prairie region. Note that some BBS routes are north of the canola cropping districts, which are mainly in the Parkland ecoregion, and these routes are therefore beyond the extent of granular use; most would be discarded by default from analyses because the typically open country species analyzed do not occur there.

BREEDING BIRD SURVEY (BBS) DATA

We extracted BBS data from the database maintained by the Canadian Wildlife Service (CWS) for the period 1971-1996 (to match the period over which agricultural statistics were available). We then superimposed the electronically digitized BBS route locations onto a map of CARs using ArcView software (Version 3.2; ESRI, 1999). Some routes crossed CAR boundaries; where 60% or more of a route (30 stops) was located in one CAR, it was allocated to that CAR. Note that we did this because the granular use index and the agricultural variables were collected at the CAR level and we therefore needed to assign BBS routes to CARs. We omitted routes that were divided equally between CARs (five routes in Alberta, five in Manitoba, and 13 in Saskatchewan). In total, 127 routes were available for analysis in Alberta, 63 in Saskatchewan, and 50 in Manitoba. Not all of these routes were run in each year; however, year was controlled for as a variable in statistical analyses. Mean densities ± SD of BBS routes per CAR were highest in Alberta (4.0 ± 0.6 routes$\cdot$10,000 km^{-2}), followed by Manitoba (3.3 ± 0.4 routes$\cdot$10,000 km^{-2}) and Saskatchewan (2.5 ± 0.3 routes$\cdot$10,000 km^{-2}).

To avoid pseudoreplication of agricultural variables (treating each BBS route separately would result in each route within a CAR being allocated the same agricultural data leading to statistical pseudoreplication) and spatial auto-correlation problems (BBS routes clustered within CARs are not independent), we took the total count made on all routes within a CAR (sum of all stops on all routes), and divided by the number of BBS routes within a CAR$\cdot$y^{-1}. Using a mean count for each species from all

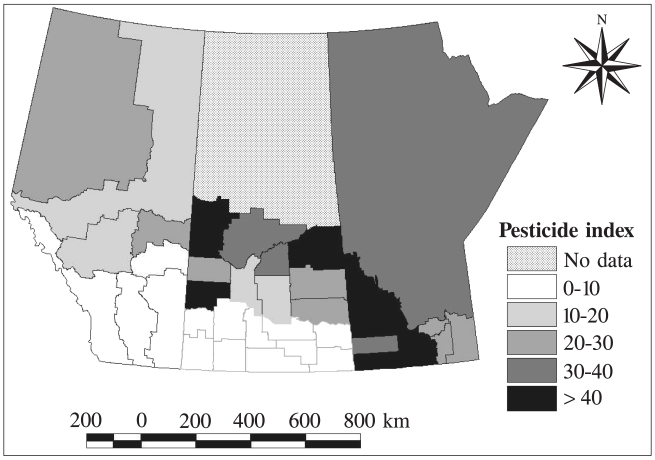

FIGURE 1. Map of the prairie region showing spatially explicit data on granular insecticide use. Note that small area units are Census Agricultural Regions (CARs) of Statistics Canada. The granular insecticide index is the proportion of cropland treated multiplied by 1,000.

routes in a CAR avoids issues involved with spatial scale (*i.e.,* independent variables measured at a spatial scale different than that of the dependent variable).

DERIVATION OF GRANULAR INSECTICIDE INDEX

Unfortunately, analyses of the type presented here are hampered by the fact that pesticide use or sale information is not routinely collected in Canada. However, we were fortunate in that geographically explicit data on insecticide use in canola were collected for each year between 1980 and 1985 as part of a study sponsored by the Canadian Entomological Society (Madder & Stemeroff, 1986). To calculate the area treated with granular products, we took the acreage of canola treated for flea beetle control in each CAR between 1980 and 1985 multiplied by the proportional market share of granular insecticides (Madder & Stemeroff, 1986). Because we decided that the index should be a function of the probability that a bird would land in a treated field, our final index of granular use was the estimated canola acreage treated with granular insecticides as a proportion of the total land in crop. Clearly, the degree to which birds use habitat other than cropland varies by species, so this will influence the assumption that the probability of birds being killed increases in direct proportion to the area treated; strictly it applies only to species that use cropland (see Discussion).

Total land in crop was obtained from the quinquennial Agricultural Censuses for each CAR (Statistics Canada, 1961-1996); because data were available only for 5-y intervals we interpolated data for the interim periods (see below). We used CARs defined by Statistics Canada, except for some modifications made by Madder and Stemeroff (1986). For example, when reporting on the chemicals used on flea beetle infestations in Saskatchewan, CARs 1A-4B were combined into one regional unit by these authors. To avoid pseudoreplication of the granular index in these CARs, we combined them into one "super-CAR" in our analyses (the numerous white sub-regions located in the southern part of Saskatchewan in Figure 1).

