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Abstract: Comprehensive information on crop damage by wildlife species is critical if effective strategies for controlling wildlife damage are to be formulated. Discriminating how landscape composition and configuration attributes influence crop damage is important for implementing landscape management techniques to resolve human–wildlife conflicts. We analyzed crop damage data from 100 corn fields and 60 soybean fields located in the Upper Wabash River Basin of northern Indiana during 2003 and 2004. We used negative binomial regression to model the rate of damage to corn and soybean crops in response to local and landscape variables. Rate of crop damage was best predicted by a combination of local and landscape variables for both corn and soybeans. Models with landscape configuration variables were better able to explain patterns of corn damage, and models with landscape composition variables (specifically, amount of wooded areas) were better able to explain patterns of soybean damage. In general, rate of crop damage was negatively related to size of the crop field and positively related to proportion of a field's perimeter that was adjacent to wooded areas, amount of wooded areas, amount of forest edge, and mean size of forest patches. Specific associations between local and landscape variables and rates of crop damage may serve as a guide to planting strategies and landscape management to minimize wildlife damage to crops.

Key words: crop damage, human–wildlife conflicts, Indiana, landscape composition and configuration, *Marmota monax*, negative binomial regression model, *Odocoileus virginianus*, *Procyon lotor*, raccoon, white-tailed deer, wildlife damage, woodchuck

Wildlife damage to crops is a widespread concern in the United States, especially in the Midwest, and the assessment and control of wildlife damage to crops has become an important component of wildlife management. Most of the land area (>80%) allocated to crop production in Indiana is situated in the northern portion of the state, where corn and soybeans are the dominant crops. About 4.5 million ha of cropland was harvested during 2002 in Indiana (U.S. Department of Agriculture 2002).

According to nationwide surveys (Conover and Decker 1991; Craven and Hygnstrom 1994; Wywialowsky 1994, 1997; Conover 1998) and regional studies (McIvor and Conover 1994, Irby et al. 1996), damage by deer (*Odocoileus* spp.) is the most widespread form of wildlife damage to crops. Deer damage has been reported extensively for field corn (Sperow 1985, Vecellio et al. 1994, Wiwialowski 1997, Tzilkowski et al. 2002) and soybeans (de Calesta and Schwendeman 1978, Tanner and Dimmick 1983). Agricultural crops, especially corn and soybeans, may comprise most of deer diets in some regions, especially during early spring (Austin and Urness 1993). Deer also consume grain throughout the fall and winter (Sparrowe and Springer 1970, Gladfelter 1984, Matschke et al. 1984, Putnam 1986).

Raccoons (*Procyon lotor*) are also a significant source of damage to vegetable and fruit crops (Figure 1). The number of wildlife agencies reporting damage by raccoons increased from

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10% in 1957 (McDowell and Pillsbury 1959) to 94% in 1987 (Conover and Decker 1991). According to Pedlar (1994), raccoons thrive in areas fragmented by agriculture due to the increased foraging opportunities and efficiencies associated with agriculture (Litvaitis and Villafuerte 1996, Oehler and Litvaitis 1996).

White-tailed deer (*Odocoileus virginianus*) and raccoon densities are increasing in the Midwest; therefore, the potential for crop damage caused by these species is relatively high. White-tailed deer densities have increased considerably since the 1900s when the species was nearly extirpated in many midwestern states; current deer densities from some regions of the Midwest range from 13 to 32 deer/km^2 (Keyser et al. 2005). In Indiana, harvest records indicate that populations of white-tailed deer remain relatively high, although harvest rates have declined since the record highs of the mid-1990s (Indiana Department of Natural Resources, unpublished data). Throughout the Midwest, raccoon populations have increased over the past century (Lehman 1977) and are currently at or near record population levels in Indiana (Plowman 2003). Raccoon densities range from 35 to 200 raccoons/km^2 in the northern portions of Indiana, where forests are restricted to small patches within an agricultural matrix, to 5.6 raccoons/km^2 in the large homogeneous forests of the southern portion of the state (Lehman 1977, 1980).

FIGURE 1. Raccoon damage to corn.

Previous studies on wildlife damage to crops have related patterns of crop damage to wildlife density (Crawford 1984, Hayne 1984, Alverson et al. 1988, Vecellio et al. 1994), and field morphology (Flyger and Thoerig 1962, deCalesta and Schwendeman 1978, Crawford 1984). Other studies have provided insights into the role of landscape attributes surrounding crop fields in relation to damage rates to crop fields (Gorynzka 1981, Vecellio et al. 1994, Braun 1996). However, most of these studies have focused on land-use composition in areas surrounding crop fields, without examining the relative influence of habitat predictors measured at different scales or representing diverse landscape attributes on crop damage. Valuable management information can be obtained through understanding the differential role of landscape composition and landscape configuration attributes on crop damage. Such information can be used to manipulate landscapes for resolving human–wildlife conflicts (Conover 2002).

