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Common Loon (*Gavia immer*) Nesting Habitat Models for North-central Minnesota Lakes

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Abstract.—Shoreline attributes and extensive field surveys of aquatic vegetation and animal presence were used to determine probabilities of Common Loon (*Gavia immer*) nesting for segments of lakeshore on 35 lakes in north-central Minnesota. Model development used both a general linear mixed model and random forest classifier approach. The resulting nesting habitat models were used to predict nesting sites for a small set of independent lakes. Shoreline segments with low mean fetch and littoral slope, fewer developed shoreline parcels, and higher aquatic plant richness had higher probabilities of nesting. In addition, significantly more nesting sites were on islands than on mainland shoreline segments. The locations of predicted nesting sites on the independent lake set compared favorably to the locations of observed nests. The ability to predict suitable Common Loon nesting sites should lead to the greater protection or restoration of these valuable areas and enhance conservation efforts across the state.
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Key words.—Common Loon, *Gavia immer*, Minnesota, nesting habitat models, shoreline development.

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The Common Loon (*Gavia immer*) is perhaps one of North America's most studied birds. Numerous studies have been conducted on various aspects of Common Loon life history, and research on nesting is particularly prevalent. Nesting site habitat is well-documented (Vermeer 1973; McIntyre 1988; Evers *et al.* 2010), and studies have identified lake-level characteristics that are associated with use by breeding Common Loons (Found *et al.* 2008; Evers *et al.* 2010; Kuhn *et al.* 2011). However, the ability to predict where they might nest along a given shoreline has been lacking despite the importance of this knowledge to local lake managers. In addition, several characteristics known to be important in Common Loon nest site selection, such as protection from wind and waves, have not been quantified. The objective of this study was to develop predictive models for Common Loon nesting habitat on Minnesota lakes that incorporate new data and provide spatial information about potential nesting locations.

The breeding range of the Common Loon is primarily in Canada, but a small proportion of the population breeds in the northern United States. Within the continental United States, Minnesota has the largest summer population of Common Loons. A 1989 survey estimated that approximately 12,000 adults summer and breed in the central and northern portions of the state (Strong and Baker 2000), and annual monitoring between 1994 and 2012 indicated that the population remains stable (Minnesota Department of Natural Resources 2012a).

The preferred breeding habitat of Common Loons is oligotrophic lakes with high water clarity and low anthropogenic development (Vermeer 1973; Meyer 2006; Kuhn *et al.* 2011). Common Loons prefer to nest near shore on vegetated hummocks, small islands, or masses of emergent vegetation. Nests are generally found in areas protected from prevailing winds and with good views to their open water territory (Yonge 1981; McIntyre 1983; Valley 1987; Evers *et al.* 2010). Males select nesting sites, and both males and females aggressively defend their territories (Piper *et al.* 2000, 2008). Suitable small lakes (< 50 ha) often have a single mated pair (Evers *et al.* 2010). Large lakes can have numerous pairs nesting in secluded bays and on small islands (Vermeer 1973). Common Loons show high site fidelity for sites that previously produced successful nests (Strong *et al.* 1987; Piper *et al.* 2008).

Human activities can disturb Common Loon nesting and chick rearing (Evers 2007). Meyer (2006) found that they did not reproduce on northern Wisconsin lakes when shoreline building densities exceeded 25 buildings/km; given that Wisconsin

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shoreline zoning regulations permit a density of 33 buildings/km, the potential for reduced Common Loon productivity in this area and others with similar zoning is substantial. Heimberger *et al.* (1983) reported that hatching success was a function of distance to development – nests within 150 m of lakefront homes had a 45% hatching success rate, whereas nests greater than 150 m from development had a 75% hatching rate. In addition, they noted that Common Loons appeared to avoid nesting in areas where there were five or more developments within 150 m. In a study of 98 randomly selected small to moderately sized lakes (< 300 ha) in northern Wisconsin and Michigan, Newbrey *et al.* (2005) found that Common Loon presence was negatively related to the number of lakefront homes.

Previously, the Minnesota Department of Natural Resources developed a model to identify sensitive lakeshore (i.e., lakeshore comprised of unique or critical ecological habitat) in central Minnesota (Minnesota Department of Natural Resources 2012b). These areas are important to a variety of wildlife species, including Common Loons, but are threatened by development and land alteration along the shoreline. Multiple biological attributes were used to identify sensitive lakeshore, including shoreline frog and vegetation-dependent fish presence, lakeshore bird richness, and aquatic plant richness. We wanted to know if these attributes, which are likely indicators of lakeshore condition, may also be associated with potential Common Loon nesting habitat.

Although Common Loons (loons) are somewhat adaptable to human activities (Titus and VanDruff 1981), efforts by lakeshore residents and lake users will help ensure that high-quality nesting habitat is retained for locally nesting loons. Actions include monitoring loon activity, alerting others to nest locations to reduce disturbance, and providing nesting rafts or platforms. In conservation plans for the Common Loon, Evers (2007) and Tischler (2011) stated the need to protect breeding habitat at a local scale and to identify site-specific habitat requirements. These goals would be facilitated by the identification of existing and potential nesting locations.

Shoreline attributes and aquatic vegetation and animal presence data were used to determine probabilities of Common Loon nesting for segments of lakeshore on north-central Minnesota lakes. We determined whether human lakeshore development influenced nest site selection, and compared important explanatory variables. The resulting nesting habitat models were used to predict nesting habitat areas for independent lakes.

METHODS

Study Area

We selected 35 lakes in north-central Minnesota for use in the models to identify suitable Common Loon nesting habitat areas (Fig. 1). Study lakes were located in Cass, Crow Wing, and Itasca Counties, and were selected based on several factors. All primary study lakes were > 202 ha in size; the three lakes under this threshold (Deep Portage, Little Boy, and Louise Lakes) were connected to larger lakes and were therefore included in the surveys (Table 1). Development on the lakes was moderate to heavy (average about seven dwellings/km), and all study lakes were facing the threat of additional shoreline development, but still had undeveloped stretches of shoreline. All lakes were deep-water, mesotrophic, glacial lakes and were important fishery and recreational lakes in Minnesota. Cass and Crow Wing County lakes were the focus of the sensitive lakeshore identification project (Minnesota Department of Natural Resources 2012b), and were subject to aquatic vegetation, aquatic frog, near-shore fish, and lakeshore bird surveys; the only exception was Leech Lake, where the size of the lake coupled with the time frame for the study made the ability to conduct shoreline bird surveys infeasible. Itasca County lakes were not part of the earlier study so biological data were not available for these lakes.