We made the critical assumption that relative granular use among CARs calculated for 1980-85 by Madder and Stemeroff (1986) was reflective of the entire period (1971-96) over which BBS and other agricultural data were collated. We believe this assumption is justified for two reasons: 1) flea beetle infestations are geographically predictable; some areas always tend to have a high risk of infestation whereas others do not (Madder & Stemeroff, 1986). This geographical stability was confirmed when a canola pest expert (I. Wise, Agriculture and Agri-Foods Canada, pers. comm.) identified CARs most in need of treatment currently. 2) The prophylactic nature of the treatment contributes to the inter-annual stability in the proportion of the crop that is treated. However, we also re-ran our abundance analyses for the shorter time period (1980-85) for which we had specific granular insecticide use data.

OTHER AGRICULTURAL VARIABLES

To consider the potential influence of other agricultural factors on bird populations, we collated data on total acreage and the proportion of affected farmland for the following variables: canola, total cropland, summer fallow, improved pasture, unimproved pasture, and land sprayed with herbicides (Table I). Increases in land in crop in the prairies (and consequently declines in extent of pasture and native grassland) have been linked to population declines in several grassland bird species (Herkert & Knopf, 1998; Murphy, 2003). Data from the Census of Agriculture were only available quinquennially. Simple interpolation was used to derive data between the 5-y intervals. A regression of agricultural variables against year (1971-1996) did indeed show that linear interpolation was adequate because most variables increased or decreased in a roughly monotonic fashion over time. Interpolation error was probably highest for canola acreage, which increased in many CARs in Saskatchewan and Alberta (but not Manitoba) in 1971 and then decreased sharply in 1976 before increasing again; this may possibly be linked to increases in the price of cereal crops in the 1970s. These interpolations provided estimated annual agricultural statistics for 1971-96 that could be matched directly with BBS bird data.

SPATIAL AND TEMPORAL COMPONENTS

Because of the large spatial extent of the study area, our primary sampling units (CARs) were located in different ecozones. Given that the abundance of many of the surveyed species differed naturally among these ecozones, we needed to control for spatial patterns of abundance before assessing the importance of the granular pesticide index, as is standard in large, regional scale analyses (see Odland, 1988; Borcard, Legendre & Drapeau, 1992; Lichstein *et al.,* 2002; Franken *et al.,* 2003). For example, areas of high granular use may coincide with a region where a species is rare (edge of range, and therefore perhaps more vulnerable to stochastic events) or where it is declining because of other limiting factors.

We corrected for spatial patterns in abundance by generating a third-order spatial map (trend surface) for the data (Legendre & Legendre, 1998). We determined the centroids of each CAR using ArcView, standardized these latitude and longitude coordinates, and then, to account for differences in each species' range, calculated a complex trend surface (longitude^2, longitude^3, latitude^2, latitude^3, longitude × latitude, longitude^2 × latitude, latitude^2 × longitude; Legendre & Legendre, 1998). The latter variables were incorporated in backwards selection

TABLE I. Loadings of agricultural variables on first four PCA components.

	PC1	PC2	PC3	PC4
Canola (ha)	0.20	0.44	0.02	-0.24
% Canola	-0.05	0.44	0.11	-0.28
Land in crop (ha)	0.37	0.29	-0.18	-0.12
% Land in crop	-0.27	0.38	-0.08	-0.26
Fallow (ha)	0.36	0.04	-0.46	0.11
% Fallow	0.10	-0.07	-0.57	0.19
Improved pasture (ha)	0.48	0.09	0.10	-0.09
% Improved pasture	0.26	-0.03	0.45	-0.17
Unimproved pasture (ha)	0.49	-0.04	0.05	0.05
% Unimproved pasture	0.22	-0.32	0.37	0.13
Land sprayed with herbicides (ha)	0.03	0.36	0.15	0.61
% Land sprayed with herbicides	-0.07	0.38	0.18	0.55

models to control for large-scale spatial patterns in the data independent of the pesticide index and spatial distribution of different agricultural activities (see discussion of individual species models below).

STATISTICAL ANALYSES

Because many of the agricultural variables used in modeling were highly correlated (especially data based on proportions), and because we wanted to reduce their dimensionality, we used principal components analysis (PCA) based on the correlation matrix to derive four orthogonal axes. We included both proportions and absolute acreages because CARs differed substantially in size and thus a high proportion of farmland in canola in a small CAR may actually be a much smaller acreage than a small proportion of farmland in canola in a large CAR. The risk of exposure to granules for birds is therefore a function of both the total acreage and the proportion of farmland in canola. We chose the first four factors because all had eigenvalues greater than one; we used these PCA factors as indices of agricultural change in all subsequent analyses.