The objective of this research was to model the rate of wildlife damage to corn and soybeans in the Upper Wabash River Basin (UWB), Indiana, based upon local and landscape habitat attributes surrounding crop fields. Information from models may allow wildlife professionals to adopt a proactive approach to preventing wildlife crop damage.

Study area

The 113,850-ha study area is located in the UWB in North-central Indiana, between the Missisinewa and the Salamonie reservoirs (Figure 2). The UWB drains an area >2,000,000 ha and represents >20% of the state's area (Swihart and Slade 2004). According to Moore and Swihart (2005), the remaining native forests (predominantly oak [*Quercus*], hickory [*Carya*], and maple [*Acer*]) in the UWB are highly fragmented; indeed, 75% of forest patches across 35 landscapes we analyzed in the basin were <5 ha. In addition, relatively large contiguous forest tracts in the basin are confined to major drainages where floodplains or locally steep topography make land unsuitable for agriculture; 86% of forest patches larger than 100 ha within the UWB were <15 km from the

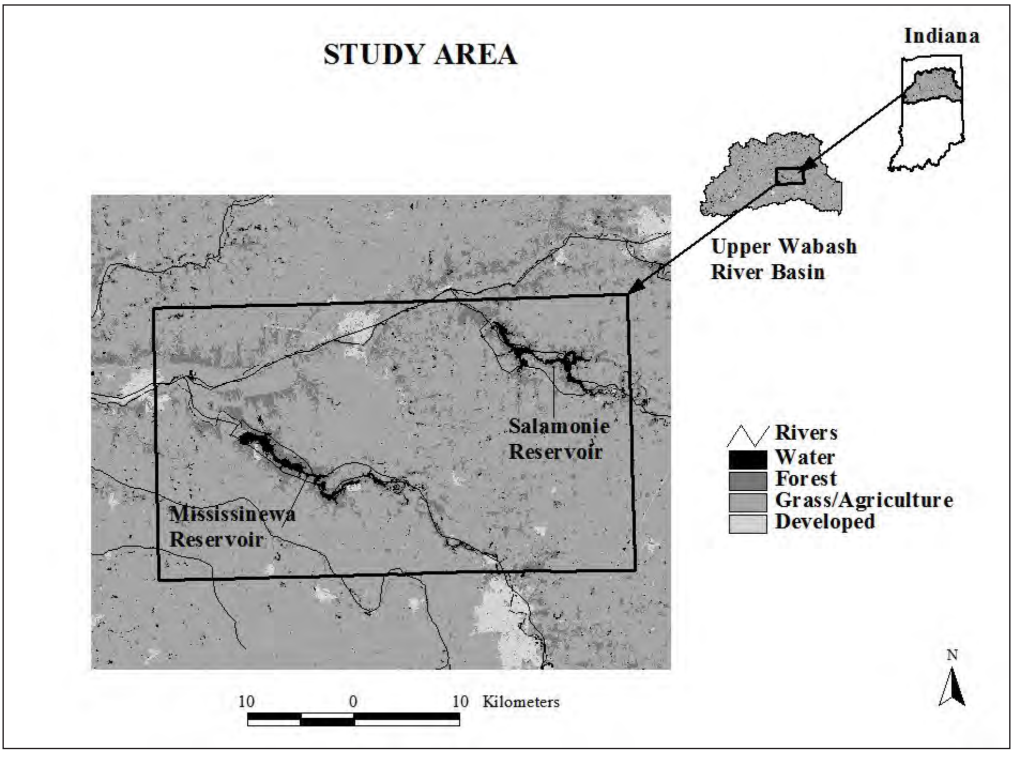

FIGURE 2. Study area located in the Upper Wabash River Basin, northern Indiana.

Wabash River (Moore and Swihart 2005). At the time of our study, 71% of the study area was in agricultural use, primarily for corn and soybean production, and 13% of the area was forested.

Our study area spans multiple landscapes across the UWB. The UWB is similar in land use to other areas of the corn belt, primarily represented by Iowa, Indiana, Illinois, and Ohio (Smith et al. 1997, Swihart and Slade 2004). For these reasons, we believe that the results of our study are applicable across most of the Midwest.