Aquatic Vegetation and Animal Surveys

The aquatic vegetation surveys were conducted using a tiered survey approach (Minnesota Department of Natural Resources 2012b). Survey components included a lake-wide assessment of the vegetation community using a grid point-intercept method, and delineation and description of emergent and floating-leaf plant beds. Most vegetation sampling was conducted during peak growth and before plants senesced (July through early September). In lakes or bays with extensive wild rice (*Zizania palustris*) stands, surveys were conducted earlier (June) to minimize damage to wild rice. The grid point-intercept vegetation survey methodology followed that of Madsen (1999). We established sur-

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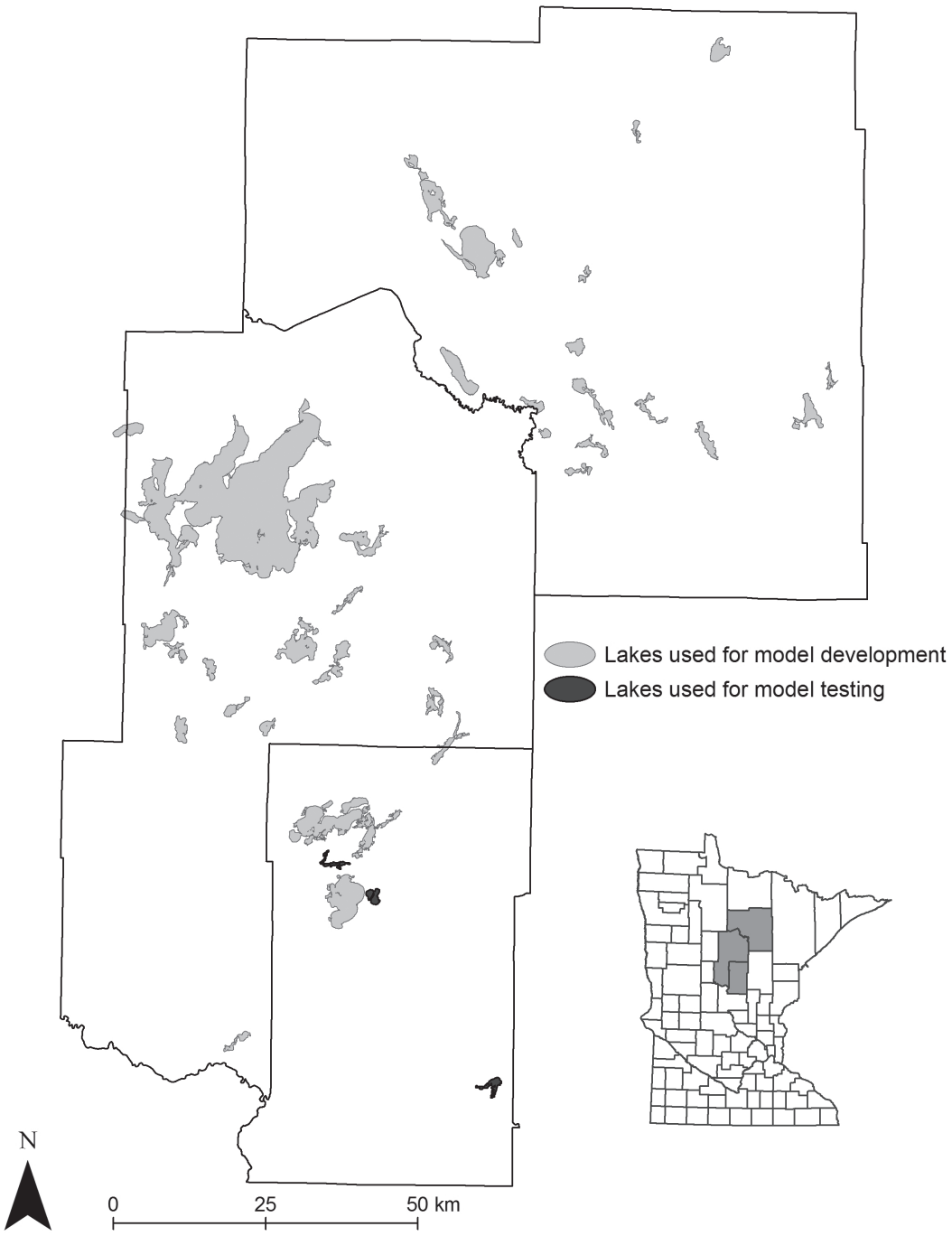


Figure 1. Study area for evaluating probability of nesting by Common Loons on shoreline segments in north-central Minnesota lakes.

vey points throughout the littoral (vegetated) zone on a grid using a geographic information system (GIS). The size of the littoral zone, the shape of the lake, and existing information about the plant community determined the number of points and the grid resolution used (Minnesota Department of Natural Resources 2012b). The maximum distance between survey points ranged from 30 m to 200 m. Sampling was conducted primarily from a boat, and global positioning system (GPS) units were used to navigate to each sample point.

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Table 1. Attributes of the 35 lakes used to develop models predicting the probability of Common Loon nesting on shoreline segments in north-central Minnesota lakes.

Lake	Number of Common Loon Nesting Sites Natural / Platform	Surface Area (ha)	Littoral Area (ha)	Shoreline Length (km)	Nesting Sites per km
Ada	5 / 2	422	172	12	0.58
Ball Club	0 / 0	3,844	442	27	0
Bass	4 / 0	2,715	569	39	0.10
Big Portage	9 / 0	387	365	12	0.75
Birch	3 / 3	511	306	25	0.24
Bowstring	0 / 0	9,528	1,980	55	0
Boy	6 / 0	1,378	812	42	0.14
Coon-Sandwick	3 / 0	594	192	15	0.20
Deep Portage	0 / 0	52	13	3	0
Deer	0 /0	1,855	572	15	0
Grave	2 / 0	523	128	13	0.15
Lawrence	0 / 0	91	35	8	0
Leech	16 / 0	44,279	23,470	369	0.04
Little Boy	5 / 0	565	189	16	0.31
Little Jessie	1 / 0	626	78	8	0.13
Long	7 / 1	375	144	25	0.32
Louise	1 / 0	13	8	2	0.50
Moose	2 / 0	1,274	145	12	0.17
Pelican	7 / 3	3,340	1,582	47	0.21
Pine Mountain	3 / 0	671	298	15	0.20
Pleasant	9 / 2	420	166	14	0.79
Prairie	1 / 0	1,168	358	29	0.03
Rice	3 / 0	852	99	19	0.16
Roosevelt	4 / 0	632	158	30	0.13
Sand Chain	4 / 0	3,904	888	50	0.06
Steamboat	0 / 0	713	215	13	0
Swan	0 / 0	2,467	289	29	0
Sylvan	9 / 1	357	149	18	0.56
Ten Mile	5 / 2	1,878	533	41	0.17
Thunder	11 / 1	533	91	26	0.46
Trout	2 / 0	1,854	170	23	0.09
Wabedo	1 / 0	515	119	18	0.06
Washburn	10 / 7	715	303	31	0.55
Whitefish Reservoir	35 / 12	5,627	2,340	185	0.25
Woman	21 / 3	2,169	790	49	0.49

Using a double-headed, weighted garden rake attached to a rope, surveyors identified and recorded all plant taxa found within an approximate 1-m^2 sample site. Plants were identified to the species level when feasible. This method produced frequency of occurrence (presence/absence) records rather than abundance estimates. Plant taxonomy followed Crow and Hellquist (2000) and nomenclature followed MNTaxa (2011). Voucher specimens were collected for most plant species (Hellquist 1993).