WHICH INDIVIDUAL SPECIES SHOW ASSOCIATIONS (ABUNDANCE OR TRENDS) WITH GRANULAR USE?

For each species, we constructed two types of models: 1) we modeled the abundance in relation to the granular index and controlled for the agricultural change index and spatial location using cross-sectional time series analyses; 2) we also modeled % annual change in abundance of species over the period 1971-96 and regressed this on the granular index while controlling for the agricultural change index and spatial location. The abundance analyses were also run on the shorter-term data set (1980-85) for which we had specific granular insecticide information. We considered this time interval too short to run trend analyses.

Cross-sectional time-series (hereafter longitudinal) models are of the form x_{it} where x_{it} is a vector of observations for each unit i in time t (Cameron & Trivedi, 1998). In these analyses, temporal variation was not a variable of direct interest necessarily, but rather we used it as a sub-sample from the primary sampling unit for which the dependent and independent variables vary over time. This approach resembles a repeated-measures analysis of variance except that multiple observations through time of the same primary sampling unit are corrected for rather than being a variable of primary interest.

To determine whether regional distributions of birds influenced the relationship between bird abundance and the granular index, for each species we included a third-order trend surface when building models. We used a backwards selection procedure with $P > 0.1$ as the removal criterion to discard trend surface parameters that were not significant and thereby to reduce the complexity of the trend surface (Legendre & Legendre, 1998). To perform the most conservative analysis, the spatial pattern in the data was modeled first with backwards removal of trend surface variables (Model 1). PC factors were then reduced by a second backwards removal process, retaining the spatial terms selected previously (Model 2) and without the index in the model. The final model (model 3) included the reduced forms of the trend surface, PC factors, and the granular index. To determine which of the models provided the most parsimonious explanation for the data, we used Akaike's Information Criterion (AIC) as a means of comparing model fit (Anderson, Burnham & Thompson, 2000; Burnham & Anderson, 2000). AIC selects models based on the principle of parsimony incorporating the log-likelihood with a penalty for added parameters (Anderson, Burnham & Thompson, 2000). Models using the fewest parameters to explain the greatest amount of variation in the data are considered to provide the best fit to that data. If the model with the lowest AIC contained the granular index and had an AIC score > two units from a model that did not contain the index, we considered that there was support for a correlation between granular use and bird abundance.

Histograms of bird abundance suggested mean abundance per year per route was not normally distributed, being skewed towards lower values. Given the discrete nature of bird abundance and the skewed distribution, we chose to model those data using a negative binomial distribution. We used a negative binomial rather than a Poisson model because the variance in the count data was often higher than the mean, suggesting overdispersion in the data (*i.e.*, heterogeneous variance). As our dependent variable was the mean number of individuals of each species detected per route per CAR, we rounded the data to the nearest whole number to allow the assumptions of count-based models to be met.

We performed trend analyses for each species within each CAR separately using a C-plus program (BBSANLYS) specifically designed to analyze BBS data (Collins, 1997); BBSANLYS follows the "estimating equations" approach described by Link and Sauer (1994). Two weighting factors were used in the analysis: 1) population represented and 2) slope precision. The population represented factor is a product of two sub-factors: a) area weight and b) local population level. The area weight is the inverse of the number of routes in a degree block (to produce an average estimate of trends for the CAR), while the population weight is the average count of birds along the route. The slope precision weight accounts for the number of observations used to estimate the population trend for the route, as well as the number of observers and years in which the route was run. These two weighting factors are averaged to produce an estimator with minimum mean squared error. We performed BBS trend analyses for each bird species (above) for each CAR separately. These analyses provided a regression coefficient (the percentage annual change in the population per year, trend hereafter) for each species. Not all of these routes were run in each year, and many were excluded because they violated the route selection criteria used in our BBS route regression analyses (Dunn, Downes & Collins, 2000). Also numbers of routes varied for different species because not all species were detected on all routes.

We used BBS trends derived for entire CARs rather than individual routes because trend statistics derived from individual routes within a CAR or region are not independent (*i.e.,* BBS routes from the same CAR may have been affected by other factors unique to a specific CAR). We then used standard regression models to test the relationship between BBS trends and overall mean granular pesticide index. A model that accounted for spatial patterns in bird trends was created using the same approach outlined for abundance. The fit of the spatial model (Model 1) was compared to the spatial model that included the pesticide index (Model 2) using AIC.