Methods

Crop damage sampling

We classified the study area according to its variation in landscape composition and configuration to stratify crop damage sampling. We overlaid a 1.6- x 1.6-km grid on a land-use map of the UWB, and values of forest to agriculture ratio, number of forest patches and length of edge between forest and agriculture were obtained for each cell of the grid, using the Patch Analyst extension in ArcView 3.3 (Environmental Systems Research Institute, Redlands, Calif., 2002). These values were used in a K-means cluster analysis (Hartigan 1975) to classify the study area into 3 clusters of greatest possible distinction according to the variables used to represent landscape composition and configuration of the study area.

We surveyed 100 corn fields and 60 soybean fields for wildlife damage during 2003 and 2004 (from April to October). We selected crop fields randomly for each cluster proportionally to the area of the cluster, using the ArcView menu item "generate random points" included in the Animal Movement extension (Hooge et al. 1999) to ArcView. The size distribution of crop fields varied among clusters from a larger proportion of smaller fields (<12 ha) in the most forested cluster to a larger proportion of larger fields (>24 ha) in the least forested cluster. Ten crop fields were not damaged and were excluded from analysis, thus reducing the sample of corn fields to 96 and soybean fields to 54.

After plant emergence, we established a series of transects in each crop field to survey for crop damage. All transects ran parallel with the fields' row plantings, and transects continued through the end cross rows to the ends of the fields. Two edge transects were established within 15 m of the edges of each field, following curvatures of field edges. Interior field transects (two for <12 ha, four for 12 ha to 24 ha, and six for >24-ha fields) were placed equidistantly within the remainder of each field. Most fields had 4 definable edges; for these fields we surveyed the 2 edges that ran parallel to the entire field row planting orientation. For fields with >4 edges (irregularly shaped fields), we surveyed the 2 major edges that ran parallel to the entire field planting orientation and any other edge of the same orientation that was >25% of the length of the field in the direction being surveyed. We chose to run all transects parallel to the rows to facilitate sampling and to avoid damage to young plants by technicians as they walked through the fields.

Survey crews of 2 observers walked in tandem along transects and documented all plants that exhibited any sign of wildlife-caused damage visible from transects (i.e., variable-width transects). Along each transect, observers recorded the number of plants damaged at each damage location. At locations where ≤20 plants were damaged, observers recorded data for each damaged plant; in areas where >20 plants were damaged, observers recorded data on 20 randomly-selected damaged plants. For each damaged corn plant, we recorded the number of ears, number of rows of kernels, number of kernels per row, remaining kernels per yield to nearest 10%, remaining leaf area to nearest 10%, whether plant was pulled or not, whether tassel was damaged or not, and the height of the damage on the plant. For each damaged soybean plant we recorded the number of seed pods per plant, number of damaged pods remaining on each plant, remaining leaf area to nearest 10%, whether the plant was pulled or not, and the height of the damage on the plant. We also recorded wildlife species responsible for damage at each damage location. Damage was identified based on bite marks, as well as type of digging and animal tracks around plants. Observers were trained to identify wildlife damage and tested prior to conducting wildlife damage sampling based upon guidelines developed by the Ohio Division of Wildlife (1999). Observers also attended a training session with district wildlife biologists of the Indiana Department of Natural Resources. Additionally, we observed wildlife damage from blinds located on some fields and recorded it on film. This information served us as a test for our ability to identify damage correctly.

All documented damage was marked clearly with paint to avoid recounting during subsequent surveys. In addition to collecting plant damage characteristics, we recorded Universal Transverse Mercator (UTM) coordinates using hand-held Geographic Positioning System (GPS) units at the epicenter of each location where we collected damage information. Surveys were conducted approximately once per month, from plant emergence until harvest. We randomized the order in which fields were surveyed to minimize bias due to observational error, day, and time of day.

Quantification of habitat attributes

We quantified local and landscape habitat attributes around crop fields using land use, rivers and streams, and road maps. Using ArcGis 9.0, we produced a land-use map for the study area by interpretation of U.S. Geological Survey digital orthophotos (DOQs) with 1-m resolution taken in 1998. The projection used for these orthophotos is UTM, and the datum is the North American Datum of 1983 (NAD83), with coordinates in meters. The land-use map presents 7 land-use classes: forest (closed-canopy forests, includes deciduous and evergreen types of forests); shrub land (from scattered trees in an open matrix to open-canopy forests); corridors (forested habitat with a width of >3m and <30 m spanning some distance between 2 larger habitats); grassland (open areas not allocated to agriculture); agriculture (all types of crops, excluding tree plantations); water (open nonlinear water bodies, rivers and streams >3 m wide); and developed (cities, farm houses delineated by the mowing line, and animal holding facilities).