Surveyors mapped floating-leaf and emergent vegetation beds using several techniques. Using a GPS, surveyors delineated bulrush stands (*Schoenoplectus* spp.) by boating or walking around the edge of any monospecific bulrush stand or mixed emergent vegetation stand that included bulrush (Radomski *et al.* 2011). Surveys were generally conducted during mid-day under low to moderate wind conditions (< 20 kmph). Aerial photographs were used to delineate wild rice and floating-leaf vegetation (FSA Aerial Photography 2003/04-2010). Species compositions of stands were verified and stand boundaries were re-delineated in the field. Emergent and floating-leaf plant stand surveys were conducted in August and early September.

Sampling stations for aquatic frog, fish, and bird surveys were established using GIS. The shoreline of each lake was divided into 400-m segments; this distance was the maximum detection distance for most species surveyed. Stations were established at the midpoint of each segment; the same sampling stations were used for all animal surveys. The entire shoreline of each lake was surveyed. Aquatic frog surveys were conducted

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between sunset and 01:00 hr from mid-June to mid-July. If rain showers or breezy conditions substantially affected hearing ability, a survey was stopped. At each station, surveyors listened for several minutes for frog and toad calls. They recorded an estimate of the abundance of frogs and a calling index for both mink (*Lithobates septentrionalis*) and green (*L. clamitans*) frogs. They also recorded the calling intensity of all other audible amphibian species.

Near-shore fish assemblages were sampled by shoreline seining, backpack electrofishing, and trapnets. Seines were 15.2 m long with a bag, and all mesh was 3.2-mm nylon. The seine was set at the shoreline and perpendicular out to the length of the seine or the maximum wading depth, and the offshore end of the seine was arced back to shore. Electrofishing was conducted using a backpack battery-based electrofisher. Surveyors conducted two shocking passes at each station sampled, one near the shoreline and one at a depth of approximately 75-100 cm. Trapnets had a 12.2-m lead approximately 1.1 m deep with two 1.5-m by 0.8-m frames and six 0.76-m hoops with an 18 cm square throat; all mesh was 6.4-mm nylon. The nets were oriented perpendicular to shore with the leader on or near the shore. Nets were set overnight and pulled the next day. After collection, surveyors identified and counted species. In places with excessive vegetation, depth, or extremely soft bottom, surveyors did not conduct seine or trapnet surveys. Between one and three samples were collected at each station, and data were pooled by station for all gear used.

Two methods were used to collect data on lakeshore birds: point counts for all bird species and call-playback surveys targeting marsh birds. Surveys were conducted during the nesting season, defined as the last week of May through the first week of July. Morning point counts for all birds were conducted between sunrise and 22:00 hr at each sample station. Depending on vegetation, water depth, and wind, the survey boat was positioned 20-50 m from shore. Surveyors recorded all birds seen or heard within a 200-m radius of the sample station. Birds seen or heard in the distance or flying overhead were recorded as present at the lake but not associated with a specific sample station. For marsh birds, call-playback survey methodology was modified from Conway (2005). Surveys were conducted in the evening before sunset and focused on survey stations with appropriate (i.e., marsh/wetland) habitat. At each station, surveyors played a tape that included the calls of six marsh birds: Pied-Billed Grebe (*Podilymbus podiceps*), American Bittern (*Botaurus lentiginosus*), Least Bittern (*Ixobrychus exilis*), Yellow Rail *(Coturnicops noveboracensis*), Virginia Rail (*Rallus limicola*), and Sora (*Porzana carolina*). Then they listened for a response. Both survey techniques were dependent on good listening conditions, and surveys were stopped if inclement conditions prevented the ability to hear bird vocalizations.

Common Loon Nest Surveys

Data on both current and historical nesting areas were used in the analysis. Surveyors conducted Common Loon nesting area surveys between 2007 and 2012. Surveys were conducted from the water by boating slowly along the shoreline and searching for incubating loons. Surveys were conducted during May and early June when adults were still incubating eggs. To avoid disturbing incubating loons, surveyors did not approach nests and marked the general nesting area location with a GPS; the exact nest location was described on the survey form and used later in the office to modify nesting area locations after importing into GIS.

Additional nesting data were obtained from volunteers. The volunteer LoonWatcher survey is administered by the Minnesota Department of Natural Resources as a way to obtain information on nesting locations and success in the State. Volunteers are often lake residents, or spend a significant amount of time on a particular lake during the summer. As part of their report, volunteers record the locations of nesting areas on a lake map and identify the nests as either natural nests or active artificial nest platforms. These volunteer data provide some historical perspective on nesting areas (volunteer-documented nesting area locations are available back to 1978). Where available, these data were used to supplement data collected by surveyors. Although locations of nesting areas reported by volunteers were not field-verified by surveyors, locations of nesting areas identified by both surveyors and volunteers generally displayed high geographical agreement.

Each Common Loon nest was associated with a specific 400-m shoreline segment; these segments are referred to as nesting sites. Two nests were more than 100 m from shore; because it was not clear which specific shoreline segment the nest was associated with, these nests were not included in the analysis. In some cases, more than one nest was recorded per shoreline segment. Because each lake was surveyed only once within the nesting season, multiple nesting attempts were not identified. In addition, the nesting area locations represent attempted nesting sites, but do not distinguish between successful and unsuccessful nests. Natural nests and artificial platforms were treated the same in the analyses. A total of 226 shoreline segments were identified as nesting sites.

GIS Analysis

The shoreline of each study lake was buffered by 25 m, 50 m, and 100 m both lakeward and landward. Study windows were created by intersecting these buffers with the 400-m shoreline segments created earlier; therefore, the grids were 25 x 400 m, 50 x 400 m, and 100 x 400 m and reached both into the lake and onto the land. All attributes (Table 2) were analyzed within these grids with the exception of littoral zone slope, which was calculated out to the full extent of the littoral zone. Using data collected during the grid point-intercept aquatic plant survey, aquatic macrophyte richness was calculated by summing the number of taxa within each lakeward study window. Emergent and floating-leaf vegetation were analyzed by calculating the percent of the window covered by either emergent or floating-leaf vegetation. Attributes containing

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Table 2. Description of explanatory variables for predicting the probability of Common Loon nesting on shoreline segments in north-central Minnesota lakes.