For data handling we used SAS software (SAS Institute, 1990). For modeling individual species we used STATA version 7.0 software (StataCorp, 1997).

Results

PCA FACTORS: LOADINGS ON ORIGINAL VARIABLES

As mentioned in the methods, we used the first four components from PCA as a measure of agricultural land use change; the loadings of the different variables on PC components (all with eigenvalues of 1 or greater) are shown in Table I. Pasture (improved and unimproved) was most highly positively loaded on PC1; canola and herbicide use were most highly positively loaded on PC2; fallow was most highly negatively loaded, with pasture positively loaded on PC3; and herbicide use was most highly positively loaded on PC4.

WHICH INDIVIDUAL SPECIES SHOW ASSOCIATIONS (ABUNDANCE OR TRENDS) WITH GRANULAR USE?

The abundances of five species, the American robin, horned lark, house sparrow, mourning dove, and western meadowlark, were negatively correlated with the granular index (Table II). Support for a positive correlation between abundance and the granular index was found only for the song sparrow and Sprague's pipit (see below). Using only data from 1980-85, for which we had direct estimates of insecticide use, we found that the abundances of American robin, horned lark, house sparrow, and mourning dove remained negatively correlated with the granular index (Table II). We also found the abundances of black-billed magpie, European starling, and killdeer were negatively correlated with the index during this period. The western meadowlark was the only species that had a negative relationship with the granular index across the entire time series for which such a relationship was not strongly supported using the 1980-85 data. However, the granular index coefficient remained negative for this species, regardless of which time series was examined.

Although the coefficient for species population trends and the mean granular index was negative for most species (76%), only three species showed strong negative relationships with the granular index over the entire trend series (Table III). Declines in the horned lark, house

TABLE II. Model parameters from cross-sectional time series analysis of mean species abundance in relation to granular pesticide index. ΔAIC scores for spatial location (Model 1), spatial location and PC factors (Model 2), and spatial location, PC factors, and granular index (Model 3). The coefficient is the slope of the relationship between bird abundance and the granular pesticide index for a negative binomial model. These cannot be directly interpreted as one unit change in the independent variable causing an X unit change in the dependent because they are non-linear coefficients. A species with missing values indicates the spatial location model would not converge. Bolded species show that inclusion of the granular pesticide index resulted in improved model fit during one or more time periods. Results shown in parentheses are for the period 1980-1985 only.

Species	Model 1	Model 2	Model 3	Coefficient	SE
American crow	10.2 (37.9)	1.5 (0)	0 (0.8)	-2.5 (-4.0)	1.8 (3.7)
American goldfinch	109.7 (0)	0 (0)	1.9 (2.0)	-0.8 (-0.3)	2.1 (4.5)
American robin	**182.4 (5.7)**	**4.3 (2.4)**	**0 (0)**	**-4.5 (-7.3)**	**1.8 (3.4)**
Baird's sparrow	8.5 -	0 -	2.0 -	-0.9 -	7.7 -
Black-billed magpie	13.0 **(10.0)**	0 **(2.4)**	1.7 **(0)**	-1.2 **(-9.9)**	2.2 **(4.7)**
Brown-headed cowbird	20.7 (8.9)	0 (0)	0.8 (0.4)	-2.4 (-6.8)	2.3 (5.3)
Bobolink	6.5 (3.5)	1.1 (0)	0 (0.7)	-4.4 (-14.8)	2.5 (12.5)
Brewer's blackbird	5.1 (0.2)	0 (0.2)	1.0 (0)	-2.1 (-4.7)	2.1 (4.8)
Chestnut-collared longspur	- -	- -	- -	- -	- -
Clay-coloured sparrow	14.2 (9.4)	0 (0)	0.9 (1.9)	-1.6 (-1.0)	1.5 (3.5)
Chipping sparrow	82.5 (0)	0 (0)	1.9 (0.8)	1.1 (-6.6)	3.3 (6.0)
Common grackle	1.6 (2.2)	0 (0)	1.2 (1.9)	-3.3 (-2.8)	3.6 (8.5)
European starling	23.4 **(3.7)**	0.7 **(3.0)**	0 **(0)**	-5.0 **(-14.5)**	3.1 **(6.6)**
Grasshopper sparrow	0 -	0 -	1.4 -	-5.2 -	6.8 -
Horned lark	**33.2 (2.1)**	**8.5 (2.1)**	**0 (0)**	**-9.1 (-11.6)**	**2.8 (5.8)**
House sparrow	**89.6 (11.7)**	**19.9 (3.5)**	**0 (0)**	**-13.0 (-11.0)**	**2.8 (4.9)**
Killdeer	107.8 **(23.7)**	0.4 **(5.8)**	0 **(0)**	-3.7 **(-14.2)**	2.4 **(5.1)**
Le Conte's sparrow	41.5 (7.4)	0 (0)	1.4 (1.9)	3.7 (2.9)	4.7 (1.9)
Loggerhead shrike	13.8 -	0 -	0.6 -	9.0 -	7.7 -
Mourning dove	**23.4 (3.6)**	**7.4 (2.4)**	**0 (0)**	**-6.5 (-13.5)**	**2.1 (6.4)**
Northern harrier	6.2 (0)	0 (0)	1.4 (1.4)	2.1 (-4.1)	2.8 (5.2)
Red-tailed hawk	185.5 (4.7)	0 (0)	1.6 (1.9)	2.0 (1.9)	3.2 (7.6)
Red-winged blackbird	11.4 (7.0)	1.4 (0.2)	0 (0)	-3.1 (6.5)	1.7 (4.4)
Savannah sparrow	71.6 (3.6)	0 (0)	0.8 (1.9)	2.5 (-1.6)	2.2 (4.4)
Song sparrow	**14.0** (1.7)	**7.9** (0)	**0** (1.9)	**5.2** (-0.9)	**1.6** (4.4)
Sprague's pipit	**16.6** (1.3)	**3.7** (0)	**0** (2.0)	**16.3** (1.0)	**6.8** (19.2)
Swainson's hawk	14.4 (0.3)	0 (0.1)	1.9 (0)	-1.9 (-19.7)	5.4 (14.1)
Vesper sparrow	29.8 (5.4)	0 (0)	0.3 (2.0)	2.9 (0.5)	2.2 (3.7)
Western meadowlark	**15.4** (6.4)	**2.8** (0)	**0** (1.9)	**-3.8** (-1.2)	**1.7** (5.5)