We used river and stream maps and road maps for the state of Indiana (U.S. Geological Survey layers downloaded from the Center for Advanced Applications in Geographic Information Systems (available at *http://danpatch.ecn.purdue.edu/~caagis/ftp/gisdata.html*.) The scale of these layers was 1:100,000, and they conformed to the UTM NAD83 Zone 16 North meters coordinate system. Using the orthophoto set, we modified the rivers and streams map by incorporating water bodies not included in the original Geographic Information System (GIS) layer for the study area. We also digitized the boundary of crop fields selected for crop damage surveys using the DOQ set.

We used GIS maps to measure the following field or habitat attributes: field attributes and local habitat attributes in the immediate proximity to the field, identified as local predictor variables (Table 1), and landscape habitat attributes in 530-ha analysis units centered on each crop field, identified as landscape predictor variables (Table 1). The size of analysis units used to measure landscape habitat attributes was selected to encompass the largest seasonal home range sizes reported for white-tailed deer and raccoons for agricultural portions of the Midwest during the months corresponding to the crop-growing season (Sherfy and Chapman 1980, Nixon et al. 1991). Emphasis was placed on white-tailed deer and raccoon home range sizes because they are considered among the main wildlife species responsible for crop damage (Conover and Decker 1991). We selected these predictor variables according to the information available about habitat requirements of white-tailed deer (Wishart 1984, Smith 1987, Nixon et al. 1991, Dusek et al. 1989, Craven and Hygnstrom 1994) and raccoons (Oehler and Litvaitis 1996, Dijak and Thompson 2000, Kuehl and Clark 2002, Chamberlain et al. 2003), as well as information resulting from previous attempts to describe habitat attributes related to wildlife damage to crops (Shope 1970, Gorynzka 1981, Garrison and Lewis 1987, Braun 1996).

We obtained the area and perimeter for each crop field and measured the field perimeter length adjacent to wooded areas, agriculture and grassland, roads, and developed areas using ArcView 3.3. We also developed 2 distance files, one from water bodies and another from road maps, and then determined the distance to the nearest water body and to the nearest road from each crop field. We also intersected analysis units centered in crop

Table 1. Predictor variables used to model corn and soybean damage by wildlife in the Upper Wabash River Basin, Indiana. Local predictors are defined as field attributes and local habitat attributes in the immediate proximity to the field; landscape predictors are landscape habitat attributes in 530-ha analysis units centered on each crop field.

Predictors		Description
Local	Area[abc]	Area (ha) of the field
	P_Wood[abc]	Proportion of perimeter of the field adjacent to wooded areas (forest, shrubland, and corridors)
	P_AGrass	Proportion of perimeter of the field adjacent to agriculture and grassland
	P_Road	Proportion of perimeter of field adjacent to roads
	P_Dev	Proportion of perimeter of field adjacent to developed areas
	D_Road	Distance (m) to the nearest road from edge of field
	D_Water[ac]	Distance (m) to nearest water body from edge of field
	D_For[c]	Distance (m) to nearest forest patch from edge of field
Landscape	L_Road	Total length (m) of roads
	L_Water	Total length (m) of rivers and streams and perimeter of ponds
	A_Wood[abc]	Area (ha) of forest, shrubland, and corridors
	A_Ag	Area (ha) of agriculture
	A_Grass	Area (ha) of grassland
	A_Dev[ac]	Area (ha) of human-developed uses
	Even[abc]	Shannon's evenness index
	F_Patch[ac]	Number of forest patches
	F_Edge[abc]	Amount of forest edge (m)
	F_Shape[abc]	Area-weighted mean shape index of forest patches
	F_Mps[abc]	Mean forest patch size (ha)

[a] Variables included in reduced set of predictors for corn damage modeling.
[b] Variables included in reduced set of predictors for soybean damage modeling.
[c] Interaction terms between SP and the corresponding habitat variables were considered in preliminary analysis to reduce the set of predictors.

fields with both water bodies and road maps to obtain the total length of water bodies and the total length of roads for each analysis unit using ArcView 3.3. Finally, we used Patch Analyst extension (Rempel and Carr, 2003) in ArcView 3.3 (Environmental Systems Research Institute 2002) to obtain landscape composition and landscape configuration variables within each analysis unit (Table 1).