Variable	Description
Shoreline Type	Shoreline was classed as mainland or island
Mean Fetch	Mean weighted wind fetch (m)
Mean Littoral Slope	Mean slope (% rise) of the littoral zone
Percent Wetland (100 m)	Percentage of land within 100 x 400-m study window that is wetland
Percent Emergent (100 m)	Percentage of 100 x 400-m lakeward study window that is covered with emergent plants
Percent Floating-Leaf Vegetation (100 m)	Percentage of 100 x 400-m lakeward study window that is covered with floating-leaf vegetation
Aquatic Macrophyte Richness (100 m)	Aquatic macrophyte richness within lakeward 100 x 400-m study window
Shoreline Development (100 m)	Number of shoreline parcels developed within 100 m of the shoreline
Shoreline Development Class (100 m)	1 – mean developed parcel size within 100 m of shoreline < 0.4 ha 2 – mean developed parcel size within 100 m of shoreline > 0.4 and < 0.8 ha 3 – mean developed parcel size within 100 m of shoreline > 0.8 and < 4 ha 4 – mean developed parcel size within 100 m of shoreline > 4 ha 5 – no developed parcels within 100 m of shoreline
Green Frog Presence/Absence	Green frog present = 1, green frog not present = 0
Mink Frog Presence/Absence	Mink frog present = 1, mink frog not present = 0
Frog Class	0 – mink and green frogs not present 1 – only mink frogs present 2 – only green frogs present 3 – mink and green frogs present
Number of Vegetation Dependent Fish Species	Vegetation dependent fish species included least darter (*Etheostoma microperca*), pugnose shiner (*Notropis anogenus*), blackchin shiner (*Notropis heterodon*), blacknose shiner (*Notropis heterolepis*), banded killifish (*Fundulus diaphanus*), bowfin (*Amia calva*), and central mudminnow (*Umbra limi*)
Number of Forest Habitat Bird Species	Number of species listed by the Minnesota Biological Survey with their primary breeding habitat as forest
Number of Fragmented Habitat Bird Species	Number of species listed by the Minnesota Biological Survey with their primary breeding habitat as fragmented habitat
Number of Open and Upland Habitat Bird Species	Number of species listed by the Minnesota Biological Survey with their primary breeding habitat as open or upland habitat
Number of Water Habitat Bird Species	Number of species listed by the Minnesota Biological Survey with their primary breeding habitat as water or shoreline
Number of Wetland Bird Species	Number of species listed by the Minnesota Biological Survey with their primary breeding habitat as wetland
Forest Habitat Bird Species (%)	Proportion of bird species observed that were classified by the Minnesota Biological Survey with their primary breeding habitat as forest
Wetland Habitat Bird Species (%)	Proportion of bird species observed that were classified by the Minnesota Biological Survey with their primary breeding habitat as wetland
Fragmented Habitat Bird Species (%)	Proportion of bird species observed that were classified by the Minnesota Biological Survey with their primary breeding habitat as fragmented habitat
Bird Richness	Number of bird species

animal data were analyzed within the landward 100 x 400 m grid only.

We also assembled or derived GIS data from existing data sources. Littoral slope was derived using lake bathymetry data (Minnesota Department of Natural Resources 2012c). Wind fetch (m) was calculated using the U.S. Geological Survey Wind Fetch Model (Rohweder *et al.* 2008). This model estimates fetch based on waterbody shape and wind direction (maximum 2-min average wind direction; National Oceanic and Atmospheric Administration 2012). We used wind data collected between April and June 2007-2012 to represent the time of the primary nest surveys. Wind fetch was calculated at 10° increments using the model; individual fetch outputs were then multiplied by the percentage of wind observed from its particular direction and summed to calculate a final weighted wind fetch (Rohweder *et al.* 2008). Mean littoral slope and mean weighted wind fetch were calculated for each 400-m study window along the shoreline.

We analyzed shoreline development using county parcel data (collected in 2008; Minnesota Department of Natural Resources 2012c). Developed parcels were defined as those that had a building or dwelling within the parcel boundaries. We summed the number of developed parcels within each 100 x 400-m landward study window; a parcel was counted if any portion of the parcel fell within the specified buffer zone. The mean size of the developed parcels within 100 m of the shoreline was also calculated for each 100 x 400-m landward study window.

Wetland data were obtained from the National Wetlands Inventory (U.S. Fish and Wildlife Service 2012). Wetlands classified as lacustrine or occurring lakeward of the shoreline were excluded from the analysis to avoid identifying the same habitat patches documented during the aquatic vegetation surveys. All other wetland types were included in the analysis. We calculated the percent of the land area covered by wetlands within each 25 x 400-m, 50 x 400-m, and 100 x 400-m study window. All GIS analyses were conducted using ArcMap (Environmental Systems Research Institute 2011).

Statistical Analysis

Contingency analyses (Fisher's exact tests) were conducted to assess the association between nesting presence and frog, fish, and bird species presence. Significant differences between mean fetch by nest presence were tested with the Tukey-Kramer (HSD). Models were developed to predict the probability of nest occurrence within a given shoreline segment using a generalized linear mixed model (GLMM; Pinheiro and Bates 2000). All statistical analyses were conducted using R (R Development Core Team 2012) with the glmmML package (Broström and Holmberg 2012). Models were fit using restricted maximum likelihood except when comparing models of different fixed effect structure with likelihood ratio tests; then models were fit using maximum likelihood. In an effort to incorporate some lake-level attributes into the analysis, lakes were modeled as random effects. The analysis assumed that data from different lakes were statistically independent.

The model development strategy followed the suggestions of Wolfinger and Chang (1995) and Zuur *et al.* (2009). The influence of wetlands, aquatic vegetation, littoral slope, wind fetch, shoreline type (main lake or island), presence-absence of other animals (frogs, fish, and birds), and shoreline development were analyzed as fixed effects. After initial testing to determine significant fixed effects, eight candidate models were developed that incorporated fixed effects for the response variable (probability of a nest present on a given shoreline segment). The changes in the AIC score were used to select a preferred model, and Akaike weights were used to quantify the strength of evidence for alternative models (Burnham and Anderson 2002). To aid interpretation of model coefficients, models were also fitted to explanatory variables on a standard scale by centering and dividing each by two times their standard deviation (Gelman 2008).

Determination of model adequacy consisted of reviews of quantile-quantile plots (Landwehr *et al.* 1984), partial residual plots, and measurements of agreement between nest observations on the modeled lakes (i.e., model residuals, in-sample error, or resubstitution accuracy). We used the area under the curve (AUC) of the receiver operating characteristic (ROC) and Cohen's kappa statistic to evaluate the predictive accuracy of the models (Fielding and Bell 1997; Pearce and Ferrier 2000; Manel *et al.* 2001). The AUC value ranges from a value of 0.5, indicating no discrimination ability, to 1.0 for models with perfect discrimination capability. Youden's index and the maximum value of kappa were used to select a probability threshold for classifying shoreline segments with likely suitable nesting habitat.