TABLE III. Model parameters from regressions of BBS trends (1971-1976) on mean granular index. Model 1 shows the ∅AIC score for the model with best-fitting trend surface, while Model 2 shows the AIC score for that trend surface and the granular index. The coefficient is the slope of the linear relationship between bird trend and the granular pesticide index. Species in bold show significant correlation (all negative) between population trend and mean granular index. Species in italics are correlated with the granular index but these relationships are driven by single outliers.

Species	Model 1	Model 2	Coefficient	SE
American crow	0	1.4	0.03	0.04
American goldfinch	1.4	0	-0.08	0.06
American robin	0	1.5	-0.03	0.05
Baird's sparrow	1.3	0	-0.39	0.23
Black-billed magpie	0	1.5	-0.09	0.14
Bobolink	1.6	0	-0.26	0.14
Brewer's blackbird	0	2	-0.01	0.05
Brown-headed cowbird	0	1.9	-0.03	0.06
Chestnut-collared longspur	0	1.8	0.14	0.42
Chipping sparrow	1.5	0	-0.27	0.14
Clay-coloured sparrow	0	2	-0.01	0.05
Common grackle	0	1	-0.12	0.14
European starling	0	1.9	0.04	0.12
Grasshopper sparrow	0	1.5	-0.19	0.3
Horned lark	**5.9**	**0**	**-0.19**	**0.07**
House sparrow	**7.9**	**0**	**-0.18**	**0.05**
Killdeer	0.4	0	-0.13	0.09
Le Conte's sparrow	0	2	-0.04	0.19
Loggerhead shrike	*6*	*0*	*0.17*	*0.08*
Mourning dove	*3.7*	*0*	*-0.1*	*0.05*
Northern harrier	0	0.7	0.11	0.1
Red-tailed hawk	0.7	0	-0.18	0.12
Red-winged blackbird	0	0.8	-0.03	0.04
Savannah sparrow	0	2	0.01	0.08
Song sparrow	0.1	0	0.17	0.12
Sprague's pipit	0.1	0	-0.38	0.38
Swainson's hawk	0	1.9	-0.32	0.22
Vesper sparrow	0.5	0	-0.18	0.11
Western meadowlark	**10.1**	**0**	**-0.17**	**0.05**

sparrow, and western meadowlark were all negatively correlated with the mean granular index (Figure 2). Population trends of loggerhead shrike and mourning dove all showed evidence of a correlation with the granular index (positive and negative, respectively). However, for these species the correlations were strongly influenced by outliers. When outliers were removed, we found little evidence to support a correlation between their population trends and the granular index.