We included an additional predictor variable (categorical) to denote the species causing most of the damage (>50%) in each crop field. Most of the corn damage was caused by raccoon (87%) and white-tailed deer (10%), and the rest of the species combined caused <3 % of the damage. Most of soybean damage was caused by deer (61%) and woodchuck (*Marmota monax*; 38%), and the rest of the species combined caused <1 % of the damage (Humberg et al. 2006). Consequently, we considered deer, raccoons, and all the other species combined for corn damage models; and deer, woodchucks, and all the other species combined for soybean damage models.

Statistical analysis

We used negative binomial regression to model the rate of crop damage in response to local and landscape variables. Poisson and negative binomial regression models are commonly used when the response variable is the counted number of occurrences of an event. We selected the negative binomial model because the variance of our response variable was much larger than its mean. To account for differences in sampling effort among crop fields of different sizes, we used the area of the field as an offset variable to model the rate of crop damage. With the negative binomial regression model, the natural log of the response variable is modeled as a linear function of the coefficients as: log(number of plants damaged/crop field's area) = intercept + b1*X1 +b2*X2 + ...+ bm*Xm.

We fitted separate models for each crop type because a different set of species causing damage was considered for each crop type. We used likelihood ratio statistics, adjusted for the number of parameters, for each effect included in full models as a preliminary basis for variable reduction. We also considered the correlation among variables to reduce their number and level of collinearity.

Using the reduced set of predictors for each crop type model (Table 1), we formulated a set of 9 candidate models for corn (Table 2) and 7 candidate models for soybean (Table 3). Candidate models included models with only local variables, models with only landscape variables, and hybrid models with both local and landscape variables. We selected landscape variables used in hybrid models to represent either landscape composition or landscape configuration (representing complexity of shape of forest patches, or amount of forest edge, or forest fragmentation metrics). We included the categorical variable species in all candidate models.

We conducted model selection using the

Table 2. AIC_c, Δ_I, and w_i used to compare a set of candidate models of corn damage by wildlife species in the Upper Wabash River Basin, Indiana.

Predictors Included in Model	AIC_c	Δ_i	w_i
SP Area_For D_Water P_Wood F_Edge F_Mps[a]	-979680.71	0.00	0.7489
SP Area D_For D_Water P_Wood A_Wood A_Dev[b]	-979678.49	2.22	0.2434
SP Area D_For P_Wood F_Edge F_Mps[a]	-979672.64	8.07	0.0131
SP Area D_For P_Wood A_Wood[b]	-979669.51	11.20	0.0027
SP Area D_For D_Water P_Wood F_Shape F_Patch[a]	-979668.20	12.51	0.0014
SP Area D_For D_Water P_Wood Even A_Dev[b]	-979665.79	14.92	0.0004
SP Area D_For D_Water P_Wood[c]	-979652.79	27.92	0.0000
SP F_Edge F_Mps[d]	-979627.49	53.22	0.0000
SP A_Wood A_Dev[e]	-979625.79	54.92	0.0000

[a] Combination of local and landscape configuration variables.
[b] Combination of local and landscape composition variables.
[c] Local habitat variables only.
[d] Landscape configuration variables only.
[e] Landscape composition variables only.

Table 3. AIC_c, Δ_I, and w_i used to compare a set of candidate models of soybean damage by wildlife species in the Upper Wabash River Basin, Indiana.

Predictors Included in Models	AIC_c	Δ_i	w_i
SP Area P_Wood A_Wood SP*A_Wood[a]	-9776471.10	0.00	0.6549
SP Area P_Wood F_Edge F_Mps[b]	-9776469.70	1.40	0.3244
SP Area P_Wood F_Shape F_Mps[b]	-9776464.19	6.91	0.0206
SP Area P_Wood Even[a]	-9776444.63	26.47	0.0000
SP Area P_Wood[c]	-9776436.75	34.35	0.0000
SP A_Wood SP*A_Wood[d]	-9776434.35	36.75	0.0000
SP F_Edge F_Mps[e]	-9776426.49	44.61	0.0000

[a] Combination of local and landscape composition variables.
[b] Combination of local and landscape configuration variables.
[c] Only local habitat variables.
[d] Only landscape composition variables.
[e] Only landscape configuration variables.

Aikaike's Information Criteria with the small-sample bias adjustment (AIC_c, Hurvich and Tsai, 1989). AIC_c was rescaled to $\Delta_i = AIC_i - AIC_{min}$, where AIC_{min} is the minimum AIC_i value from all the candidate models being compared (Burnham and Anderson 2002). We also calculated Akaike weights (w_i) as:

$$W_i = \frac{\exp(-\tfrac{1}{2}\Delta_i)}{\sum_{r=1}^{R} \exp(\tfrac{1}{2}\Delta_r)}$$

Akaike weights normalized the model likelihoods such that they summed to one and may subsequently be treated as conditional probabilities. These weights were used as the weight of evidence in favor of a certain model in the set of candidate models as being the best model in the set (Burnham and Anderson 2002).