The random forest classifier, a type of recursive partition method for constructing classification trees, was used to challenge the analyses of the structured model-building approach (Breiman 2001). We used the randomForest package (Liaw and Wiener 2002). Based on trials to minimize error with Common Loon nesting, the random subset of variables at each node of a tree was set at three with 500-classification tree forests constructed. Given that nesting presence constituted a small fraction of the data, each tree in the forest was constructed from a balanced sample of presences and absences by using all of the shoreline segments with nests present and an equal number of shoreline segments without nests. The measures of variable importance from the random forest calculations, computed by the mean decrease in the Gini index for each variable over all trees in the forest, were compared to the explanatory variables from the GLMMs. Patterns in partial dependence plots, which are plots of the marginal effect of a predictor variable when other variables are held constant, were compared to the *a priori* linear responses of GLMMs (of particular interest was the plot area between the first and tenth deciles as the patterns at both of the margins are influenced by few data). In addition, the out-sample predictive abilities of the random forest approach were tested by using a two-fold random cross-validation where the

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training dataset was created by randomly withholding 25% of the shoreline segments (i.e., random shoreline segments were selected from random lakes). The withheld sampled segments were then used as a test dataset for determining the AUC out-sample accuracy measure.

Finally, we used a small independent lake set to compare the location and number of predicted Common Loon nesting sites to the location and number of nests documented by volunteers. The three independent lakes were located in Crow Wing County and were representative of the lake size and nest abundances found throughout the study area.

RESULTS

Common Loon nesting prevalence on north-central Minnesota lakes was fairly low. Surveys documented 258 nests on 35 lakes, and 226 nesting sites (shoreline segments with nests) were identified within 3,359 shoreline segments (Table 1). Eighty-three percent of the nesting sites had a natural nest present at some time, and many artificial platforms were located near or within areas previously used by naturally nesting Common Loons. Thirty-seven of the nesting sites contained artificial platforms only. The density of known nesting sites on lakes with nests ranged from 0.03 to 0.75 nesting sites per shoreline km (mean = 0.36 nesting sites/km, coefficient of variation = 77%).

Observed nesting sites were not randomly distributed. Significantly more nesting sites were on islands than on mainland shoreline segments (Fisher's exact test, $P = 0.000$); Common Loons were 4.2 times more likely to nest on island shorelines than mainland shorelines. Average mean wind fetch differed significantly between shoreline segments with nests present and those without (Tukey-Kramer HSD test, $P < 0.05$). Nesting sites were also associated with green and mink frog breeding locations (Fisher's exact test, $P = 0.000$ for green frog presence and $P = 0.0001$ for mink frog presence). Common Loons were 4.7 times more likely to nest in shoreline segments with green frogs present and 2.0 times more likely to nest in segments with mink frogs present than in shoreline segments without frogs. There was also a slight association between Common Loon nesting sites and number of vegetation-dependent fish species present at a shoreline segment (Fisher's exact test, $P = 0.049$). Nest presence did not appear to be strongly associated with shoreline development class (Fisher's exact test, $P = 0.1846$).

Initial testing of GLMMs suggested that littoral slope, shoreline development, frog class, and bird community composition might be important variables to predict probable nesting sites. The highest ranked model for lakes where bird surveys were conducted included shoreline type, mean fetch, frog class, bird composition, and mean littoral slope (Table 3). Based on the quantile-quantile plots, the models appear to fit the data with no major departures from model assumptions. The es-

Table 3. Suite of candidate generalized linear mixed models used to understand the relative influence of variables on Common Loon use of shoreline segments for nesting in north-central Minnesota lakes. Fixed effects included mean fetch, shoreline type, mean slope, shoreline development, frog class, and bird community composition (proportion of bird species that were forest habitat species and proportion of bird species that were fragmented habitat species). Akaike Information Criterion (AIC) values were estimated by maximum likelihood. Models are ranked by increasing AIC and decreasing area under the curve of the receiver operating characteristic (AUC) based on in-sample validation. Cohen's kappa statistic summarizes the confusion matrix.

Model	Mean Slope	Shoreline Development	Frog Class	Bird	ΔAIC	AUC	Kappa
All shoreline segments							
1	X	X	X		0	0.83	0.08
2		X	X		1	0.83	0.09
3	X		X		5	0.83	0.07
4	X	X			18	0.82	0.07
Shoreline segments with bird surveys							
A	X		X	X	0	0.83	0.14
B	X	X	X	X	1	0.82	0.13
C		X	X	X	9	0.81	0.13
D	X	X			27	0.79	0.11

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timates of random lake effect were correlated with nest density.

Several GLMMs were of moderate to high quality in prediction of nesting sites. AUC values generally exceeded 0.8, indicating that the models were able to distinguish correctly between nesting presence and absence over 80% of the time after accounting for all variables. Cohen's kappa values indicate fair model performance (Table 3). In order of importance, the probability of nesting on a shoreline segment increased with island shorelines, lower mean fetch, the presence of both aquatic frog species (green and mink frogs), and lower shoreline development (the number of developed shoreline parcels within 100 m of the shoreline) (Table 4). Other important explanatory variables to predict nesting sites included mean littoral slope and bird composition. For Model 1, the predicted probability threshold using Youden's index was 0.1, meaning that values greater than 0.1 may be classified as nesting habitat and values below 0.1 may be considered likely unsuitable habitat in the modeled lakes. This threshold resulted in a model prediction sensitivity, or proportion of correctly predicted positive observations, of about 70%, and it predicted about three times more suitable nesting sites than observed nesting sites (Range = 1.0-5.3 times observed); whereas, based on the maximum value of kappa, Model 1 predicted

Table 4. A summary of the generalized linear mixed models for Common Loon use of shoreline segments for nesting in north-central Minnesota lakes. Models are described in Table 3. Fixed effects and their coefficients are presented. To aid interpretation of model coefficients, models were also fitted to explanatory numeric variables on a standard scale by centering and dividing each by two times their standard deviation (standardized coefficients, SC). Lakes were modeled as random effects.