For abundance of American robin, when both PC factors and spatial location were controlled the sign of the relationship with the granular index was reversed from models not controlling for PC factors (but still controlling for spatial effects). Including just the granular index and any one of the PC factors resulted in a positive relationship, but including PC2, PC3, and PC4 in any combination produced a negative relationship. Similarly, the relationship between Sprague's pipit abundance and the granular index was negative when just the index was included in models, but as soon as PC2 and PC3 were included in the model the sign of the relationship switched to positive. The difference in patterns for the population trend (negative relationship with granular index for Sprague's pipit) is likely due to the fact that we did not model PCA factors in that analysis.

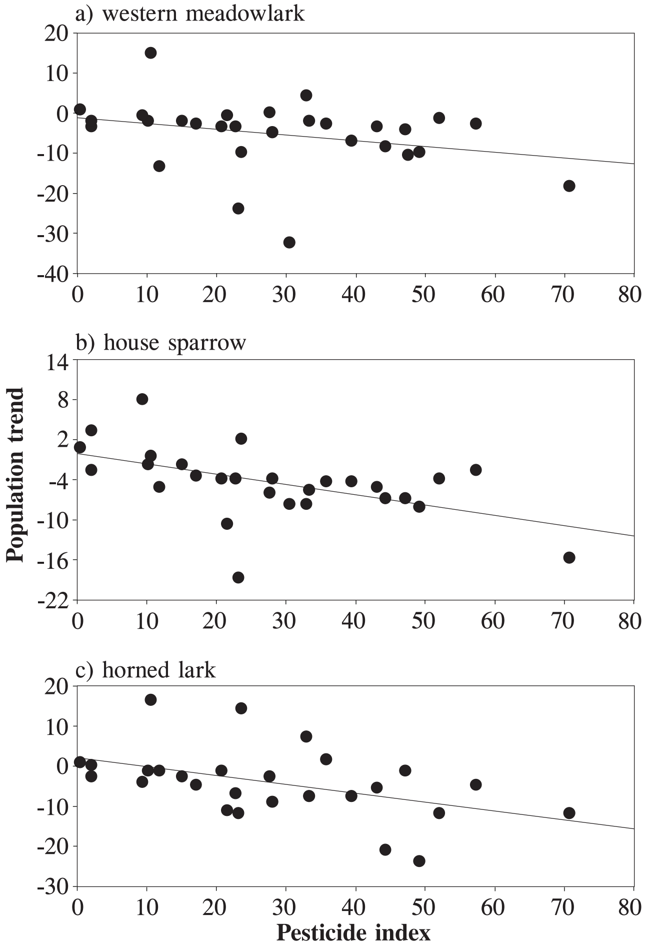

FIGURE 2. Regression models of BBS trends in three bird species in relation to granular pesticide use after controlling for spatial autocorrelation. The granular insecticide index is the proportion of cropland treated multiplied by 1,000.

Discussion

Our results suggest that the abundances of as many as nine species were negatively associated with the granular insecticide index. Only two species showed positive associations with the granular index (Sprague's pipit and song sparrow). Furthermore, a negative correlation was found between population trends in 22 of 29 species examined and the mean granular index. These trends were significant for three of the five species from the first analysis (horned lark, house sparrow, and western meadowlark), which provided corroborative evidence for the abundance relationships we examined.

Some of the species showing the strongest statistical relationships were those that make extensive use of canola fields in Saskatchewan, such as horned lark (present in 37.8-81.7% of surveyed fields; Martin, Arnold & Forsyth, 2005). Such species might be expected to be particularly susceptible to ingestion of granules. Other species, like the house sparrow, are commensal with humans, and while they were not recorded in canola fields in Saskatchewan (Martin, Arnold & Forsyth, 2005), they may be exposed to granular insecticides through accidental spillage in farmyards and along roadsides. Mortality has been recorded from at least one of the granular products in use. Surprisingly, we found no relationship between granular use and abundance for savannah or vesper sparrow despite their relative abundance in Saskatchewan canola fields (occurring at 32.3-46.7% and 18.1-26.7% of fields, respectively; Martin, Arnold & Forsyth, 2005) and their known susceptibility to granular insecticides.