We used the deviance-based dispersion statistic (sum-of-squared deviance residuals divided by degrees of freedom) as a first test of model specification. Values lower than 1.5 indicated a good fit of the negative binomial regression to the data. We assessed model assumptions by examining diagnostic plots of the model deviance residuals against predicted values, deviance residuals against predictor variables, and, finally, a normal scores plot of deviance residuals (Hoffman 2004).

To assess for spatial autocorrelation in the response variable not accounted for by predictor variables, we calculated Moran's *I* for residuals resulting from damage models across a set of distance categories (Cliff and Ord 1981). Locations close together in space are likely to exhibit more similar attributes (in this case less variance in number of plants damaged) than are locations far apart. This phenomenon may result in violations of independence assumptions of statistical models, resulting in artificially narrow confidence intervals for parameter estimates and false conclusions about the importance of predictor variables (Legendre 1993). We defined 10 neighborhoods, considering 0 m and 5,000 m as the lower and upper distance bounds, respectively. These bounds were selected such that no crop fields would become islands. The total number of neighborhoods was defined according to the maximum spatial distance between crop fields in the dataset.

Results

In corn and soybeans, hybrid models, including local and landscape variables, showed much stronger support than models using exclusively local or landscape variables (Tables 2 and 3). For corn damage models, evidence of support for a hybrid model including only landscape configuration variables (*wi* = 0.74) was much stronger than for a hybrid model that included only landscape composition variables (*wi* = 0.24; Table 2). The opposite was observed for soybeans, where support for a hybrid model that included only landscape composition variables (*wi* = 0.65) was stronger than for another hybrid model that included only landscape configuration variables (*wi* = 0.32; Table 3).

Rate of corn damage was negatively related both to the area of the field and the distance to the nearest forest patch from the edge of the field. In addition, the rate of corn damage was positively related to the perimeter of the field adjacent to wooded areas, the distance to the next water body from the edge of the field, the amount of wooded areas, the amount of developed areas, the amount of forest edge, and the mean forest patch size in an area of 530 ha centered on crop fields (Table 4).

The rate of soybean damage was negatively related to the area of the field. In addition, the rate of soybean damage was positively related to the perimeter of the field adjacent to wooded areas, the amount of wooded areas, the amount of forest edge, and the mean forest patch size in an area of 530 ha centered on crop fields (Table 4). An interaction term between species and amount of wooded area was included in the soybean damage models, indicating a differential influence of this variable on the rate of damage according to which species was causing most of the damage to crop fields. The slope of the regression line for deer was steeper than the slope for other species, indicating that the magnitude of soybean damage by deer increased more rapidly than the magnitude of damage by other species for similar changes in the amount of wooded area. Deviance-based dispersion statistics lower than 1.5 for both models indicated that model specification was appropriate. Diagnostics plots did not show any strong violation to model assumptions. Finally, tests for spatial autocorrelation showed no spatial autocorrelation in residuals.

Discussion

Rate of crop damage was best predicted by a combination of local and landscape variables for both corn and soybeans. Corn and soybean damage models with either landscape composition or configuration variables were well-supported, suggesting that a combination of factors examining not only how the landscape is composed, but also how it is configured, might be best suited to explain patterns of damage in both types of crops. However, models with landscape configuration variables seem to be better supported to explain patterns of corn damage, and models with landscape composition variables (i.e., amount of wooded areas) seem to be better supported to explain patterns of soybean damage. The heights of the 2 crops may explain this difference. When mature, corn is higher than deer and offers ideal cover. Hence, mature cornfields offer both food and cover for deer, so deer may stay in them for long periods of time. In contrast, mature soybeans are not high enough to provide cover to a mature deer. Nixon et al. (1991) found that deer in east-central Illinois were able to occupy small woodlots and linear strands of forest associated with streams and rivers during summer because of the additional cover and food that corn crops provided. Consequently, the amount of wooded areas for cover may be a limiting factor for deer use of mature soybean fields, but nor for cornfields.