Source of Variation	Coefficient (SC)	SE	*Z*	*P*
Model 1				
Intercept	0.0724	0.3833	0.189	0.8500
Shoreline Type – Island	0	—	—	—
Shoreline Type – Mainland	-1.7965	0.2761	-6.507	< 0.0001
Mean Fetch	-0.001101 (-1.0594)	0.0003	-4.024	< 0.0001
Mean Slope	-0.0865 (-0.1894)	0.0508	-1.703	0.0886
Shoreline Development	-0.0566 (-0.2713)	0.0187	-2.484	0.0130
Frog Class – 0	0	—	—	—
Frog Class – 1	0.3131	0.3489	0.897	0.3690
Frog Class – 2	0.7747	0.2270	3.414	0.0006
Frog Class – 3	1.3239	0.2901	4.564	< 0.0001
Model 4				
Intercept	-0.1691	0.3300	-0.5126	0.6080
Shoreline Type – Island	0	—	—	—
Shoreline Type – Mainland	-1.5764	0.2136	-7.379	< 0.0001
Mean Fetch	-0.0014 (-1.3897)	0.0002	-5.820	< 0.0001
Mean Slope	-0.0933 (-0.2041)	0.0438	-2.131	0.0331
Shoreline Development	-0.0560 (-0.3262)	0.0168	-3.332	0.0009
Model A				
Intercept	1.8272	0.5678	3.218	0.0013
Shoreline Type – Island	0	—	—	—
Shoreline Type – Mainland	-1.8183	0.3105	-5.856	< 0.0001
Mean Fetch	-0.0013 (-1.2657)	0.0004	-3.525	0.0004
Mean Slope	-0.1026 (-0.2246)	0.0525	-1.953	0.0508
Frog Class – 0	0	—	—	—
Frog Class – 1	0.5405	0.4137	1.306	0.1910
Frog Class – 2	0.8144	0.2358	3.453	0.0006
Frog Class – 3	1.3400	0.3027	4.427	< 0.0001
Proportion of Bird Species that were Forest Habitat Species	-1.8972 (-0.3133)	0.7052	-2.690	0.0071
Proportion of Bird Species that were Fragmented Habitat Species	-2.4105 (-0.4387)	0.6104	-3.949	< 0.0001

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about 1.4 times more suitable nesting sites than observed (Range = 0.1-2.0).

The random forest classifier generated similar results to the GLMMs in that the majority of the top predictor variables identified by both analyses were the same. The top four continuous predictor response variables identified by the random forest classifier for the all shoreline segment dataset were mean fetch, mean littoral slope, shoreline development, and aquatic macrophyte richness. The partial dependence plots showed negative, mostly linear trends in nesting site occurrence for mean fetch, mean littoral slope, and shoreline development for the interdecile range of the data (Fig. 2). The random forest classifier also noted the importance of aquatic macrophyte richness, which was not a significant predictor variable in the GLMMs. The partial dependence plot shows a linear relationship between aquatic macrophyte richness and the logit of predicted probability of nesting occurrence. The random forest classifier also had high accuracy as estimated with out-sample AUC (random forest classifiers on the all shoreline segments and those shoreline segments with bird surveys datasets both had an AUC of 0.8). Maps depicting the probability of Common Loon nesting on shoreline segments in two lakes (selected to represent the range of observed nesting site densities) are shown in Fig. 3.

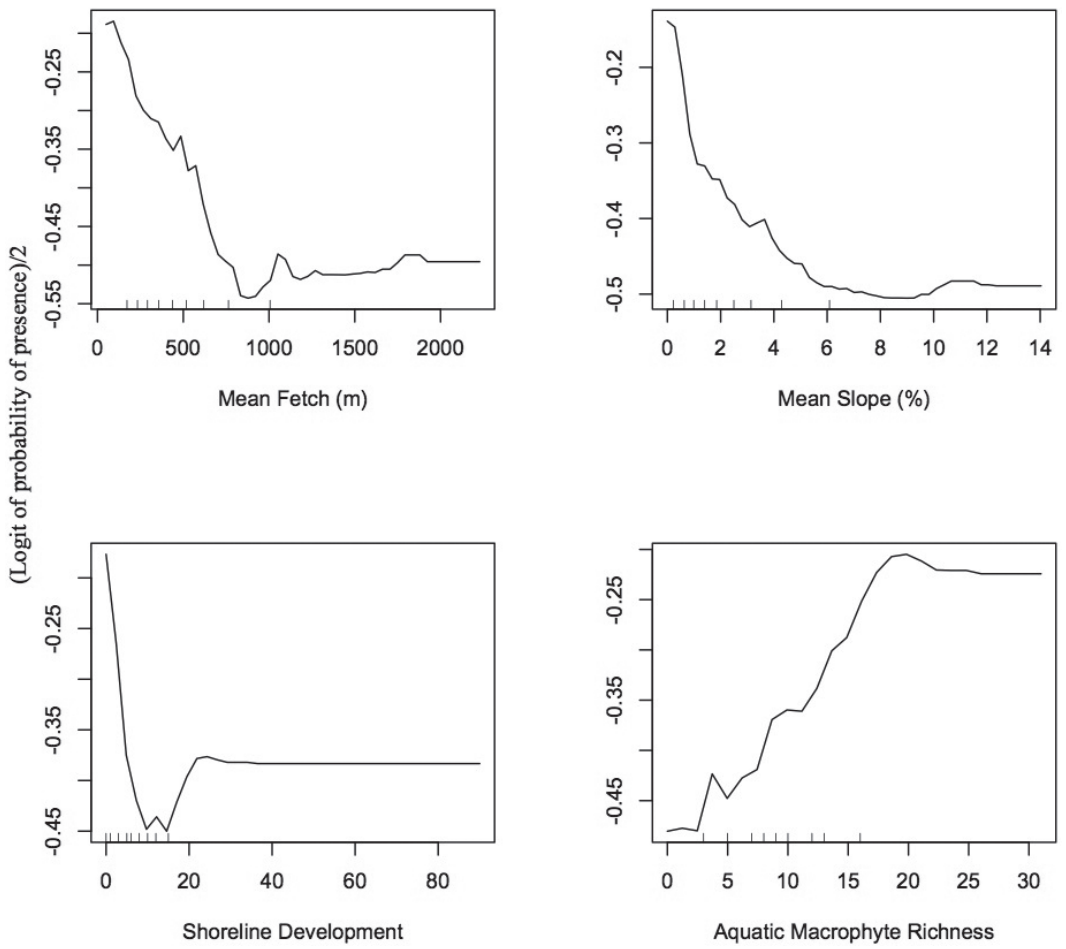


Figure 2. Partial dependence plots for variables of a random forest classifier of Common Loon nesting sites. Small ticks on the x-axis indicate deciles of the variables. The y-axis is one-half the logit of the occurrence probability. See Table 2 for variable descriptions.