We believe that some causal link between regional population declines and granular insecticide use (in concert with other factors) is plausible for at least five reasons: 1) Very large numbers of migratory and resident bird species forage in newly planted canola fields where granules are applied prophylactically at seeding (Martin, Arnold & Forsyth, 2005). Thus, the impact of seeding a field extends beyond those individuals resident in or around that field. 2) Several bird species are known to ingest granular insecticides, including the corncob formulations used in canola in the prairies (Appendix I). 3) Seed drills used for seeding canola leave many granules on the soil surface (Maze *et al.*, 1991; S. L. Tank, L. W. Brewer, J. M. Stafford, W. Erickson & L. MacDonald, unpubl. data) and spillage inevitably occurs (especially at field edges where machines turn around), sometimes doubling the amount of seed/granules available at the soil surface (de Leeuw *et al.*, 1995). 4) The kill rate will be very high for birds exposed because of the extreme toxicity of the granules (see Mineau, 1993 for carbofuran and P. Mineau, unpubl. data for terbufos). 5) The birds killed are often adults; hence, such mortality could have a direct effect on the breeding population.

According to field trials and records of incidents, at least 21 of the 29 species in this study have been poisoned in fields treated with granular carbofuran, whether the corncob-based granule used in canola, the silica-based granule used in other crops, or both (P. Mineau, unpubl. data; Appendix I). Some of the largest mortality incidents recorded have been of horned larks (800 individuals; G. M. Booth, M. W. Carter & C. D. Jorgensen, unpubl. data), savannah sparrows (500-1,000 in turnip fields in British Columbia), and Lapland longspurs; it is estimated that > 2,000 longspurs migrating through the Canadian prairies en route to the arctic breeding grounds were killed in a canola field by corncob granular carbofuran formulation (Mineau, 1993; US Environmental Protection Agency, 1998). Based on the ratio of the number of carcasses found and counts of territorial individuals, horned lark, vesper sparrow, chipping sparrow, and house sparrow were all species thought to be particularly susceptible to poisoning by carbofuran silica-based granules in crops in the United States (M. Booth, M. W. Carter, D. L. Fischer, C. D. Jorgensen, L. B. Best & R. W. Whitmore, unpubl. data). Furthermore, a recent study conducted in canola fields in Manitoba and Saskatchewan revealed carcasses of vesper, savannah, clay-coloured, and chipping sparrow as well as arctic-nesting Lapland longspur poisoned by the corncob formulation of carbofuran (P. Mineau, unpubl. data; Carbofuran Technical Review Committee, unpubl. data; S. L. Tank, L. W. Brewer, J. M. Stafford, W. Erickson & L. MacDonald, unpubl. data). No comparable studies exist of the impacts of terbufos, although we would expect similar results. Of the previously mentioned species, we found evidence to suggest the possibility of regional population-level effects in the horned lark and house sparrow.

If kills are large enough to cause population effects, then one might ask why are not more bird kills reported? The converse might also be asked: if kills reveal susceptibility to poisoning by granular insecticides (*e.g.*, vesper sparrow), then why were no population-level effects detected in such species in this study? In response to the first question, we emphasize that documenting bird kills, especially kills of small songbirds, is extremely difficult for three reasons: 1) their carcasses are extremely hard to find, and they disappear rapidly from agricultural fields (Balcomb, 1986; Mineau & Collins, 1988); 2) because granules are applied at seeding, farmers are unlikely to return to fields until germination and therefore are unlikely to witness or report incidents; and 3) most canola fields are large and isolated. Nonetheless, occasionally kills are reported. The second question is more difficult to answer. Even though some species are apparently abundant in canola fields and have been poisoned by insecticide granules, their populations may be stable or increasing because other landscape changes are generally favourable and compensate for the increased mortality caused by insecticides. An example may be the savannah sparrow, which has been increasing in numbers in the prairies, perhaps in relation to expansion of land in crop (increased biomass) and declines in summer fallow. To reduce soil erosion, an increasing number of prairie farmers are controlling weeds through multiple herbicide applications, leaving crop residue and standing stubble in place on the soil surface, providing more attractive habitat for some prairie species (Martin & Forsyth, 2003). Savannah sparrows in the prairies have only been associated with crop fields since the advent of no-till in the 1990s (B. Dale, Canadian Wildlife Service, pers. comm.) and require tall swards because they will not forage in open fields due to predation risk (Marcus, Palmer & Bromley, 2000). It is feasible that such changes may have positive effects that outweigh mortality by granular insecticides.

We caution that our findings are correlational only and that habitat variables or agricultural practices that we did not address explicitly may co-vary with the extent or intensity of granular insecticide use on the prairies and contribute to changes in bird abundance or trends. On the other hand, because flea beetle infestation levels follow a clear east to west cline (Figure 1), we have been extremely conservative in our analysis by giving precedence to the spatial model before introducing the insecticide use index. Our index of granular insecticide use is unavoidably somewhat imprecise, and we had to perform extrapolations for agricultural statistics; all of these manipulations lead to a weakening of our predictive models, especially the one including an insecticide-use index. Ideally, Canadian pesticide regulatory authorities should be collecting spatially explicit information on pesticide use as is being done in other jurisdictions, *e.g.*, California. Our analysis is meant to reflect regional large-scale rather than local effects, and scale can affect patterns in bird abundance data (With & King, 2001).