Although damage caused by wildlife to both types of crops was associated with a slightly different suite of variables, 5 local and landscape variables were consistently represented in the best models for both crop types: area of the field, proportion of the perimeter of the field adjacent to wooded areas, amount of wooded areas, amount of forest edge, and mean forest patch size. Consistent with Flyger and Thoerig (1962), Shope (1970), and Prior (1983), we found that the rate of crop damage was negatively related to field size, with larger crop fields presenting smaller damage rates. However, other authors have found an inconsistent relationship between field size and rate of damage (deCalesta and Schwendeman 1978, Braun 1996).

Positive effects of the proportion of a field's perimeter associated with wooded areas and negative effects of the distance between crop fields and wooded areas on crop damage received support in this and previous studies. DeCalesta and Schwendeman (1978), Crawford (1984), Garrison and Lewis (1987), and Braun (1996) detected heavier crop loss along field edges bordered by wooded areas than along edges that had no adjacent wooded cover. In addition, Thomas (1954) and Hartman (1972) found that rate of crop damage was negatively related to the distance between fields and wooded areas.

Amount of wooded areas was a significant predictor of the rate of crop damage to both corn and soybean crops in this study. This finding was consistent with those of other studies that also suggested that fields in heavily

Table 4. Parameters estimates, SE, 95% confidence limits for wildlife damage models with strongest weight of evidence as the best models in the set of candidate models for the Upper Wabash River Basin, Indiana.

Parameter	Estimate	SE	95% CI		Estimate	SE	95% CI	
	Corn				Soybeans			
Intercept	1.0250	0.5405	-0.0343	2.0842	2.2508	0.5828	1.1087	3.3930
SP								
Deer	0.4624	0.4928	-0.5035	1.4284	1.7558	0.6621	0.4581	3.0535
Raccoon	1.0397	0.4554	0.1471	1.9322	NA	NA	NA	NA
Woodchuck	NA	NA	NA	NA	4.4191	0.9497	2.5577	6.2806
Others	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
D_Water	-0.0351	0.0053	-0.0455	-0.0246	-0.0690	0.0079	-0.0845	-0.0534
D_For	0.0012	0.0004	0.0005	0.0019	NA	NA	NA	NA
P_Wood	-0.0040	0.0008	-0.0056	-0.0025	NA	NA	NA	NA
F_Edge	1.8919	0.4530	1.0041	2.7797	1.4683	0.8337	-0.1658	3.1024
F_Mps	0.0001	0.0000	0.0000	0.0001	NA	NA	NA	NA
A_Wood	0.0600	0.0312	-0.0011	0.1211	NA	NA	NA	NA
SP*A_Wood	NA	NA	NA	NA	-0.0072	0.0082	-0.0233	0.0088
D_Water								
Deer	NA	NA	NA	NA	0.0277	0.0087	0.0107	0.0447
Woodchuck	NA	NA	NA	NA	0.0173	0.0104	-0.0031	0.0378
Others	NA	NA	NA	NA	0.0000	0.0000	0.0000	0.0000

NA: not applicable; predictor not included in model wooded areas suffer more crop damage than those in lightly wooded areas (Gorynzka 1981, Beringer et al. 1994, Braun 1996, Alverson and Waller 1997). This is not a surprising finding considering the importance of wooded areas to wildlife species, mainly deer and raccoons, that cause damage to crops. In areas of sparse forest, the distribution and density of deer varies directly with abundance of riparian or other woody cover (Smith 1987, Dusek et al. 1989). Raccoons, on the other hand, exhibit considerable plasticity in terms of habitat requirements and may thrive in landscapes containing a diversity of cover types (Oehler and Litvaitis 1996). However, raccoons select mature hardwood habitats when available; this possibly was due to the opportunities for foraging and availability of dens that hardwood trees provide, as well as the availability of water in these areas (Chamberlain et al. 2003). Even when they can den in different habitats, female raccoons often select tree dens over other potential den sites, especially during lactation (Endres and Smith 1993, Henner et al. 2004). Woodchuck (*Marmota monax*) dependence on wooded areas, however, may vary according to the life cycle of the species; indeed, this species uses mainly open areas and prefers wooded areas just for hibernation (Kwiecinski 1998). Such less strict association of the species with wooded areas may explain the differential influence of amount of wooded area on soybean damage caused by woodchucks and deer.

Areas more heavily forested are likely to support larger densities of wildlife species that cause damage to crops, possibly imposing greater foraging pressure on field crops. Crop damage has been directly related to deer density (Flyger and Thoerig 1962, Shope 1970, Vecellio et al. 1994, Braun 1996). Moreover, in a theoretical modeling effort of deer damage to crops, Yoder (2002) found that deer damage can be minimized by reducing deer densities.