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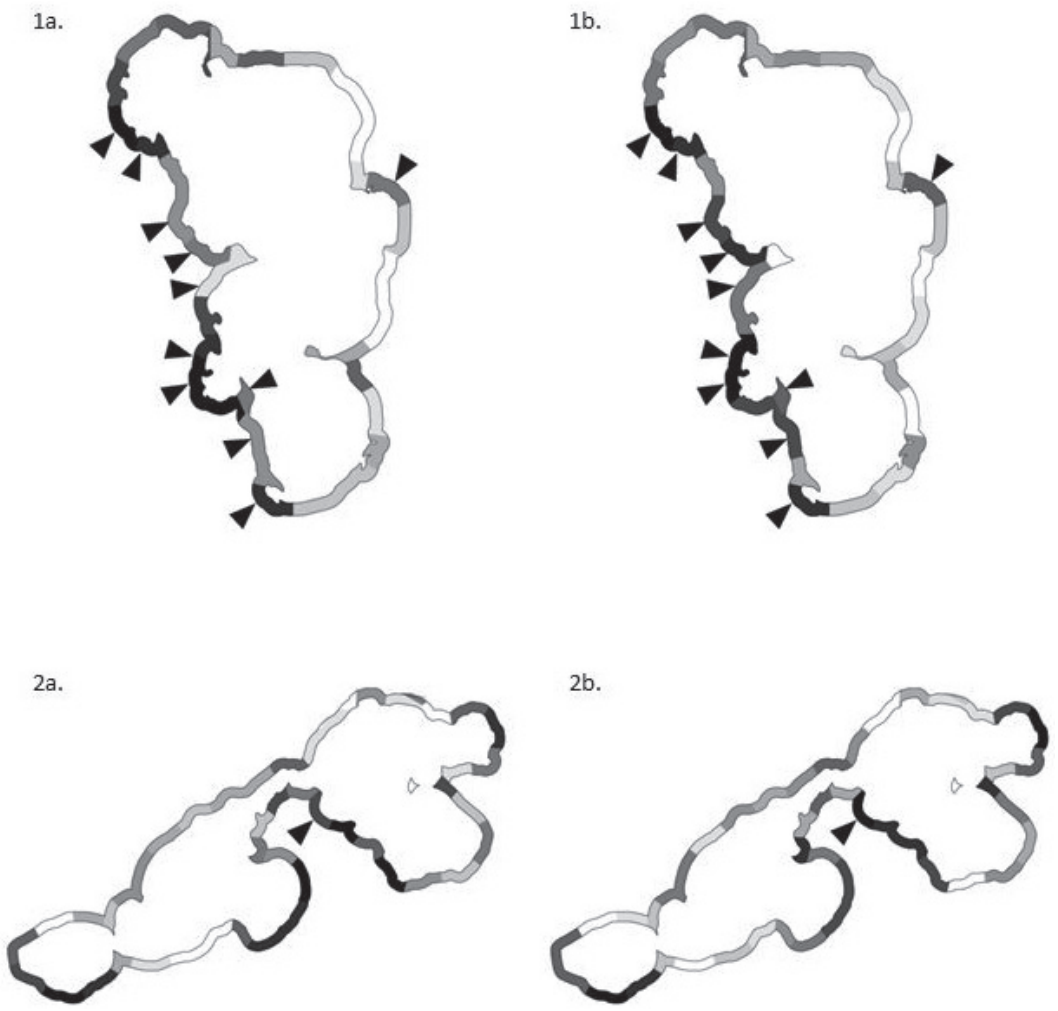


Figure 3. Probability of Common Loon nesting habitat predicted by the generalized linear mixed-effects Model 1 (1a, 2a) and a random forest classifier (1b, 2b) for two Cass County study lakes chosen to represent the range of observed nest densities (high nest density – Pleasant Lake (1a, 1b); low nest density – Wabedo Lake (2a, 2b)). Darker colors indicate increased probability. Locations of observed nests are denoted by triangles.

The location of predicted Common Loon nesting sites on the independent lake set compared favorably to the location of nests observed during volunteer surveys (Fig. 4). Most of the observed nesting locations were concordant with higher probabilities of nesting habitat as predicted by the GLMM.

DISCUSSION

We found strong evidence that Common Loon nesting sites were related to various geomorphological and biological attributes. In particular, we determined that mean fetch was an important variable for predicting nesting sites within lakes. Although several studies have noted that Common Loons often nest in sheltered areas such as bays (Olson and Marshall 1952; Vermeer 1973; McIntyre 1975), this attribute had been previously unquantified. We found that shoreline segments with low mean fetch had higher probabilities of nesting. On larger lakes, in particular, nests are highly susceptible to washout caused by large waves crossing unobstructed expanses of water. Nesting sites protected from wave and wind action are necessary for nesting success (Yonge 1981). Young

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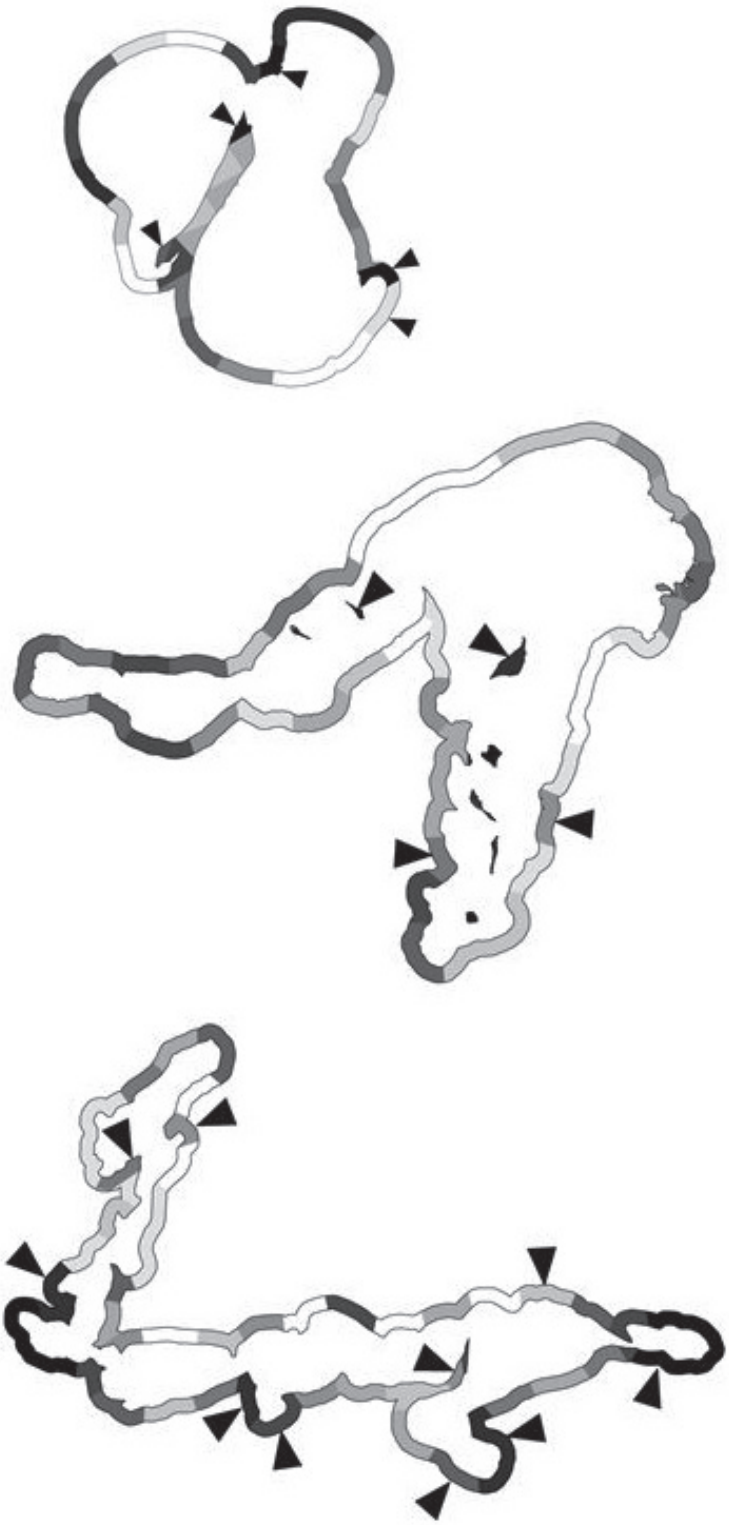


Figure 4. Probability of Common Loon nesting habitat predicted by the generalized linear mixed-effects Model 4 on three independent lakes (top to bottom: Horseshoe, Borden, Ossawinnamakee) in Crow Wing County. Darker colors indicate increased probability. Locations of observed nests are denoted by triangles.