We recognize that avian survey data such as those from the BBS may not always adequately assess demographic processes, particularly the effect of source-sink dynamics (Brawn & Robinson, 1996; Villard, Schmidt & Maurer, 1998). Neither did we take into account differences in observer skill or time of day differences (Rosenberg & Blancher, in press) that may contribute to noise in estimates of species' abundance on BBS routes (Sauer, Peterjohn & Link, 1994). Other effects that we did not consider known to be important to farmland birds include drought and other pandemic effects, factors on the non-breeding areas, and changes in the intensity, extent of use, and type of other insecticides. As mentioned, information on pesticide use is not routinely collected, which hampers our ability to look for possible impacts. Even were such data available, we emphasize that few insect pest complexes are as geographically stable as flea beetle infestations in canola. Identifying possible linkages between use of other insecticides and bird species population trends is far more challenging because of the extremely variable nature of many pest outbreaks (*e.g.,* grasshoppers or Bertha armyworm [*Mamestra configurata*], two other major prairie insect pest complexes).

We re-emphasize that demonstrating effects of pesticides on bird species is extremely difficult because of the multiple factors involved in determining bird population change (Campbell *et al.,* 1997); even with species such as the grey partridge it has taken 30 y of intensive and extensive study to irrefutably demonstrate that pesticides have caused declines (Potts, 1997). We therefore consider it meaningful that our analyses provide suggestive evidence that regional declines in three to five species are associated with use of granular insecticides in the Canadian prairies. Despite the fact that a maximum of 7% of the farmed area is ever treated heavily with granular insecticides, we believe that this practice could create population sinks (*sensu* Best, 1986; Pulliam, 1988), where productivity does not compensate for mortality and population declines result. Our analyses suggest that we should restrict the use of pesticides that are potentially lethal to birds as part of the efforts required to reverse population declines in farmland and grassland birds.

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APPENDIX I. Species used in study and incidence of mortality by granular insecticides.

Species	
American crow (AMCR)[a]	*Corvus brachyrhynchos*[1]
American goldfinch (AMGO)	*Carduelis tristis*[1,2]
American robin (AMRO)[a]	*Turdus migratorius*[1]
Baird's sparrow (BAIS)	*Ammodramus bairdii*
Black-billed magpie (BBMA)[a]	*Pica pica*
Brown-headed cowbird (BHCO)[a]	*Molothrus ater*[1,2]
Bobolink (BOBO)	*Dolichonyx oryzivorus*[1]
Brewer's blackbird (BRBL)[a]	*Euphagus cyanocephalus*[1]
Chestnut-collared longspur (CCLS)	*Calcarius ornatus*
Clay-coloured sparrow (CCSP)[a]	*Spizella pallida*[2]
Chipping sparrow (CHSP)	*Spizella passerina*[1,2]
Common grackle (COGR)	*Quiscalus quiscala*[1]
Grasshopper sparrow (GRSP)	*Ammodramus savannarum*
Horned lark (HOLA)[a]	*Eremophila alpestris*[1]
House sparrow (HOSP)	*Passer domesticus*[1,2]
Killdeer (KILL)[a]	*Charadrius vociferus*[1]
Le Conte's sparrow (LESP)	*Ammodrammus leconteii*
Loggerhead shrike (LOSH)	*Lanius ludovicianus*[1]
Mourning dove (MODO)	*Zenaida macroura*[1]
Northern harrier (NOHA)[a]	*Circus cyaneus*[1]
Red-tailed hawk (RTHA)[a]	*Buteo jamaicensis*[1]
Red-winged blackbird (RWBL)[a]	*Agelaius phoeniceus*[1,2]
Savannah sparrow (SASP)[a]	*Passerculus sandwichensis*[1,2]
Song sparrow (SOSP)[a]	*Melospiza melodia*[1]
Sprague's pipit (SPPI)[a]	*Anthus spragueii*
European starling (EUST)[a]	*Sturnus vulgaris*[1]
Swainson's hawk (SWHA)[a]	*Buteo swainsoni*
Vesper sparrow (VESP)[a]	*Pooecetes gramineus*[1,2]
Western meadowlark (WEME)[a]	*Sturnella neglecta*

[1] Species killed by sand-core formulations of carbofuran in other studies.

[2] Species killed by corncob formulations of carbofuran in other studies.

[a] Recorded in surveys of canola fields by Martin, Arnold, and Forsyth (2005).