The rate of crop damage was positively associated with the amount of forest edge in this study. Landscapes with larger amounts of edge are likely to support larger populations of wildlife species with affinities to edges and provide more opportunities for wildlife species to access crop fields. Consequently, edge availability may increase wildlife foraging pressure on crops. The species causing most of the damage to corn and soybeans have an affinity for edge habitat. Deer particularly thrive in agricultural areas well-interspersed with woodlots and riparian habitat, favoring early successional stages, which keep brush and sapling browse within reach (Craven and Hygnstrom 1994). Furthermore, deer presumably benefit more from forest edge than from dense, old-growth forests where they can have access to shrubs and forbs, which comprise some of their main forage sources (Wishart 1984). Raccoons are considered to be edge species and generally are more abundant along forest edges adjacent to agricultural fields, streams, and grasslands (Dijak and Thompson 2000, Kuehl and Clark 2002). Woodchucks occur in woodland–field ecotones, as well, and they prefer wooded areas for hibernation and fields for breeding and foraging (Kwiecinski 1998).

Damage to corn by wildlife.

In this study, rate of crop damage also was positively associated to mean forest patch size. Mean patch size can be used as an index of fragmentation; a landscape with a mean patch size for the target patch type greater than another landscape might be considered less fragmented (McGarigal and Mark 1995). Larger forest patches are more likely to provide more suitable cover and food resources to wildlife species than do smaller forest patches. Even though wildlife species causing damage to crops may be favored by more complex

Corn damaged by birds.

landscapes providing more forest edge, the size of forest patches might also play a key role in determining species distribution and abundance. Larger and more complex forest patches might be more favorable to wildlife species than smaller and less complex patches.

Two variables were uniquely present in corn damage models: the amount of developed areas in analysis units and the distance to a water body from the edge of the field. In this study, these relationships may be driven mainly by raccoons, the main species causing damage to corn. Corn damage was related positively to the amount of developed areas. Raccoons have affinity to urban and suburban landscapes where they can have access to both human-generated food and buildings where they can den (Bogges 1994). On the other hand, areas farther away from a water source received more damage than areas closer to water. The nature of this relationship was somewhat unexpected, considering the importance of water availability to raccoons. According to Stuewer (1943), and Dorney (1954), availability of water may be a primary factor limiting raccoon distribution and abundance. Furthermore, raccoons often concentrate their movements along streams or other water bodies (Sherfy and Chapman 1980), so, it might be expected that larger densities of raccoons and potentially more crop damage occur near water sources. On the other hand, water sources might increase the availability of alternate foods for raccoons and thereby reduce their need to forage on crops. Indeed, water bodies provide access to crayfish, one of the most important animal foods for raccoons (Lotze and Anderson 1979). Likewise, a reduced variety of preferred food resources in areas farther away from water sources might diverge foraging pressure by raccoons to more readily available food resources, such as corn, in those areas.

Management implications

Most previous studies have focused on field crop attributes and deer densities as predictors of wildlife damage to crops. Only a few studies have also included landscape variables in their modeling efforts. Our study showed that the rate of crop damage was best predicted by a combination of local and landscape variables. In addition, a combination of factors relating to both landscape composition and configuration might be best suited to interpret patterns of damage to corn and soybeans in an agricultural landscape of northern Indiana.

The importance of forested habitats as sources of food and cover for wildlife species inhabiting highly fragmented landscapes is indisputable. In agricultural landscapes, many nongame species (e.g., passerine birds, bats, small mammals, reptiles, amphibians) also rely heavily on small forested habitats for food, cover, and breeding areas (e.g., Kolozsvary and Swihart 1999, Rosenblatt et al. 1999, Menzel et al. 2005). Paradoxically, those patterns of landscape composition and configuration that contribute to the permanence of wildlife species in highly fragmented agricultural landscapes may also enhance the opportunities for wildlife species to access and potentially damage agricultural crops. However, we do not advocate removal of woodlots to alleviate crop damage in heavily agricultural areas. Instead, we suggest that protecting corn and soybean crops may be accomplished most effectively by manipulating the configuration of landscape elements.

Specific associations between landscape attributes and rate of crop damage detected in this research may be useful when planning manipulations of crop fields or the landscapes surrounding them to prevent or minimize wildlife damage to crops. Specifically, strategies that maximize the size of the field and minimize the amount of forest edge in close proximity to crop fields are advised to control wildlife damage in areas of intense agricultural production. When establishing crop fields at a distance from forest patches is not feasible, selective planting of less palatable crop types in close proximity to forest patches and more palatable crop types in core areas of crop fields merits strong consideration by the landowner.

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