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chicks are also vulnerable to wind and waves, and successful nurseries will need protection from these elements (McIntyre 1983). Bays and other low wind fetch shoreline areas, such as pockets or points, may also experience reduced boat traffic. Finally, Titus and VanDruff (1981) noted that nests were more difficult to find when located within or near shoreline features such as bays or peninsulas, and documented that less visible nests were significantly more successful than nests with greater visibility. In addition, we found that shoreline segments with low littoral slope also had increased nesting probabilities. Although Common Loons sometimes use sites with steep drop-offs to allow them to approach and exit their nests underwater (McIntyre 1988), this is not a consistent predictor of nest location. In an earlier study on the Whitefish Chain of Lakes, Valley (1987) found that many nests were located in shallow areas with a low-sloping lake bottom. Mean fetch and littoral slope likely jointly represent small, shallow bays or coves that provide nesting loons protection from wind and recreational lake use. Our analyses also supported previous work that documented a strong preference for nesting on islands (Olson and Marshall 1952; Vermeer 1973; Yonge 1981). The simplest GLMM we found had mean fetch and shoreline type (island or mainland) as the most important variables (Model 4). Along with littoral slope and shoreline development data, this model along with a random forest classifier provided reasonable means to predict suitable nesting habitat. In more complex models, frog presence, aquatic macrophyte richness, and bird community composition provided some gain in predictive performance.

We also found evidence that nesting site location was negatively related to shoreline development. As the number of developed shoreline parcels within 100 m of the shoreline increased, the chance of nesting within a shoreline segment decreased. This is consistent with the findings of other studies. Found *et al.* (2008) noted that breeding Common Loon presence was negatively related to human activity and disturbed shorelines, and occurrence was positively related to the proportion of forested shoreline. To predict the presence of Common Loons on northern Wisconsin lakes, Newbrey *et al.* (2005) used a multiple logistic model with three variables including the number of houses on the lake; they found that loon presence was positively related to lakes with forested riparian areas and negatively associated with high levels of human habitation. Human activities along shore degrade habitat (Christensen *et al.* 1996; Radomski 2006; Radomski *et al.* 2010) and water quality (Carpenter *et al.* 1998), which may indirectly affect Common Loon abundance. Human activity may also decrease nesting success and increase chick and adult mortality via disturbance, impact with watercraft, and ingestion of lead fishing tackle (Titus and VanDruff 1981; DeSorbo *et al.* 2007; Rattner *et al.* 2008). Common Loons appear to select areas away from intense human activity for nesting, perhaps as a mechanism for increasing nesting success.

Although several studies have attempted to predict Common Loon occurrence on lakes (e.g., Blair 1992; Found *et al.* 2008), there have been few studies predicting nesting habitat across a range of lakes. There are several challenges in predicting nesting habitat. First, it is difficult to predict low probability events, and predictions of these rare events are susceptible to model errors. Given that Common Loon nesting has low prevalence, the selection of threshold criteria on nesting probability predictions to create potential nesting habitat maps can be subjective. Freeman and Moisen (2008) recommend that if the goal is to identify all potential habitats, then use of a threshold that gives the highest possible specificity while meeting a user-defined required sensitivity is most appropriate. We used a threshold that minimized the mean error rate of positive observations and the error rate for negative observations (i.e., Youden's threshold) and a threshold that results in a maximum value of kappa. While these criteria are independent of prevalence, they have a tendency to overpredict rare events.

In addition, because Common Loons are territorial, all suitable nesting habitat will likely not be used in a given year or even

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across a period of years. However, our goal was to identify *potential* nesting sites and not necessarily to determine whether or not a Common Loon is actually going to nest on a given shoreline segment. As shoreline development and lake use change over time, protection of these potential nesting sites may be as important as protecting current nesting sites. As others have recommended, managers should use probability maps to identify potential habitat areas (Lobo *et al.* 2007; Freeman and Moisen 2008). Using probability maps for nesting habitat, including providing advice on artificial platform placement on a range of lakes, may be helpful to lake residents interested in promoting the conservation of Common Loons.

The ability to predict suitable Common Loon nesting areas should lead to the greater protection or restoration of these valuable areas. In addition, it will aid in the identification of potential areas for placement of nesting platforms. Kuhn *et al.* (2011) developed multiscale models to identify explanatory variables at the catchment, riparian, and nesting scale to predict breeding Common Loon presence and nesting locations. They found that road densities were lower and open water areas were greater within a 150-m buffer of the nest (the latter may have been due to Common Loon preference for nesting on islands). These models allowed them to make specific recommendations at the watershed and lake scale. For a single New Hampshire lake, McCarthy and Destefano (2011) found that areas were more likely to be used for nesting as the distance to buildings and boat launching areas increased. Based on our analysis and the work of others, we can provide both general and lake-specific recommendations for identifying and improving nesting habitat. One such recommendation is the preservation of island shorelines, particularly those shoreline segments that are not exposed to wind and waves. In addition, those portions of the mainland shoreline protected from wind and waves with gentle littoral slopes and sustaining frog populations should be identified as valuable habitat and treated as such. Our models also provided probabilities of nesting suitability for specific lakes, and application to an independent lake set showed potential to provide management advice across an even wider range of lakes.

As lakes continue to be developed and human disturbance forces Common Loons to nest in less optimal locations, the development of simple predictive models to identify potential areas for placement of nesting platforms will provide wildlife managers with valuable information for Common Loon conservation. Wildlife managers will also have to address Common Loon territoriality when providing this advice. The appropriate placement of artificial nesting platforms may offset increasing human disturbance and habitat degradation. The use of artificial nesting platforms may also increase nesting success, especially in lakes with fluctuating water levels (Piper *et al.* 2002; DeSorbo *et al.* 2007). Analysis of long-term trends in Common Loon abundance in places like Minnesota may provide evidence of the merits of these mitigation measures. Prediction of nesting or other important habitats for other species may also be applicable to future conservation efforts.

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